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How to quantify the environmental profile of stainless steel

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Background

Stainless steel is intuitively perceived as environmentally friendly. All over the world people associate stainless steel with pots and pans, cutlery, household and restaurant equipment, dairies, hospitals etc. It is well known that stainless steel is used where cleanliness and hygiene are required.

Industry knows stainless steel as corrosion resistant and durable. Even in severe industrial environments the material usually lasts for many years. And when process equipment is finally scrapped, stainless steel is recycled back to stainless steel melting shops, for conversion to new high quality products. Due to the inherent value of stainless steel scrap, a scrap handling industry has been in profitable existence for many years. No taxation or legislation is needed to drive this recycling business.

In summary, this means that stainless steel is a material which truly contributes to sustainable development. This fact is well recognized by the general public and the end users of stainless steel, and it has for many years been taken for granted by the stainless steel industry. However, little has been communicated to the not-already-convinced, and very few efforts have been made to quantify the environmental profile of stainless steel.

The development of peer-reviewed and ISO-standardized methodologies for Life Cycle Inventory (LCI) and Life Cycle Assessment (LCA) now offer new possibilities. The purpose of this paper is to

- describe how to apply LCI data for stainless steel products
- recommend a simple standard for LCA practitioners dealing with stainless steel

Availability of global LCI data for stainless steel

Over recent years, LCI data for various stainless steel products have been developed. Following an initiative taken by the European stainless steel industry, LCI data have also been developed for Japan, Korea, and USA. During the same period of time, LCI data for the most important alloying elements for stainless steel, Cr, Ni and Mo, have been developed by the relevant industry organizations. (Ref 1)

TEAM software from Ecobilan (Ref 2) has been used throughout this work to facilitate the integration of all the data to a set of average, global, cradle-to-gate LCI data for eight different stainless steel products. Table 1 specifies the products and one parameter (article) total primary energy.

Although TEAM software was used for this work, any other established LCI software would probably have given similar results.

Table 1

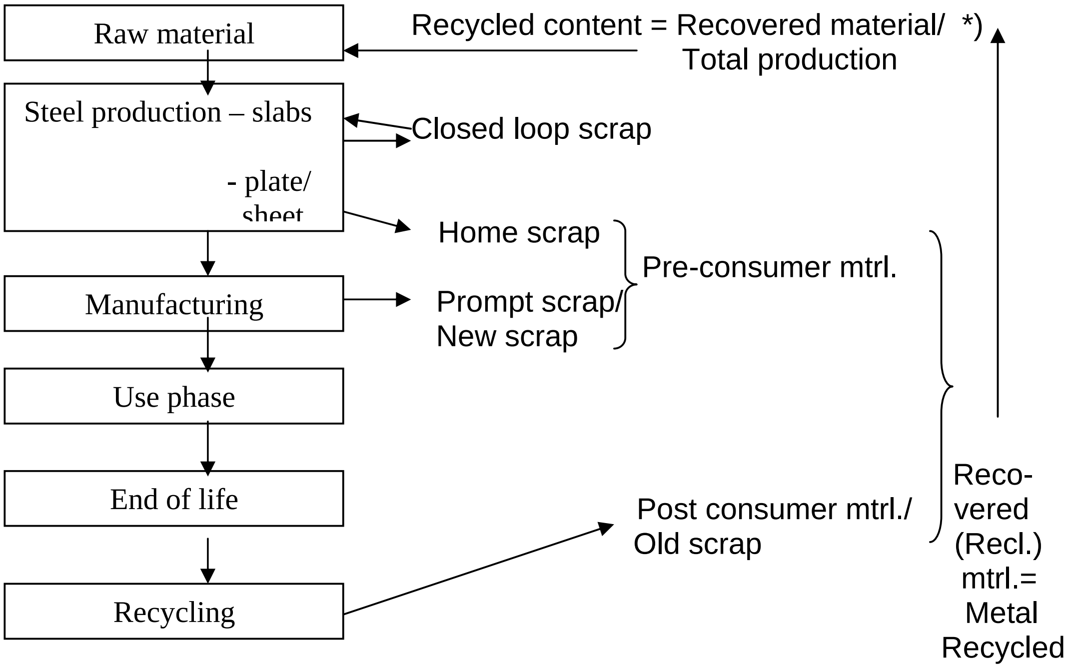
Products	LCI total primary energy (MJ/kg)
304 2B	54.0
304 BA	53.5
304 WHR	42.0
316 2B	62.3
409 2B	47.7
430 2B	52.2
430 BA	52.7
2205 2B	72.1

The existence of this set of LCI data is a first and vital step towards quantification of the environmental profile of stainless steel. In these cradle-to-gate data, the effects of recycling on process parameters are included. However, in order to assess more accurately the profiles of stainless steel products, credits for recycling at end-of-life must also be considered.

Value of recycling for stainless steel

Recycling can be defined in many ways. Figure 1 illustrates the terminology used by ISO. Tables 2 and 3 specify the definitions. The ambition in this work is to follow the ISO definitions.

Figure 1



Recycling ratio (= material recovered as scrap / total scrap from end of life products = EOL collection rate = EOL Recycling Efficiency Rate)

*) = Recycling Input Rate (RIR) = Scrap ratio

Table 2

Name	Formula
Recycled content	= recycled material /total production = RIR
Recycling ratio	= material recovered as scrap / total scrap from end of life products = EOL Recycling Efficiency Rate

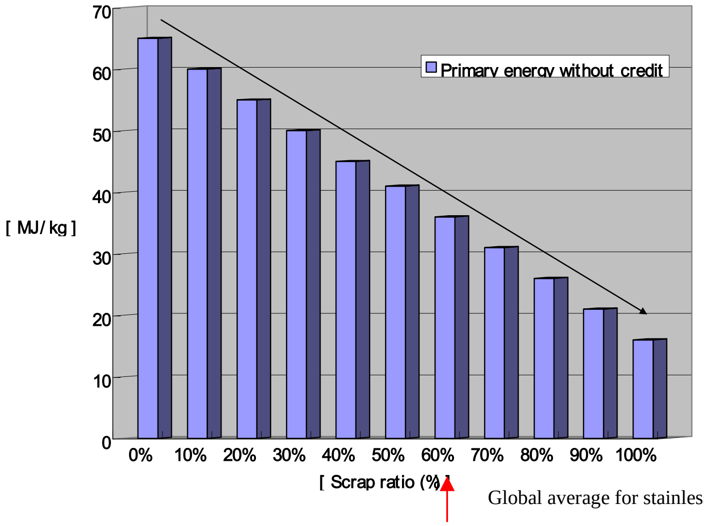
Table 3

ISO Term	ISO Definition
Post-consumer material	Material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose. This includes returns of material from the distribution chain.
Pre-consumer material	Material diverted from the waste stream during the manufacturing process. Excluded is reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it.
Recovered [reclaimed] material	Material that would have otherwise been disposed of as a waste or used for energy recovery, but has instead been collected and recovered [reclaimed] as a

	material input, in lieu of new primary material, for recycling or manufacturing process.
Recycled content	Proportion, by mass, of recycled material in a product . Only pre-consumer and post-consumer materials shall be considered as recycled content.
Recycled material	Material that has been reprocessed from recovered [reclaimed] material by means of a manufacturing process and made into a final product or into a component for incorporation into a product.

From the short perspective, it may be tempting to see a high recycling content as positive and desirable, both from an environmental and a cost point of view. . Figure 2 shows how the total primary energy embodied in stainless steel decreases with increasing recycling content. (TEAM software calculations based on real LCI data)

Figure 2 (304 2B)



Global average for stainless steel: 60%

According to a study made by the International Stainless Steel Forum (ISSF), the global average for recycled content for stainless steel (stainless plus carbon steel scrap) is 60%. (Ref 3)

By increasing the recycled content, the primary energy decreases. However, from a sustainability point of view, recycled content is in fact no relevant concept. One simple reason is that a supply chain with very low material yields will deliver large volumes of pre-consumer material. These large volumes will boost the recycled content, for a supply chain, which, however, due to the low yields, clearly is neither efficient, nor sustainable.

Fundamentally sustainability is a medium- to long term concept. Therefore it is not sufficient to study only what happens at present. Future recycling at end of life must somehow be taken into account.

For each type of stainless steel product , a net must be assessed

> Recycled material released for new use at end of life – (less)
> Recycled material used during manufacturing

If this net is positive, more recycled material will be available for future use. If the net on the other hand is negative, more primary resources will have to be used in the future.

A simple example:

- When pulp & paper plants are modernized (or closed) most redundant stainless steel equipment is easily sold to scrap dealers. Recycling ratios are normally very high, say 95%
- Using the global average, the recycled content during production of stainless steel is 60%
- Hence, for each ton of stainless steel originally produced, 600 kgs were recycled from the global stock of stainless steel scrap.
- At end of life, 950 kgs per ton of scrapped equipment, are recycled to the global stock of stainless steel scrap.
- Consequently, a net of 950 – 600 = 350 kgs of recycled material (scrap) is being saved for future generations to use.

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In order to quantify this net value of recycling, the methodology established for carbon steel by the International Iron and Steel Institute (IISI) (Ref 4.) has been applied.

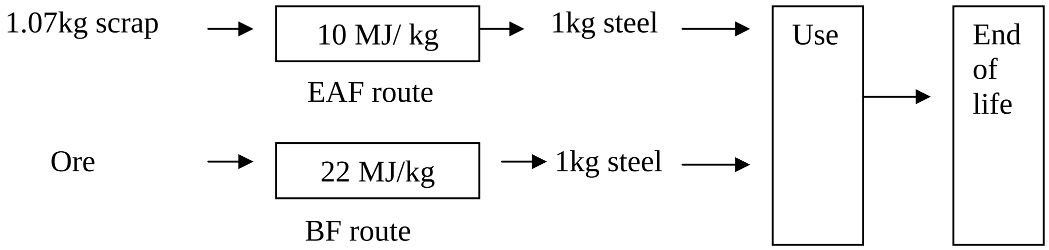
By saving recycled material (scrap) for future use, less stainless steel will need to be produced based on primary raw materials. For each ton of scrap recycled, one ton of primary-raw-materials-based stainless steel is saved. This saving can be quantified:

$$\text{LCI-data}_{(\text{Saving})} = \text{LCI-data}_{(100\%\ \text{primary})} - \text{LCI-data}_{(100\%\ \text{scrap})}$$

where LCI-data stands for total primary energy, carbon dioxide emission, waste etc.

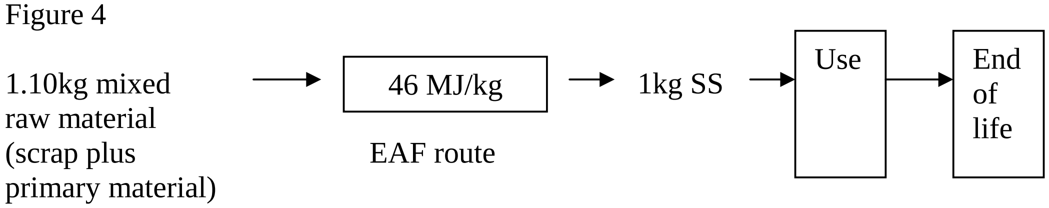
In the case of carbon steel two “extreme” production routes exist, the blast furnace route (100% primary) and the electric arc furnace route (100% scrap). Since LCI data for both routes exist, calculation of the saving is simple. Figure 3 illustrates the carbon steel situation.

Figure 3



For stainless steel a mixed production route, based on primary raw materials plus scrap, is used all over the world. Almost no “extreme” production routes exist. However, the principle is basically the same: one ton of recycled material (scrap) replaces one ton of primary raw material based stainless steel. Figure 4 shows the situation for stainless steel.

Figure 4



As no “extreme” production routes exist for stainless steel, LCI-data$_{\text{(100\% primary)}}$ and LCI-data$_{\text{(100\% scrap}}$) must be calculated. As mentioned above, global LCI data for stainless steel are based on an average 60% scrap + 40% primary raw materials route. In order to calculate 100% scrap and 100% primary data, two steps are required:

1) Proportional scaling up of 60% scrap material and 40% primary material to 100% scrap and primary materials, respectively
2) Adjustment of scrap and primary materials input in order to balance final product chemical composition requirements

In the absence of “extreme” production route data, these calculations are based on the assumption, that the energy requirements in the processes are the same for the two extreme cases.

Proportional scaling up to 100% scrap is illustrated below. 100% primary data can be calculated in a similar way

Original factory data

Input kg for 1 kg product

Scrap
304: x1
316: x2
409: x3
430: x4
external:x5
subtotal: X
Primary material
Carbon steel scrap: y1
Iron (pure): y2
Ni(electrolytic): y3
Ni(briquette): y4
H/C FeCr: y5
L/C FeCr: y6
FeNi: y7
subtotal: Y
Grand total: X+Y

➡

Proportional scaling up
(100% scrap case)

304: x1* (X+Y)/X
316: x2 * (X+Y)/X
409: x3 * (X+Y)/X
430: x4 * (X+Y)/X external:x5 * (X+Y)/X
Grand total: X+Y

Different methods of adjusting the input, to match final product chemical composition, have been tested. In the case of AISI 304, scaling up, as outlined above, gives virtually the same results as an input of 100% AISI 304 scrap. For simplicity, the latter has been used.

For the 100% primary route, the following types of raw material have been used,

- Carbon steel scrap (Fe: 100%)
- H/C FeCr (Cr: 52%)
- H/C FeNi (Ni: 32%)

and the volumes have been adjusted in order to meet the AISI 304 specification (Cr=18%, Ni=8,3%)

Table 4 illustrates the results of these calculations.

Table 4

304 2B	100% primary case	100% recycled case
Energy (MJ/kg)	73	23
CO2 (kg/kg)	7.1	3.9
Waste (kg/kg)	2.8	0.6

Methodology for allocation of credits for recycling

Two methods for allocation of recycling credits have been developed and tested for carbon steel: single cycle recycling and multi cycle recycling (Ref 4-6). Both methods have now been tested for stainless steel.

Definitions and equations:

a) Single cycle equation (often referred to as the “IISI Appendix 5”equation)

$$\underline{X = \mathrm{Xprimary} + (\mathrm{Xrecycled} - \mathrm{Xprimary}) \times \mathrm{RR} \times Y}$$

where

X = LCI data with recycling credit
Xprimary = X in the case of production based on 100% virgin material
Xrecycled = X in the case of production based on 100% recycled scrap
RR = Recycling ratio (= material recovered as scrap / total scrap from end of life products, or Metal recycled (from EOL scrap)/Metal available for recycling (EOL scrap))
Y = Yield (=Useful recycled product / Input of scrap as raw material)

b) Multi cycle equation:

$$\underline{X = (\mathrm{Xprimary} - \mathrm{Xrecycled})[(1-r) / (1-r^{n})] + \mathrm{Xrecycled}}$$

where

X is defined above
r = Yield of useful recycled product < 1
n= Number of life cycle stage (primary: n=1)

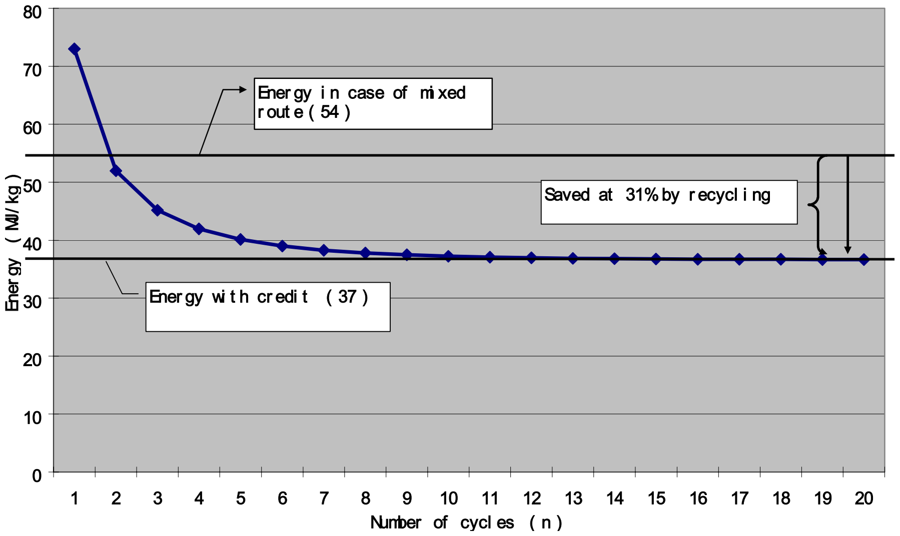
When n approaches ∞,

$$\underline{X = \mathrm{Xprimary} + r(\mathrm{Xrecycled} - \mathrm{Xprimary})}$$

and the two equations become identical, as $r = RR \mathrm{x} Y$

Figure 5 demonstrates the results of the two methods for stainless steel (304 2B).

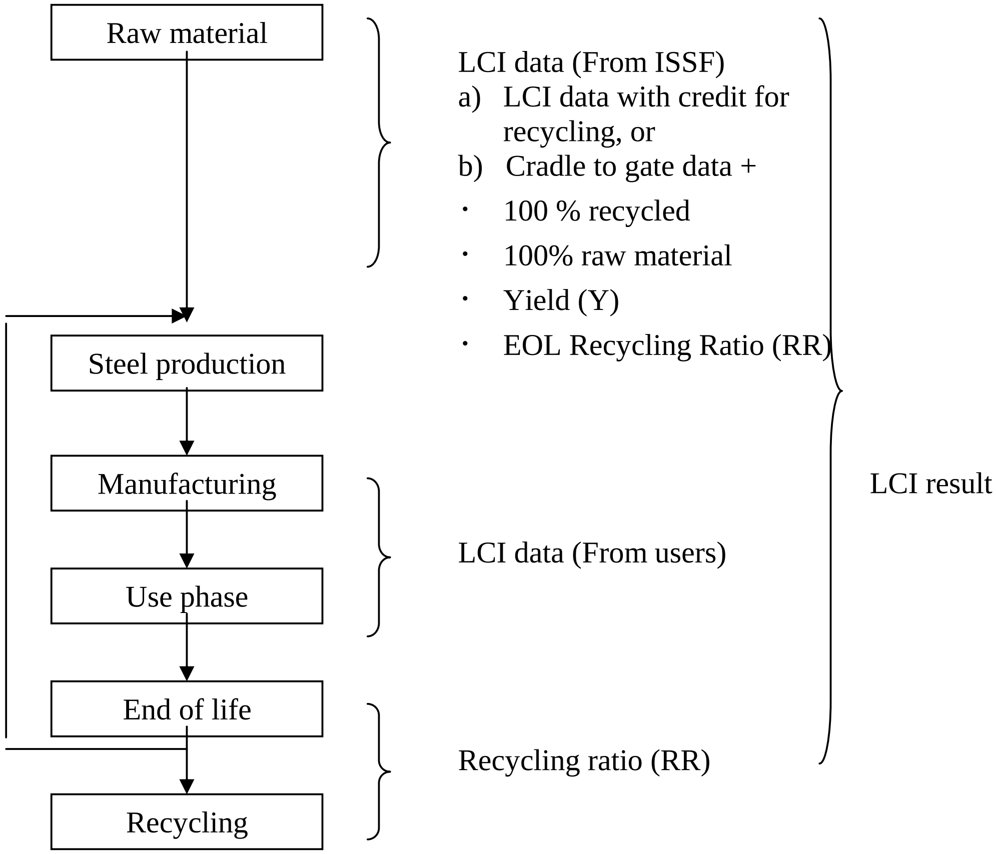
Figure 5



Template for LCA practitioners dealing with stainless steel products

Figure 6 is a simplified template for stainless steel. The template is recommended for application when stainless steel LCI data are used to assess the impact of stainless steel on the environment. ISSF has access to cradle to gate LCI data for eight stainless steel products (Table 1) and is building a database for Recycling Ratios for different stainless steel product sectors.

Figure 6



LCI result = LCI data with credit plus LCI data from Manufacturing and Use

By visiting the ISSF website (www.worldstainless.org), LCA practitioners can initiate individual dialogues regarding their respective projects. At present (autumn 2005) some manual calculations are required to produce LCI data with recycling credits. In the future, data with credits included will be delivered automatically, unless otherwise specified.

The LCA practitioners are themselves assumed to have access to LCI data for the product manufacturing and use phases**.**

Simplified case studies

By applying the template to a stainless steel roof, its use for assessing energy savings and reduction of CO2 emissions can be demonstrated.

Roof details:

Steel grade: 304 2B
Thickness: 0.5mm
Area studied: 0.5mm×1m×1m

Weight of area studied:

Density of Stainless steel: 8.0
Weight of roofing: 4kg/m2

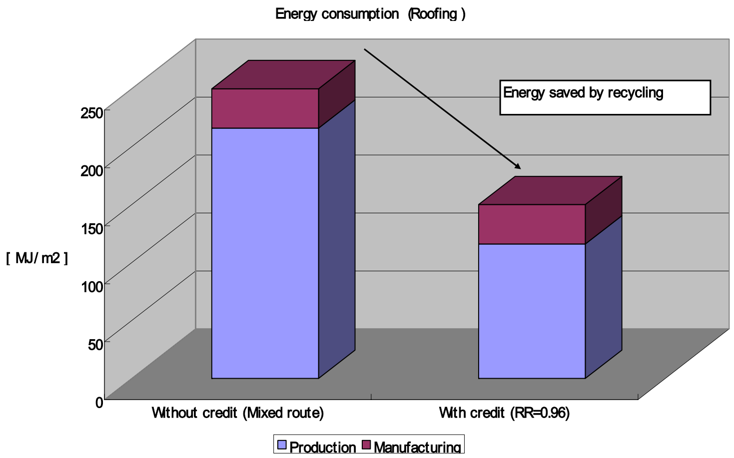
a) Energy saving

Template:

Raw material and steel production:	Primary energy + 100% recycled: 23 MJ/kg (92 MJ/m2) + 100% raw material: 73 MJ/kg (292 MJ/m2) + Mixed route: 54 MJ/kg (216 MJ/m2) Yield: 1/1.10 Recycling Ratio: 0.96 Primary energy with recycling credit: 29 MJ/kg (116 MJ/m2) ("IISI Appendix 5 equation")
LCI data from manufacturing:	Primary energy: 8.5 MJ/kg (34MJ/m2) (Ref 4)
LCI data for use phase:	Primary energy: 0 MJ/kg
LCI result: stainless steel roof:	Total primary energy: 150 MJ/m2

Figure 7 illustrates the results and the significant energy saving achieved by recycling of stainless steel.

Figure 7



b) Reduction of CO2 emissions

Template:

Raw material and steel production:	CO2 emissions + 100% recycled: 3.9 kg/kg (15.6 kg/m2) + 100% raw material: 7.1 kg/kg (28.4 kg/m2) + Mixed route: 6.1 kg/kg (24.4 kg/m2) Yield: 1/1.10 Recycling Ratio: 0.96 CO2 emissions with recycling credit: 4.3 kg/kg (17.2 kg/m2) ("IISI Appendix 5 equation")
LCI data from manufacturing:	CO2 emissions: 0.4 kg/kg (1.6 kg/m2) (Ref 4)
LCI data for use phase:	CO2 emissions: 0
LCI result: Stainless steel roof:	Total CO2 emissions: 18.8 kg/m2

Figure 8 illustrates that by recycling stainless steel roofs, a reduction of as much as 28% of CO2 emissions can be achieved.

Figure 8

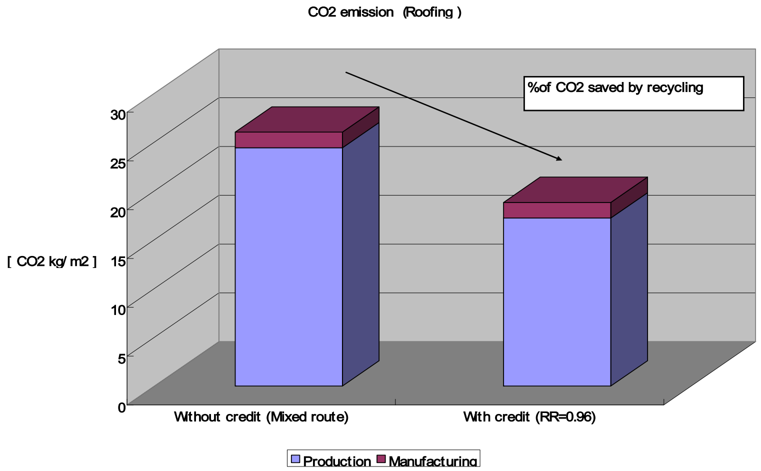


Table 5 demonstrates the sensitivity of the parameters in the "IISI Appendix 5" equation, i.e. Xprimary, Xrecycled, RR and Y. As can be seen, the total primary energy is affected most by ±10% variations of the parameters Recycling Ratio and Yield.

Table 5

Sensitivity – effects of ±10%, parameter variations

Standard condition: Xp=93, Xr=23, RR=0.8, Y=1/1.07
Equation: "IISI Appendix 5"

Parameter	Effect on Energy	% change versus standard
Xprimary	34-37	±3-6%
Xrecycled	34-37	±3-6%
RR	32-39	±8-11%
Y	31-39	±8-14%

Energy: MJ/kg

Figures 9 and 10 illustrate the strong impact of an improved Recycling Ratio, at end-of-life, on energy saving and CO2 emissions.

Figure 9

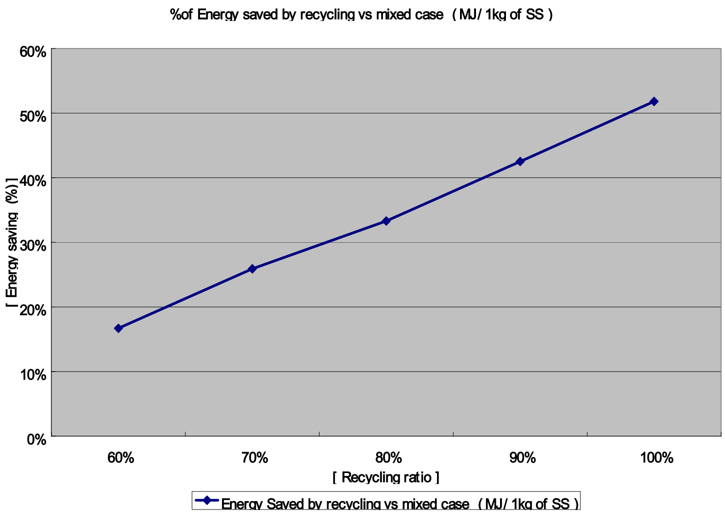
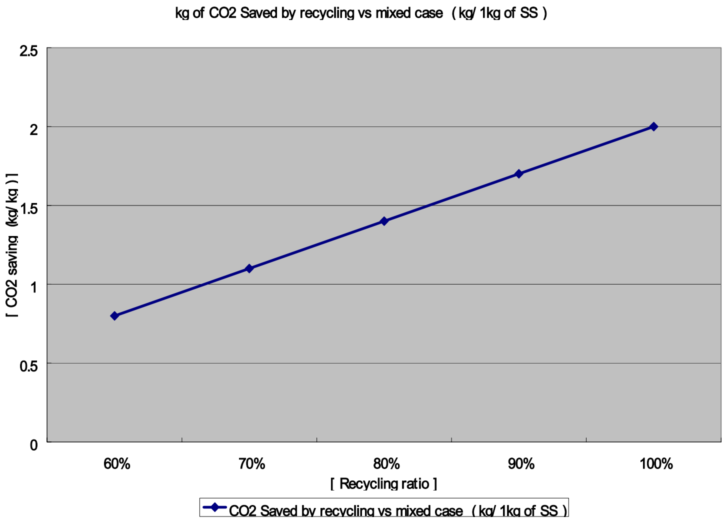


Figure 10



Discussion

There are two basic areas of use for LCI data. One is for benchmarking of manufacturing processes in terms of potential impacts on health & environment. A second, and larger area, is about the potential impact on health & environment of products, over their total life cycles.

In the former case, relative comparisons of processes are made, and it is not necessary to include credits for recycling at end of life. However, when LCI data are to be used for products, e.g. for Environmental /Product Declarations (EPD) or Eco Design, it is imperative to include all recycling effects.

This paper demonstrates that the well established methodology developed for carbon steel can also be used for stainless steel. Although outside of the scope for this paper, it has been demonstrated that the same methodology successfully can be applied for other metals. It is strongly recommended that LCA practitioners use one methodology, such as the one demonstrated in this paper, when assessing different material options.

Please note that this paper presents a simplified and easy-to-use model. In more sophisticated metal analyses the differences in Cr- and Ni contents between different stainless steel grades must be considered. However, as the standard 304/316 and 409/430 types dominate the market, and can be seen as two separate, almost closed loop systems, the error caused by this simplification is negligible for practical purposes.

Another simplification is that some 10% of carbon steel scrap is used in the average global production of stainless steel, and is treated here as stainless steel scrap. This carbon steel scrap, to a certain extent, also replaces primary raw material based stainless steel. Hence, even this simplification can be seen as reasonable.

Finally, as mentioned above, the estimations of LCI data for 100% primary and 100% scrap cases, are based on the simplification, that process parameters are not significantly affected by changes in raw material mix. This is an area where more research is recommended.

Conclusions

- A methodology for inclusion of recycling credits in LCI data for stainless steel has been developed
- The methodology is consistent with the ISO standard conforming methodology used by IISI for carbon steel
- The same methodology can successfully be applied for other materials
- It has been demonstrated that recycled content is not a good argument for sustainability
- A template has been recommended for LCA practitioners dealing with stainless steel (e.g. regarding Environmental Product Declarations or Eco Design)
- The environmental profile of stainless steel has been quantified in a few simplified cases. High levels of recycling, well established for many stainless steel products, reduce energy consumption and save CO_2 emissions in the range of 30%, compared with no recycling.
- The Recycling Ratio at end of life is a very significant factor when assessing the environmental profile of a metal like stainless steel.
- More real industry data regarding End-Of-Life recycling ratios are needed
- The work indicates quantitatively that stainless steel is a highly sustainable material.

References

1 International organizations

- NI = Nickel Institute (www.nickelinstitute.org/index.cfm/ci_id/317.htm)
- ICDA = International Chromium Development Association (www.chromium-asoc.com)
- IMOA = International Molybdenum Association (www.imoa.org.uk)

2 Ecobilan（http://www.ecobalance.com/uk_lca.php）

3 ISSF website (https://extranet.worldstainless.org/Worldstainless/Portal/Categories/LCI_LCA/)

4 IISI website and publication

- Web：https://extranet.worldsteel.org/Worldsteel/Portal/Categories/LCA%20(Life%20Cycle%20Assessment)/
- Publication：International Iron and Steel Institute (2002) *Appendix 5 "Application of the IISI LCI data to Recycling Scenarios* ", Life cycle inventory methodology report 2002

5. Amato A, Brimacombe L, and Howard N (1996) *Development of quantitative methodology for assessing embodied energy of recyclable and reusable materials/products.* Ironmaking and Steelmaking, 23 (3) 235-241

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Acknowledgements

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