DISCUSSION ON THE USE OF STAINLESS STEEL IN CONSTRUCTIONS IN VIEW OF SUSTAINABILITY

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Recent years have seen an increase in the use of stainless steel in buildings, mainly owing to its corrosion properties and therefore long service life. Among stainless steels, ferritic and lean duplex grades are characterized by low nickel content resulting in a more cost-stable and economic material compared to austenitic stainless steels. These grades have comparable (or even higher) strength than carbon steel and good corrosion resistance at lower cost. That is why, lately, they have been more often used in structural components. In this paper, attention is firstly paid to the advantages associated with the use of stainless steel in recent construction projects in view of sustainability. Secondly, life cycle analysis and the background of the new European standard EN 15804 are introduced, including Module D, which allows credits to be taken now for the eventual reuse or recycling of material in the future, at the end-of-life stage. Life cycle inventories of stainless steel products (cold-rolled coils and quarto plate) are presented. Depending on the fraction of material recovered at the end of the lifespan, two potential impacts (Primary Energy Demand and Global Warming Potential) are presented for four grades: 1.4301 (AISI 304) and 1.4401 (AISI 316) austenitic grades, 1.4016 (AISI 430) ferritic grade and 1.4462 (AISI 2205) duplex grade. The influence of module D is underlined.

STAINLESS STEEL IN CONSTRUCTION APPLICATIONS

General introduction

Stainless steel is a steel alloy that contains more than 10.5% of chromium. The chromium content in mass ranges from 10.5% to 30% [1]. Depending on the microstructure, four families of stainless steel exist: martensitic, ferritic, austenitic and austeno-ferritic (duplex) stainless steels.

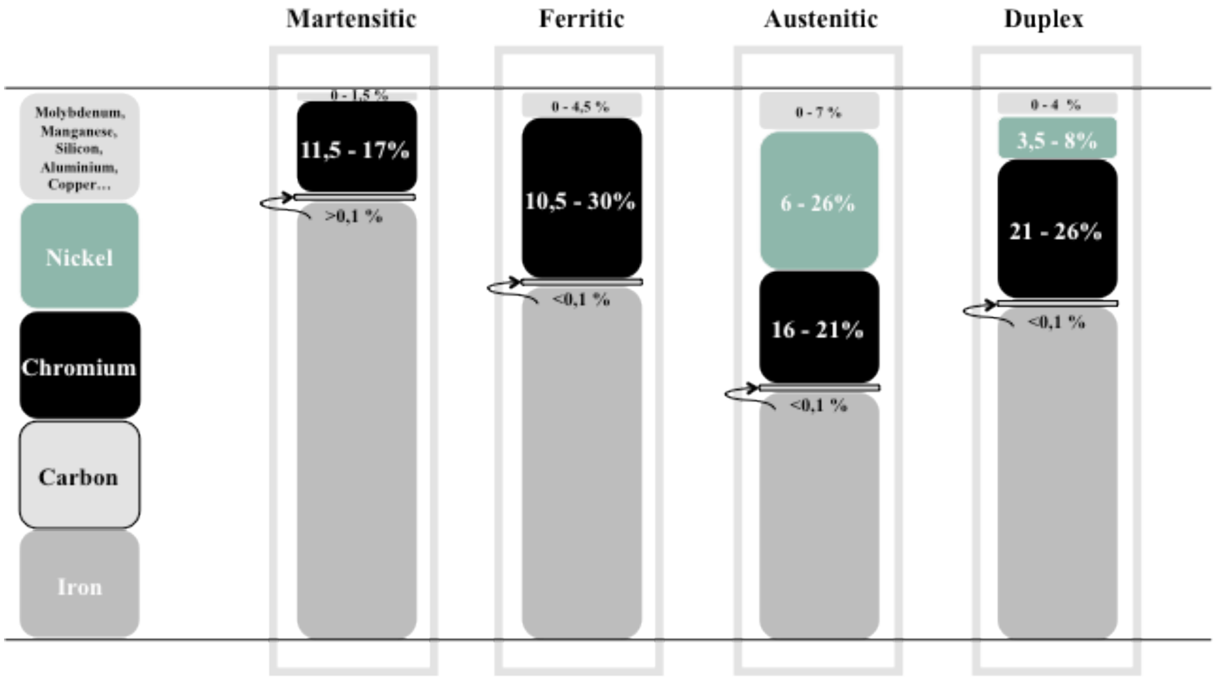

Figure 1. Indicative chemical composition depending on the family of stainless steel.

Their physical, chemical and mechanical properties vary with the chemical composition (and consequently the family) but each of them is characterized by the ability of forming a self-repairing protective oxide layer providing corrosion resistance, a higher chromium content enhancing the corrosion and oxidation resistance. In addition to this, nickel – which is present in the chemical composition of austenitic and duplex grades – extends the scope of aggressive environments that stainless steels can support. Figure 1 shows the range of chromium and nickel content of the four families of stainless steels.

The most popular grade is the austenitic grade 1.4301 (AISI 304) containing 18% chromium and 8% nickel. This grade has excellent corrosion resistance and is highly ductile. In the construction domain, this grade is available in the following forms: sheet, plate, welded mesh, bar and sections. More specific alloy additions enhance the corrosion resistance. The 1.4401 (AISI 316) grade containing an addition of molybdenum has improved corrosion resistance and is usually regarded as the outdoor grade (sometimes even labelled as the marine grade). While in atmospheres containing chlorides (e.g. indoor swimming pools), especially if the surface cannot be cleaned regularly, specific grades, such as super austenitic grades 1.4529 and 1.4565 for example, offer good alternatives.

Ferritic grades do not contain nickel. At ambient temperature, the stress-strain behaviour of these grades is similar to the one of traditional carbon steel while austenitic grades present a large strain-hardening domain up to 50% of elongation at fracture (see Figure 2). Ferritic grades differ principally from austenitic grades in that they have higher mechanical strengths (approx. 250-330 N/mm^2 0.2% proof strength) and lower thermal expansion (10 to 12 10^{-6}K^{-1}).

Duplex types, presenting a microstructure made of austenite and ferrite, share some of the properties of both families, and are mechanically stronger than either ferritic or austenitic types. Among the duplex family, one distinguished the new lean (low alloy) duplex steels, characterised by comparable strength to duplex grades and good corrosion resistance at, also, lower cost.

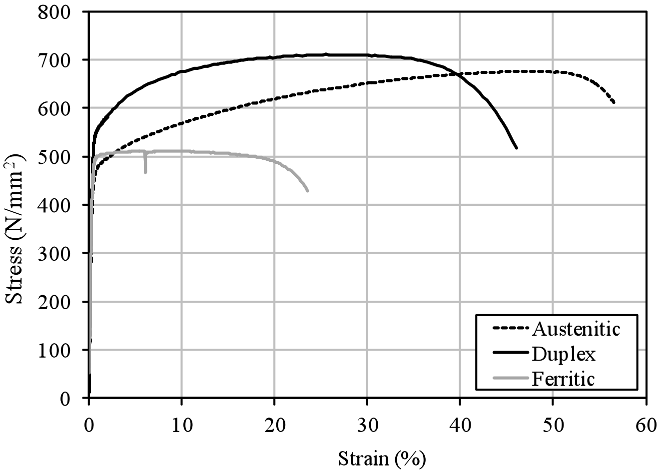

Figure 2. Typical stress-strain curves for austenitic, ferritic and duplex stainless steel [2].

Examples of applications in the construction domain

Stainless steel is perceived as a highly decorative material, durable and easily maintained as well as very expensive. In the construction domain, stainless steel was mainly used as cladding (inside or outside) thanks to its aesthetic expression: the *Francois Mitterand Library* in Paris (Arch. Dominique Perrault) where stainless steel mesh was used for the interior ceiling, the *Torre Caja* in Madrid covered with patterned stainless steel cladding, the *New Justice Palace* in Anvers (see Figure 3) characterized by a shiny stainless steel roofing [2].

Limited examples of stainless steel used in structures – i.e. thanks to reasons such as higher strength, higher ductility or better retention of strength and stiffness at high temperature – can be quoted especially because of the higher price of stainless steel compared to carbon steel equivalent.

New Justice Palace - Anvers
Richard Rogers Partnership, VK Studio architects, planners and designers, Ove Arup and Partners
© Régie des Bâtiments

Glass Center - Lommel
Samyn and Partners
© Samyn and Partners

Figure 3. Two examples of Belgian architectural realizations using stainless steel.

One can nevertheless cite, amongst others, the *Glass Centre* in Lommel (see Figure 3) where stainless steel supporting frames are combined with glass in a transparent conical dome, the cable stayed structure of the *Stonecutters bridge* in Hong Kong (Arch. Ove Arup and Partners) where stainless steel was used for the outer skin of the upper sections of the bridge towers, the structure of the *Science City* in Paris (Arch. Adrien Fainsilber), the structure of the *Metro Station Sainte-Catherine* in Brussels (Arch. Ney & partners), the structure of the *Saint-Pierre station* in Ghent (Arch. Wefirna), the composite floors of the *Luxembourg Chamber of Commerce* (Arch. Vasconi Architects), the structure of the *Parliament House* in Helsinki (Arch. Helin & Co Architects) and the *Cala Galdana bridge* structure (Eng. Pedelta).

Speaking of bridges, stainless steel is usually chosen in recognition of its long-lasting appearance combined with low maintenance requirement. That is the reason why duplex grades have occasionally been used in bridges, such as the 1.4462 (AISI 2205) grade used for the *Millennium footbridge* in York (Whitby bird and partners) or the lean duplex 1.4162 in the *Siena bridge* in Ruffolo (Eng. Pistoletti). The latter does not contain nickel and is therefore leading to a more economic design as well.

Other structural parts made of stainless steel can also be listed such as glass façade spiders (carrying the weight of the glass), cladding anchors, post tension tie rods, cables anchoring heads, fasteners as well as, though in limited examples, rebar in concrete structures. For more information, the interested reader can refer to [4] to [13].

Certainly, new opportunities for stainless steel take place in the current context of sustainable development. Firstly, stainless steels have no need for protection (galvanisation or painting) and maintenance over their life cycle. This has therefore an influence on the total life cycle environmental impacts and costs. Secondly, certain grades such as the ferritic and lean duplex grades have no nickel in their chemical compositions. Those grades are therefore much cheaper and more cost-stable than other – perhaps "even more popular" – grades. Both reasons taken together can lead to economically and environmentally attractive solutions in structural applications. Nevertheless, those grades are currently under-used in the construction domain due to a lack of information about stainless steel in general and about their structural behaviour in particular.

STAINLESS STEEL WITH RESPECT TO SUSTAINABILITY

Introduction

The construction industry is recognised as vitally important sector because manufacturing the necessary products and methods for putting in place our physical stock of facilities and infrastructures. The construction sector directly employs around 20 million people in Europe, but according to the European Construction Industry Federation, it indirectly influences over 40 million workers. It represents more than 10% of Europe's gross domestic product. In the current context of resource depletion, the sector plays a quite important role: it uses the greatest deal of raw materials, is taking a great deal of the energy consumption (processing and transport of construction material represent between 5 to 10% of Europe's energy consumption), and it is the most contributor to world solid waste. It has thus a significant impact, both in positive and negative terms, on society and environment.

Sustainability is nowadays rather well defined…at least conceptually. Despite the absence of a single and largely shared definition, the use of the terminology sustainability in the construction domain is rapidly spreading. After its fast development over the past century – such as remarkable progress in green technologies, material science and erecting techniques – we are facing an increasing complexity of the demand to achieve sustainability in the whole production chain. Particularly, the building sector is receiving increasing attention in worldwide policies for sustainable development. This attention arises from its energy consumption (buildings are responsible for more than 40% of Europe's energy consumption) and Green House Gas (GHG) emissions. Certainly, in the current context of resource depletion, sustainable buildings are often confused with energy efficient buildings. However, the awareness that sustainability – both in the building domain and in the construction sector in general – has to consider various aspects is increasing. Worldwide, the scientific community agrees that it is a complex function, which is difficult to optimize. Firstly, it is a multi-facets concept: it lies in the interrelations between the environmental (ecology, potential impacts, resources, waste, toxicity, recyclability…), social (comfort, space, shelter, security, respect, aesthetic, history, culture, heritage…) and economic (cost, investment return, durability, longevity…) dimensions. Secondly, it is a time dependent concept requiring life cycle thinking. Thirdly, it is a spatial dependent concept: current evaluations are most of the time limited to the physical boundaries of the edifice, but the importance of the interaction of the construction with its surrounding environment is gradually recognised as a key issue.

Stainless steel advantages with respect to environmental assessment scoring methods for buildings

In the scoring systems – such as LEED (Leadership in Energy and Environmental Design) which is a voluntary certification system developed by the U.S. Green Building Council (usgbc.org) since the nineties, composed of point scales used to assess if building (commercial and homes) are designed and built following certain environmental criteria (energy savings, water efficiency, CO_2 emissions reduction etc) providing the user with a score – the energy performance of buildings (operational energy use) and associated emissions is the most highly weighted factor. Stainless steel outdoor cladding and roofing have important roles to play in this category: corrosion resistance and therefore longer service life and low maintenance and high protection against air leakage or infiltration and heat losses. Another important advantage of the use of stainless steel in regard to LEED is its high recycled content and recapture rate as well as the possibility of material reuse in the case of a renovation. Some problems have nevertheless been underlined by authors [14], such as the fact that LEED associates no point to material longevity and that it is not possible to obtain more points when longer service life is offered. The same author also mentions that one part of the scoring system can be favourable to the use of stainless steel in buildings: the heat island effect. It refers to the increase in temperature occurring during summer in urban areas. Cool roof systems and wall panels with high solar reflectance and low emittance can lead to a reduction in air conditioning costs. The author underlines that stainless steel finishes are not included in public databases providing these physical properties.

In [15], a description of the standard mill finishes and the mechanically treated surfaces finishes indicated in EN10088-2 are provided. To determine the combined effect of the reflectance and emittance on the surface temperature, the Solar Reflectance Index (SRI) is used, it varies from 100 (for a standard white surface) to zero (for a standard black surface). The higher the SRI, the cooler the surface remains. Emittance, also known as emissivity of a surface, is a measure of the surface capacity to emit heat; it ranges between 0 and 1. Most opaque non-metallic materials encountered in the built environment (such as concrete, masonry, and wood) have an emittance between 0.85 and 0.95. Stainless steel emittance ranges from 0.85 to less than 0.1 (highly polished stainless steel) depending on the surface finish [16]. Moreover, smooth, bright metallic surfaces will be characterized by directional reflection of light (low roughness, low dispersion). For stainless steel, to a mirror finish will correspond a high reflectivity, to a matt-rolled finish will correspond an intermediate reflectivity and to a patterned finish will correspond a low reflectivity. It is thus possible to recommend the finish, depending on the application, to control the SRI.

Stainless steel structural advantages

In structures, recent years have seen an increase in the use of stainless steel grades owing to their resistance to corrosion. If in aggressive environments (structures facing the sea, bridge crossing seaway or swimming pools), stainless steel is occasionally chosen as the alternative. One example concerns the use of stainless steel reinforcements in concrete bridges crossing the sea, numerous studies, [17] to [19], were undertaken to assess the economic interest of such applications. Abundant literature is available for the choice of the appropriate grade in such environment. In chloride rich environments, elements carrying loads can usually not be maintained regularly, such as for example, in suspended ceilings above swimming pools. In this case, stainless steel grades, such as super austenitic 1.4529, 1.4547 and 1.4565, can be advantageously used. Unless the concentration of chloride ions in the water is ≤ 250 mg/l, in which case the grade 1.4539 is also suitable.

As stated in the introduction, still limited examples of stainless steel used in the construction domain thanks to its mechanical properties (such as higher strength or greater ductility) can be quoted especially because of the higher (perceived) price of stainless steel compared to carbon steel equivalent. The use of stainless steel for its mechanical properties combined with good corrosion resistance can nevertheless be referred to, especially in bridges where it is usually chosen for its durability combined with high ductility and strength [5]. Especially, recent applications have seen the introduction of new lean (low alloy) duplex steels, characterised by comparable strength to duplex grades and good corrosion resistance at lower cost. It is worth pointing that a life cycle cost analysis is generally (implicitly or in details) performed to evaluate the relevance of the use of stainless steel under these circumstances. The greater ductility or superior fire resistance of stainless steel is also the topic of recent researches: behaviour of stainless steel connections, structural sections exposed to fire, stainless steel blast barriers etc, [20] to [23].

In sum, stainless steel's structural characteristics are:

- Improved strength especially for the duplex family leading to lighter structures,
- Corrosion resistance reducing maintenance or replacement in the future,
- Superior strength and stiffness retention at high temperature,
- Good low temperature toughness.

Other advantages with respect to sustainability

Stainless steel presents other important characteristics that should be underlined as regards sustainability:

- The recycled content of the materials,
- The recycling/reuse potential including the in-situ reuse,
- The stability in the unlikely eventuality of burying in a landfill,
- The construction site waste management through manufacture off-site.

LIFE-CYCLE ANALYSIS (LCA) OF STAINLESS STEEL

Introduction to LCA and standards

LCA is increasingly being used to assess the environmental potential impacts associated with the entire life of products. It is usually used to calculate the environmental impacts associated with the production, use, disposal, and recycling of products, including the materials from which they are made. It quantifies the resource use and environmental emissions associated with the evaluated product (Life cycle inventory, LCI) and the corresponding potential impacts (such as Global Warming Potential, Eutrophication Potential, Acidification Potential…). Those potential impacts are potential effects resulting from the release of gases in the atmosphere or substances in the rivers for instance. As an example, Global Warming Potential, expressed in terms of equivalent mass of CO_2 per considered unit (e.g. kg equivalent CO_2 per kg of EN 1.4003 stainless steel) is the standard measure of how much heat a considered gas is able to trap and so how much this gas is capable of increasing the earth temperature. To each gas i is associated a characterization factor GWP_i by which the mass is multiplied to obtain the contribution of this gas to greenhouse effects. A GWP_i is calculated over a specific amount of time (conventionally 20, 100 or 500 years).

The importance of LCA has long been recognized by the European Commission as the best framework for assessing the potential environmental impacts of products and it was mainly developed for designing low environmental impact products. The framework and generic methods of environmental LCA are standardised in the ISO series 14040-14044 [24]-[25] and for environmental analysis of products, it has achieved good international agreement. The interest of using LCA for entire buildings evaluations began to rise in the last decade and, today, several building LCA tools have been or are under development in different countries. Since 2010, the work of the Technical Committee TC350 [26] (which is responsible for the development of standardized methods for the assessment of the sustainability aspects of new and existing construction works and the standards for the environmental product declaration of construction products) has been implemented into a new suite of European standards, some of which are still under progress under the guidance of the committee. Quantitative indicators for the environmental, social and economic performance of buildings are (or will be) provided.

Among the aforementioned suite of standards intended to assess the sustainability of construction works (Figure 4), EN 15804:2012 [28] provides a structure to ensure that all Environmental Product Declarations (EPD) of construction products are derived, verified and presented in a harmonised way. As stated in EN 15804:2012, *an EPD communicates verifiable, accurate, non-misleading environmental information for products and their applications, thereby supporting scientifically based, fair choices and stimulating the potential for market-driven continuous environmental improvement.*

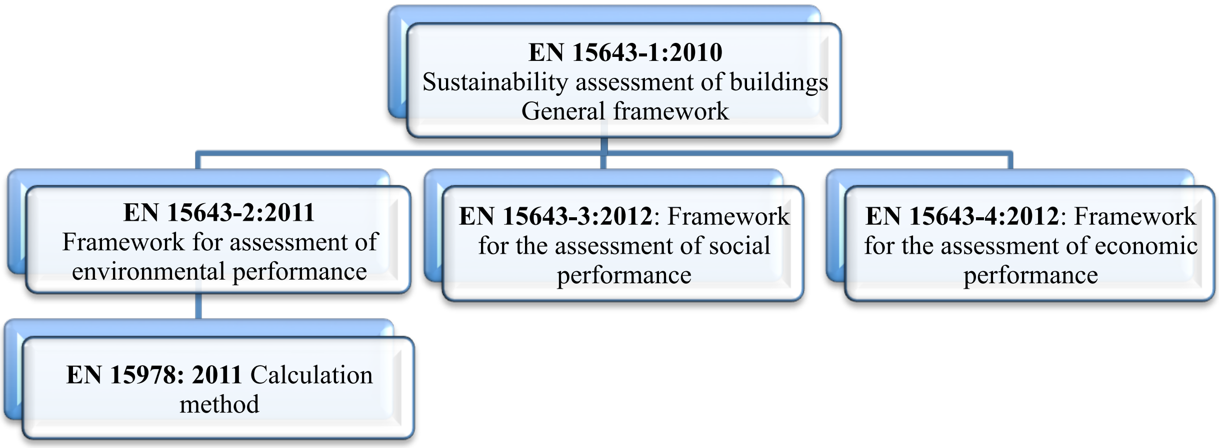

Figure 4. European standard suite for the assessment of the sustainability of building (credits to [29])

Data provided in EPDs are based on LCA and the information may cover different life cycle phases. Two prevailing EPDs exist plus a third one which may include an optional stage:

- "*cradle to gate*" i.e. the product stage only: raw material supply, transport, manufacturing and associated processes are included (modules A1 to A3 in EN 15804:2012);
- "*cradle to gate with options*" contains the product stage (modules A1-3) whereas installation into the building (modules A4-5), use, maintenance, repair, replacements and refurbishment (modules B1-7), demolition, waste processing and disposal (modules C1-4), reuse, recovery and/or recycling potentials, expressed as net impacts and benefits (Module D) are optional modules i.e. they may or not be included.

The module D therefore allows benefits to be taken now for the eventual reuse or recycling of material in the future. The third one "*cradle to cradle*" includes all modules except the module D, which remains optional, meaning that it is never obligatory to take it into account.

Today, recycling is becoming more widespread but it often implies downgrading of the material, and reusing the material in this downgraded form, whereas selective dismantling and material recycling/reuse results in significant environmental and economical benefits. For indefinitely recyclable materials, the inclusion of module D is of prime importance. This is explained in the next section.

Stainless steel recycling and World steel methodology

There are two types of scrap in the stainless steel production: reclaimed scrap (post-consumer or old scrap) and industrial scrap (pre-consumer or new scrap). Industrial scrap includes industrial returns or production offcuts while reclaimed scrap corresponds to industrial equipment, tanks, washing machines, refrigerators and building products that have reached the end of their service life. The intrinsic value of its constituent elements is the reason why stainless steel recycling has been a common practice and therefore there is no need for external financial incentives or political pressure for enhancing it. Today, stainless steel is made up of approximately 60% *recycled content* including about 25% reclaimed scrap, 35% industrial scrap and 40% new raw materials (worldstainless.org). Sophisticated technologies are needed to separate and prepare each type of alloy during the recycling process. The scrap is chemically analysed and stored by type: chrome steels, nickel alloys and other types of stainless steels. After amalgamation into piles for specific customer requirements, the scrap is transported to the mills. Scrap along with other raw materials is blended into the electric furnace. Within the furnace, carbon electrodes are used to increase the temperature and melt various scraps of steel, chromium alloy as well as other additions that depend on the grade. The liquid material is then transferred into an Argon Oxygen Decarbonization vessel, where the carbon levels are reduced and the final alloying elements added. Liquid raw stainless steel is then casted into ingots or continuously casted into slabs or billets. Further hot rolling allows forging the shape into its final form (e.g. slabs into hot-rolled coils). And cold rolling is used to further reduce the thickness as in sheets or draw into smaller diameters as rods and wire. Most stainless steels receive further annealing (a heat treatment that softens the structure) and pickling (a surface treatment used to remove impurities, such as stains, inorganic contaminants or rust and naturally promotes the passive surface film). In conclusion, production and recycling are not separate steps in the life cycle of the material as the most important ingredients in stainless steel production are recycled stainless steels and other steel alloys.

Another important figure is the stainless steel *recovery rate* (*RR*), which today is close to 90% as indicated in Table 1. Seen the very high *RR*, why is the recycled content only 60%? This can be explained by the increasing demand (stainless steel world production long-term average growth rate is about 5% annum) and exceptionally long service life of stainless steel products (products-in-use are still too new to require replacements) i.e. even if 100% of the available material is returned, the recycled content may not increase, it may even decrease.
And so, in conclusion, as opposed to *open-loop* materials or materials that are down-cycled, stainless steel is a *closed-loop* material because indefinitely recyclable with no changes in its inherent properties.

Table 1 Stainless steel recovery rates per application sectors, [31].

Main application sectors	Use of finished stainless steel in manufacturing	Average life (years)	To landfill	Collected for recycling	
				Total	As stainless steel
Building	16%	50	8%	92%	95%
Transportation	21%	14	13%	87%	85%
Industrial machinery	31%	25	8%	92%	95%
Household appliances	6%	15	18%	82%	95%
Electronics	6%	-	40%	60%	95%
Metal goods	20%	15	40%	60%	80%
Total	100%	22	18%	82%	90%

How are we supposed to take into account the end-of-life (EOL) stage in LCA? If the life cycle stages taken into account in LCA include the EOL stages, credits and loads should be calculated and properly allocated. ISO standards advise to firstly avoid allocation by either subdivision of processes or by system expansion (i.e. intermediate treatment, subsequent LCA, avoided waste treatment thanks to co-products included in LCA…). Besides, two principle methods exist: the *Cut-off method* in which secondary products are considered according to the recycled content in the product at issue and so all credits/burdens of recycled products belong to the next system; and the *Avoided burden method* in which all avoided burdens are attributed to the product that delivers the secondary product after its service life. None of these are fully representative of stainless steel production. In the first one, scrap is considered as a raw material with neither burden, nor credit; in the second one, the recovery and reuse of scrap saves energy and reduces the environmental impacts but none of them consider the whole life cycle of indefinitely recyclable materials.

World Steel Association has provided a methodology to follow in order to include the EOL treatment and recycling of steel, see [32] to [36]. Discussion over this methodology with respect to ISO and EN standards is given in [37]. The principles of this methodology are:

- Steel is considered as a closed-loop material and the main steps of its LCA are the manufacture, the use phase and the EOL phase;
- LCI data include the manufacture and EOL steps, practitioners will have to add the use phase.

In order to include the credits and loads related to the EOL phase, the LCA indicators (such as Global Warming Potential or Primary Energy Demand) must be known in the case of primary production (blast furnace route) as well as in the case of secondary production (electric arc furnace route), namely the two extreme production routes.

At this stage, two important parameters must be defined:

- Already described above, the recovery rate *RR*, the fraction of material that is recaptured after one life cycle, it includes the pre-consumer scrap generated during the manufacturing process and the EOL scrap (post-consumer scrap);
- The yield *Y* representing the ability of the secondary process to convert scrap into steel.

If we consider *X* as our main indicator e.g. the Global Warming Potential (*GWP*, [kg eq. CO_2 / kg]), at the end of the life:

- *y* tonnes of scrap saves $y \cdot X_{prim}$ where *"prim"* relates to primary manufacture in which there also exists a scrap input *S*;
- For the production of stainless steel using *y* tonnes of scrap, $y \cdot X_{rec}$ are released where *"rec"* relates to secondary manufacture.

As a result, the LCA indicator *X* including EOL credits and loads is,

$$X = X_{prim} - (RR - S) \cdot Y \cdot \left(X_{prim} - X_{rec}\right) \quad (1)$$

In the case of stainless steel, no extreme production routes exist. In this case, X_{prim} and X_{rec} must be assessed. The original data are the factory data (based, on average, on 60% scrap material and 40% primary materials) for which the manufacturer knows exactly the scrap input (i.e. the mass of each scrap input per grade) and primary material inputs (i.e. the mass of carbon steel scrap, iron, nickel…). Proportional scaling up of to 100% scrap (0% primary material) and 100% primary materials (0% scrap) respectively must then be considered [31], [34]-[35] to compute the theoretical indicators X_{prim} (associated to 100% of primary material in the production process) and X_{rec} (associated to 100% of scrap in the production process).

Life cycle environmental potential impacts of stainless steel

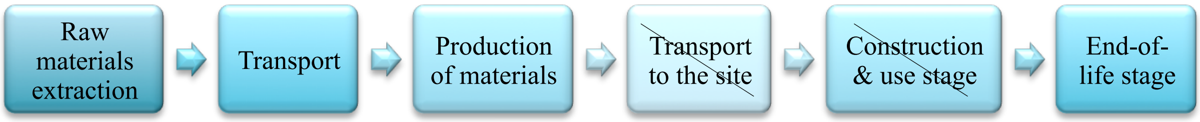

Figure 5. System boundary [29]

This section presents two potential environmental impacts considering the production of crude stainless steel considering the aforementioned methodology [31]. LCI data have been released through EUROFER Stainless (www.eurofer.org), which provides European average LCI data for stainless steel flat coil (CRC) and quarto plate (QP, hot rolled) products (2010). The functional unit (FU) is one kilogram of either CRC or QP. The study is a cradle-to-gate study covering all the production steps from raw materials "in the earth" (i.e. the cradle) to finished products ready to be shipped from the factory (modules A1 to A3). The transport to the construction site, construction and operation stages (modules A4-5) are not included in the analysis (Figure 5). The study also includes EOL stages (waste processing and disposal) as well as benefits associated with the recycling i.e. Module C and D. If the user adds modules A4 to A5 (construction processes) and B (use phase), the analysis would therefore become a *cradle-to-cradle* analysis.

Two potential impacts are calculated: Global Warming Potential (GWP, kg CO_2 eq. / kg of considered grade) and Primary Energy Demand (PED, MJ / kg of considered grade). The characterization factors are taken from [38]. Figure 6 and Figure 7 present the results for 1 kilogram of CRC made of 1.4301 (AISI 304) and 1.4401 (AISI 316) austenitic grades, 1.4016 ferritic grade (AISI 430) and last 1 kilogram of QP made of 1.4462 (2205) duplex grade. The

PED is divided in energy from renewable resources and energy from non-renewable resources. Both potential impacts are provided considering three different *RR* underlining the importance of module D.

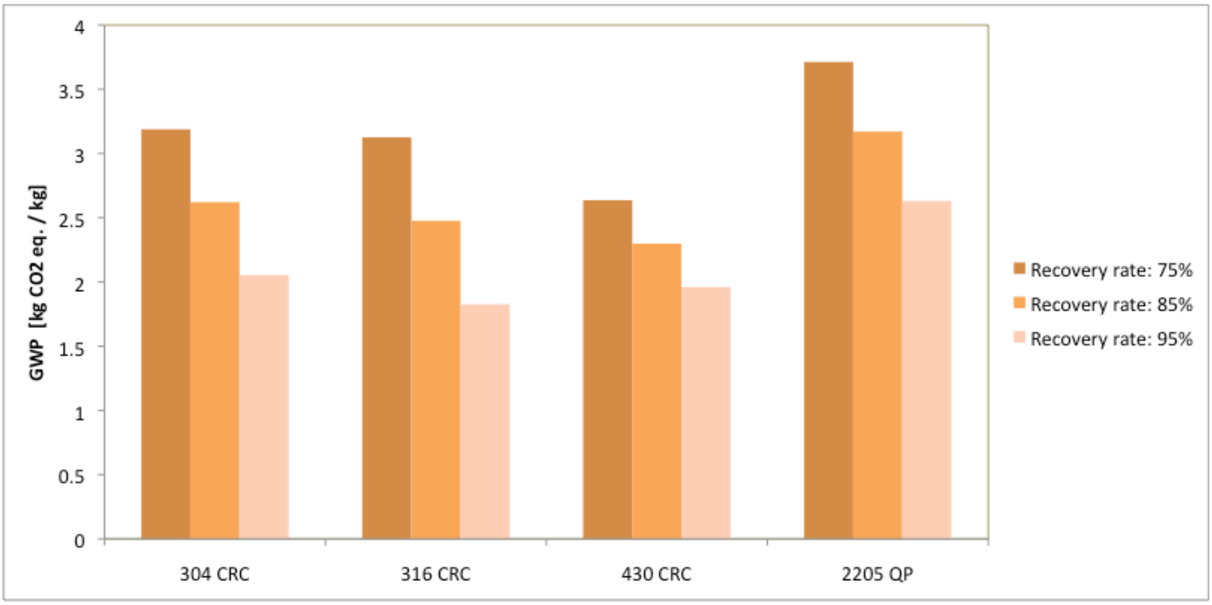

Figure 6. Global Warming Potential for the four grades considering three *RR*.

It is seen that, in terms of GWP and PED, the 1.4016 (AISI 430) ferritic grade has lower impacts than the other considered grades, see for instance Table 2 summarizing the LCA results for *RR* equalling 95%.

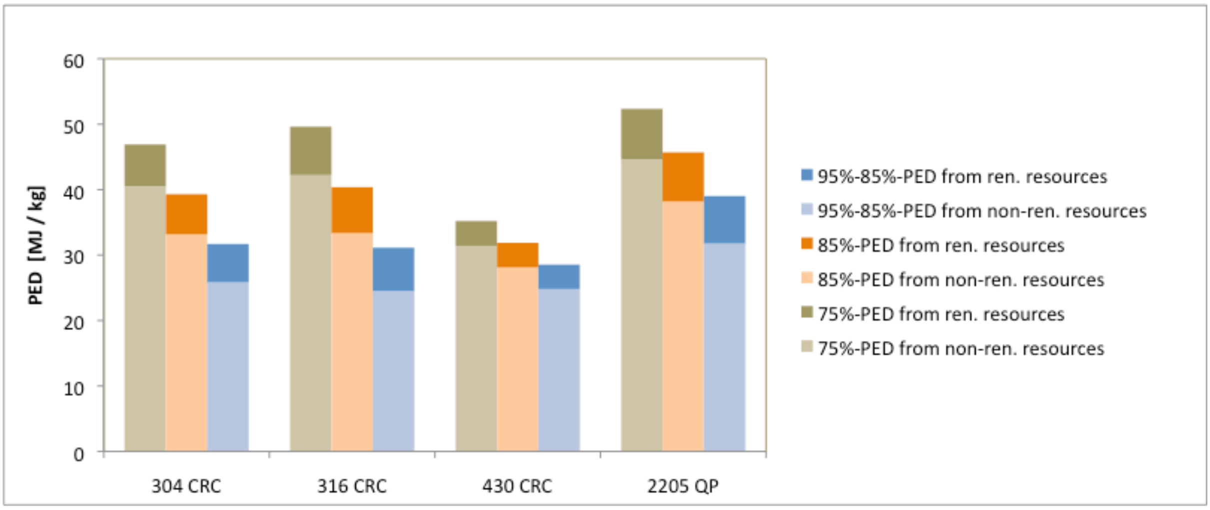

Figure 7. Primary Energy Demand divided in Renewable and Non-Renewable resources for thefour grades and three different *RR*.

Table 2 Environmental potential impacts considering *RR*=95% (2010).

	304 CRC	316 CRC	430 CRC	2205 QP
PED - [MJ / kg]	31,7	31,1	28,5	39,0
GWP - [kg CO_2 eq. / kg]	2,0	1,8	1,9	2,6

Outokumpu has also released an EPD for a declared unit of 1 tonne of cold-rolled stainless steel for various applications for building and civil work [39]. In this document, the PED and GWP are also furnished at the Product stage and after Benefits and loads beyond the system boundary (Module D), the sum of each equals respectively 36,5MJ/kg and 1,85 kg CO_2 eq. / kg. For this analysis, an average recycling rate of 85% is chosen together with 60% of scrap input. In this analysis, for *RR* equalling 85%, the average PED for all grades equals 39.3MJ/kg and the average GWP equals 2.6kg CO_2 eq. / kg.

By sake of comparison, the same indicators for two exterior wall sidings have been evaluated using LCI data extracted from BEES database (geographic area: U.S. market): Trespa Meteon wood based façade cladding and Generic stucco which is a cement based plaster used to cover exterior wall surfaces. The functional unit (FU) is one square meter of wall finish. The interested reader can refer to [40] to obtain (1) the product list; (2) the description of the functional unit; (3) the system boundary for each product; (4) the considered EOL scenario. Even if the data indicated in Table 3 should be considered cautiously as the comparative analysis does not include any sensitivity analysis, it can be seen that the order of magnitude of the two considered potential environmental impacts are in the same range for generic stucco and stainless steel cladding.

Table 3 Indicative environmental potential impacts for 1 m^2 of three different wall finishes.

	PED [MJ / FU]	GWP [kg CO2 eq. / FU]	EOL scenario
Trespa Meteon	759,3	23,9	50% reuse + 50% landfill
Generic stucco	144,2	12,7	not recycled
Stainless steel Thickness=0,8mm	195,5	11,5	*RR* = 95%

CONCLUSIONS

Stainless steel use in building envelope applications dates as far back as the 1920s. Numerous examples of austenitic grades used in building façades can be quoted. Above all, for the reason that stainless steel has excellent corrosion properties, which makes its pleasing appearance long lasting. Looking at life-cycle management, stainless steel does not require coatings resulting in low maintenance costs that generate long-term value to the building owner. Certainly, the use of such a durable material has saved the owners considerable expense over the years.

In load-carrying elements, stainless steel has been used in limited amount. The corrosion resistance is still regarded as the main parameter leading to economic advantages in structural applications such as rebar in marine environment, structural members in offshore applications or swimming pools. The mechanical properties – such as the ones offered by duplex grades sharing the advantages of austenitics (great ductility, high corrosion resistance) and ferritics (higher strength) – are profitably used in bridge design, leading to lighter structures and therefore lower transportation costs and smaller foundations. Research into this has increased over the past decades leading to a better prediction of the strength of members made of stainless steel, especially, for ferritic and, less remarkably though, lean duplex grades, which are cheaper and more cost-stable grades.

Both in envelope products and in structural elements, life cycle environmental and cost analyses can be helpful to evaluate the relevance of the use of stainless steel with what regards sustainability. Stainless steel is highly recovered and recycled at the end of its life. This can be taken into account in life cycle assessment through the Module D of the new European standards EN 15804:2012 i.e. by performing a "*cradle to cradle*" analysis. That is the reason why, in the present paper, cradle-to-gate results including the recycling are presented. According to the new European standards, the Module D is optional. However, it was shown that taking into account the fact that stainless steel is indefinitely recycled is highly influencing the results. In this paper, four grades were described in terms of two environmental potential impacts (Primary Energy Demand and Global Warming Potential) considering three different *Recovery Rates*. For all four grades, the smaller the *Recovery Rate* the higher the impacts. As underlined in [31], this conclusion helps support recycling efforts beyond the justifications of material use or waste impacts.

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