STAINLESS STEEL IN STRUCTURES IN VIEW OF SUSTAINABILITY

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Recent years have seen an increase in the use of structural stainless steel, mainly owing to its aesthetic and architectural qualities alongside durability. Among stainless steels, ferritic grades are characterized by low nickel content resulting in a more cost-stable and economic material compared with austenitic stainless steels, allowing a balanced approach between economic and environmental aspects. As an introduction, this paper presents the recent research outcomes especially concerning the currently on-going RFCS project “Structural Applications of Ferritic Stainless Steels”. Then, attention is paid to the advantages and challenges associated with the use of this material in recent construction projects in view of sustainability. Life cycle analysis is explained. The background of the new European standard EN 15804 is described, including Module D, which takes now into account the end-of-life phase. 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, several potential impacts such as the Primary Energy Demand and Global Warming Potential are compared 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 the end-of-life credits and loads is underlined.

1 Introduction

Stainless steel principally contains iron and more than 10.5% of chromium. Depending on the microstructure, four families exist: martensitic, ferritic, austenitic and austeno-ferritic (duplex) stainless steels (Figure 1).

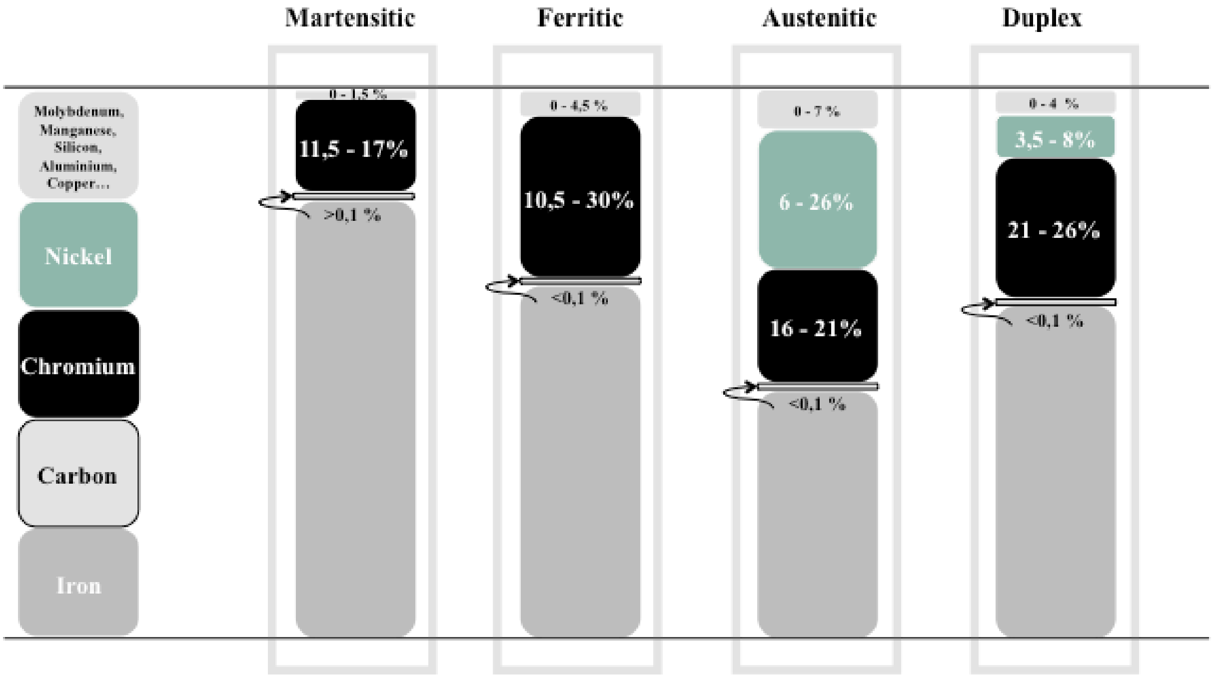

Figure 1. Stainless steel families and corresponding indicative chemical compositions.

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 the 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. The most popular austenitic grade 1.4301 (AISI 304) containing 18% chromium and 8% nickel has excellent corrosion resistance and is highly ductile which makes it used for sinks and saucepans for example. This grade is usually available in the following forms: sheet, plate, welded mesh, bar, pipe, decorative tube etc. More specific alloy additions also 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. Austenitic grades are non-magnetic (or weakly ferromagnetic) whereas the

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other families are ferromagnetic. The mechanical behaviour of ferritic grades is similar to traditional carbon steel at ambient temperature 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 have lower thermal expansion (10 to 12 $10^{-6}K^{-1}$), high thermal conductivity and are easier to cut and work. They can sometimes be subjected to pitting corrosion, the resistance to which is made optimal if the surface is highly polished. 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.

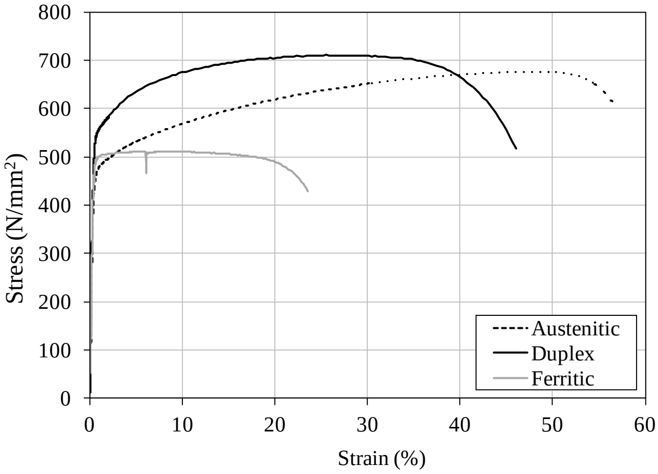

Figure 2. Typical stress-strain curves for austenitic, ferritic and duplex stainless steel [1].

1.1 Stainless steel in construction applications

Stainless steel is perceived as a highly decorative material as well as durable and easily maintained. A lot of examples of buildings in which stainless steel has been used (inside or outside) for its aesthetic expression and durability exist: 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 highly decorative stainless steel roofing, The *Glass Centre* in Lommel (see Figure 3) where stainless steel supporting frames are combined with glass in a highly transparent conical dome, etc.

Still limited examples of stainless steel used in the construction domain for its interesting mechanical properties, such as better resistance to fire, can be quoted especially because of the higher price of stainless steel compared to carbon steel equivalent. However, the use of stainless steel for its mechanical properties (strength and ductility, retention of strength and stiffness at high temperature) combined with good corrosion resistance is nevertheless growing especially in the current context of sustainability. One can cite amongst others 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 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 *Cala Galdana bridge* structure (Eng. Pedelta), etc. In bridges, stainless steel is usually chosen in recognition of its attractive appearance as well as durability (low maintenance requirement), good fatigue resistance, ductility combined with high strength. That is the reason why duplex grades are often prescribed in bridges, such as the lean duplex 1.4162 in the *Siena bridge* in Ruffolo (Eng. Pistoletti) or the 1.4462 (AISI 2205) grade used for the *Millennium footbridge* in York (Whitby bird and partners). Other structural parts made of stainless steels can also be listed such as rods, cables, anchoring and fasteners as well as, though in limited examples, rebar in concrete structures in corrosive environment. For other realizations, the interested reader can refer to [2] to [9].

Additionally, the shift towards more sustainable development is opening up new opportunities for structural stainless steel, as the construction (initial) cost is not anymore the only concern of stakeholders. First, contrarily to galvanised or painted steel, stainless steels have a self-repairing corrosion resistant surface layer so there is no need for protection and maintenance over the life cycle. Second, seen that no nickel enters their chemical compositions, ferritic grades are cheaper and more cost-stable than other grades of stainless steel, which makes them economically attractive. Nevertheless, ferritic grades are currently under-used as load carrying members due to a lack of information about its structural behaviour.

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 remarkable Belgian architectural realizations using stainless steel.

2 Recent research emphases into ferritic stainless steel

2.1 Material modelling

Stainless steels are characterized by nonlinear stress-strain behaviour with no precise yield point and a significant amount of strain hardening in comparison to annealed carbon steel. Ferritic stainless steels have different mechanical properties from other families of stainless steels. The mechanical properties for various ferritic stainless steels are provided in guidance such as the European EN 10088-2 standards [10].

For instance, the 1.4003 ferritic grade, commonly known as 3Cr12, exhibits similar mechanical properties to traditional carbon steel. This grade can be used in mildly corrosive environments where localised corrosion stains are acceptable or desirable, and are weldable for structural purposes. The main room-temperature mechanical characteristics of this grade are: (*i*) 0.2% proof stress $\sigma_{0.2\%}$=280 MPa, (*ii*) elongation after fracture ε_u=20% and (*iii*) ultimate tensile strength σ_u=450 to 650 MPa. The mechanical properties of this grade, together with other ferritic grades, have been studied in [1], [11] to [13]. In [11], classical uni-axial tensile tests in the rolling direction (RD), the transverse direction (TD) and at 45° from RD are used to define the elastic parameters such as Young's modulus (E) and Poisson's ratio (υ). Overall, the values obtained for each direction were relatively similar. The average values of E and υ, provided in [11], were 1.78×10^5 MPa and 0.298 respectively. A biaxial experimental arrangement is also used to perform additional monotonic and cyclic simple shear tests as well as orthogonal tests in the RD, TD and at 45° from the RD. The objective of these tests was to enable characterization of the anisotropy of the material (yield surface shape) and the hardening behaviour. The results showed that the grade 1.4003 has relatively low anisotropy. Also, the parameters of the two stages Ramberg-Osgood material model developed by Mirambell and Real [14] and Rasmussen [15] traditionally used to reproduce the stress-strain response of metallic materials with a nonlinear behaviour are provided.

In [12], a series of tensile and compressive tests are achieved to determine the stress-strain response of coupons taken from square (SHS) and rectangular hollow sections (RHS) made of grades 1.4003 and 1.4509. The flat coupons were extracted from each of the four faces of the specimens in the longitudinal direction. Average tensile and compressive flat material properties are provided and compared to the ones stated in the codes and the literature for other grades.

In [1], a laboratory testing programme is conducted to investigate the influence of cold-working on the strength of cold-formed structural sections through a series of tensile coupon tests on material extracted from cold-formed tubular sections. A total of eighteen cross-section geometries were considered including twelve SHS, five RHS and one circular hollow section (CHS). A range of stainless steel grades – austenitic (1.4301, 1.4571 and 1.4404), ferritic (1.4509 and 1.4003), duplex (1.4462) and lean duplex (1.4162) – and one structural carbon steel grade (S355J2H) were included. The results from the test programme have been combined with existing measured stress-strain data on cold-formed stainless steel sections from the literature and revised values for the material model parameters for commonly used stainless steel grades including ferritics are recommended. Young's modulus values obtained in this study are also compared with their respective codified values. The measured values show good agreement with all the codified values except for the EN 1993-1-4 [16] high Young's modulus of 220000 N/mm^2 for the ferritic grades. It is recommended that an average value of 195000 N/mm^2 may be adopted for all stainless steel grades.

Research on Young's modulus of ferritic grades is limited, in particular for 1.4509 and 1.4521 grades and measurements of Young's modulus are not always appropriately achieved: devices used to measure the strain, practical issues such as misalignment or bending of the specimens extracted from cold-formed section as well as the procedure used to analyze the data and compute the Young's modulus have been highlighted as having a significant effect on the accuracy of the measured values. Also, the direction of loading has an effect on the measurements because the microstructure changes due thickness reduction greatly affect Young's modulus. The manufacturer generally performs tensile tests in the TD i.e. perpendicular to the RD (mill certificate data according to [10]) because the material is frequently "stronger" in the RD. As for codified values, only EN 1993-1-4 gives a constant design value whereas other standards gives different values for the RD and the TD, mostly lower than the previously cited one. Looking into the literature, on average, authors provide lower values in the RD (190MPa) as well as in the TD (210MPa) and so, in overall, EN 1993-1-4 values are always higher regardless the direction of measurement and sense of loading which is in accordance with the recommendation in [1]. However, very recent measurements by Outokumpu and KULeuven using the Impulse Excitation Method [17], according to ASTM C1259–08 show higher averages: 210MPa for 1.4003 and 211MPa for 1.4509.

More generally, in [13] a predictive model for harnessing the strength increases in cold-formed sections as a result of plastic deformation during fabrication is also proposed. Statistical analyses are carried out to ensure that the current level of reliability of the European design standards is maintained when the new predictive model is incorporated in design. The new proposed model provides good predictions of the test data, is simple to use in structural calculations and is applicable to any metallic structural sections.

Last, in [18], a material model equation is proposed. It is flexible to accommodate any number of measured or recommended material parameters. The general formula is applied on the set of parameters typically available for structural stainless steels in Europe (0.2% and 1.0% proof strength and ultimate strength) and compared to the existing models by curve fitting of analytical equations to measured stresses and strains of austenitic, duplex and ferritic stainless steels. The comparisons clearly showed that a three-stage application of the generalized multistage model yields more accurate results compared to the existing material models both in its direct and inverse form.

2.2 Experiments on members made of ferritic stainless steel

The strength of thin-walled stainless steel columns has been investigated extensively over the past few years. In European standards, the concept of section classification for determining the cross-section capacity is used. In this system, for Class 4 cross-sections, the Effective Width Method (EWM) must be used to account for the effect of local buckling. In [12], four hollow sections made of 1.4003 and 1.4509 grades are studied. Eight stub column tests, sixteen flexural buckling tests, eight beam tests are performed and used to assess the applicability of the cross-section classification limits provided in the current EN 1993-1-4 [16] and North American [20] provisions to ferritic stainless steel internal elements.

Because of the complexity and limitations of the EWM, other methods have been developed, such as the Direct Strength Method (DSM, [19], [20]) for cold-formed thin-walled profiles and the Continuous Strength Method (CSM, [21]), initially established for members made of nonlinear metallic materials. In the CSM, to take advantage of strain hardening, a deformation-based design approach employing a continuous relationship between the cross-sectional slenderness and the cross-sectional deformation capacity is used. To a large extent, the CSM yield accurate predictions, especially in the low slenderness range where the current DSM design procedures for members submitted to pure compression tends to produce conservative predictions, for materials with pronounced strain hardening such as stainless steel alloys. Based on experimental tests, improvements of the DSM equations have been proposed over the past ten years by Lecce [22], Lecce and Rasmussen (2006) [23], Becque et al. (2008) [24], Rossi et al. (2010) [25] and [26], and Rossi and Rasmussen (2012) [27]. These formulations propose modifications to the typical equations to account for (1) the interaction between local and member buckling and (2) the pronounced strain hardening of stainless steel alloys which leads to conservative predictions of the current DSM equations in the low slenderness range.

More particularly, in [25] and [26], a total of 30 full-scale tests on press-braked ferritic stainless steel lipped channel sections subjected to concentric compression was achieved. The test specimens were fixed at the ends using closely-fitting 20 mm deep plates in order to prevent cross-sectional deformations and to prevent lateral displacements, rotations and warping. As such, the specimens were designed so that distortional buckling developed in the section prior to overall flexural-torsional buckling. The dimensions of the channels were 50 *x* 100 *x* 12mm with 1.5mm thickness. Ten different lengths were examined, ranging between 400 and 3200 mm and each test was repeated three times. For short columns, distortional buckling failure modes were observed. For columns with intermediate lengths, the failure mode was a combination of the distortional buckling and the global flexural-torsional buckling modes, while a purely global flexural-torsional mode was identified for longer columns. The obtained test results were compared to the codified design strengths and a new DSM equation intended for the design of stainless steel lipped channels taking account of failure by combined distortional and overall flexural-torsional buckling was proposed.

In [27], it is highlighted that the current DSM does not allow stresses beyond the 0.2% proof stress to be used in the design and limits the cross-section resistance to A x $\sigma_{0.2}$. It thus provides slightly poorer agreement against the tests results for stocky sections than the CSM, which permits stresses above the 0.2% proof stress to be used in the design of members made of stainless steel alloys. The paper proposes an improvement of the current DSM for the design of stainless steel thin-walled section columns failing by distortional, local or combination of local and overall buckling which leads to higher design strengths in the low slenderness range. The efficiency of the new proposal for the calculation of the carrying capacity is demonstrated against a wide amount of test results.

About ferritic stainless steels only, the Steel Construction Institute (SCI) is currently coordinating a three-year European study into the structural applications of ferritic stainless steels (SAFSS) with the aim of increasing their use in load-bearing structures. The other partners include AcerInox (Spain), Aperam (France), Arup (UK), Institute of Metals and Technology (IMT) (Slovenia), Outokumpu Stainless Oy (Finland), Universitat Politechnica de Catalunya (UPC) (Spain) and VTT Technical Research Centre of Finland (Finland), as well as subcontractors University of Liège. The project includes material and member testing as well as analytical and numerical studies. Three target applications most suited to ferritic stainless steels have been identified: lattice roof trussed and space frame structures, exposed decking in composite floor systems and signage and security structures. Its final aim is to provide design guidance to practitioners for the specification of ferritics in structures. The work packages include studies into: (*i*) Mechanical properties; (*ii*) Structural performance of light gauge members; (*iii*) Structural performance of steel decking in composite floor systems; (*iv*) Structural performance at high temperatures; (*v*) Structural performance of bolted and screwed connections; (*vi*) Structural performance of welded connections; (*vii*) Corrosion resistance; (viii) Design guidance and implementation into Eurocode 3. The study focuses on five grades with varying levels of corrosion resistance: 1.4003, 1.4016 (AISI 430), 1.4509 (AISI 441), 1.4521 (AISI 444) and 1.4621. Work package 4 called "Structural fire resistance" seeks to obtain information on the performance of structural members when exposed to fire loading. Strength and stiffness retention factors have been derived from the results of tensile tests carried out under isothermal and anisothermal conditions. The test data obtained will be employed to establish stress-strain relationships for this range of temperatures in accordance with the stainless steel model in EN 1993-1-2 Annex C [28]. In addition, a number of loaded member tests subject to fire loading have been carried out in order to calibrate a numerical model. Columns fire tests have been conducted on SHS and RHS together with identical columns at room temperature in order to fully identify the effects of the fire loading. The columns ends were fixed through a bolted end plate welded to the base of the section (Figure 4). The standard ISO fire curve was applied to the columns. The applied load was chosen as 30% of the codified buckling capacity. Table 1 provides the time and temperature at failure for the three columns while Figure 5 shows one of the failure mode characteristic of fully restrained ends with plastic hinges occurring in the middle, at a third and two thirds of the length. Furthermore, tensile tests have also been carried out at room temperature on material coupons from the members in order to establish the actual stress-strain characteristics. The aim of the study is to confirm that the ferritic stainless steel columns can provide a better buckling performance than those comprising carbon steel. These observations have yet only been validated for austenitic stainless steels.

Figure 4. Left to right – bottom end plate with holes for bolts, supporting concrete block with waiting steel bars, column top end with plate mounted on concrete block.

Table 1 **Times and temperatures at failure.**

#	1	2	3
Section (mm)	80 *x* 80 *x* 3	80 *x* 80 *x* 3	120 *x* 80 *x* 3
Length (mm)	3000,0	2500,0	2500,0
θ_{tests} (^{o}C)	709,4	707,7	705,0
T_{tests} (min)	12,15	12,00	11,85

Figure 5. **Failure mode for the specimen # 1 (3m long).**

3 Sustainability

3.1 Introduction to sustainable constructions

Sustainability often refers to the junction of social, environmental and economic aspects or described as the topic that takes into account cultural-social (comfort, space, shelter, security, respect, aesthetic, history, heritage…), environmental-ecological (potential impacts, resources, waste, toxicity, recyclability…) and economic (cost, investment return, durability, longevity…) facets. Everyone agrees that sustainability should be accomplished in each domain, at each stage of the product life and that appropriate methods and data should be made available for its long-term measurement.

The construction industry is recognised as “a vitally important sector manufacturing the built environment and putting in place a physical stock of facilities and infrastructures that determines our degree of freedom and flexibility for anything up to 100 years after construction” (ICLEI). In the current context of resource depletion, the sector plays a quite important role: it uses the greatest deal of raw materials, is the most energy consumer than of all European industrial sectors and the most contributor to world solid waste. It has a significant impact, both in positive and negative terms, on society and environment, and is thus a key sector for sustainable development. After its fast development over the past century – such as remarkable progress in material science and erecting technologies – there remain dozens of challenges at each stage of the life cycle of any edifice that may contribute to sustainability. We are facing an increasing complexity of the demand to achieve sustainability in the whole production chain.

Life cycle assessment (LCA) is one of the methods increasingly being used to assess the environmental impacts associated with the entire life of construction works, including the materials from which they are made. Merely looking at building LCA, the literature shows that the use phase has the highest environmental impacts (62 to 98% of the total), while the construction and dismantling phases account for much less [29]. So, trying to reduce fluxes (energy, water and waste) during the utilisation phase seems to be the first action to achieve in buildings. As a result of this, so far, most of the research was centred on building energy efficiency while the other phases were rarely addressed. However, with ever-growing concern on green technologies for generating energy in buildings, the system boundaries have crucial importance: the design, execution and end-of-life (EOL) phases are as essential as the use phase in view of sustainability.

In structures, recent years have seen an increase in the use of structural materials owing to their durability (resistance to corrosion, longevity of aesthetic and mechanical properties) and high (even ultra-high) strength and the designers have nowadays the possibility to create more slender and lighter structures and subsequently reduce the transportation costs as well as foundation size. Furthermore, environmental EOL strategies are carefully studied. Recycling is becoming more widespread but, except for metallic materials, it often implies downgrading of the material, and reusing the material in this downgraded form, whereas selective dismantling and reuse of components result in significant environmental and economical benefits. The comprehension of the recycling methodologies is mandatory for selecting environmental EOL strategies at the design stage.

3.2 Stainless steel advantages and challenges for sustainable constructions

Stainless steel manufacturers and retailers as well as construction engineers and architects agree to say that this material has a great potential in the market for sustainable constructions thanks to its intrinsic properties:

- Durability thanks to the protective oxide layer;
- Ease of maintenance (washable, sometimes removed and simply polished);
- Indefinitely recyclable and highly recovered at the end of its life;
- Stable in the unlikely eventuality of burying in a landfill;
- Combined with intelligent fixations, it is adaptable to future changes in the case of renovation (entire parts can sometimes be reused);
- Good mechanical properties (resistance, ductility, strength and stiffness retention at high temperature);
- It is also characterized by interesting physical properties such as low thermal expansion for ferritic grades and low emittance if polished;

As stated in the introduction, still limited examples of stainless steel used in the construction domain for its mechanical properties (resistance and ductility, retention of strength at high temperature) can be quoted especially because of the higher price of stainless steel compared to carbon steel equivalent. The use of stainless steel for its mechanical properties combined with good corrosion resistance is nevertheless growing fast especially in bridges where it is usually chosen for its attractive appearance and durability (low maintenance requirement) combined with high ductility and strength. The challenges for the use of stainless steel in structures are mainly:

- Greater cost especially for families containing nickel;
- Larger deflections owing to the nonlinear stress-strain curve (stiffness decreases as stress increases);
- Higher expansion coefficient than carbon steel equivalent (in restrained structural frames, additional forces develop at high temperature) except for ferritic grade.

3.3 Environmental assessment scoring methods for buildings

LEED (Leadership in Energy and Environmental Design) is a voluntary certification system developed by the U.S. Green Buidling Council (usgbc.org) since the nineties. It is 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. As underlined in [30], (1) the system awards points to low Volatile Organic Compound (VOC) products whereas no points are given to materials with no VOC emissions (like stainless steel); (2) the system associates no point to material longevity and it isn't possible to obtain more points when longer service life is offered; (3) products suppliers have worked actively in order to associate extra points to "green" or "certified" products. The same author also mentions that two parts of the scoring system can be favourable to stainless steel use in buildings: heat island effect and optimizing energy reduction. The first one 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 and the necessary testing should be performed and made available by the industry. An extremely wide amount of surface finishes is available. In [31], description of the standard mill finishes and the mechanically treated surfaces finishes indicated in EN10088-2 are provided. To determine the effect of the reflectance and emittance on the surface temperature, the Solar Reflectance Index (SRI) (incorporating both solar reflectance and emittance) 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 [32]. Moreover, smooth, bright metallic surfaces will be characterized by directional reflection of light (low roughness, low dispersion) while ceramic (high roughness, high dispersion) for instance will be characterized by a diffuse reflection. 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. Alternating stripes of matt and mirror polished finish can also be used to control this parameter. It is thus possible to recommend the finish, depending on the application, to control the SRI. If detrimental to comfort (dazzling of pedestrians) or security (air or road traffic applications), a matt patina should be advised. The other advantages of stainless steel in regard to LEED are: long service life, high recycled content and recapture rate, stainless steel has low roof runoff that could make filtration unnecessary for obtaining valuable non-potable water, material reuse if renovation.

BREEAM (Building Research Establishment Environmental Assessment Method, breeam.org) is an environmental assessment method designed for many building types: retail offices, education, prisons, courts healthcare etc. It was established in 1990, frequently modified, especially in 2008. It provides the user with a scoring system addressing environmental issues that should have a positive influence on the design, construction and management of buildings. In 2009, BRE and the French Centre Scientifique et Technique du Bâtiment (CSTB) decided to work together to develop a unified European method. In France, the equivalent standard is the so-called Haute Qualité Environnementale (HQE, ademe.fr, assohqe.org) that specifies criteria for managing the impacts on the outdoor environment and creating a pleasant indoor environment. In Belgium, the Bureau de Contrôle Technique pour la Construction (SECO) initiated the VALIDEO (valideo.org) system in 2008. The system focuses on (1) the construction site and the construction management (location, waste management, materials choice, reassignment potential); (2) operational resources, water and waste management; (3) comfort and health; (4) social value of the building (accessibility, tally of life).

In summary, in the scoring systems, the energy performance of buildings (use phase) and associated emissions is the most highly weighted factor. Stainless steel outdoor cladding and roofing have important roles to play in this category: long-term appearance, durable surface finishes, low maintenance, high SRI, integration of renewable energy technologies, protection against air leakage, heat losses or air infiltration, highly glazed façades… The embodied environmental impacts, recycled content of the materials, recycling/reuse potential, in-situ reuse are also considered. Construction site waste management through manufacture off-site may also be accounted for in scoring systems.

3.4 Structural aspects

The previous paragraph focuses on the existing certification scoring systems for buildings and, on the same occasion, on the use phase during which stainless steel can be of interest thanks to its durability and high SRI mostly. But stainless steel presents other important features that should be underlined as regards sustainability:

- Corrosion resistance in aggressive environment;
- Great ductility especially for the austenitic family;
- Good strength and stiffness retention at high temperature.

This time, stainless steel alternative is chosen neither for its aesthetic expression nor for its “green” properties but for structural ability: its structural durability in special environments or against accidental situation. If in aggressive environments (structures facing the sea, bridge crossing seaway or swimming pools), stainless steel is often chosen as the alternative. 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. Another example concerns the use of stainless steel reinforcements in concrete bridges crossing the sea, numerous studies,[33] to [35], are undertaken to assess the economic interest of such applications. As also stated in the introduction, the ductility or fire resistance of stainless steel is also the topic of many recent researches: behaviour of stainless steel connections, structural sections exposed to fire, stainless steel blast barriers etc, [36] to [39]… 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.

3.5 Standards for the assessment of sustainability & Life-cycle analysis (LCA)

The life-cycle analysis (LCA) is generally cited as the most important method in the construction domain to assess sustainability. It is generally 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 product evaluated (Life cycle inventory, LCI) and the corresponding potential impacts (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, 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 (global warming). 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 effect. A GWP_i is calculated over a specific amount of time (conventionally 20, 100 or 500 years).

LCA was mainly developed for designing low environmental impact products. The interest of using LCA for entire buildings evaluations began to rise in the last decade and, today, several building LCA tools are under development in different countries. The general LCA methodology is defined in [40], [41] and its application for construction products and entire building is now described in European standards, some of which are still under progress under the guidance of the Technical Committee CEN/TC 350 "Sustainability of construction works" 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. Quantitative indicators for the environmental, social and economic performance of buildings are (or will be) provided.

Most importantly, EN 15804:2012 [42] 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.* This European Standard is part of the aforementioned suite of standards that are intended to assess the sustainability of construction works (Figure 6).

Data provided in EPD are based on LCA and the information may cover different stages. Mainly two EPDs exist plus a third one which may include an optional stage:

- "*cradle to gate*": The product stage only: raw material supply, transport, manufacturing and associated processes are included (modules A1 to A3 in EN 15804:2012);
- "*cradle to grave*": The product stage (modules A1-3), installation into the building (modules A4-5), use and maintenance, replacements (modules B1-7), demolition, waste processing for reuse, recovery, recycling and disposal (modules C1-4) are included.
- "*cradle to cradle*": Same as in previous EPD plus the information module D "*Benefits and loads beyond the system boundary*". The presence of module D in EN 15804 allows credits to be taken now for the eventual reuse or recycling of material in the future.

For metals, the inclusion of module D is of prime importance because they are indefinitely recyclable. This is explained in the next section.

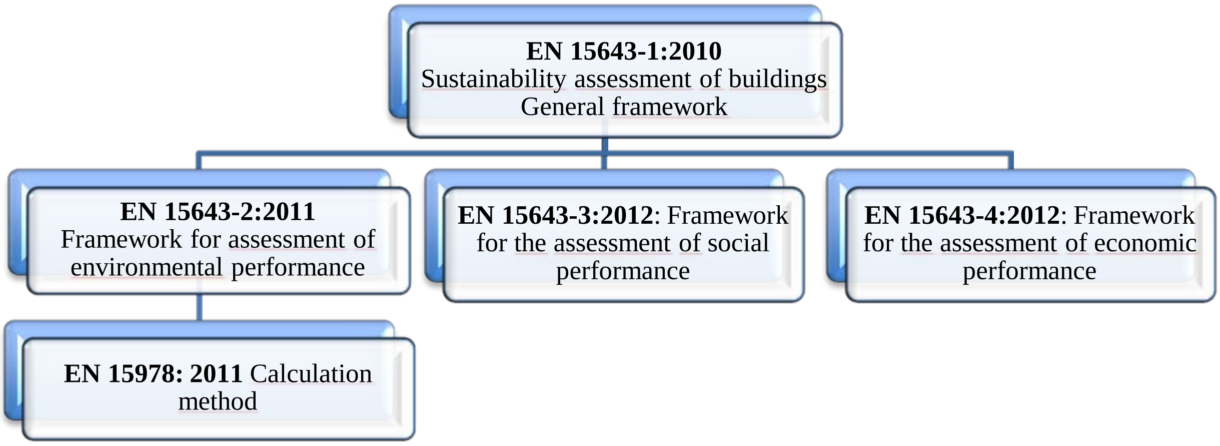

Figure 6. European standard suite for the assessment of the sustainability of building (credits to [43])

3.6 Cradle-to-gate including module D (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: 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 drawn into smaller diameters as in 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 helps promote the passive surface film that naturally occurs). 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): even if 100% of the available material is returned, the recycled content may not increase! It may even decrease!

Table 2 Stainless steel recovery rates per application sectors, sources: ISSF and recycle-steel.org (2010).

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%

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.

How are we supposed to take into account the EOL stage within LCA of metals? The life cycle stages taken into account in LCA must include the EOL credits and loads and those should be 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 provides the methodology to follow in LCA in order to include the EOL treatment and recycling, see [44] to [47]. This methodology is inline with the rules described in EN standards.

The principles of World Steel 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), what we will call 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.

Let first consider Global Warming Potential (*GWP*, [kg eq. CO_2]**)** as our main indicator, at the end of the life:

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

And so, the LCA indicator including EOL credits and loads is,

$$GWP = GWP_{prim} - (RR - S) \cdot Y \cdot \left(GWP_{prim} - GWP_{rec}\right). \qquad (1)$$

The same reasoning can be made for any LCA indicator, namely X herein,

$$X = X_{prim} - (RR - S) \cdot Y \cdot \left(X_{prim} - X_{rec}\right). \qquad (2)$$

Second, let consider an indefinite number of cycles n, the total mass of material produced is:

$$M = 1 + Y \cdot (RR) + \ldots + (Y \cdot (RR))^{n-1}, \qquad (3)$$

in which when $n=1$, we have 100% primary materials production.

While the total LCA indicator X

$$X = X_{prim} + Y \cdot (RR) \cdot X_{rec} + \ldots + (Y \cdot (RR))^{n-1} \cdot X_{rec} \,. \qquad (4)$$

And so, per kg of material, our indicator is provided by (4) / (3) which can be rephrased in

$$X = (X_{prim} - .X_{rec}) \cdot (1 - Y.\,(RR)) / (1 - (Y.\,(RR))^{n}) + X_{rec}\ , \qquad (5)$$

using the definition of the sum of the terms of a geometric series.

When n tends toward ∞, this ratio becomes

$$X = X_{prim} - RR \cdot Y \cdot \left(X_{prim} - X_{rec}\right). \qquad (6)$$

In the case of stainless steel, no extreme production routes exist: one cannot straightforwardly say that the recovery of x tons of scrap will save y tons of CO_2 emissions. In this case, X_{prim} and X_{rec} must be calculated. The original data are the factory data (based on average on 60% scrap material and 40% primary material) for which the manufacturer knows exactly the scrap inputs (mass of each scrap input: 1.4301, 1.4401…) and primary material inputs (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 be considered [46]. Doing so, it is possible to compute theoretical indicators: the first one (X_{prim}) considers 100% of primary material in the production process and the second one (X_{rec}) considers 100% of scrap in the production process.

3.7 Life cycle environmental potential impacts

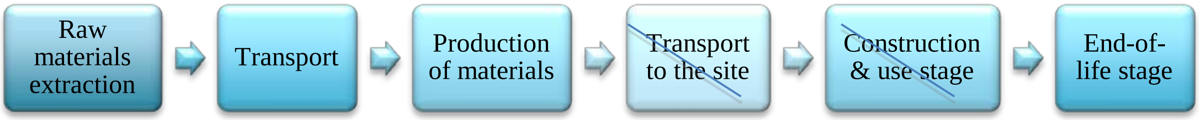

Figure 7. System boundary [43]

This section presents two potential environmental impacts considering the production of crude stainless steel including the rolling processes and thermal treatments as well as the EOL credits and loads considering World Steel methodology. 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 kg of either CRC or QP. The study is a cradle-to-gate study: it covers all the production steps from raw materials "in the earth" (i.e. the cradle) to finished products ready to be shipped from the factory. The construction and operation stages or the transport to the construction site are not included in the analysis (Figure 7). It also includes the credits and loads associated with the recycling (Module D: Benefits and loads beyond system boundary). Two potential impacts are calculated: Global Warming Potential (GWP, kg CO_2-eq. / kg) and Primary Energy Demand (PED, MJ / kg). The characterization factors are taken from [48]. Figure 8 and Figure 9 present the results for 1 kg of CRC made of 1.4301 and 1.4401 austenitic grades, 1.4016 ferritic grade and last 1 kg of QP made of 1.4462 duplex grade considering three different *Recovery Rate* underlining the importance of Module D in LCA. The PED is generally divided in energy from renewable resources and energy from non-renewable resources as depicted in Figure 10.

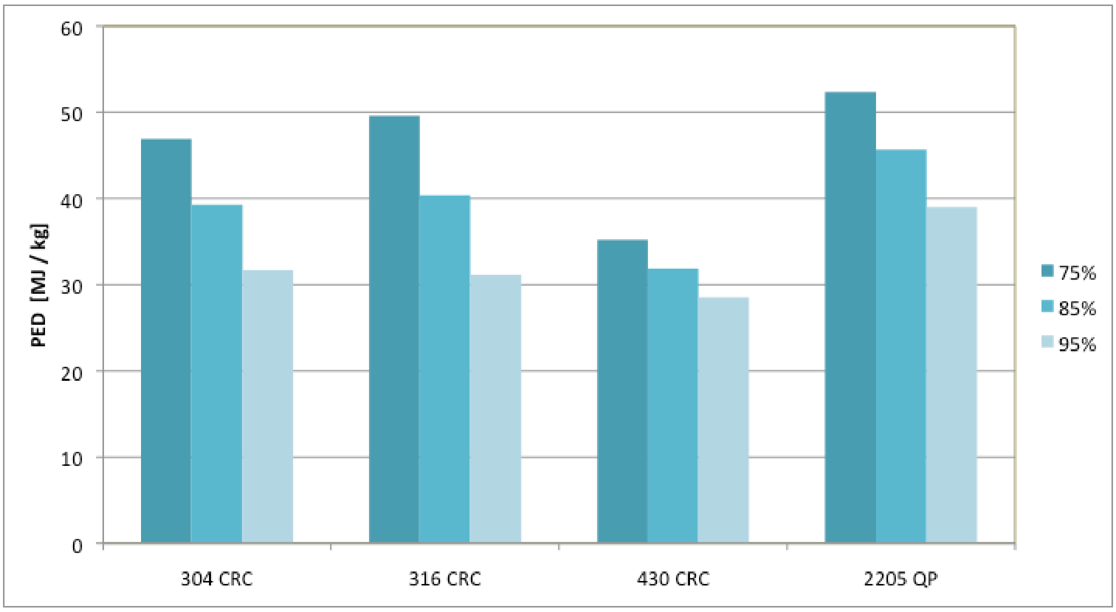

Figure 8. **Primary Energy Demand for four grades considering three recovery rates.**

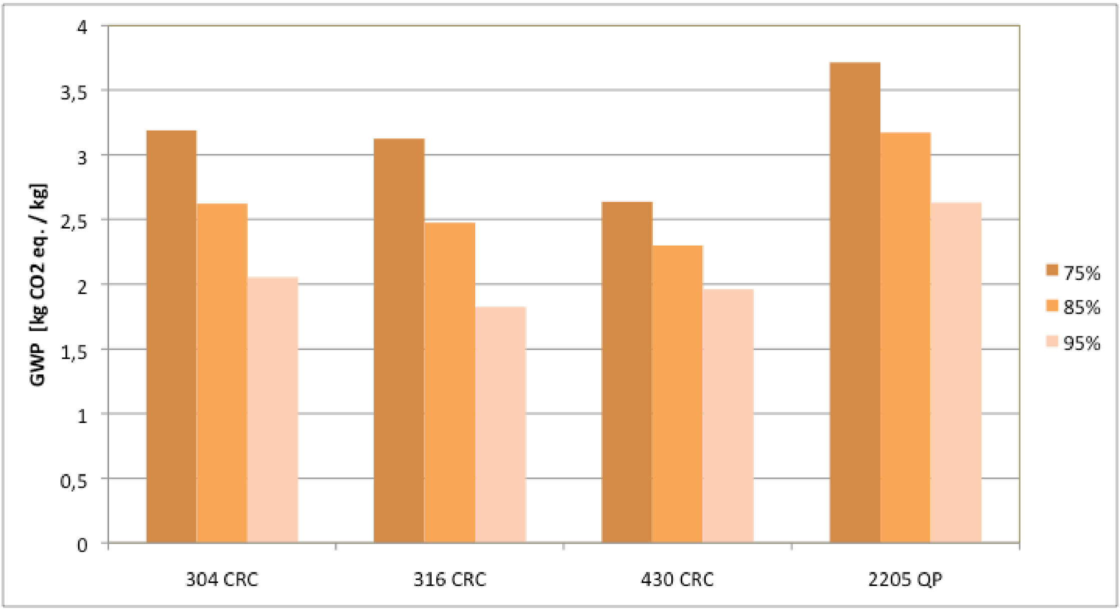

Figure 9. **Global Warming Potential for four grades considering three recovery rates.**

Outokumpu has also released an EPD for a declared unit of 1 ton of cold-rolled stainless steel for various applications for building and civil work [49]. 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 1,85kg CO_2 eq./kg. For this analysis, an average recycling rate of 85% is chosen together with 60% of scrap input.

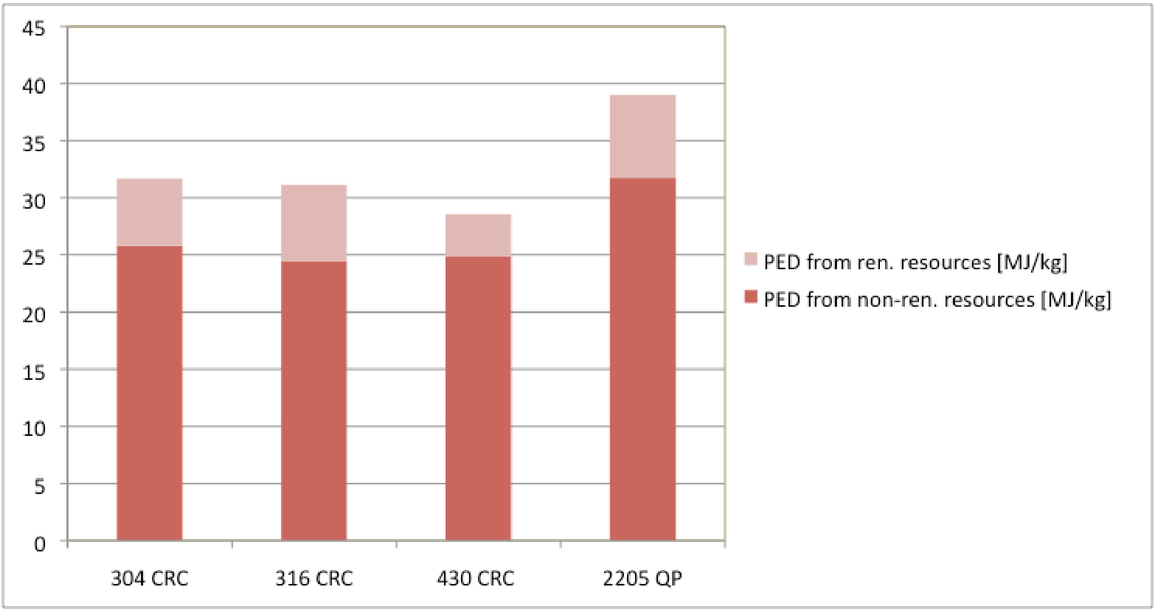

Figure 10. **Primary Energy Demand divided in Renewable and Non-Renewable resources for four grades considering 95% of recovery rate.**

4 conclusions

Stainless steel use in building envelope applications dates as far back as the 1920s. Numerous examples of austenitic grade used in building façades can be quoted. Above all, for the reason that stainless steel has excellent corrosion properties, which makes its pleasing aesthetic appearance long lasting. Looking at life-cycle management, stainless steel requires no maintenance or coatings. The result is a sustainable design with low maintenance costs and low environmental impacts that generates long-term value to the building owner. Certainly, the use of such a durable material has saved the owners considerable expense over the years.

Other than that (long-term appearance, durable surface finishes, low maintenance), stainless steel outdoor cladding and roofing have important roles to play with respect to sustainability: high Solar Reflectance Index; protection against air leakage, heat losses or air infiltration; ease of integration of renewable energy technologies; low roof runoff which is interesting for obtaining valuable non-potable water. Specifically, in this paper, four grades are described in terms of two environmental potential impacts: Primary Energy Demand and Global Warming Potential. Both impacts are provided considering three different recovery rates underlining the importance of module D in stainless steel LCA. The 1.4016 (AISI 430) ferritic grade, not alloyed with nickel and so stable on price, demands less energy than the other considered grades, see Table 3 summarizing the LCA results for *RR* equalling 95%.

Table 3 **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/kg]	2,0	1,8	1,9	2,6

By comparison, the same indicators for two more 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 plaster used to cover exterior wall surfaces. The FU is one square meter of wall finish. The interested reader can refer to http://ws680.nist.gov/bees/ to obtain (1) the product list; (2) the description of the FU; (3) the system boundary for each product; (4) the considered EOL scenario. Those data, indicated in Table 4 should only be considered as order of magnitude as the comparative analysis does not include any sensitivity analysis.

Table 4 **Indicative environmental potential impacts for 1 m^2 of three different wall finishes.**

	PED [MJ / FU]	GWP [kg CO2 eq. / FU]	EOL scenario
Trespa	759,3	23,9	50% reuse + 50% landfill
Generic stucco	144,2	12,7	not recycled
Stainless steel 0,5mm	140,5	7,2	*RR* = 95%
Stainless steel 0,8mm	191,7	11,3	*RR* = 95%

However, as stated in this paper, some other characteristics are nowadays taking an important place in the decision making process at the design stage: its corrosion resistance properties still but taken as an advantage (economic and environmental) in structural applications (e.g. rebar in marine environment, structural members used in offshore applications or swimming pools); its mechanical properties such as the ones offered by duplex grades sharing the advantages of austenitics (great ductility, corrosion resistance) and ferritics (higher strength) profitably used in bridge design; strength and stiffness retention at high temperature offering superior fire resistance; when the building is no longer in service, it is highly likely that the materials will be recycled; last, as for steel, higher strength material obtained by cold-working are also available and, if in a range of compact to medium slenderness, can positively influence the material consumption leading to lighter structures, lower transportation costs and smaller foundations. Life cycle cost analysis is generally performed to evaluate the relevance of the use of stainless steel under these circumstances.

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