JERNKONTORET RESEARCH

EVALUATION REPORT

D 851

The Steel Eco-Cycle

ENVIRONMENTAL RESEARCH PROGRAMME

Closing the loop in the manufacture and use of steel in society

Programme Evaluation

2004-2012

MISTRA

The Swedish Foundation for Strategic Environmental Research

www.stalkretsloppet.se

Executive summary

In 2012 a report entitled "Turn down the heat: why a 4°C warmer world must be avoided" was released by the World Bank Group [1]. The possible severity of the global environmental state received massive attention in the media worldwide. The first two sentences in the foreword written by Dr. Jim Yong Kim, President of World Bank Group, state the following:

"It is my hope that this report shocks us into action. Even for those of us already committed to fighting climate change, I hope it causes us to work with much more urgency."

Already in 2004, the Swedish steel industry, in close collaboration with academia, research institutes and the Swedish Foundation for Strategic Environmental Research (Mistra) launched the first truly holistic research programme, in one of the world's most energy-intensive industries, with the aim of increasing the energy and resource efficiency by closing the loop in the steel life cycle. The eight-year long programme, entitled The Steel Eco-Cycle, was completed in 2012 and the potential environmental as well as economic benefits associated with the development and use of advanced steel is now reported.

The programme's cross-disciplinary approach, along with its strong financial support, has shown how Sweden can be world leading within the field of eco-friendly as well as resource-efficient production and use of steel. The results consist of process optimisations and pilot plant trials along with instrument and model developments. The environmental and economic potential of the programme has also been quantified in order to aid decision-makers in their implementation of new process technology and use of products supporting a sustainable development.

While decreasing the environmental impact, the research addresses a large number of opportunities that are set to play a key role in maintaining and increasing the competitiveness of the Swedish steel industry on the global market. This report describes the extensive work undertaken in order to fully utilize the environmental benefits associated with the fact that steel, a key construction material in modern society, is not a consumable but a permanent material capable of being recycled infinitely. It clearly shows that environmental and economic gains are not contradictory.

In order to proceed towards a sustainable society, it is crucial that the environmental issues are treated scientifically and that a life-cycle approach is adopted within the industry as well as within the society as a whole. The Steel Eco-Cycle research shows that the development towards even stronger and more resistant steel is a very powerful part of the solution to climate change. Unfortunately, this is currently not emphasized in the climate debate.

Mistra´s launch of the Steel Eco-Cycle has given the programme participants tools to tackle new environmental requirements in a professional manner.

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Introduction

Historical aspects

The use of metals has had a dramatic impact on the development of humanity, from ancient times to the modern era. Today, our industrialized society is constructed out of steel which is illustrated by the enormous amounts of material incorporating steel produced worldwide. In 2012, for example, annual global steel production amounted to 1.5 billion tonnes [2], a quantity corresponding to approximately 5 times the weight of the living global human population [3]. The steel use of a modern country is strongly related to its degree of industrialization. During the transition from an agricultural to an industrial society the steel consumption will increase drastically. This has been shown historically in e.g. Europe, North America, Australia and Japan, and the same phenomenon is currently repeating itself in China, India and other developing countries. The dramatic recent increase in Chinese steel demand, along with the more slowly increasing markets in India and Brazil, is illustrated in Figure 1.

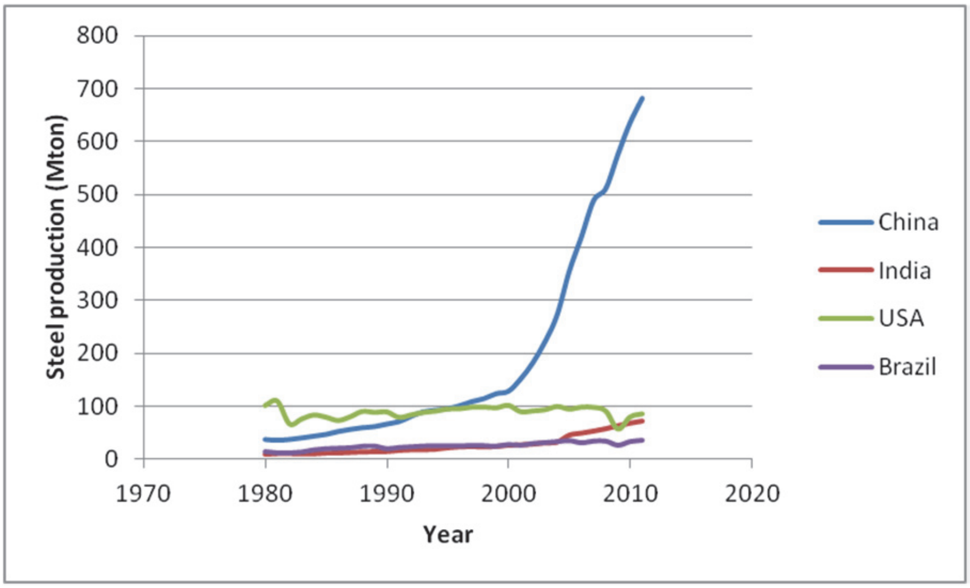

Figure 1. Annual steel production during the period 1980-2012 in China, India, USA and Brazil [2]

When studying Figure 1 it is clear that US steel production, in contrast to the others, has been more or less constant during the last 30 years. This is not due to a lack of development in the society but rather related to several of the properties of steel. As the process of industrialization begins, the national demand for steel rapidly increases. Steel is needed in order to construct buildings, bridges, cars, consumer goods, industrial equipment etc. Once produced, the demand for replacement products will be relatively low, on average 20-30 years, due to the long lifetime of steel products.

This has two important implications. Firstly, the national increase in steel demand will be highest during a nation’s industrialization phase and lower once the country is industrialized. Secondly, the total amount of recycled steel will, in practice, never reach the total produced amount, no matter the efficiency of the recycling process. This is due to the fact that significant amounts of the material are invested and used in society; it is available for recycling only when considering long time periods of several decades. Figure 1 illustrates that China is currently in a very expansive phase while *e.g.* India and Brazil have only started the expansion process.

The global production of materials in general has increased rapidly during the period of the Steel Eco-Cycle programme. Figure 2 illustrates the sustainability problem associated with the increasing demands for materials and energy, particularly in the rapidly developing economies like China and South Asia. There is an obvious need for solutions that can increase the energy and resource efficiencies.

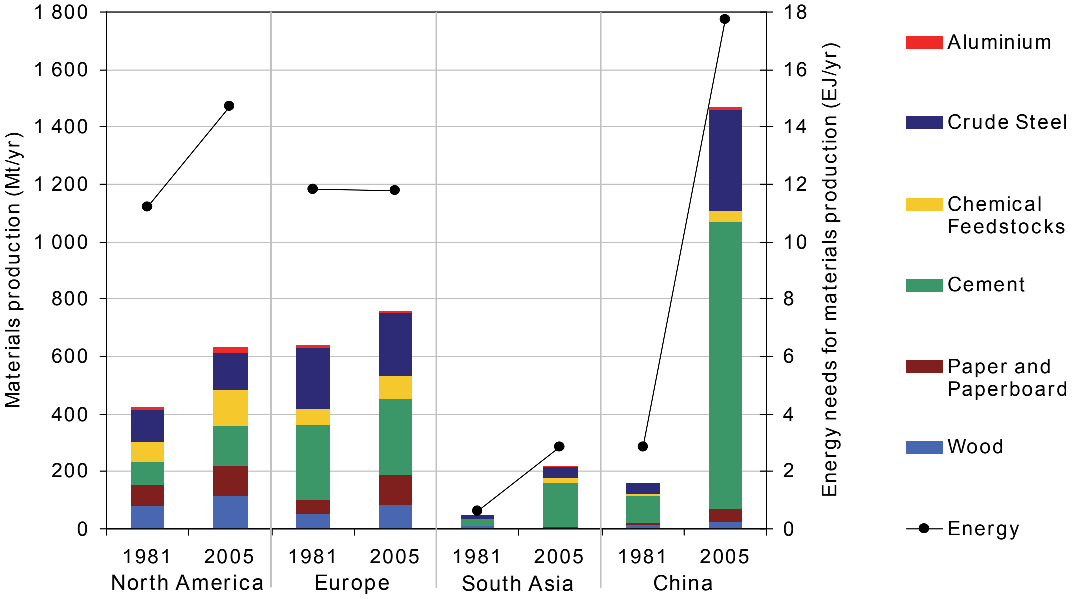

Figure 2. Production of materials and use of energy 1981-2005 (source IEA)

The use of steel in Europe is also increasing, although at a lower rate compared to southern Asia. The consumption of steel in the EU27 countries was 313 kg per capita in 2011, compared to 337 kg in 2001, a decrease of 7 % (w/w). In Sweden, the development has been different; the consumption was 425 kg in 2011, compared to 348 kg in 2001, *i.e.* an increase of 22 % (w/w). This increase in steel consumption illustrates the need for a holistic research approach covering all aspects of the steel eco-cycle.

State of the European steel industry

In 2009, the European Commission released a report entitled “Study on the Competitiveness of the European Steel Sector – ENTR/06/054” [4]. Along with the latest facts and figures, the report includes a SWOT analysis which highlights the current and future challenges of the European steel industry. Part of the SWOT analysis is summarized in Table 1.

Strengths	**Weaknesses**
• Product development leadership and high quality output with focus on value creation • High R&D capabilities	• Dependence on imported raw materials • Energy intensity of the industry
Opportunities	**Threats**
• Upstream process and raw material efficiency • Cleaner and safer technologies • More efficient technologies and processes and intelligent manufacturing • Partnerships as platform for innovation and new market opportunities • Cooperation with scrap suppliers to improve the organization of recycling • High-end products and value creation	• The competition from other countries • Imbalances in demand and supply for raw materials • Access to energy and malfunctioning energy markets • Environmental legislation

Table 1. Part of the SWOT analysis presented in the European Commission’s report “Study on the Competitiveness of the European Steel Sector – ENTR/06/054”

The report [4] concludes that the EU steel industry "focuses on high quality products, product innovation and value creation supported by technological development, efficiency and skilled manpower. The report states:

"The steel sector is confronted with major challenges, notably in terms of costs and access to raw materials and energy, which have a serious impact on the industry's performance. Moreover, the increasing capacity, production and international engagement outside the EU constitutes a threat as market share is being lost to non-European countries such as China, the C.I.S., India and Brazil. Furthermore, the EU steel industry is vulnerable vis-à-vis the new and expected tightening of (EU-specific) environmental legislation."

Research and development should therefore be focused on securing the supply, reducing the demand and reducing the cost of raw materials and energy. Increased resource efficiency together with cutting edge technology for recycling and waste utilization would address this challenge directly and also prepare the EU for the expected tightening of environmental legislation.

Still in 2012, on-going high-level round table deliberations on the future of the European steel industry emphasize the importance of a reinforced development of high-grade speciality steel, an increased focus on life-cycle approaches, increased resource and energy efficiencies along with strong focus on fair environmental regulations and environmental trade systems[5].

As the Steel Eco-Cycle shows the production and utilization of resource efficient, high strength steels for low weight products and structures would also have a large impact on the resource and energy efficiency of additional industries such as the manufacturing industry and the transport sector.

Background to the Steel Eco-Cycle programme

As in the rest of Europe, the Swedish steel industry is today highly specialized and globally competing with high quality products rather than high quantity, low-cost production. The European SWOT analysis presented in Ref. [4] overlaps to a large extent with analyses performed by Swedish industry and academia. Many of the fields of actions proposed in the report were identified already 10 years ago by Swedish companies and organizations. This was the major reason that the research programme, The Steel Eco-Cycle, was suggested in 2004. The programme was designed to transform end-of-life and residual products of the steel industry into useful, eco-friendly and financially beneficial resources, *i.e.* to close the loop of steel making while still continuing to improve the quality of newly produced Swedish steel products.

The research programme has been unique in its holistic and multi-disciplinary approach, including everything from human attitudes to process development and optimisation, theoretical modelling and technical hardware development throughout the whole lifecycle of steel from material production to residual material handling. All research has been carried out with social, economic and environmental values in close consideration.

The value of this unique research approach, which involves industry as well as academia and research institutes, is multiplied since several of the industrial opportunities and strengths are realized and utilized simultaneously. Several of the industrial weaknesses and threats are, in practice, interdependent which makes the holistic approach even more appealing if not necessary. For example, turning a residual product such as vanadium-rich slag into a useful resource does not only imply development and implementation of clean technology but it also increases the efficiency of the steel making process while decreasing the dependence on imports of virgin raw material. It saves energy and reduces landfill use, *i.e.* it has direct as well as indirect environmental benefits which diminish the threat of changes in the legislation, while lowering production costs for the industry and providing a good example to the public of the cleanliness of Swedish steel industry. The focus in the Steel Eco-Cycle has been to evaluate the environmental parameters *i.e.* the improvement potential of the material, the carbon dioxide and energy efficiencies of the research and also to estimate the economic benefits.

Significance for resource efficiency

To increase the resource efficiency of a product or process is always beneficial. However, the concept is given different meanings in various contexts. The traditional unit when discussing or trading steel products is X € per tonne material, *e.g.* the cost of steel is X € per tonne or the CO_2 emission associated with steel production is Y tonnes of CO_2 per tonne of produced steel.

When evaluating the environmental impact of products, life-cycle analysis (LCA) is commonly used. The basic unit in LCA is the so called functional unit, *i.e.* a unit based on the purpose and use of a certain product. For example, in a roof construction situation the functional unit may be an amount of material related to a certain area rather than an amount of material of a certain weight. A high strength steel capable of lowering the weight of a structure by 50% by only using half the amount of material may definitely be beneficial compared to using twice the amount of a traditional steel even though the energy consumption and cost of production per tonne material may be slightly higher when producing the high strength steel.

As this report shows, the resource efficiency per functional unit is often significantly increased when replacing traditional steel with high strength steel, even though the energy consumption and cost of production per weight unit of steel is slightly increased. To communicate and establish the concept of functional unit with steel customers, as well as with decision makers and the public is crucial in order to realize the possibilities of high strength steels.

The research in the Steel Eco-Cycle programme clearly illustrates and quantifies the advantages of using high strength steels instead of traditional steels and describes how the slight increase in energy consumption and cost of production per weight unit is compensated many times over by its corresponding increase in function and durability. These tools developed are crucial instruments to educate and inform about the benefits of high strength steels, a crucial step in implementing truly eco-friendly materials. Many of the beneficial factors of high strength materials are also multiplicative, *i.e*. if a high strength steel can decrease the amount of energy needed to produce the material for one functional unit by 1/2 and simultaneously increase the lifetime of the same functional unit by 2, the gain in resource efficiency is a factor of 4.

The Steel Eco-Cycle research shows that this magnitude of increase in resource efficiency is realistic today and the environmental as well as the economic benefits are quantified and reported. The research also focuses on the increased quality of scrap handling and yield of metals in melting processes. The close cooperation between the Swedish steel industry and the users of advanced steel will give Sweden a strong competitive edge in this field also in the future.

Significance for residual products or raw materials

High quality products imply narrow tolerances on material properties, putting high demands on the raw materials and processes used. Furthermore, high quality products often result in high value residual products. For example, an efficient recycling of expensive alloying elements would have dramatic direct and indirect environmental benefits along with a significant economic value, all the while lessening the dependence of Sweden on the global raw material market. There are, therefore, several industrial incentives to recycle residual materials and to optimise their processes in order to further improve the end-products or to maintain the quality of the products while using lower quality raw materials.

All materials degrade to some extent over time. In practice, this is often one of the most crucial properties of a material to determine its usability. Plastics, polymers, steel or other metals are known to degrade through corrosion and the rate of corrosion often defines the lifetime of a product. However, there is one crucial property which differentiates metallic materials from most other. Even though all materials are degradable on a macroscopic level, only atomic materials such as metals and steel are non-degradable on a microscopic level. This is unlike molecular materials such as plastics and polymers. This makes steel intrinsically indestructible and also infinitely recyclable.

The principle is clearly illustrated by comparing the re-melting and re-forming capabilities of *e.g.* a tin soldier compared to a plastic toy. Whereas the first can be reproduced simply through melting and re-forming, the other would need complex chemical processes in order to restore its former state after melting. This is due to the fact that the fundamental building blocks of plastics are destroyed in the heating process while the building blocks of metals are indestructible by nature. The potential to efficiently recycle one of the world's most widely used construction materials, steel, is consequently very high.

The non-degradability of metals, along with the long lifetime of steel products, imply that the amount of steel scrap which will be available within the next 30 years is, to large extent, already determined. The global steel production is also predicted to almost double in the next 40 years resulting in even larger future scrap volumes. In 30 years' time approximately 1.5 billion tonnes of steel scrap will be generated annually, material which is already produced and currently being used in *e.g.* infrastructure and consumer goods. This is three times the amount of scrap generated today. The Steel Eco-Cycle research has shown that large amounts of scrap as well as other kinds of residual materials are abundant and of significant financial value. Processes, with corresponding hardware and software, capable of realizing this potential value have now been developed and industrially evaluated.

The results from the Steel Eco-Cycle programme contain novel concepts of steel making and recycling along with the quantitative and qualitative benefits and consequences of adopting the same. Along with the attitudes of the decision makers and employees of the industry, as well as those of the public and academia, it provides a unique possibility for the industry to make and implement well-founded future decisions that are economically, socially and environmentally beneficial for Sweden and the Swedish steel industry.

Conclusions

- ***Steel is a key construction material in modern society and global steel production is increasing at a high rate.***

- ***Steel recycling is well established but the global amount of scrap available is insufficient to accommodate the raw material demand in the steel industry due to its rapidly growing nature.***

- ***The amount of steel produced globally implies that an increased use of advanced steel grades and process improvements are associated with large potential environmental improvements.***

The Steel Eco-Cycle programme

The Steel Eco-Cycle was designed to pursue research related to all stages of the steel life-cycle simultaneously rather than to suboptimise one part of the process. This approach offered the industry something unique and also broadened the mind of all involved researchers by means of continuous communication with colleagues from other eco-cycle stages. The long-term research effort attacking the same problem from a large number of different angles clearly constituted a case in which the whole gets to be bigger than the sum of the parts.

Mistra´s international scientific review panel concluded the following on April 26, 2004:

"The programme addresses a very important and relevant area not only for Sweden but also in a global perspective. The competitiveness of the Swedish steel industry will benefit considerably from a successful programme." (Jean Pierre Birat, Jonathan Aylen, Rolf Steffen, Patrick Taylor and Göran A Persson).

The programme contained everything from people's attitudes to the steel life-cycle to extensive attempts to quantify the potential for steel development, use and recycling. These efforts were carried out in parallel to other programme components focused on increasing the energy efficiency of the steel making process itself. Large research efforts were also invested in how to maximize the realization of the high potential value in Swedish residual products. Scrap yard mining is truly an example of a case in which residual products associated with high economic costs and environmental risks are converted into valuable resources and raw materials. It also reduces the problem of landfill while opening up new business possibilities. In order to realize this, broad research efforts ranging from analysis of waste flows to development of analysis techniques, instruments and processes related to handling of the available rest materials were required.

Key to achieving progress ranging from blue skies research to commercialization and true industrial implementation was the close collaboration and involvement of academia, research and the industry. During the period of the Steel Eco-Cycle, cross-disciplinary brainstorming led to designs of new experiments, laboratory test and pilot plant trials. The research also led to patents and business opportunities on both a national and international scale.

Programme Board

In order to ensure that the Steel Eco-Cycle kept its high industrial relevance throughout the course of the programme, a Programme Board of key industrial representatives was appointed. The programme board also included a representative from Mistra as well as the programme director from the Swedish Steel Producers' Association, Jernkontoret. Jernkontoret was appointed host for the programme and responsible for the administrative services. The members of the programme board and their corresponding organizations are listed in Table 2.

Name	Organization
Jarl Mårtensson, Chairman*	Ovako AB
Ulf Arnesson	Stena Recycling AB
Hans Lindh	Volvo Car Corporation
Peter Samuelsson	Outokumpu Oyj
Jan Eckerlid	Svensk Kärnbränslehantering AB
Fredrik Gunnarsson	Mistra
Göran Andersson, Programme Director	Jernkontoret
**) Former Chairmen: Göran Carlsson and Martin Pei, SSAB*	

Table 2. Programme Board of the Steel Eco-cycle

Organization

Ever since the mid-18th century, Jernkontoret has had well-established contacts with leading figures in the Swedish as well as in the international steel industry. Represented by the programme director, Göran Andersson, Jernkontoret maintained a close contact and frequent communication with the Programme Board which functioned as an advisory committee. The Programme Director had the responsibility to ensure that each individual involved stayed committed to their corresponding responsibilities and that the research progressed as planned. A continuous communication between researchers and industry representatives was achieved by frequent meetings and discussions, involving not only the Programme Board and the Programme Director but also researchers and industry representatives. The structure of the organization is illustrated in Table 3.

Programme Board		
|		
Programme Director	→	Administrative service
|		
Programme components	→	Researchers / Industrial participants

Table 3. Programme organization chart

Programme participants

To achieve a successful research programme of not only academic interest but also industrial relevance, and with the capability of strengthening Swedish industrial competitiveness while benefiting the environment, a large variety of programme participants were moulded into a complex research team.

Mistra´s international scientific review panel concluded the following on April 26, 2004:

"The review panel has judged the programme on a scale high, medium, low and found the overall relevance, the originality, the scientific quality and the competence of scientists to be high. In addition, the probability to reach the programme goals is high." (Jean Pierre Birat, Jonathan Aylen, Rolf Steffen, PatrickTaylor and Göran A Persson).

The industrial value of the research was reflected in the large numbers of participating industrial companies. Several academic partners from Kalmar in the south of Sweden to Luleå in the north were included in the programme to contribute unique technical facilities and know-how regarding the latest global trends in steel-related research. Several research institutes specializing in applied research and knowledge transfer from academia into the industry were also included. This cemented the foundation of the research programme as being industrially relevant even further and helped in the communication between academia and the industry. It also greatly expanded the experimental facilities available within the research programme and made pilot plant trials possible.

A cornerstone of a dynamic and developing industry is small and medium-sized enterprises (SMEs). Several consulting as well as technical SMEs were therefore included in the programme. SMEs often operate without extensive economic margins and their willingness to participate and contribute in the Steel Eco-Cycle should therefore be interpreted as a clear illustration of the industrial relevance and financial potential of the programme. A complete list of all programme participants is given in Table 4. More detailed information regarding the individual research actors is found in Appendix A.

Industries	**Universities, institutes, consultants, associations and SMEs**
AB Järnbruksförnödenheter	Linnaeus University
AB Sandvik Materials Technology	Royal Institute of Technology
Bombardier Transportation	Luleå Technical University
Cargotech HIAB	
Green Cargo	Swedish Environmental Research Institute
Harsco Metals Sweden AB	Swerea MEFOS
Höganäs AB	Swerea KIMAB
LKAB	
Metso-Minerals	Ekerot Resources AB
MultiServ AB	Kobolde & Partners AB
Outokumpu Oyj	PM Technology AB
Outokumpu Oyj	Minpro AB
Ovako Bar AB	World Steel Association
Ovako Steel	Jernkontoret
Rautaruukki Oyj	
RHI Refractories Nord AB	
Saab	
Scania	
SSAB AB	
SSAB EMEA	
SSAB Merox	
Stena Recycling AB	
Uddeholm Tooling AB	
Volvo Car Corporation	
Volvo Truck	
Volvo VCE	

Table 4. Participating companies and organizations

Conclusions

- ***The Steel Eco-cycle is a holistic programme taking on the future challenges of the steel industry as one complex question***
- ***The eight-year long programme is designed to be transparent with a high degree of industrial insight and control***
- ***A large number of Swedish industrial companies from varying sectors are involved in the programme***

Programme components

The Steel Eco-Cycle is one research programme tackling a highly complex societal and industrial challenge with a joint effort from a large number of contributors and not a number of parallel research projects. However, the work towards the common goal, *i.e.* to close the loop in the manufacture and use of steel and to increase Sweden's competitiveness by realizing the economic potential available in an eco-friendly industry, was for practical reasons divided into several programme components addressing key issues in different parts of the Steel Eco-Cycle. The most influential companies and research actors in each part of the eco-cycle formed groups addressing well-specified problems. Each group constituted not only a close collaboration within the group itself but also took on a responsibility to inform and respond to opinions put forward by other programme members not primarily involved in the particular work. This research structure forced all involved partners to maintain the focus on the overall goal of the programme and not only on the proposed deliverables of each individual component.

Mistra´s international assessment by the scientific review panel concluded the following on April 26, 2004:

"This particular programme has a clear focus on minimizing the impact of steel production on the natural eco-system including research on CO_2 reduction, decreased energy consumption, recycling and waste minimization. This is a crucial issue of international importance. Sweden is almost unique worldwide in placing so much emphasis on steel and the environment. The proposal represents a position of world leadership in thinking about these issues". (Jean Pierre Birat, Jonathan Aylen, Rolf Steffen Patrick Taylor and Göran A Persson)

The number of programme components was kept at a level which ensured that sufficient funding could be made available in order to deliver relevant results with a high probability of achieving industrial implementation, during or soon after the end of the programme. This joint effort also enabled several of the participating companies to take part in research which for financial and practical reasons would have been impossible to conduct on their own.

The overall structure of the programme is illustrated in Figure 3. The individual programme components can be categorized in four categories.

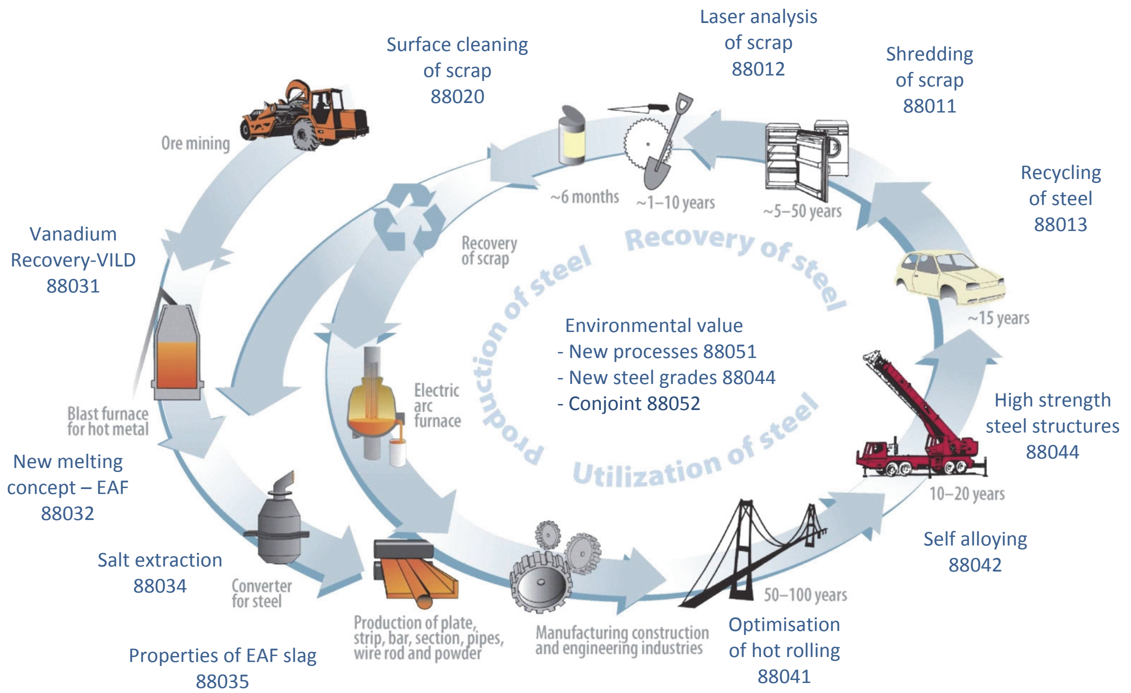

Figure 3. Overall structure of the Steel Eco-Cycle including component projects

Steel production

Steel is produced from virgin materials, steel scrap or a combination of the two. Producing ore for steel production is a necessary yet energy-intensive process. Since the global demand for steel is growing, the available scrap would not be sufficient to satisfy the need for raw material in the steel industry even if the recycling had been 100%. Since all ore mining is associated with an environmental as well as with a financial cost, it is crucial that the steel industry makes the most out of the available raw material. Steel production also leads to a residual product called slag. The slag always contains metals to some extent, metal atoms which are trapped in a residual product rather than utilized in the final steel. A slag containing expensive metal atoms is associated with a high potential value, a value which could be realized if the industry had a way of extracting the valuable fractions from the residual product.

When a metal-rich slag is sent to landfill it may leach hazardous elements into its surroundings. Had the leaching mechanisms been better understood, the leaching could be minimized which would transform the slag from a waste to a raw material used as *e.g.* a filling material in road construction, a source of nutrients in mariculture or as a construction material for tiles. The Steel Eco-Cycle has led to ways of minimizing the amount of metal caught in the slag during the steel making process. It has also developed methods for extracting the value that is available in slag, methods which are now patented and already tested industrially. The leaching mechanisms of the remaining slag have also been studied and a number of possible applications and uses of slag is proposed. The programme components related to the steel production process are briefly described below. For more detail see the corresponding scientific reports.

- ***88031 – Recovery of vanadium in LD-slag – VILD***

The project has developed several cost-efficient methods for production of vanadium products based on Swedish and Finnish LD (BOF)-slag. These have been developed and verified on pilot and industrial scale tests. One of the methods is already undergoing a commercialization process and another one is under industrial evaluation. The project, including detailed LCA analysis and initial CAPEX and OPEX studies, has shown the great economic and environmental potential of the developed methods.

- ***88032 – Optimisation of unit processes in steelmaking countering the loss of metal values in slags and dust***

Research related to minimization of metal losses to slags and dusts by studies of thermodynamic processes. Computer models have been developed and used as a tool in combination with laboratory and industrial trials. Cr-losses were significantly lowered by replacing the oxygen with CO_2 in the injected gas during decarburization of steel melts both in the EAF and AOD process. A new process was invented for Mo addition in EAF furnaces and the Mo yield was increased from 90% to 99.5% in the full-scale 70 tonne EAF. This is a significant achievement in the process optimisation of Uddeholms AB. Ovako Steel, Outokumpu Stainless and Sandvik Materials Technology have also shown strong interest in applying this process.

- ***88034 –Development of a novel process route for recovery of metal values from slags and dust by molten salt extraction***

Research, including laboratory and industrial studies on a pilot scale, related to extraction of metal from slag was performed. The project has resulted in reports on extraction, electrolysis, synthesis and condensation in this new scaled-up process. Successful electrode position of ferrochrome from the salt bath after salt extraction of Cr_2O_3-containing slags has been demonstrated. This process has been extended to the recovery of rare-earth metals from electronic wastes. Process developments towards the recovery of Fe and Mn from steel slags by oxidation-electromagnetic separation route were carried out successfully and nano manganese ferrites with optimised magnetic properties could be precipitated out of the slags by this innovative process.

- ***88035 – Leaching mechanisms and long-time quality of steelmaking slag and 88033 – Stabilization and reuse of AOD, EAF and ladle slags***

The short and long-term quality of original and modified steel slags with a focus on leaching properties was studied. Theoretical investigations on a laboratory scale as well as industrial full scale trials were conducted in order to present and develop scientifically based recommendations regarding slag compositions and handling processes with a view to making slag a marketable and valuable product. Several of the recommended techniques are today adopted and used by the Swedish steel industry.

Steel applications

Even though steel production requires large amounts of energy, the vast majority of the energy consumption related to a steel product is often not related to the production but rather to the use of a product. Some steel structures are passive during their lifetime *e.g.* buildings and bridges. However, many products are active and used in dynamic systems such as cars, trains, factory components, etc. As the research of the Steel Eco-Cycle shows, large energy savings can be achieved in the use-phase of the product by choosing more advanced steel. The Steel Eco-Cycle has addressed two challenges in the steel application phase of the life cycle; how to minimize the energy consumption when producing high strength steels and how to quantify the material saving effects of replacing traditional steels with advanced high strength steels. The programme components related to steel applications are listed below, for more detailed information see the corresponding scientific reports.

- ***88041 – Improving high strength steels with energy efficient processing routes for environmental benefits***

The project has studied how mechanical properties of steels can be maintained while decreasing the energy consumption of the production process by lowering the temperature during processing or by eliminating process steps. Laboratory and full scale pilot tests have been performed, resulting in more energy efficient rolling processes without compromising the quality of the end-product. Recommendations have been given to the strip, heavy plate and long products producers about the most promising processing parameters for obtaining the best mechanical properties of the studied steels. For example, an 80°C reduction in slab reheating temperature before rolling can reduce energy consumption by up to 8%. Knowledge from this project provides the possibility to eliminate a hardening process and improve the productivity during hot rolling of heavy plate and strip.

- ***88042 – Optimizing retained alloy elements in new steel sheet products***

Semi-products from vanadium recovery can be used for alloying instead of FeV, providing considerable savings. Less expensive alloying with recovered alloys can also decrease the use of other purchased alloys, *e.g.* Nb. 88042 ended by 2008 and transferred to 88031.

- ***88044 – High strength steel structures for reduced environmental impact***

Life-cycle analyses have been performed in order to understand and quantify the environmental benefits associated with an increased use of Swedish advanced high strength steels. The awareness of the significant upsides of using less material without compromising the durability of a structure has been raised in the industry and in the public sphere by efficient communication of the results. A numbers of case studies, software for calculation of the environmental and economic benefits and a handbook on assessing the environmental value of using high strength steel grades are all effective tools in the communication process.

Steel recovery

Even though the lifetime of a steel product can be very long, iron bridges from the 18th century and steel bridges from the 19th century are still in use, eventually all products will reach their end-of-life stage. The recycling potential in steel is very large due to its indestructible atomic nature which makes it infinitely recyclable. The recycling rate is also very high already today. It should be emphasized that the fact that the steel production is partly based on virgin material does not mean that the recycling is not 100% but rather that the global production is expanding and that the amount of steel available is not sufficient to meet the raw material needs of the industry. Furthermore not all produced steel is available for recycling since a large amount of the produced material is still used in our modern society in the form of buildings, cars and consumer goods etc.

However, the recycling process is not without its challenges. Humans tend to form complex products out of a combination of several materials which complicates the recycling process. An attractive raw material produced in a recycling plant should be relatively homogenous and not too complex in nature. The elemental content of the material should be well specified and the supply of the material should be in suitable quantities and associated with functioning logistic systems. The Steel Eco-Cycle includes an extensive survey of the past, present and future scrap flows in our society; an important tool for decision makers within the industry when it comes to adopting future techniques for scrap-based production. It is also a valuable tool for making prognoses of future scrap prices and supplies. The programme also involves the development of a fast laser-based technique for on-line scrap analysis which enables the recycling industry to further specify what kind of material they are supplying. A more well-specified material enables a better use of the material in the steel production process. The process of scrap usage within the steel plants has also been developed. A process for removing unwanted zinc from scrap by using chlorine-rich plastics, which in turn is usually considered to be a problematic waste, has been tested on a pilot plant scale with promising results. The individual programme components are summarized below and more information is available in the corresponding scientific reports.

- ***88011 – Mapping and development of the shredder product stream***

Methodologies that could be used by shredders to improve practice and products have been developed and reported. 88011 ended by 2008 and the knowledge was transferred to 88013.

- ***88012 – On-line classification of steel scrap using intelligent evaluation from a CCD-spectrometer equipped LIBS***

A laser-based technique and prototype instrument have been developed for fast on-line analysis of steel scrap. The prototype has been evaluated and tested in laboratory as well as in industrial settings. The programme component has also been part of a European research collaboration partly financed by the European Research fund for coal and steel, RFCS. The work has been awarded the Greentech award by the Swedish Association of Graduate Engineers and the 2011 prize from H.M. King Carl XVI Gustaf's fund for Science, Technology and Environment.

- ***88013 – Recycling of steel in society***

A model to illustrate the iron and steel flows in Swedish society and a new method to evaluate the alloy content in steel scrap deliveries have been developed. Furthermore, a model for steel scrap usage optimisation from the viewpoint of economy, energy and carbon footprint, named RAWMATMIX has been developed. Within the project, a method for random sampling analysis of different steel scrap piles has been evaluated to decrease the number of costly test melts for certain steel scrap classes. The project has also generated an increased knowledge within steel scrap metallurgy, which has been integrated into education in this field at KTH. An annual seminar in this field was started where industry and researchers meet at the "Scrap yard metallurgy summit". The outcome of this had led to research continuation, *e.g.* through a collaboration with China through a VINNOVA financed pre-study.

- ***88020 – Surface cleaning of steel scrap***

A method has been developed for surface cleaning of steel scrap by making use of plastic waste. The development of the concept has been through both small-scale experiments and large-scale pilot trials. Pilot-scale equipment has been constructed and erected. The concept has been tested and important lessons for the future industrial implementation of the concept have been learned. Test results have indicated successful removal of zinc and organic compounds on the scrap but further process optimisation is needed. The project has also received funding from the Research Programme of the Research Fund for Coal and Steel RFS-PR-09028, SSAB EMEA and the Swedish steel industry, through Swerea MEFOS joint research.

Environmental evaluation

In order to realize the potential industrial, environmental and social advantages related to the research performed within the Steel Eco-Cycle, clear communication is an absolute necessity. Quantifying environmental as well as economic effects of research implementation is a prerequisite for sound decision-making at the industrial as well as at the national and international levels. Estimates of the environmental effects of all projects within the Steel Eco-Cycle have therefore been performed from a life-cycle approach. However, research reports as well as declarations and promises of savings are worthless if key individuals are not open to implementing change in their corresponding organizations. The good arguments for adopting the results of the research obtained in the Steel Eco-Cycle are therefore accompanied by a research report clarifying the attitudes of industry representatives and decision-makers in order to further understand why some technical solutions are fully implemented while others are not.

- ***88051 – Evaluation of environmental impacts***

88051 has quantified the environmental impact of the Steel Eco-Cycle programme, based on assessments in cooperation with each individual programme component. The environmental data obtained, using a LCA approach, is considered a key element in the communication of the programme results. The LCA approach has also introduced comprehensive analyses of the project technologies as part of manufacturing chains, including upstream and downstream processes.

- ***88052 – Attitude and knowledge – a basis for an efficient environmental communication***

Attitudes towards environmental issues have been studied for the steel industry and its stakeholders. The project has assessed which factors influence environmental decision-making (knowledge, public concern, legislation, economy etc.) The results can be utilised in two different ways; first, key stake holders' attitudes to environmental issues have been identified and this knowledge comprises a basis for strategic environmental decisions. Secondly, an easy-to-use manual on the method used in the project has been written and can be used to conduct similar surveys in future by the industry itself.

Conclusions

- ***The programme involves research from all stages of the steel eco-cycle, from raw material handling to steel production, use and recycling***
- ***The overall goal is to improve the quality of recycled materials, to minimize the value losses in each production stage without compromising the end product quality and to produce eco-friendly and usable residual products***
- ***Quantifications of the research potential have been performed and are presented along with results from attitude surveys which enable efficient knowledge transfer and technology implementation***

Programme results

Mistra´s international scientific review panel concluded the following on April 15-17, 2008:

"The on-going programme and the proposed programme are technology development programmes with a scientific approach and led by very competent researchers from a variety of disciplines." (Louis Brimacombe, Paul Tardy, Jonathan Aylen and Göran A Persson).

The review panel noted that the contacts between academia and industry were considerably strengthened during phase one (2004-2008) and that they were key features of the proposal and for a successful implementation of research results. The programme goals in phase one were fulfilled. In fact, the energy savings and the reduction of carbon dioxide emissions were considerably higher than predicted in the programme proposal. The review panel rated the on-going and proposed programme on a scale 1 – 5 and found the overall relevance, the scientific quality, programme structure, skills and networks to be very good (3) for phase one and excellent (4) for phase two (2009-2012). The weaknesses of phase one were dealt with in the new proposal (2009-2012).

General achievements

The results from the Steel Eco-Cycle are focused on two questions. Part of the research was related to improving the processes associated with steel production. Considering the whole steel eco-cycle, our evaluation shows that substantial energy savings, reduced carbon emissions and cost reductions can be achieved in the Swedish steel production. In addition to this, large environmental and economic benefits associated with an increased use of advanced high strength steel have been shown.

Two very important conclusions can be formulated, for detailed reasoning see Appendices B and C.

1) A reduction of energy consumption or carbon emissions in the steel production process is associated with even larger savings in the raw material production phase, typically by a factor of 3-6.

2) A reduction of the amount of steel needed per functional unit is directly beneficial in the steel production but most importantly, the largest environment gains associated with reduced emissions and energy consumption are in the use phase of a product or a structure.

The savings from the use phase are often ascribed to the steel users rather than the steel manufacturers. This is done even though the Steel Eco-Cycle evaluations show that a saved tonne of CO_2 emission in the production of steel when changing to a stronger steel for lighter structures is multiplied by a factor of 20-40 (see Appendix B) for active structures like vehicles when the use-phase is included.

Figure 4. Illustration of the fact that reduced CO_2 emissions from improvements in steel production typically result in 3-6 times larger savings in the raw material production stage and 20-40 times larger savings in the use phase of the finished product. This should be kept in mind when discussing potential savings from steel industrial developments. For details see Appendices X and Y.

An economic potential evaluation has been performed to convert energy savings and reduced carbon emissions into benefits in terms of an industrial and social perspective, considering the whole steel eco-cycle. The conversion shows that large economic savings can be made by optimising and adopting new process technology in steel production. In addition, even more economic benefits arise when replacing conventional steel with more advanced steel grades. Furthermore, such an evaluation makes it possible to compare the economics associated with a reduction of energy consumption with the cost for carbon credits.

The Steel Eco-Cycle research clearly shows that the most important financial incentive is to save material resources in steel products and constructions and reduce energy consumption in the steel industry, even if the costs related to carbon dioxide emission allowances and future carbon capture costs increase. This implies that in order to have an effective driving force for the change to a more sustainable society, the incentives should rather be related to material and energy savings in combination with reduced carbon dioxide emissions instead of solely related to carbon credits.

Potential in process improvements

The environmental value of the Steel Eco-Cycle including each individual programme component has been evaluated by the Swedish environmental institute IVL, based on present ISO standards. The results for eight process improvements are found in Appendix X. The savings are expressed in three quantities, energy, carbon emissions and raw material savings, assuming that developed technology and methods are adopted in the Swedish industry.

According to the environmental evaluation in the programme, the energy saving potential of the technical processes including upstream and downstream processes is 5,300 GWh/year, almost 10 times the formulated goal in the planning of the Steel Eco-Cycle research programme. Furthermore, the emissions of CO_2 could be decreased by an amount corresponding to 1 300 ktonnes/year. This is 130% of the original goal.

The distribution of the potential improvements of energy and carbon dioxide emissions between the steel industry and the raw material industry is shown in Table 5. It shows that environmental improvements in the steel industry normally result in a 3-6 times greater improvement at the supplier of raw materials. Consequently, it is necessary to have a life-cycle approach to process improvement decisions if sustainable development is to achieve a breakthrough in terms of actual results.

Description	**CO_2 (ktonne/year)**	**Energy (GWh/year)**
Raw material	1 100	4 100
Steel production	200	1 200
Total savings (Programme goal)	**1 300** (1 000)	**5 300** (600)

Table 5. Environmental value per year of the technical improvements resulting from the Steel Eco-Cycle

The carbon dioxide and energy quantities can also be converted into economic terms by inferring a price on carbon credits and energy. The Swedish energy agency publishes data on carbon credit pricing over time and, based on that data, a price of 7.5 € per tonne emitted CO_2 was assumed.

Furthermore, the energy savings were converted into SEK. Different energy types are associated with varying costs and a weighted mean based on numbers from the Swedish energy agency was therefore used. Based on numbers from 2011, the average price assumed was SEK 481.50/MWh. Concerning reduced use of alloying elements, the prices vary drastically between approximately SEK 7 000 and SEK 300 000 per tonne. In order to guarantee an underestimation of the savings the lower end price of SEK 7 000 per tonne was assumed as an overall price for all saved alloys. Concerning savings from reduced use of limestone and iron ore pellets, the prices of iron and raw limestone were used. For details and references, see Appendix C.

A summary of the financial potential in the process improvements is shown in Table 6 from which it can be seen that the major financial incentive to implement process improvements are reduced energy costs followed by raw material savings. It is also clear that improvements in the steel industry have even larger effects in the raw material industry.

Description	**CO_2 (M€)**	**Energy (M€)**	**Material (M€)**	**Total (M€)**
Raw material	8	210		218
Steel Production	1	57	69	127
Total savings	**9**	**267**	**69**	**345**

Table 6. Financial value per year of the Steel Eco-Cycle research related to process improvements

It is noteworthy that even if the price of carbon credits rises to a level of 100€/tonne, as predicted to happen in 2050 in the European roadmap [6], the total saving from reduced CO_2 emissions is 130 M€. This is still less than half of the savings associated with reduced energy consumption.

Two main conclusions can be drawn from the presented economic data. First, the economic potential for developed technologies applied to the Swedish steel industry and scrap handling industry shown in the Steel Eco-Cycle is of the order of SEK 3-4 billion per year. The value refers to the whole value chain, including the upstream value of raw material. Secondly, the ratio of economic savings due to reduced energy consumption relative to economic savings associated with reduced CO_2 emission costs is approximately 30:1 today. This implies that the economic industrial incentive to implement the Steel Eco-Cycle research is not primarily related to carbon credits but to material and energy savings and economic values associated with the latter. The future price of carbon credits is hard to foretell but even at a level 30 times that of today the savings from reduced energy consumption will equal the costs originating from carbon emissions.

It should be noted that all numbers given in this paragraph exclude the potential of using new steel grades identified from the programme component 88044 – High strength steel for reduced environmental impact. Furthermore, benefits from *e.g.* extraction of 5 000 tonnes of vanadium for re-use from slag, with avoided landfills and other environmental issues as consequences, are not included. It should also be clarified that in the figures given when estimating the potential of the research, no investment costs related to hardware or process upgrades have been considered.

Potential in increased use of advanced high strength steels

In addition to the environmental and economic gains associated with process improvements, significant savings can be achieved by replacing traditional steels with advanced high strength steels (AHSS) for lightweight constructions. Using AHSS reduces the energy consumption, CO_2 emissions and raw material demand in the manufacture of new functional units. In addition, active structures such as cars, trains, boats, industrial equipment etc. will also lead to savings throughout their use-phase because of weight reductions.

The environmental potential in light weight constructions can be exemplified by investigating the effects of increased use of AHSS in vehicles. This is desirable from a safety point of view as well as from a product improvement perspective.

Table 7 shows the potential improvements in energy use and carbon dioxide emissions if 1.3 million tonnes of conventional steel is replaced by 1.0 million tonnes of high-strength steel in the European vehicle fleet. It shows that the energy and carbon dioxide improvements in the use-phase of the products are about 20 times greater than the improvements obtained in the steel production phase.

This is yet another indication of the fact that it is necessary to have a life-cycle approach to environmental improvements *i.e.* to include the upstream and downstream improvements if decisions on sustainable development are to be implemented in practice. It also illustrates that the development of even stronger and more resistant steel is a way to increase the resource efficiency in the society.

Description	**CO_2 (ktonne)**	**Energy (GWh)**
Raw material	200	850
Steel production	500	2 150
Vehicle use	7 300	28 000
Total savings	**8 000**	**31 000**

Table 7. Potential environmental improvements when 1.3 million tonnes of conventional steel is replaced by 1.0 million tonnes of advanced high strength steel in the European vehicle fleet.

Two examples of the environmental potential in replacing traditional steel with AHSS are given in Appendix B. The first example is a passive structure, Friends Arena in Stockholm. In this building a replacement of traditional steel by high strength steel has been evaluated as part of the Steel Eco-Cycle programme. By introducing high strength steel the weight of the fixed roof was reduced from 4 584 tonnes to 4 000 tonnes which saved 1 340 tonnes of CO_2 emissions, 5.5 GWh of energy and SEK 23 million in production costs. In order to do this, a dispensation from the current codes was needed and given, which highlights the importance in keeping codes up to date if eco-friendly material use is desired.

To illustrate the potential of advanced high strength steel in active structures, the Swedish transport sector was investigated. Through life-cycle analysis the environmental and economic potential benefits of introducing a relatively moderate amount of AHSS in cars, trains and ships were evaluated. By upgrading 50% of the vehicle fleet in Sweden, emissions of approximately 4 million tonnes of CO_2 were avoided when considering the complete life of the vehicles. Furthermore, approximately 15 TWh of energy was saved and these two effects combined correspond to an economic value of approximately SEK 18 billion. It should be emphasized that roughly 90% of these savings originate from the use of the end product. Consequently, encouraging and enabling material and process development in the steel industry gives large spin-off effects in other sectors.

To obtain a Swedish projection of the Steel Eco-Cycle results, 1 300 ktonnes of the yearly production of high strength steel in Sweden was assumed to be delivered for upgrading of structures. Half of that amount was assumed to be delivered to the transport segment and the rest for passive structures. The total Swedish steel production in 2012 amounted to 4 300 ktonnes. Besides the annual environmental improvements, the economic potential has been estimated based on results from the case studies performed in the research programme and from the energy costs associated with the savings. This is further discussed in Appendix B.

The introduction of high strength steel in structures and products is an on-going process. The yearly improvement potential, based on the assumptions made above, is shown in Table 8.

Description	**Physical balance**		**Economy**		
	CO_{2e} (ktonne)	**Energy (GWh)**	**CO_{2e} (M€)**	**Energy (M€)**	**Total (M€)**
Steel production	295	1 180	2	66	68
Use of vehicles	1 000	4 240	98*	560	658
Total vehicles	1 295	5 420	100	626	726
Passive structures	560	2 285	4	130	134
Total savings	**1 855**	**7 705**	**104**	**756**	**860**
**) This figure refers to Swedish carbon dioxide tax on fuel applied on the whole volume, the Swedish part of it is 20 %*					

Table 8. Annual potential reduction in carbon dioxide emissions, primary energy consumption and the corresponding economic value if Sweden were to export advanced high strength steel for upgrading of structures and vehicles

The potential benefit of using advanced high strength steel is large in terms of reduced carbon dioxide emissions as well as in terms of increased energy efficiency. When converting the improvements to the total Swedish production of advanced high strength steel the annual potential savings are 1.9 million tonnes of carbon dioxide and 7.7 TWh of energy corresponding to a societal value of SEK 7.5 billion per year.

The quantification of the large potential by increasing the use of AHSS, as shown in the Steel Eco-Cycle, is a substantial step forward towards a more sustainable society.

Conclusions

- ***There are strong, not only environmental, but also economic incentives associated with implementation of efficient technology in the steel industry***
- ***Environmental savings in the steel industry are associated with even larger savings in the corresponding down- and upstream processes***
- ***Increased use of light weight advanced high strength steels is associated with significant environmental effects in general and with active structures in particular.***
- ***Economic savings associated with energy and material efficient processes outweigh costs associated with carbon emissions***
- ***Continued steel development and accelerated use of advanced steel grades are key for a sustainable development***
- ***Research and industrial investments must be based on a life-cycle approach in order to support sustainable development***
- ***Mistra's launch of the Steel Eco-Cycle has given the programme participants tools to tackle new environmental requirements in a professional manner***

What is the next step?

The serious message of the 2012 Climate Report from the World Bank is obvious. In 2013-2014 the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) will follow and provide a second opinion regarding global climate change. However, the World Bank is not the only organization emphasizing the need for immediate actions towards decreasing the environmental impact of our industry. When the European Union provides more than € 31 billion to the future research programme Horizon 2020 the two major concerns that are addressed are "climate change and developing sustainable transport and mobility". Close to € 18 billion will also be used to "strengthen industrial leadership in innovation". The European ambition is further summarized in Roadmap 2050 – a practical guide to a prosperous, low-carbon Europe. The roadmap states "an objective to reduce greenhouse gas emissions by at least 80% below 1990 levels by 2050". For the period 2010-2015, the number one priority identified for immediate action in the coming 5-10 years is the transition to energy-efficient processes through the whole economy

The research from the Steel Eco-Cycle not only clearly shows the magnitude of various energy saving potentials but has already initiated the process of increasing the energy efficiency of the steel industry. One of the questions addressed in the roadmap is if Europe can afford this transition to a low-carbon emission union. When looking at the figures from the Steel Eco-Cycle, at least in some industrial sectors, the question should perhaps be if Europe can afford not to become a low-carbon emission union.

The bold decision by Mistra, in collaboration with Swedish industry, to finance an extensive 8 year long research programme with the ambition to close the steel eco-cycle has positioned Sweden as one of the global pioneers in the development and implementation of green technology in the steel industry. The decision has also significantly strengthened the position of Swedish research institutes which enable Sweden to act as an European and global expert in questions and projects related to eco-friendly technology. The research programme has also increased the status of recycling within the steel industry. This is illustrated by the establishment of a yearly Swedish workshop regarding scrap yard metallurgy which started in 2011. The workshops have been visited by both national and international speakers and it provides an excellent opportunity for scrap dealers, scrap buyers, the recycling and the steel industries to discuss and find common solutions to present challenges.

One major concern formulated by the steel industry has been a lack of competence in potential future employees regarding steel recycling. As a consequence of the Steel Eco-Cycle, a course in scrap yard metallurgy is now available at the Royal Institute of Technology (KTH). To the best of our knowledge, a university course within this subject is not offered anywhere else. The holistic approach adopted in the Steel Eco-Cycle has been very well received internationally and several countries are today considering similar programmes.

One of the most important general conclusions from the Steel Eco-Cycle is that increasing industrial energy efficiency does not necessarily imply costs but could rather generate significant profits for industrial companies. This profit could be obtained by the industry through adopting more energy-efficient processes or by realizing the value in residual products. In the construction sector environment-friendly choices could generate profits by enabling correct and well-founded material choices. From a consumer and societal perspective, profits could be generated by preferring *e.g.* light-weight vehicles or long-life products. Thanks to the significant investments made by Mistra, the Swedish steel industry, academia and research institutes are well suited to meet future environmental demands. The research presented within the Steel Eco-Cycle also provides politicians with the tools necessary for formulating policies and taking decisions which will make this transition occur as fast as possible. The Steel Eco-Cycle has shown that traditional industrial residual products might in fact be looked upon as industrial products and that environmental challenges are solved by innovations and not legislation.

Dissemination of results

Number of scientific publications: 69

Number of national conferences attended: 32

Number of international conferences attended: 60

Number of press appearances: 26

Number of academic degrees: 23

Number of awards: 5

Number of patents: 9

Programme economy

	Mistra financing (MSEK)	**Industrial financing (MSEK)**	**Total financing (MSEK)**
2004-2008	42	34	76
2009-2012	55	98	153
2004-2012	97	132	229

Table 9. Financial contribution from Mistra as well as from the industry

Evaluation group

The programme has been evaluated by the following persons:

Professor Seshadri Seetharaman (Royal Institute of Technology)

Professor Jan-Olof Sperle (Royal Institute of Technology/Uppsala University)

Professor Carl-Erik Grip (Luleå University of Technology)

Dr. Jonas Gurell (Swerea KIMAB)

Graduate student Pelle Mellin (Royal Institute of Technology)

Programme director Göran Andersson (Jernkontoret)

Acknowledgements

Mistra's investment in The Steel Eco-Cycle has significantly strengthened Swedish industry and research through acquisition of new knowledge, new processes and new technologies. The research programme has positioned the Swedish steel industry as global leader regarding eco-friendly technology and processes.

The research actors have adjusted and optimised ideas, innovations and technologies to meet the industrial demands and requirements. The industrial commitment in the research has been substantial and ensures that the results will be turned into practice.

During the 8-year period 2004-2012, new processes and technologies have been developed, all showing how to reduce the need for virgin material and energy with positive effects on the emissions of greenhouse gases as a consequence.

By developing modeling tools, the environmental gain of adopting process improvements and increasing the use of high strength steels has been quantified from a life-cycle perspective. The research enables the Swedish steel industry to face the future challenges in the environmental area.

The support from all participants of the Steel Eco-Cycle including international evaluators, Jernkontoret and Mistra is gratefully acknowledged.

Additional documents

The Steel Eco-Cycle programme final reports comprise a set of documents and a website information page beyond this Evaluation Report:

a) Scientific Report 2004-2012.

b) Popular version, 2004-2012. Only in Swedish: Populärteknisk rapport

c) Key note book. Only in Swedish: Faktabok 2013.

d) Website : www.stalkretsloppet.se

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[5] High-level Round Table on the future of the European Steel Industry – Recommendations, 12 February 2013, available at: http://ec.europa.eu/enterprise/sectors/metals-minerals/files/high-level-roundtable-recommendations_en.pdf

[6] Roadmap 2050 – A practical guide to a prosperous, low-carbon Europe, Technical Analysis, Executive summary, Volume 1 – April 2010

Appendix A: Research actors

KTH – The Royal Institute of Technology (www.kth.se)

KTH accounts for one third of Sweden's technical research and engineering education capacity at the university level. KTH was founded in 1827 and the main campus is located in central Stockholm. KTH has 2 800 employees, 248 professors and 1 444 active doctoral students. The departments involved in the Steel Eco-Cycle are Applied Process Metallurgy (with one professor, two associated/guest professors, one docent and two senior researchers/PhDs and 16 doctoral students) and Materials Process Science (with one associate professor, one docent, one professor emeritus and 12 doctoral students).

LTU – Luleå Technical University (www.ltu.se)

Luleå Technical University conducts research in the Faculty of Engineering and the Faculty of Arts and Social Sciences. A university college was established in 1971 and became Sweden's first university of technology in 1997. The university has 1 600 employees, 180 professors and 600 doctoral students. The research group involved in the Steel Eco-Cycle is Process Metallurgy (with three professors and one adjunct professor, four senior researchers/PhDs and 10 active doctoral students).

LNU – Linnaeus University (www.lnu.se)

The Linnaeus University was established in Kalmar as a university college in 1977 and received university status in the natural sciences in 1999. The university has 2 000 employees, 140 professors and 380 doctoral students. The research group involved in the Steel Eco-Cycle is the research centre for Environmental Science & Technology (with nine professors and two associate professors, eight senior researchers/PhDs and 21 doctoral students).

Swerea KIMAB (www.swereakimab.se)

Swerea KIMAB is the oldest industrial research institute in Sweden, founded in 1921. Swerea KIMAB develops and improves solutions for material research, including applied research with focus on customer benefit. The main research areas are: materials application, corrosion, material and process development. Swerea KIMAB is situated in Kista and has over 150 employees with a high percentage of post graduate researchers.

Swerea MEFOS (www.swereamefos.se)

Swerea MEFOS is a research institute situated in Luleå, Sweden. Swerea MEFOS creates, improves and disseminates research results within the areas: process metallurgy, heating, machining, environment and energy technologies for mineral, steel and metal industries, suppliers and other interested parties. Swerea MEFOS is known the world over for its unique, large-scale experimental equipment and its ability to conduct extremely large research projects. Swerea MEFOS employs about 90 people of which about 55 are research engineers.

IVL – Swedish Environmental Research Institute (www.ivl.se)

The Swedish Environmental Research Institute (IVL) is an independent, non-profit research institute, owned by a foundation jointly established by the Swedish Government and Swedish industry. IVL Swedish Environmental Research Institute was established in 1966 and, since then, has been involved in the development of solutions to environmental problems at the national and international level. IVL works with applied research and contract assignments for an ecologically, economically, and socially sustainable growth within business and society at large. The institute employs around 200 experts which makes IVL a leading institute for applied environmental research and consultancy services.

Appendix B: Environmental and economic effects of using advanced high strength steel

Abstract

The improvement potential in using advanced high strength steel is considerable in terms of reduced carbon dioxide emissions, lower consumption of energy resources and associated economic savings also. The potential improvement associated with utilising the Swedish production of high strength steel in passive as well as in active structures like *e.g.* the Swedish vehicle fleet is 1 855 ktonnes of carbon dioxide equivalents and 7 705 GWh in energy resources, corresponding to an economic value of €860 m. annually.

The introduction of high strength steel in structures and products is an ongoing process and the example described here is chosen mainly to illustrate the inherent potential there is in using advanced high strength steel in terms of material and energy efficiency and decreased consumption of natural resources, all the while achieving economic benefits. The great improvement potential in respect of material efficiency and economy shown in the Steel Eco-cycle together with use of the developed knowledge and assessment tools can lead to a substantial step forward towards a more sustainable society.

IMPROVEMENTS BY USING HIGH STRENGTH STEEL

The introduction of high strength steel takes a relatively long time. The companies and sectors that are in the forefront of the development are the transport and crane segments. The motor car segment, in particular, has been under pressure for a long time to reduce greenhouse gases and, at the same time, to meet the growing demands from safety standards. In recent decades, demands regarding *e.g.* safety and improved comfort have increased. This has led to auto manufacturers, in particular, successively increasing the share of advanced high strength steel in the car body to meet those demands rather than to make large weight reductions. This is, of course, an excellent way of using advanced high strength steel for increased material and energy efficiency, but it is not trivial to transform those benefits to pure weight reductions. Reductions in greenhouse emissions have also been achieved by other means like more efficient power trains, decreased drag and alternative fuels.

In the following analysis, the potential improvement in environmental and economic results also includes the benefits achieved for other purposes than weight reductions, by comparing with the scenario where advanced high strength steels had not been used.

Manufacturers of large trucks and earthmoving machinery have been using high strength steel for some time; however, they need to take the next step and use more advanced high strength steel. The main obstacles to this are associated with too low consistency and quality in the production process, especially for welded structures. Mobile crane manufacturers have successively used ultra high strength steel with strength levels of 900-1100 MPa for the outer parts of the crane boom where the load spectrum is less fatigue critical.

In spite of the fact that companies in some segments already use high strength steel, there is still a very large potential for increased use of these materials *e.g.* for various types of bodywork for trucks, trailers, machinery, railway rolling stock and so on where many SME companies are involved in the manufacturing process. The increased focus on environmental issues should promote such a development.

One should also remember that even if carbon dioxide emissions can be reduced in the future there will still be a need for resource- and energy-efficient transportation, independent of the type of energy source. This means that reductions in the mass of such products will be of crucial importance in the future.

The vehicle segment is very important in terms of possible environmental reductions since vehicles are so called active structures, capable of reducing their environmental impact during the whole lifetime when the weight is reduced.

Life-cycle improvements in the Swedish vehicle fleet

One way of making a calculation of environmental and economic improvements is to base the calculation on yearly carbon dioxide emissions for different vehicle segments. By assuming a percentage of possible weight savings and a fuel saving efficiency η related to the average driving cycle of the specific vehicle, the lifetime improvement potential for carbon dioxide emissions during the use phase of active structures could be derived from Equation 1. From that result also primary energy resources as well as economic improvements could be estimated.

$$\Delta M_{impr} = \Sigma(M_{em,y} * WR_{segm,y}/100 * \eta * LT_y)_n \quad (1)$$

where

ΔM_{impr} = Total lifetime improvement by upgrading in terms of tonne of CO_{2e}

$M_{em,y}$ = Total yearly CO_{2e}-emissions from segment y in tonnes

$WR_{segm,y}$ = Average weight reduction in segment y in %

η = Efficiency defined by: Energy saving (%) = $\eta*$Weight saving (% of gross weight)

LT_y = Lifetime considered for active structures in years

n = Number of segments

The analysis has been performed for the road, rail and water transport segments in Sweden assuming 50% fleet penetration. Input to this calculation is based on data from Eurostat [1], Trafikverket [2], ACEA [3], Anfac [4] and IEA [5]. The transport segment structures included in the analysis are those for road transport, rail transport and domestic water transport which together represent one third (22 million tonnes) of the greenhouse gases emitted in Sweden.

The primary energy resources have been calculated by the Swedish Environmental Research Institute (IVL), considering the energy content in each respective energy resource to consist of crude oil, natural gas, coal, lignite and uranium.

The assumed weight reduction varies from 17% to 20% for upgraded parts in active structures and 30% for upgraded parts in passive structures, which is included in the analysis in the following section.

The economic potential related to the fact that less steel needs to be produced and transported after an upgrading than before is, both for active and passive structures, calculated by multiplying the energy saving by the general energy price for Sweden assumed to be0.0561 €/kWh.

The economic gains in the use phase have been calculated by multiplying the energy savings by the energy price for the respective energy source (0.1823 €/kWh for gasoline, 0.1641 €/kWh for diesel and 0.0561 €/kWh for electricity). The value used for carbon dioxide emission allowances in steel production is 7.5 € per tonne emitted CO_2. For the use of vehicles, a carbon dioxide tax of 0.291€ (= SEK 2.50)/litre of fuel has been used to calculate the economic improvements related to the carbon dioxide emissions in the use phase. Also see Appendix C for more reference and conversion data. The results, which are presented in detail in [6], are summarised in Table 1.

Table 1. Lifetime improvements in greenhouse emissions, primary energy consumption and in economic terms for the Swedish vehicle fleet

Description	Physical balance		Economy		
	CO_{2e} (ktonne))	Energy (GWh)	CO_{2e} (M€)	Energy (M€)	Total (M€)
Steel production	**365**	**1460**	**3**	**82**	**85**
Use of vehicles	**2 805**	**11 875**	**272***	**1 563**	**1 835**
Total vehicles	**3 170**	**13 335**	**275**	**1 645**	**1 920**

) This figure refers to Swedish carbon dioxide tax on fuel

The corresponding figures for Europe is about 50 times higher than those shown in Table 1.

The introduction of high strength steel in structures and products is an ongoing process. The example described here aims to illustrate which inherent potential there is in using advanced high strength steel to further improve the environment, increase the material efficiency thereby lowering the use of natural resources and energy as well as improving the economy.

Example of a passive structure, Friends Arena

The steel construction segment is by far the largest segment in terms of steel usage. However, advanced high strength steel has not yet been used to a large extent due to issues related to overall stability and local buckling conservatism as well as conservative standards which discredit these steels.

Despite that, Sweco has designed the Friends Arena (Sweden's national arena in Stockholm) using 32% high strength steel; by doing so the weight of the fixed roof had been reduced by 13% from 4 584 tonnes to 4 000 tonnes. A calculation published in a Master's thesis [7] has been performed of a reference arena in conventional steel and a futuristic design with 52% high strength steel; the results show that it would be possible to design an even lighter roof structure using more high strength steel. Steel grades, weights and weight reductions are shown in Table 3. Table 4 shows results from the actual arena and results from the calculation of an arena designed with 54% high strength steel, in comparison with the reference arena, with a total weight of 4 854 tonnes.

Table 2. Grades and steel weights before and after upgrading for upgraded parts

Before upgrading				After upgrading					
Reference						Alternative A		Alternative B	
Grade	Yield strength [MPa]	Weight alt. A [tonne]	Weight alt. B [tonne]	Grade	Yield strength [MPa]	Weight [tonne]	Weight reduction [tonne]	Weight [tonne]	Weight reduction [tonne]
S355	355	1 506	564	S355	355	1 508	-2	561	4
S355	355	1 149	2 091	S460	460	920	230	1 719	372
S355	355	600	600	S690	690	307	293	307	293
S355	355	107	107	S900	900	43	64	43	64
Total		3 362	3 362	Total		2 778	584	2 630	732

Table 3 Friends Arena – Total weight of fixed roof, savings in weight, environmental impact and in economic terms; the reference arena in steel S355 weighs 4 584 tonnes

Alternative	Weight fixed roof tonne	Weight reduction roof tonne	Weight reduction roof %	Environmental savings CO_{2e} tonne (over whole life)	Savings CO_{2e} %	Savings in energy resources MWh	Economic saving MSEK
A - Actual arena 32 % AHSS	4 000	584	13	1 340	16	5 490	23
B - "Future" arena 54 % AHSS	3 852	732	16	1 675	21	6 870	(29)*

**) Estimated*

Increasing the amount of high strength steel from 32% to 54% might seem to result in a fairly low additional benefit but the increase in yield strength expressed in terms of the weighted average is only about 80 MPa (23%) and 120 MPa (34%) larger than for the reference arena, for cases A and B respectively.

The weight reduction associated with such an increase in yield strength, according to the rule of thumb, the root formula [6] represented by the blue dotted line in figure 1, is lower than the actual weight reduction of upgraded parts in this case. The final result here seems to be more a 1:1 relationship between yield strength and weight reduction, the red line in Figure 1 [8 and 9]. The conclusion is that the possible relative weight reduction for passive structures is larger than for active structures like vehicles. The economic saving is mainly related to production of the roof elements since lower sheet thickness can be welded with less filler material, less preheating and less workforce.

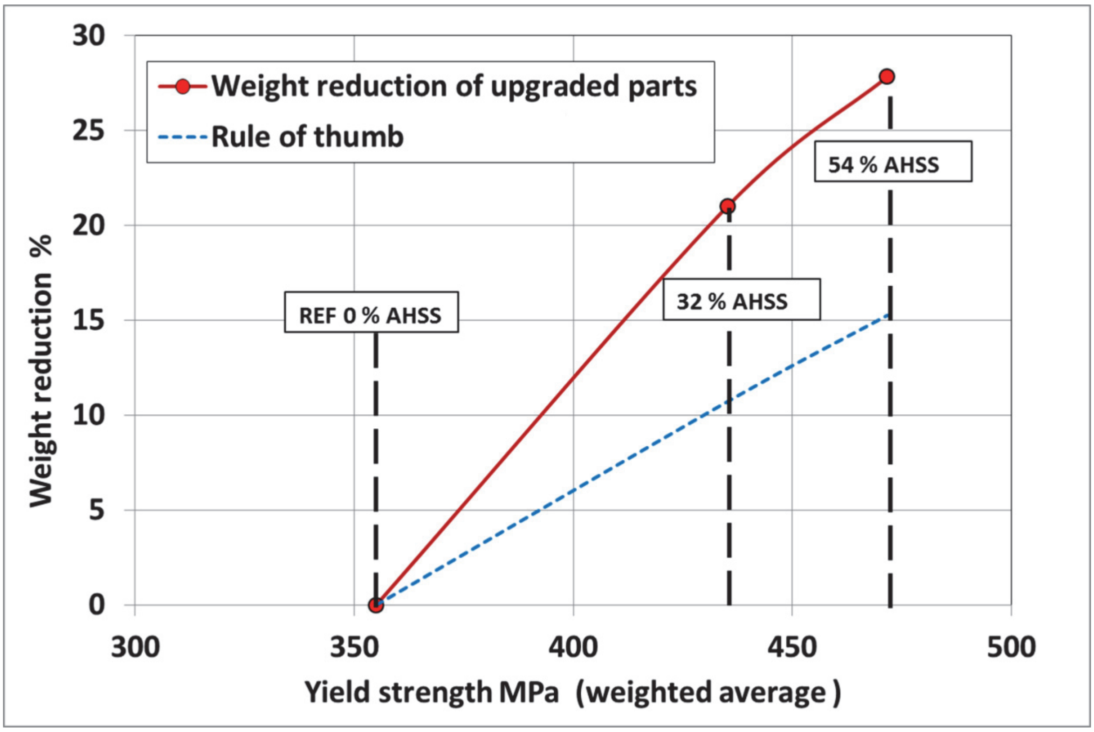

Figure 4. Friends Arena, weight reduction vs. weighted values of the yield strength

Steel supply to meet upgrading

The time to penetrate 50% of the road vehicle fleet is calculated as 6.2 years on average considering the age of fleet, new registrations, fleet growth and vehicles coming to an end of their life [6].

This means that about 130 ktonne/year of high strength steel is needed to implement the scenario outlined above. This is far below the amount of carbon steel strip and plate products produced in Sweden today. The largest steel works in Sweden producing such products plans to produce 50% advanced high strength steel by the year 2015. This means about 1 300 ktonnes. Let us assume that half of that amount is supplied to the transport segment and the rest for passive structures.

To acquire a Swedish reference point, the vehicle fleet in Sweden has been used in the above scenario even though a lot of vehicles and steel are imported and exported. Consequently we can also say that Sweden has the potential to supply advanced high strength steel to other countries to an extent that corresponds to the upgrading of 5 vehicle fleets like the Swedish one with 50% penetration, which is 650 ktonne/year. This is equal to 10% of the European vehicle fleet with the same penetration rate. This gives an *annual* improvement potential shown in Table 2. Improvements are here given per year to make the figures comparable with improvements from the process projects. The average life for the vehicles considered is 14 years [6 and 10].

Table 2. Annual savings in greenhouse emissions, primary energy consumption and in economic terms if Sweden exports advanced high strength steel for upgrading

Description	Physical balance		Economy		
	CO_{2e} (ktonne)	Energy (GWh)	CO_{2e} (M€)	Energy (M€)	Total (M€)
Steel production	**295**	**1 180**	**2**	**66**	**68**
Use of vehicles	**1 000**	**4 240**	**98***	**560**	**658**
Total vehicles	**1 295**	**5 420**	**100**	**626**	**726**
Passive structures	**560**	**2 285**	**4**	**130**	**134**
Total	**1 855**	**7 705**	**104**	**756**	**860**

****) This figure refers to Swedish carbon dioxide tax on fuel applied on the whole volume, the Swedish part of it is 20 %***

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Appendix C: Economic potential of process improvements

Abstract

The “Environmental Potential Evaluation” by the Swedish Environmental Research Institute (IVL) has shown considerable potential savings in emissions, energy and materials. In this appendix, a calculation of the potential economic effects associated with these savings is made. It results in a potential economic saving of the order of 395 M€/year. The main factor was the reduced energy consumption. The economic effect of reduced CO_2 emissions was lower, but higher allowance prices in the future can increase its importance.

The result is associated with uncertainties in *e.g.* price levels and factors limiting additivity. A very conservative approach was used to avoid optimistic values. The effect of this approach on the result is discussed at the end of this appendix.

Background: environmental evaluation

The potential effect of the Steel Eco-Cycle results on environment and resource consumption has been extensively evaluated using life cycle assessment (LCA) methodology [1]. Table 1 shows the expected effects on greenhouse gases and energy consumption. The scope of this report is to express these improvements in economic terms.

Table 1. Improvement potential in upstream and downstream processes according to Table 5 in IVL’s report entitled “Environmental Potential Evaluation” written as part of the Steel Eco-Cycle programme

Process savings		**Goal**	**Total (including upstream processes)**[1]
CO_2	ktonne/year	1 000	1 300
Energy	GWh/year	600	5 300
Other savings (additional values)		**Goal**	**Total (including upstream processes)**
FeV (as pure V)	tonne/year		5 000
Cr	tonne/year		28 000
Ni	tonne/year		2 600
Mo	tonne/year		310
Mn	tonne/year		0
Iron pellets	tonne/year		510 000
CaO	tonne/year		81 000
Crushed aggregates from rock	tonne/year		200 000
Landfilling of slag & dust	tonne/year		300 000
Waste management of ASR[2]	tonne/year		76 000

[1] Total emissions of CO_2 and inputs of energy resources for the whole steel industry system including upstream processes (production of raw materials and energy). The energy resources are accounted for as inputs of non-renewable and renewable natural resources (e.g. crude oil, coal, uranium etc.). Note that the efficiency of electricity generation from the non-renewable energy resource uranium is only about 33 %.

[2] Automotive shredder residue (ASR).

Method

One central task was to find the correct and transparent pricing of CO_2 allowances, energy and alloys. The pricing used for each component is introduced in this part, officially available prices being the preferred choice to avoid suspicion of bias.

Decreased need for CO_2 allowances

The savings by reduced CO_2 emissions were evaluated using the available price of EU allowances. The present value could be estimated at around € 7.50 according to Figure 1. The diagram is from a report on the CO_2 allowance market by the Swedish Energy Agency [3] .

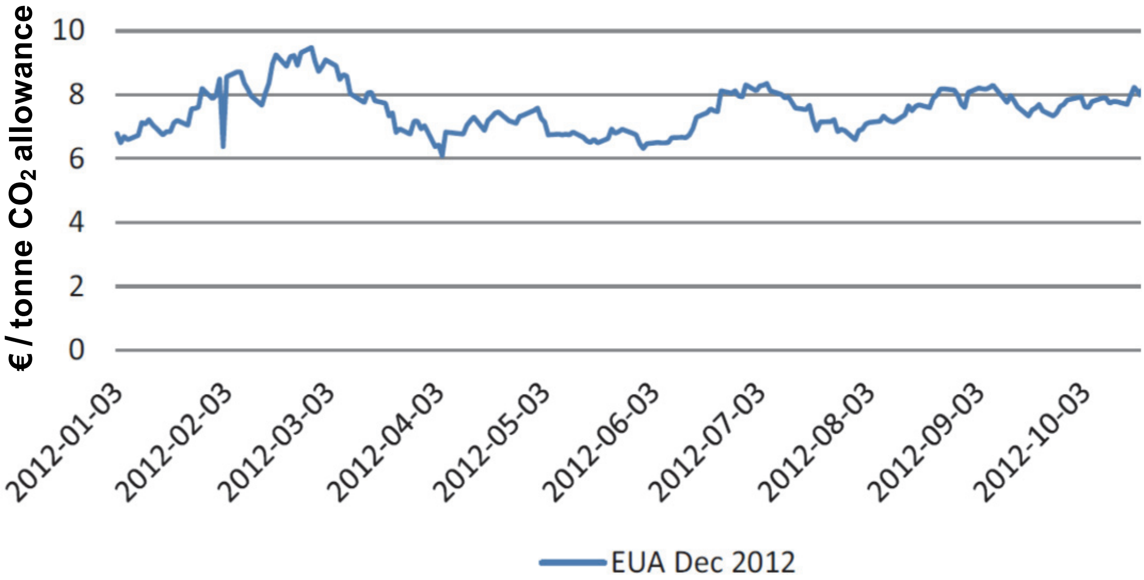

Figure 1. Price development of CO_2 allowances during the first part of 2012 [3]

Decreased energy consumption

Where energy costs are concerned, the data in Table 1 are not sufficient to clarify the exact distribution between the energy types included in the calculation. The best solution is probably to use a mean price. The Swedish Energy Agency publishes yearly good consumption statistics for all energy types used in the Swedish industry [4], and also good statistics on the price level of the same energy types. A weighted mean of these data resulted in a mean energy price for industrial energy of 48.15 öre/kWh during 2011. One complication was that the price was missing for a small amount of district heating used in some industries. However, in the household statistics of the same types of energy the price of district heating was 47.5% of the electricity price. The same relation was assumed for the district heating used by industry. It should be noted that the amount of heating is small so an error in that estimation is of limited influence (50% error gives a 1% change).

Decreased alloy consumption due to materials savings

For the alloy savings, official market prices for steelmaking alloys were used, see the summary in Figure 2. The Ni price is from the raw material page of "Dagens Industri" The other prices were found on the website Metal pages [9]. The prices vary over an extremely wide range (around 7 000-300 000 SEK/tonne). A logarithmic scale was therefore chosen in Figure 2.

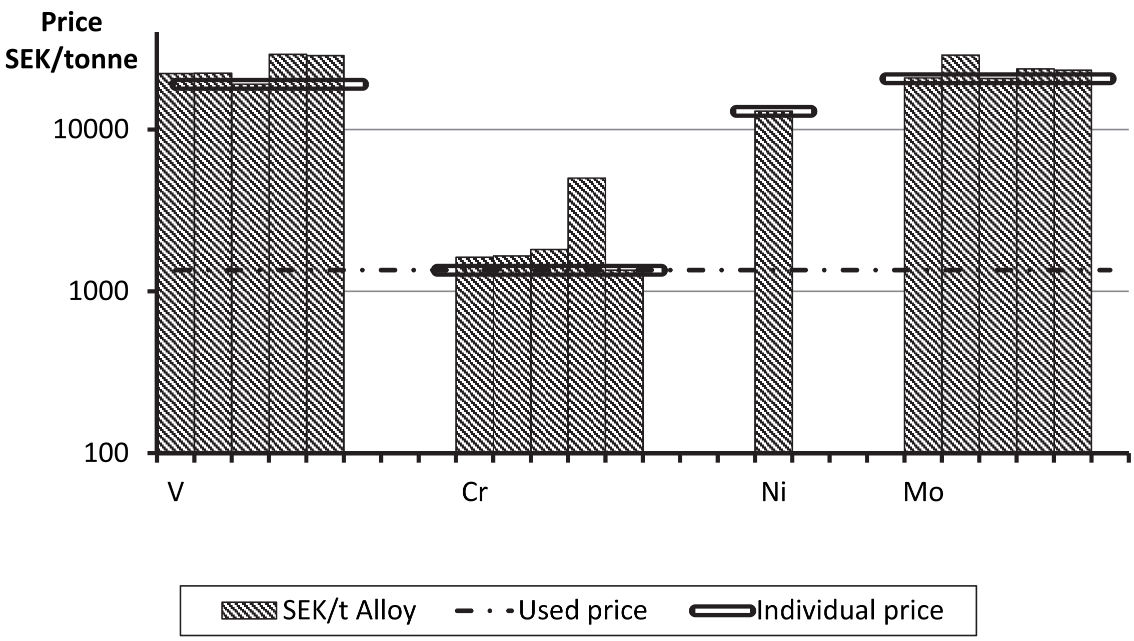

Figure 2. Prices for steelmaking alloys according to Refs. [8] and [9]

For these widely spread data it does not seem viable to base the calculations on a mean or median value of the prices. Instead a price at the lower end (7 000 SEK/tonne) was used in the calculations. It was chosen as if everything were FeCrC to give alloy savings that were securely underestimated, so that overoptimistic estimations are avoided.

One complication was that the reductions in CO_2 emissions and energy consumption due to a decrease in the use of an alloy were already included in the data given in Table 1. They were therefore subtracted from the total balance before they were used to calculate the economic saving.

Hollappa [12] studied the environmental effect of the production of four alloys, resulting in emissions of about 55 $MtCO_2$ for production of 27.77 Mt alloys which gives a CO_2 factor of 1.99 tonne CO_2/tonne alloy. The energy consumption was calculated for the energy intensive alloy FeCrC, showing an energy consumption of the order of 9 000 kWh/tonne and a CO_2-emission of the order of 1.62 tonne CO_2/tonne ferroalloy. These values were used in the calculation. The weight of the alloy was converted from alloy element to ferroalloy before calculation; also FeV was excluded as it is a new downstream product not a saving.

A similar approach was chosen for the effects of the decrease in consumption of iron ore pellets and lime. In this case the main CO_2 and energy effects are from the pellets and lime burning and they also are a considerable part of the refining cost. In this case the costs of iron ore [10] and raw limestone [11] were used instead to avoid these effects. A very limited CO_2 and energy burden remained. This could be calculated from available LCA data and subtracted.

The value exchange rates of February 4 2013 according to the Swedish Central Bank ("Riksbanken") [7] have been used to convert prices given in different currencies.

An important aim has been to not overestimate the calculated benefits, *i.e.* when data are uncertain a conservative calculation was chosen in order to give a result which is safely underestimated.

Results

The potential economic effects are summarized in Table 2.

Table 2. Potential economic effect of improvement in climate gas emission and energy consumption

Description	Physical balance			Economy			
	CO2	Energy	Material	CO2	Energy	Material	Total
	Ktonne	GWh	Ktonne	M€	M€	M€	M€
Process improvement	1 201	4 768		9	267		276
Ferroalloy			53			29	29
Iron ore for pellets			510			37	37
Limestone for lime			145			2	2
Total Steel Production	1 201	4 768	708	9	267	69	345

A total cost saving of the order of350 Million € can be seen. Figure 3 shows that the energy savings are dominant, and that the contribution from CO_2 allowances is almost negligible.

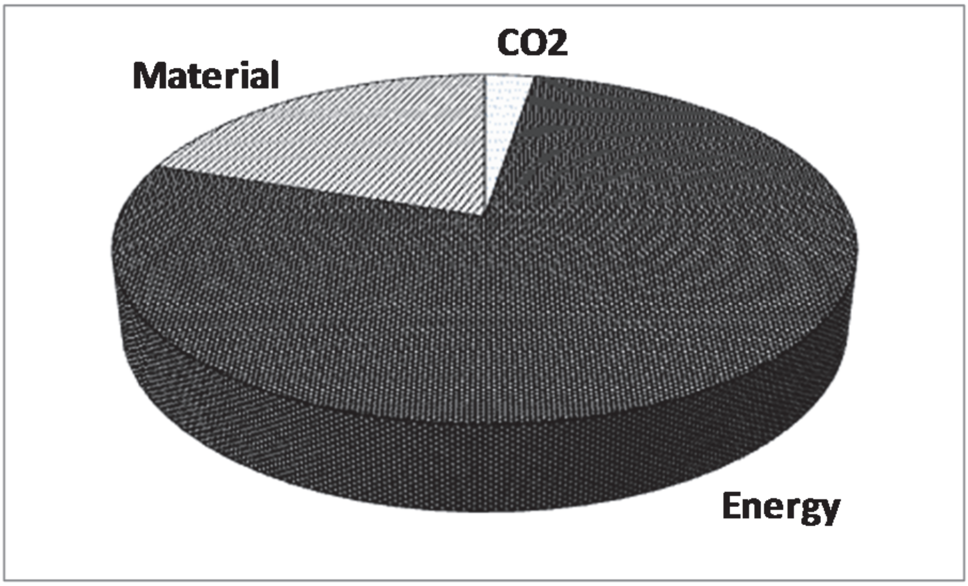

Figure 3. Distribution between types of cost saving

Discussion

Long term effect of the CO_2 price

The economic effect of the CO_2 emission depends on the price of EU allowances, which has fluctuated over the years. It was of the order of 20-25 € when the system started [2]. After 2009 there were several years of depression, the industrial production decreased, with decreased emissions and need of allowances, and the allowance price decreased to its present level of around 7.50 € [3]. It is expected to rise again when the allowances become rare. According to Carbon Point [5] it can then be expected to be of the order of 31 € in 2020. According to the forecasts of the European roadmap [6] the CO_2 price in 2050 is expected to reach a level corresponding to a carbon capture and storing cost of around 100 €. The effect of such a change can be seen in Figure 4.

It is interesting to note that even if the price of carbon credits rises to a level of 100 €/tonne, as predicted to happen in 2050 in the European roadmap, the total saving from reduced CO_2 emissions is 130 M€. This is still less than half of the savings associated with reduced energy consumption.

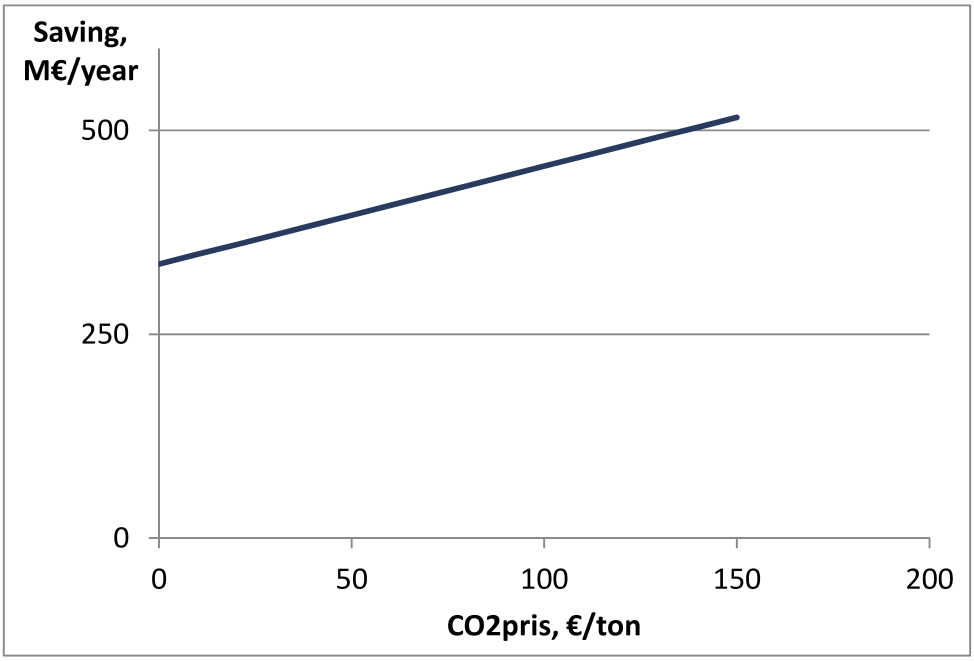

Figure 4. Effect of an increase on the calculated cost effect

The diagram shows that the increase will substantially increase the economic effect, at the 100 €/tonne level the saving is doubled and the CO_2 price will be an important factor.

Saving of alloys and raw materials: risk of double accounting of CO_2 and energy

Table 2 includes savings in raw materials (ore, limestone and alloys). A complication is that the savings in steel production already includes the energy effects of decreased raw material use. It is important to avoid double accounting when the raw material data are added to the total saving. For iron ore pellets and lime, only the prices of primary materials (limestone and raw ore) were included. This was to avoid including the effects from the energy and CO_2 intense burning processes. The remaining cost effect from energy and CO_2 were calculated and subtracted from the first row in Table 2. It should, however, be noted that that value was very small, far less than 1 M€/year. Thus the effect does not influence the values of Table 2, which are rounded to 1 M€/year.

Use of a conservative level for alloy prices

The effects to be subtracted already included CO_2 and energy and are well known for FeCr [12], which was also the least expensive alloy. The calculation was performed as if everything was FeCr, to ensure a less optimistic calculation. The result, however, was that the alloy saving was of the same magnitude as the subtracted CO_2 and energy, so maybe the approach was too pessimistic. Furthermore, the FeCr market price is presently at a very low level. It should be pointed out that this means that the alloy saving mainly consists of energy, not that it is of lower value.

Effects that were not included

Some effects listed in Table 1 are not included in the summary in Table 2 because of uncertain price levels:

Crushed aggregates from rock: 200 000 tonnes/year. An example from one distributor's pricelist [16] indicates a price of SEK 50/tonne which would give around 1 M€/year, however, a big question mark is the transport cost for a low value material.

Landfilling of slag and dust: 300 000 tonnes/year. The landfill cost is not very certain. A cost of SEK 200-300/tonne would result in a total cost of 7-10 M€/year.

Waste management of ASR: 76 000 tonnes/year. It is difficult to find a certain COS, also depending on the method used when treating it. The following conclusion from a paper of Simić [17] might give a hint,

"*The introduction of stringent ASR recycling quota will not endanger the Japanese vehicle recycling system. However, automakers profitability will be reduced for approximately 16 €/tonne of collected ASR*."

A cost of 16 €/tonne would result in a total cost of around 1 M€/year.

The value of vanadium: it is a new product from the system not a saving.

Luleå February 24, 2013

Carl-Erik Grip

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