Impact of the Secondary Steel Circular Economy Model on Resource Use and the Environmental Impact of Steel Production in Chile

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Abstract. The circular economy is a closed loop minimizing materials, energy and environmental deterioration without restricting economic growth or social and technical progress. Steel is considered an emblematic case of the circular economy given its high capacity for recycling and reutilization, in addition to its reparability, extending its useful life. Thus, the aim of this study was to evaluate the impact of secondary steel production on resource extraction and the environmental impact on steel production in Chile, as a circular economy model. The assessment was carried out through Material Flow Analysis (MFA) and Life Cycle assessment (LCA) methodologies. The MFA considered national steel supply for 2015 from the EW-MFA framework, while the LCA was done using primary data from the secondary steel industry in Chile for the same period. Primary steel flows in Chile enter the system through imports (62%), followed by domestic production of steel rods and profiles (27%). Residual steel flow for 2015 was established at 1 Mt, which would allow secondary steel production to grow up to 78%. This would allow for domestic extraction used (DEU) to be reduced and for efficiency in the production of steel rods and profiles to be improved. In parallel, issues such as abiotic depletion, eutrophication, acidification and climate change demonstrate decreases of 59%, 50%, 46% y 45% respectively. Based on these results, it can be concluded that increased secondary steel production in Chile generates environmental benefits, raises efficiency and reduces domestic resource demand, significantly improving environmental performance in the industry.

1. Introduction
The relationship between industry and the environment is crucial to the performance of industrial business. Environmental impacts have gradually increased pressure on industrial businesses [1], accelerating the transition towards more sustainable social and technological systems [2]. Environmental problems such as biodiversity loss, water, air and soil pollution, resource depletion and excessive land use are increasingly endangering support for life on Earth [2]. These environmental problems threaten the integrity of natural ecosystems as well as economic stability [3], creating a
growing scientific interest in the circular economy model (CE) with a view to providing a better alternative to the economic development model of “take, make and waste” [4].

The circular economy is a closed loop that minimizes materials, energy and environmental degradation without limiting economic growth or social and technological progress [1]. Within this framework, the chemical industry has achieved energy reductions of between 6 and 11%, mainly by closing various cycles at different stages in the life cycle of a product [5]. Following the circular economy model, the steel industry has succeeded in reducing greenhouse gas emissions by 40% and energy consumption by 20% [6].

Various conceptual frameworks explain why the CE is the most efficient model for use of materials, given that its goal is to minimize resource extraction and increase product value from cradle to grave. However, there is no unified methodology with regard to how to implement and evaluate it. The European Environment Agency identifies the main points that should be considered in CE policy, among which are: input/product analysis, eco-design and life cycle assessment [7].

In light of the lack of specific methodologies to evaluate the CE, Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) are adequate tools for its evaluation. These methodologies are widely used to assess and manage environmental impact and resource use [8]. The latter use could help to assess environmental impact and efficiency of resource use in a way which would promote a CE paradigm [9].

Following the ISO 14044 standard, the LCA quantifies potential environmental aspects and impacts throughout the life cycle of a product from the acquisition of the primary materials, through production, use, final treatment, recycling and final disposal [10]. On the other hand, the MFA is the main tool used in industrial ecology to quantify and calculate the metabolism of materials and to identify resource availability [11].

Diverse LCA and MFA studies of the steel industry have revealed the significance of the industry regarding its consumption of materials and environmental impacts associated with the life cycle of its products. Approximately 15% of energy consumed in China is caused by the steel industry [12]. On a global level, steel production is responsible for 9% of carbon dioxide emissions of the energy and industrial sectors, and specifically for the latter industry 25% of all emissions [13].

Metals are considered essential resources in modern society and their efficient use is key to sustainable development [14]. Hence metals are particularly attractive given their capacity to be recycled almost indefinitely [15]. On a global scale, 75% of steel production comes from iron as a primary resource, while the remaining 25% is derived from scrap metal, which accounts for 100% of secondary steel production.

Scrap metal is the only alternative to iron for large-scale steel production. Among its advantages are its high energy efficiency and easy recycling. Use of scrap metal in steel production can reduce energy consumption by 40% and SO₂, MP and CO₂ emissions by 55%, 89% and 60%, respectively [16].

Several studies on secondary steel have focused on life cycle [17] [18] and materials flow [19]. The LCA studies have shown lesser impact throughout the life cycle of secondary steel production [18], while studies on materials flow demonstrate a reduction in the use of resources at industrial, domestic [19], and continental levels [15]. Although both methodologies have been applied together in industrial ecology studies [8], no study has assessed the influence of secondary steel production on environmental impact and resource extraction at the national level.

Therefore, the aim of this study was to assess secondary steel industry effects on environmental impact and its resource use intensity in Chile.

2. Methodology
The methodology proposed by this study consists of two steps: first, to analyse steel materials flow, to determine the amount of steel available in Chile in 2015 and to obtain levels of extraction, consumption and resource intensity. Second, to perform a LCA to assess the environmental impact of secondary steel production and its effects on different production areas in Chile.

The MFA was carried out to estimate steels flows for 2015. Data for imports and exports were obtained through foreign trade indicators, the Central Bank of Chile and verified through National
Customs Service statistics for Chile. The years used for data collection were established on the basis of the useful life for each product, expressed as a product unit and mass to be standardized subsequently through conversion factors. Domestic production was obtained via the National Geology and Mining Service of Chile.

2.1. Life cycle assessment
The LCA methodology was carried out in accordance with standard ISO 14040/44 [10], requirements. The product system took into consideration all processing units for reinforcing bars and steel profiles throughout their life cycle, in a single focus from cradle to grave. Given that the impact of rods and profiles while in use is considered of little significance [20], this phase was left beyond the scope of the system.

Complying with the study objectives, two functional units (FU) were established: the first at the (secondary) steel production level and the second at the domestic level. At production level, the FU was 1 t of secondary steel products, while the domestic level FU included primary and secondary steel produced in Chile in 2015.

All the input and output flows related to materials and energy were obtained from production sites. Data for the inventory were collected directly from secondary steel production plants in Chile. The energy mix of the Chilean Central Interconnected System was modelled in SimaPro to adapt international databases and processes to local conditions as carried out [21].

The impact assessment was performed using software SimaPro 8.3 by selecting the CML-IA baseline in accordance with product category rules (PCR 2012-01 v.2.01). The impact categories chosen were global warming, ozone layer depletion, acidification, eutrophication, photochemical ozone, abiotic resource depletion (elements) and abiotic resource depletion (fossil fuels). SimaPro version 8.3 software was used to analyse the data.

3. Results and discussion

3.1. Material flow analysis
Domestic production of rods and profiles accounts for 27% of steel supply nationally while the main source comes from imports at 62% (Figure 1).

![Figure 1](image)

Figure 1. Model results of Chile's steel flow analysis during 2015 (Mt)

In 2015, domestic steel consumption of reached 3.23 Mt. In this period, 1 Mt (Figure 1) of residual steel was produced, 44% of which was used in the secondary industry while the remaining 56% went to final disposal. Domestic demand remained constant and supply of secondary steel fluctuated; domestic extraction used (DEU) was analysed as well as production efficiency. As seen in Figure 2, the DEU decreases in response to the increase in secondary steel availability nationally. Reductions of up to 42%
of resource extraction can be achieved when secondary steel represents 60% of domestic production. Conversely, efficiency increases by up to 78% in response to secondary steel availability, though this increase exceeds that obtainable by DEU.

![Figure 2. Effects of variation in resource extraction and efficiency of steel production in Chile](image)

### Table 1. Environmental impacts of 1 tonne of secondary steel produced in Chile and other countries

| Impact category                        | Unit     | Secondary steel of this study | Secondary steel produced in United Kingdom [22] | Secondary steel produced in Italy [23] | Primary steel produced in Chile [24] |
|----------------------------------------|----------|-------------------------------|-----------------------------------------------|---------------------------------------|--------------------------------------|
| Global Warming (GWP 100a)              | kg CO₂ eq| 866                           | 890                                           | 796                                   | 2,560                                |
| Ozone Layer Depletion                  | kg CFC-11 eq | 8.67 E-05                     | 8.39E-05                                      | 1.00E-05                             | 1.38 E-04                            |
| Acidification                          | kg SO₂ eq | 4.1                           | 3.94                                          | 1.02                                 | 12                                   |
| Eutrophication                         | kg PO₄³⁻ eq | 1.0                           | 0.377                                         | 0.36                                 | 3.8                                  |
| Photochemical Oxidation                | kg C₂H₄ eq | 1.2                           | 0.2639                                        | 0.59                                 | 36.4                                 |
| Abiotic Depletion (elements)           | kg Sb eq  | 6.01 E-04                     | 1.50E-04                                      | 0.01                                 | 3.16 E-03                            |
3.3. Environmental impacts of domestic steel bar and profile production
The environmental impacts caused by domestic production (Table 1) were obtained with reference to domestic production of primary and secondary steel for 2015, totalling 943,275 t (FU) for the year. Since primary steel production represents about 80% of environmental impacts from domestic steel production, these impacts at a national level decrease significantly with a rise in secondary steel production supply (Figure 3). Indeed, impacts were discovered to dip by up to 69% in the photochemical oxidation category when secondary steel production was increased by up to 78% to meet domestic demand. This trend is observed in the categories of abiotic resource depletion (elements), eutrophication and acidification, by 59%, 50% and 46%, respectively.

| Abiotic Depletion (fossil fuels) | MJ  | 13,110 | 13,664 | 10,703 | 36,900 |
|---------------------------------|-----|--------|--------|--------|--------|

![Figure 3. Variation of environmental impacts of steel production in Chile](image)

3.4. The circular economy
The circular economy is a closed loop that minimizes material, energy and environmental degradation without restricting economic growth or social and technological progress [1]. Through the paradigm of this model, the secondary steel industry achieves the goals of the circular economy through lower resource extraction and environmental impact statistics than those of the primary industry. This is due to the use of raw materials being only 31% in secondary production, as opposed to that of primary production. Energy is no exception as it also represents 93% less consumption per t/product. These benefits coupled with the fact that the secondary industry uses scrap metal and ceases to mine a resource such as iron ore, allow the industry to achieve higher efficiency scores throughout the product life cycle. The economic aspects of the model were not evaluated by this study, given that the model already exists in the market and produces revenue, thus proving its profitability.

4. Conclusions
Tools for life cycle assessment and material flow facilitate measuring both the environmental impacts and the use of resources by the steel industry in Chile within a circular economy framework. The life cycle assessment methodology allows for the quantification of environmental impacts and thus demonstrates that they are lower for the secondary industry, primarily due to limited use of raw materials and energy. Energy is a critical factor in this process. To achieve the goals proposed by Chile to attain...
an energy grid using 70% renewables for 2050, decreases are expected in impact categories such as global warming, ozone layer depletion and photochemical oxidation, among others.

Material flow analysis facilitates defining where the largest flows of steel are in Chile, how much steel is in the stock phase and how much steel was available for 2015. In this model the industry is estimated to be able to grow to satisfy 78% of domestic demand, thus reducing environmental impact of the process and use of resources, increasing efficiency in domestic steel production.

As the secondary steel industry demonstrates greater efficiencies in its process, DEU decreases when secondary steel production is promoted.

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