



The climate change challenge and transitions for radical changes in the European steel industry

Christophe Rynikiewicz

► To cite this version:

Christophe Rynikiewicz. The climate change challenge and transitions for radical changes in the European steel industry. Journal of Cleaner Production, 2008, 16 (7), pp.781-789. <10.1016/j.jclepro.2007.03.001>. <halshs-00005052>

HAL Id: halshs-00005052

<https://shs.hal.science/halshs-00005052v1>

Submitted on 20 Oct 2005

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

The climate change challenge and transitions for radical changes in the European steel industry

Paper presented at the 10th European Roundtable on Sustainable Consumption and Production (ERSCP) – Antwerp 5-7 October 2005, Belgium - (submitted for publication in Journal of Cleaner Production)
DRAFT October 2nd 2005

C.Rynikiewicz¹

¹Lepii-EPE CNRS/Univ. Grenoble -
Département Energie et Politiques de l'Environnement (ex IEPE), Grenoble, France
Christophe.rynikiewicz@upmf-grenoble.fr

Abstract

This paper aims at presenting transitions envisaged in the steel industry from cleaner production to systems innovation. Limits of the socio-technical system and the climate change challenge would induce changes in the production, distribution and consumption patterns of steel and other materials. Insights from industrial economics and evolutionary theory on innovation for sustainable development are needed to assess the rationale behind the adoption and diffusion of breakthrough technologies. Evolution in material consumption patterns deserves a special research agenda looking at long term evolution of the consuming sectors as major changes in the infrastructures and products that support our many energy and material dependent services (mobility, shelter, heat, light, etc.) are expected. These changes will be significantly amplified by greenhouse gas emission constraints

Keywords: Climate Change, eco-efficiency, steel making, eco-restructuring, sufficiency innovations

1 INTRODUCTION

The concept of systems innovation [1,2] and transitions to sustainability has increasingly gained attention over the past years in academic and policy arenas as transition to a far lower carbon world is needed. The attention has shifted from cleaner production to “*regime transformation*”, “*industrial transformation*”, “*technological transition*”, and “*socio-economic paradigm shift*”. Indeed, industry experts say that after 2010 the necessary greenhouse gases (GhG) emissions reductions require major technological changes as the improvement of existing processes will not be sufficient.

In OECD countries 36% of the primary energy demand is used by industry to manufacture products that are consumed in society. A large part of the energy is dedicated to the production of basic materials used in the products. Preliminary research indicate that 50-75% emissions reduction is needed in industrialised countries. System innovations in energy intensive industries are also of great importance for the Developing Countries in their industrialisation period enabling them to leapfrog. Considering the important challenge of “factor4”, it is still hard to comprehend how economies could evolve towards a much less carbon-intensive path.

Any reduction goal compatible with climate stabilisation will have considerable effects on economic activities, markets and behaviours. The demand side (in particular buildings and transportation) will be impacted, via their materials content. Therefore detailing the approach of material efficiency is of great promise.

Following work by Geels and Kemp [3], three basic change processes in socio-technical systems can be

distinguished. “*Reproduction*” refers to incremental change along existing trajectories ; “*transformation*” refers to a change in the direction of trajectories and “*transition*” is a discontinuous shift to a new system and trajectory. Transition in the material industry would consist, in this case, of a combination of several systems innovations.

This paper is focused on the steel industry and divided into three parts. First, we highlight the different strategies for the steel industry to diminish its contribution to global warming. In section 2, we focus on the possible transformation of the current technological trajectory via the new ULCOS (Ultra Low CO₂ Steelmaking) breakthrough technologies. In section 3, we have a look at the possible contribution of steel in Product Service Systems and dematerialisation. We argue that the iron and steel system is like the unsustainable *frozen pea* system in the UK studied by Green and Foster [4] : changes are required at the levels of systems of production, distribution as well as consumption patterns of this especially important vegetable, symbolically, if not quantitatively or nutritionally for the UK diet.

2 THE CLIMATE CHALLENGE, ECO-RESTRUCTURING AND TRANSITIONS IN THE STEEL INDUSTRY

2.1 The Climate change challenge

The UN Convention on Climate Change states that the policy goal should be to limit average global temperature increases to no more than 2°C of pre-industrial levels, which would already have serious impact. Therefore, meeting this climate objective will require a peak in world

emissions within a few decades and a strong decrease to stabilise the concentration in atmosphere.

Most scientific work available has thus far assumed that reaching the 2°C target would translate into a long-term greenhouse gas (GhG) concentration maximum level between 400ppmv and 550 ppm CO₂ equivalent [5] (which means 450 ppmv CO₂ only) in the atmosphere. Such level of concentration is still subject to uncertainty and new scientific knowledge may become available in the future, specially on the climate sensitivity factor [6]. The German Advisory Council (WBGU) has recommended the stabilisation of CO₂ concentration in the atmosphere below 450 ppmv [7].

A recent study "GhG Reductions Pathways" [8] looked at options for a future climate change regime. A concentration level of 550ppm CO₂e would translate into a global reduction of GHG emissions of 15 – 20 % by the year 2050 compared to 1990 emission levels or by 50 – 60 % compared to a "business as usual" scenario. The challenge would be particularly important for industrialised countries, as reduction would be important to enable emissions of developing countries to increase.

Considering the hypothesis in the Common POLES-IMAGE (CPI) work [8], the resulting global reduction challenge is shown in the figure 1. The baseline describes the development in the main driving forces (population and economic growth) and environmental pressures (energy, industrial and land-use emissions) for the 1995-2100 period with « Technical Change and Policy as usual ». It serves in particular as a benchmark for the assessment of alternative policy schemes.

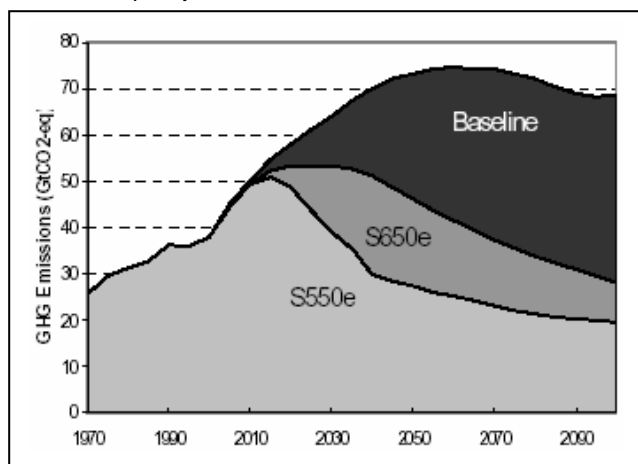


Figure 1: World emissions profile for different CO₂e concentrations in atmosphere. Source : IMAGE2.2 [8].

The different GhG emitting sectors have to face this "carbon constraint" and limit their emissions. Any reduction goal compatible with climate stabilisation will have considerable effects on economic activities, markets and behaviours.

2.2 Linking innovation in production and consumption patterns

A growing literature aims at understanding and promoting the transformation of the structural characteristics of technological regimes along to environmental signals and ecological principles, reshaping entire trajectories of technological innovation [9] and shifting away from the current technico-economic paradigm [10].

The typology of Abernathy and Clark [11] provides a useful caveat to link innovation in the modes of production and consumption.

The typology identifies two dimensions. The first dimension relates to the technology and production competences of a firm, involving : design of technology, production systems/organisation, skills (labour, managerial, technical), material/suppliers relations, capital equipment, knowledge and experience base. The second dimension consists of linkages between the firm and customers : customer applications, channels of distribution and service, customer knowledge and modes of customer communication.

Abernathy and Clark list four types of innovation and the concept of "architectural innovations or AI" enables us to link changes in the technology and changes on the user side, introducing new functionalities and user practices.

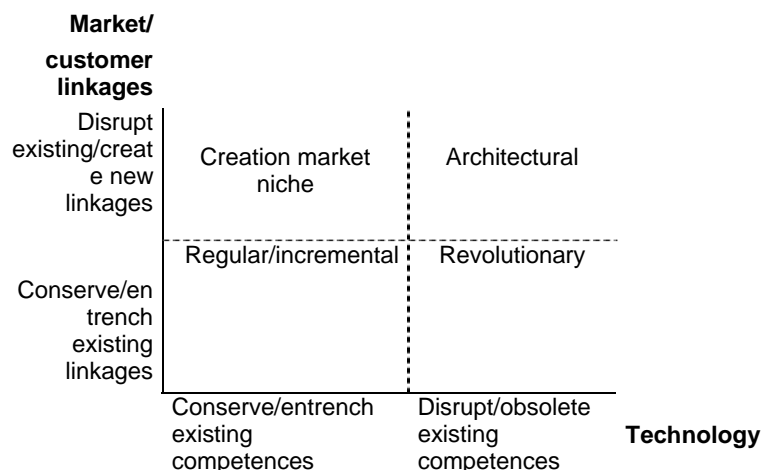


Figure 2: Typology of innovations [11]

Geels [12] proposes to add the issues at stake in studies on public policies, infrastructures, maintenance networks to define the systems innovation, describing it as an "AI. writ large".

The decoupling strategies are coherent with a scheme proposed by the Industrial Transformation Science Plan (figure 3), which identifies three stages from end of pipe to product redesign and system changes. It is arbitrarily estimated to take place along time scales on the order of 10 to 25 years. Figure 3 from the Industrial Transformation Science Plan [28] illustrates the relation between various response modes, the time scale, and the geographic scale involved.

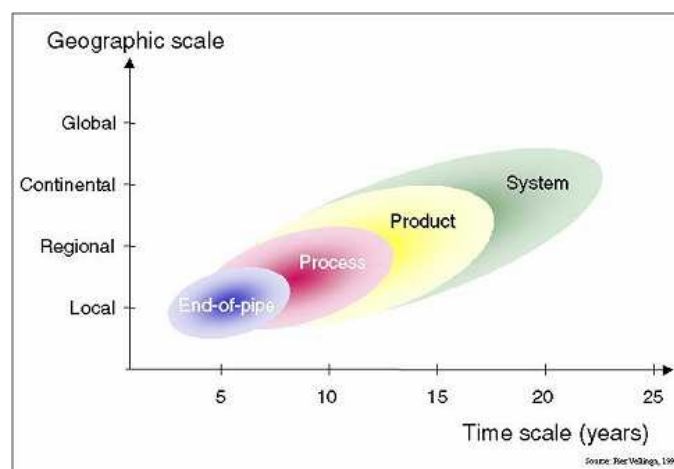


Figure 3: Societal responses to the issue of environment source [28].

Necessary emission reductions of a factor 4 or 10 require major technological changes and also that innovation arises out of a more integrated arena. The concept of systems change is proposed as a combination of technical change and societal change.

The paper is focused on the system innovation in the steel industry. Indeed, steel is a key industrial product in the growth and prosperity of a nation. This sector also provides a classic example of an evolving industrial ecosystem. Since the first industrial revolution and over the past 200 years, technological innovations in steel making have always been important for the industry itself and for the rest of the economy [13].

It is an energy intensive sector and therefore energy and climate change are particularly high on the sustainability agenda of the steel industry. According to Ecofys [14] or OECD [15], steel industry accounts for 7-12% of anthropogenic GhG (greenhouse gases) emissions and is the largest energy consuming manufacturing sector in the world. Moreover, according to OECD/IEA (2000), energy costs typically account for 15-20% of the costs of steel production. Therefore, with growing concern regarding global warming issues, additional costs have to be anticipated in the context of Kyoto Protocol commitments and future climate policies (Post2012). Advances in steelmaking have historically evolved in response to factors such as industrial expansion, competition, world wars, technological innovation, and sheer creativity. Transitions to sustainability for the steel industry will concern production and consumption patterns.

2.3 Transitions issues in the steel industry

The studies on technological transitions, like the studies on GhG emissions reduction potentials have traditionally been focusing on energy, mobility and sometimes agricultural system [16]. Technological transitions in energy intensive industries and in the use of materials is of great promise.

The issue of the measure of inputs of materials has been developed [17,18] and is of particular interest as the composition of this flux reveals the economic structure of a country and may enable to anticipate the environmental consequences of its development.

Then, improvement in material efficiency seems to be a more cost effective way and deserved at least to be favoured in parallel with energy system optimisation or evolution. Indeed, the MATTER Project (MATERials Technologies for green-house gas Emission Reduction) found that up to one-third of the reduction of greenhouse gas emissions in Western Europe can be achieved by materials management [19,20].

Literature on environment has identified for long the need for decoupling environmental impact from economic growth. Lovins' earlier "factor4" book argued that numerous technical and organisational opportunities exist for quadrupling resource productivity, enabling a doubling of wealth whilst halving resource use [21]. The ability to realise such decoupling is crucial considering the likelihood of continued economic growth in developed countries and rapid economic growth in many developing countries with high populations. It is therefore of great interest to know how well decoupling has succeeded so far and what potential there is for future decoupling.

The different possibilities for decoupling CO₂ and GDP growth are listed in the equation of figure 4. Four strategies are listed.

"Process innovation" deals with the radical or incremental innovations that would decrease the CO₂ emissions per tonne of material. "Transmaterialisation" implies a recurring industrial transformation in the way that economic societies use materials [22,23].

"Dematerialisation" is a commonly used concept. Emissions associated with the demand for energy-intensive materials (steel, aluminium, cement...) could be reduced :

- by more efficient use of these materials (by improving their design or material properties),

Ecodesign has been a promising and growing field of research, which delivers part of the solution, and it is particularly interesting for facilitating the collection and sorting of materials for recycling. However, ecodesign objectives may fail to account for absolute limits of the global ecosystem.

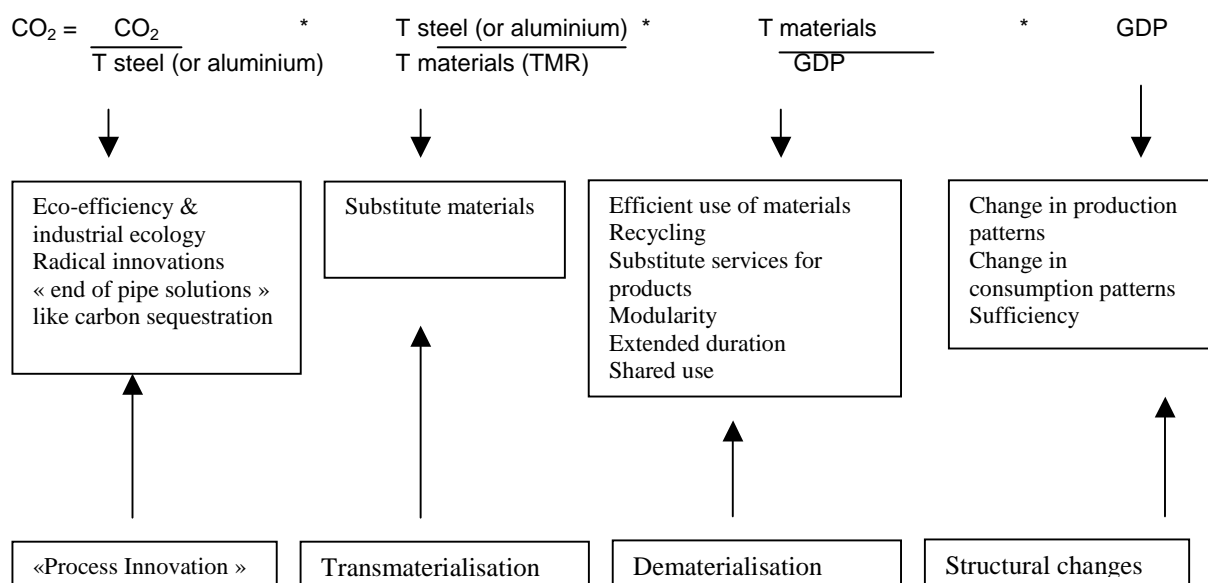


Figure 4. Various strategies to decouple environmental and resource impact from economic growth, Criqui & Rynkiewicz, adapted from [24,25].

In the next sections, we will explore what could be the promising steps for transition to more sustainable consumption and production patterns in the steel industry.

- by increased recycling or substitution of those materials by less energy-intensive or biomass based materials. The central idea of “industrial ecology” is to optimise the flow of materials and energy between different industries and in that way to propose new “industrial metabolisms”. It derives partly from a desire to see societies endogenise these impacts through new models of economic development and conceptualisations of societal ‘progress’. Zero waste and 3R (reduction, recycling and recovery) approaches have become common concepts and they are often included in the strategic policy of companies, which view the environmental issues as a priority as much as more traditional aspects concerning productivity, production cost cuts, etc. [26, 27]. Like the Kalundborg case, these loop-closing activities have slowly developed over time as firms have identified and characterised waste sources and sinks.

- by a shift from products to services

A change in the products and services sold implies however different institutional frameworks regarding property, liability and fiscal system. We will discuss this option in part 5.

3 CURRENT TECHNOLOGY TRANSITIONS AND THE POSSIBLE FUTURE OF ULTRA LOW CO₂ STEELMAKING (ULCOS)

We focus on the steelmaking industry from Europe and other industrialised countries as we assume that trade, industrial structure, capital, environmental constraints but also national demand is different in other countries. Links between industrialisation paths and sectoral strategies for leapfrogging are to be addressed separately in other papers.

3.1 New windows of opportunity for incremental and radical innovations

Considering the relative contribution of iron and steel and intensive manufacturing industries to global warming, studies have for long focused on short and long-term energy efficiency improvement. Historical data provide examples how energy efficiency has improved in the industry since the 70s, owing to process innovation. However, industry experts say that after 2010 the necessary emission reductions require major technological changes, as the improvement of existing processes will not be sufficient.

Indeed, steel industry has a strong path dependency to the integrated mill according to the theoretical framework developed by Arthur [29] resulting in the lock-in in sub optimal technologies because of increasing return to adoption.

This issue has been quite extensively studied in the carbon based energy systems [30]. In the steel industry, Luiten [31] showed the lock-out of strip casting even if its huge capital cost advantage were already noticed back in the 19th century. This step-wise reduction in the specific energy consumption of steelmaking, doing away with the need for reheating and hot rolling mill did not enable to go “Beyond efficiency” [31].

Smelting reduction is one of the promising technologies which have been intensively studied [32,33]. However, on the short term, the most promising answer to limit GhG

emissions is recycling (up to 250kg of scrap per ton of steel in the blast furnace). Increasing the scrap input in the oxygen converter induces the same GhG reduction effects as by changing the process routes, but the approach can be applied to existing Integrated Mills within a reasonable time scale. This is also the solution, which exhibits the lowest substitution cost per tonne of avoided CO₂. Moreover, it does not require drastic revisions of steelmaking practices, as would be the case when switching high-end flat steel production from the integrated to the EAF route.

The limits of energy efficiency serve as an entry point to the understanding of the limits of the socio-technical system. There seems to exist a momentum for the renewal of this industry. Mini-mills based on scrap recycling have been a response to the drawbacks of the integrated steel plants for some years but there is now a change in the “selection environment” of new technologies.

3.2 The limits of the socio-technical system and the ULCOS technologies

In the “book of steel” [34], two industry experts explain that the giant integrated steelworks has attained a level of technological perfection, which leaves little room for future progress and is poorly suited to the economic context likely to appear in decades to come, at least in industrialised countries. By analogy with the evolution of species, Birat and Steiler call it a sort of Darwinian dead end, the equivalent of a dinosaur.

Birat and Steiler identified that technological rupture in the steel industry is the conjunction of several factors :

- saturation of the prevailing technology
- modification of the economic context, in terms of raw materials and markets, the coming to maturity of alternatives technologies and the development of more radical technologies (ULCOS) which we will describe
- lacks of flexibility and reactivity as the lead time to fulfil an order remains long (30 days still represent an ambitious objective). Moreover, the capital investments are colossal.

As previously identified, the conflict has been growing between the target of the steel production for large scale uniform and low production cost and the demands of customers for tailored products, encompassing very diverse applications. The Strategic Research Agenda of the Steel Industry towards 2030 is targeted at investigating a more flexible and multifunction production chain [35].

In parallel, as the momentum grew so that emissions reduction was faced, an European viewpoint on the challenges to the steel industry was given [36,37]. The ultimate objective of the ULCOS project is to achieve a reduction in CO₂ emissions of more than 50% compared to the benchmark ore-based iron and steelmaking. This initiative is a joint European RFCS-FP6 project, linked to the Technological Platform. Similar projects are carried out in the States, in some developing countries (China, Brazil) and at the world level (IISI CO₂ breakthrough program).

Production of steel is energy intensive due to thermodynamically needs of the chemical reaction of iron ore reduction at high temperature by the carbon contained in coal. New innovative concepts for ULCOS technologies involve a reflection on the basis of steelmaking and a change in the reducing agent as indicated in figure 5.

Among the paths under investigation, one can identify :

- carbon-based reduction of iron ore, with full exhaustion of the reducing power of carbon by removing and later sequestering CO₂ and recycling of the top gas,
- use of carbon with short life cycle, i.e of plant biomass
- use of carbon-lean energy and carbon-lean reducing agents, with electricity or hydrogen vectors
- increased use of natural gas in more innovative ways
- and combinations of all of the above

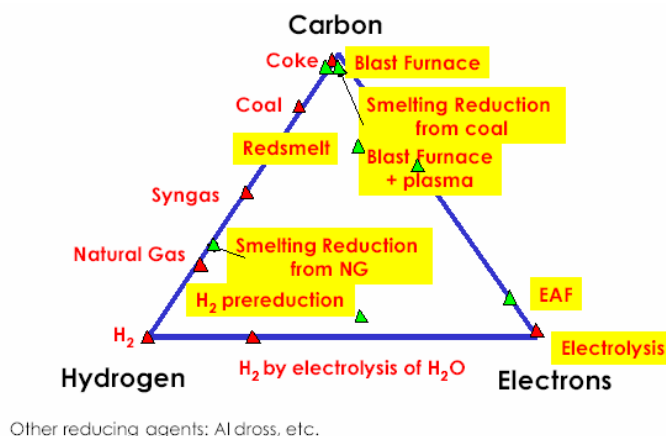


Figure 5 : Conceptual representation of the various "breakthrough" steel production routes

Selection of the technologies before testing the pilots at industrial scale is at the heart of the ULCOS research project. Depending on the relative prices of raw materials, energy, etc, the order of merit of the different technologies will vary. The optimal economic and organisational size of the plant may also change. However, this calls for a complete paradigm shift steering steelmaking process technology away from today's mainstream practices.

3.3 Uncertainties of the technological discontinuity

The emergence of a technological discontinuity will depend of a number of key characteristics, amongst them technological and economical uncertainties. From the technological point of view, each envisaged technology viability depends on key uncertainties :

Firstly, the Electric Arc Furnace is not the back-stop technology as it is highly sensible to the carbon-intensity of the electricity used in the process as well as scrap prices and availability.

Secondly, when considering to change the reducing agent :

- Natural gas is the only alternative to carbon as a reducing agent that has any realistic existence today, being used in the most common prereduction processes. However, availability and price are subject to significant change.
- Availability and price of energy vectors (electricity and hydrogen) as well as acceptability of their production mode are highly uncertain.
- Although it is not implemented in the steel Industry, electrolysis could in theory be applied in different ways to Steel production.

From the economics point of view, the evolution of production costs (raw materials, energy, CO₂ price, labour) and the market structure will change the order of merit of the ULCOS technologies. It is presumed that these technologies are more expensive than the existing ones and will experience learning curves. The theoretical debate on the determinants of the adoption of new technologies is beyond the scope of this paper. From an empirical point of view, work is performed using a sectoral equilibrium model of the steel industry, developed at IPTS [38] and linked with the POLES model. Industrial dynamics theories provide good insights on the conditions of adoption and diffusion of radical innovations under imperfect competition.

Steel industry might be one of the first sectors to experience "industrial transformation". Technology could be seen as the entry point of more radical shift in the socio-technological regime]. Indeed, one can suppose that the carbon constraint and sectoral trends may induce structural changes in urbanisation, transport systems, housing. The major point is to look at the future of materials, which exhibit a strong potential for change, as far as sustainability is concerned. This will change the competition among materials and among consumer goods, in terms of ecodesign, durability and environmental friendliness. Needless to say, steel has a strong claim to belonging to the class of the better performing materials [35].

4 CHANGING PATTERNS OF STEEL CONSUMPTION AND TRANSITIONS TO PSS

For some time now, on the business side, a (limited) number of companies position themselves as service providers but quite independently from their environmental aspirations. In the first part of the paper, we indicated that climate protection imperative and energy price trends may change the operating conditions of companies. It is important that social and technical solutions emerge to enable the implementation of the climate policies. Therefore, one should systematically address the contribution of modification of consumption patterns and Product Service Systems (PSS) to GhG reduction.

4.1 Introducing the sufficiency paradigm

An expert group, commissioned by the EU DG research Commission in 2001 addressed the issue of what type of Research, Technology Development and Innovation policies and actions would support the move towards a competitive and sustainable European production system in the period to 2020. The group developed an integrated view of competitive and sustainable production. This view links production technology, technologies in products 'in use' whether as artefacts and materials, to the socio-technical systems in which they are embedded. It also argues that purposeful change and innovation in socio-technical systems involve the participation and collaboration of many actors in the networks that surround these systems.

The report argues that two types of (complementary) strategies are to be followed: efficiency and sufficiency [39]. Literature and practical experimentations by the WBCSD are much more prolix on eco-efficiency and some best practices are already economically viable.

Sufficiency is based on the notion of moving from selling product (with its material throughput philosophy) to providing performance, managing the material content of products together with their asset value.

A growing literature is trying to bridge the gap between the two approaches and is dealing with the modification of consumption patterns.

The challenges are to help in the construction and implementation of new ways to meet social needs [40]. This empirical research seems to be promising, in particular to indicate whether dematerialisation options could be coherent and compatible with business strategies in the material industry that go beyond eco-efficiency and process optimisation. Types of business strategies are listed in table 1.

Moreover, an appropriate framework has to be designed so that economic instruments may deliver benefits to the early movers in this field.

	Types of business Strategies	
Increased resource efficiency:	closing material loops: technical strategies	closing liability loops: commercial / marketing strategies
reducing the VOLUME of the resource flow:	Eco-products Dematerialized goods Multifunctional goods	Eco-marketing More intensive utilization of goods Shared utilization of goods Selling utilization instead of goods
reducing the SPEED of the resource flow:	Re-manufacturing Longer utilization of goods Long-life goods Service-life extension of goods	Re-marketing Away-grading of goods and of components Re-marketing services New products from waste
reducing VOLUME AND SPEED of the resource flow	Technical system solutions Krauss-Maffei PTS plane Transport system "skin" strategies	Systemic solutions Lighthouses Selling results instead of goods Selling services instead of goods

Table 1: Resource efficiency and business strategies in the Service Economy, adapted from [41].

4.2 Promises of Product Service Systems (PSS)

The idea of shifting from products to services is now more than 40 or even more years old [42]. In the last decade, it has resurfaced and a growing literature has dealt with theoretical concepts and practical examples. A more systematic perspective on the combination of products and services is needed. The provision of use is at the forefront and its aim is to increasingly satisfy consumer's needs. It is also consistent with current emerging notions of functional society [43,44].

PSS is a system of products, services, supporting infrastructure that is designed to be competitive, satisfy customers needs and have a lower environmental impact than traditional business models.

However the definition of Product-Service-System is still in construction [45,46,47,48,49,50]. Innovative products or services can clearly increase resource efficiency without adverse effects on functionality or usefulness. There have been a rapid development of PSS ideas in the utility sector and among chemicals industry but case studies are still few. Few attempts have also been made to devise

methodologies for developing PSS [51,52]. More research is still needed to strengthen the market for PSS and see if it is a way to enable more "aggressive" climate protection strategies.

4.3 Engaging steel consumers in PSS strategies : rewarding the steel advantages

Simulations of the long term trends in the consumption of steel have used both economic, input-output models and integrated system assessment models. Hypothesis on the input coefficients for materials in the GDP and the trends towards absolute or relative dematerialisation [53,54]

However, more investigation is needed on the quality of steel needed or scrap recycled but also on the material flows of raw and secondary materials and of material flows in manufactured products.

The Strategic research Agenda of the European Steel technology Platform establishes also an agenda for the scientific and technical development of steel as a material for 2030. For now, steel is mainly consumed in the transport and construction sectors and the majority of studies looked at inter-material substitution between materials (steel, aluminium, plastics, cement). A more subtle rationale is being investigated within the ULSAB-AVC (for Advanced Vehicle Concept) Project and Ultra-Light Steel Automotive Body by the Steel Industry within the IISI organization, where improved properties are being used to increase the safety of the car and generate savings in CO₂ emissions, which are larger than the emissions caused by the making of the material.

Very few studies have been published on the demand side modification of steel consumption when a carbon constraint is introduced resulting in relative or absolute decoupling of steel consumption and GDP. It is however of great promise as it would enable the exploration of the substitution between materials and new use of materials. The conceptual framework of transmaterialisation implies a recurring industrial transformation in the way that societies use materials.

Moreover, steel industry imagines long-term shifts in various economic sectors, which are more than likely in the context of climate change and resource depletion. Changes in the residential, services, transportation, agriculture sectors will imply different material demand in quality and quantity. One could think about the implication of changes in mobility or car-sharing as studied by Meijkamp [55] on the steel or aluminium demand.

Use of steel in construction and transport sector will be explored in two sub-programs as stated in the Steel Strategic Research Agenda. The Research program may consider how the steel industry could benefit from a move towards the concept of Eco-efficient Services.

Sufficiency strategies seem to be more dependent on the choices of final consumers than eco-efficiency strategies and usually include sharing and pooling of products. Consumers are hesitant towards alternatives of consumption without ownership, such as sharing and renting. PSS implies a change in thinking about categories of ownership and consumption at the consumers level. In the steel industry, the Business to Business relationship is particularly important. More research from the social sciences is still needed.

5 CONCLUSION

The traditional approach in the climate policy arena has been decoupled for too long with material efficiency approach.

Cleaner Production via incremental or radical solutions, Industry Ecology and Life-Cycle thinking are the basis for circular economy approach. The aim of this paper was to explore the contribution of steel industry to systems innovations via the irruption of technological breakthrough. It is also to call for other studies to assess the potential and the determinants of the engagement of material industry in transitions towards sustainability.

In the conditions to run business, the challenge is to assess the design and contribution of sufficiency strategies. An appropriate framework is needed to foster the development of these activities and enable new comers to contribute to the solution. Stakeholder participation will be essential for an effective transition [56]. To be global and not only virtual, this picture will have to take into account the evolution of the world steel industry and industrial dynamics in the adoption of new technologies.

6 ACKNOWLEDGEMENTS

I would like to thank Jean-Pierre Birat (ARCELOR Research), Brian Roddis (CORUS) and researchers involved in the ULCOS project as well as Patrick Criqui and Prof Daniel Brissaud for their useful comments and discussions. Research was made possible thanks to a PhD grant of ARCELOR and ADEME. All responsibility for the content rests with the author.

7 AUTHOR'S VITAE

Christophe Rynikiewicz worked primarily as an engineer in papermaking and printing industries and then moved to Arthur Andersen consultancy firm, contributing to studies on industrial strategies and innovation for sustainability. He spent 8 months in Latin America in 2002, working with Development and Environment NGOs on projects under the CDM (Clean Development Mechanism) and priorities of Sustainable Development and regional integration in the Conosur.

Working on the ULCOS project and evolution of the material industry under carbon constrained scenarios, he is now involved in a PhD course in economics at the University of Grenoble / CNRS on "Global Change and Induced Technical Change : towards trajectories of radical innovations in the steel industry".

8 REFERENCES

- [1] Elzen B. and Wieczorek A., (2005), transitions towards sustainability through system innovation, *Technological Forecasting and Social Change* 72, pp. 651–661.
- [2] Berkhout F., Smith A., Stirling A., Socio-technical regimes and transition contexts in Elzen B., Geels FW., Green K. (Eds.), *System innovation and the transition to sustainability : theory, evidence and policy*, Edgar Elgar, Cheltenham, 2004.
- [3] Geels F., Kemp R., Transitions, Transformations and Reproduction: Dynamics in socio-technical systems, DRUID
- [4] Green K., Foster C., (2005), Give peas a chance: transformations in food consumption and production systems, *Technological Forecasting and Social Change* 72, pp. 663–679.
- [5] Eickhout B., Den Elzen M GJ, Vuuren DP van. Multi-gas emission profiles for stabilising greenhouse gas concentrations : Emission implications of limiting global temperature increase to 2°C. *Report 728001026, RIVM, Bilthoven, The Netherlands*. 2003.
- [6] Hare B., M. Meinshausen, (2004), "How much warming are we committed to and how much can be avoided? ", *PIK report n°93 (submitted to Climatic Change)*.
- [7] Grass I., Schellnhuber H.J., et al., (2003), "Climate Protection Strategies for the 21st Century : Kyoto and Beyond", *WBGU, Berlin*.
- [8] CNRS/LEPIL-EPE (France), RIVM/MNP (Netherlands), ICCS-NTUA (Greece), CES-KUL (Belgium). Greenhouse Gas Reduction Pathways in the UNFCCC process up to 2025. European Commission, Brussels. 2003. (Full version can be found at <http://europa.eu.int/comm/environment/climat/studies.htm>)
- [9] Van de Poel I., (2002), the transformation of technological regimes, *Research Policy*, 32 (1):49-68
- [10] Freeman C., (1992), *The Economics of hope : essays on technical change, economic growth and the environment*, Pinter, New York, 243 p.
- [11] Abernathy, W. J. and Clark, K. B. (1985). Innovation: Mapping the Winds of Creative Destruction. *Research Policy*, 14, 3-22.
- [12] Geels, F.W., 2005, *Technological Transitions and System Innovations: A Co-evolutionary and Socio-Technical Analysis*, Cheltenham: Edward Elgar
- [13] Barnett D.F., Crandall R.W., (1986), *Up From the Ashes : The Rise of the Steel Minimill in the United States*, Washington, DC: The Brookings Inst.
- [14] De Beer, Jeroen; Kornelis Blok and Ernst Worrell (1998), Future Technologies for energy-efficient iron and steel making, *Annual Review of Energy and Environment*, 23, pp. 123-205.
- [15] OECD (2002), *Iron and Steel Industry in 2000*, Paris: OECD.
- [16] Quist J. and Vergragt P., (2004), Multiple Sustainable Land-use in Rural Areas: an Attractive Sustainable System Innovation? *European Roundtable on Sustainable Consumption and Production*, 12-14 May 2004, Bilbao, Spain
Quist J, Vergragt P (2003) Backcasting for Industrial Transformations and System Innovations towards Sustainability: is it useful for Governance? *Berlin 2003 Conference on 'Governance for Industrial Transformation'*, Berlin December 5-6, Germany.
<http://www.fuberlin.de/ffu/akumwelt/bc2003/download.htm>
- [17] Adriaanse A., et al., (1997), Resources flows : the material basis of industrial economies, *World Resources Institute*, Washington.
- [18] Wernick I.K. and Ausubel J.H., 1995, National Materials Flows and the Environment, *Annual Review of Energy and the Environment* 20:462-92.
- [19] Gielen D.J., Materialising dematerialisation, Integrated energy and materials systems engineering for greenhouse gas emission mitigation, thesis University of Delft, The Netherlands, 1999.
- [20] Gielen D.J. and Kram T., (1998), Western European integrated energy and materials scenarios for sustainable development. *Netherlands Energy Research Foundation*.
- [21] Von Weisacker E., Lovins A.B., Lovins L.H., (1997), *Factor four : doubling wealth, halving resource use*, Earthscan, London.
- [22] Labys W.C, Dematerialisation and transmaterialisation : What have we learned ?, *RRI Working paper*, 2004

- [23] Labys, (2001), "Transmaterialisation", *Handbook of industrial ecology*, Edward Elgar.
- [24] Ehrlich P.R., Holdren J.P., (1971), "Impact of Population Growth." *Science* 171, pp. 1212-17
- [25] Holmberg J., Azar C., Sten K., (2002), "Decoupling. Past trends and prospects for the future", *Environmental Advisory Council Ministry of the Environment of Sweden*, Physical Resource Theory, Chalmers University of Technology and Göteborg University
- [26] Ayres R.U., Ayres L. W., (1996), *Industrial Ecology : Towards closing the materials cycle*, Edward Elgar, Cheltenham, UK / Brookfield, USA.
- [27] Bringezu S., (2003), "Industrial ecology and material flow analysis: basic concepts, policy relevance and some case studies", in *Bourg, D. and Erkman, S. (eds.), Perspectives on Industrial Ecology*, Greenleaf, Sheffield; UK.
- [28] Vellinga P, Herb N (eds.). *Industrial Transformation Science Plan report*. International Human Dimensions Programme (IHDP), Bonn. 1999.
- [29] Arthur W. 1989. Competing technologies, increasing returns, and lock-in by historical small events. *Economic Journal* 99: 116-31
- [30] Unruh, G.C., (2000). 'Understanding carbon lock-in', *Energy Policy*, 28, pp. 817-830
- [31] Luiten EEM., Blok K., (2003) Stimulating R&D of industrial energy efficient technology : the effect of government intervention on the development of strip casting technology, *Energy Policy* 31
- [32] Nill, J. (2003b): Technological Competition, Time, and Windows of Opportunity – the Case of Iron and Steel Production Technologies. *IOEW-Diskussionspapier Nr. 58/03*, Berlin. Download: www.ioew.de/home/downloaddateien/DP5803.pdf
- [33] Daniels B., (2002), *Transition Paths towards CO2 Emission Reduction in the Steel Industry*, PhD Thesis, RIJKSUNIVERSITEIT GRONINGEN.
- [34] Birat JP., Steiler JM., (1995), Emerging developments., Chapter 63 in *The Book of Steel*, G. Sanz, G. Henry & G. Béranger, scientific editors, Lavoisier
- [35] Steel Strategic Research Agenda to 2030, (2005), EU Steel Technological Platforms European Commission/Eurofer
- [36] Birat JP., Innovation paradigm for the steel industry of the 21st century, future directions for the steel industry and climate change , *Dr Manfred Wolf Symposium, May 10-11, 2002, Zürich*, 102-128 ,
- [37] Birat JP., (2002), The challenge of global warming to the steel industry, a European viewpoint
- [38] Hidalgo I., Szabo L., Ciscar J.C., Soria A., (2005), Technological prospects and CO2 emission trading analyses in the iron and steel industry: a global model, *Energy* 30 583-610
- [39] European Commission, (2001), "Sustainable production : challenges and objectives for EU research policy", *EUR 19880*, Brussels. <http://europa.eu.int/comm/research/growth/pdf/etan-report.pdf>
- [40] Ehrenfeld J., (2001), "Designing 'Sustainable' Product/Service Systems", Presented at *Ecodesign 2001*, Tokyo, December 15.
- [41] Gianrini, Orio and Stahel, Walter R., (1989/1993) *The Limits to Certainty, facing risks in the new Service Economy*, Kluwer Academic Publishers, Dordrecht, Boston
- [42] Becker G.S., (1962), "Irrational behaviour and economic theory", *Journal of Political Economy*, vol. 70, pp. 1-3
- [43] Stahel W. R., (1995), "Product stewardship : increased competitiveness due to a higher resource productivity and a system design", ISWA Conference 1995, October 17-18, Vienna.
- [44] Stahel W. R., (2003), "The Functional society: the service economy", in *Bourg D. and Erkman S. (eds.), Perspectives on industrial ecology*, with a foreword by Jacques Chirac, President of France, March, 384 p.
- [45] Manzini E., (1996), "Sustainable product services development, Pioneer industries on sustainable service", in Workshop organised by UNEP-WG-SPD in *the INES Conference Challenges of sustainable development*, 22-25 August, Amsterdam, Netherlands.
- [46] Montt O., (1999), "PSS : shifting corporate focus from selling products to selling product service system, a new approach to sustainable development", *AFR report 285*, Lund University.
- [47] Tukker A., Tischner U., (2003), "First report of PSS review", *Suspronet Report*.
- [48] Oosterhuis F., Rubik F., Scholl G., (1996), *Product policy in Europe : new environmental perspectives*, Kluwer, London.
- [49] White A.L., Stoughton M., and Felg L., (1999), "Servicizing : the quiet transformation to extended producer responsibility", Tellus Institute, Boston.
- [50] Behrendt S., Jasch C., Kortman J., Hrauda G., Pfitzner R. and Velte D., (2003), *Eco-service development: reinventing supply and demand in the European Union*, Greenleaf Sheffield
- [51] Brezet J.C., Bijma A.S. et al, (2001), The design of eco-efficient services : method, tools and review of the case study based "designing eco-efficient services" project. Delft, Delft University of Technology : 46.
- [52] Vergragt P.J., (2001), How to achieve system innovation : some lessons from visioning and backcasting projects, *Proceedings of Greening of the Industry ASIA 2001*.
- [53] Van Vuuren, D.P., Strengers, B.J. and de Vries, H.J.M., Long-term perspectives on world metal use – a systems dynamics model, *Resources Policy* 25, 239-255 , 1999.
- [54] Rynkiewicz et al, (2005), TRANSMAT : a tool for building scenarios on future steel and material demand, *Working paper Lepii-EPE*, Forthcoming
- [55] Meijkamp R.G., (2000), *Changing consumer behaviour through Eco-efficient Services; An empirical study on Car Sharing in the Netherlands*, PhD dissertation Delft University of Technology
- [56] Van de Kerkhof M. and Wiczorek A., (2005), Learning and stakeholder participation in transition processes towards sustainability: Methodological considerations, *Technological Forecasting and Social Change* 72, pp. 733-747



