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

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Abstract

This paper presents ideas pertaining to transitions that are envisaged in the steel industry from Cleaner Production (CP) to Systems Innovation. Limits of the socio-technical system and the climate change challenge will 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 new breakthrough technologies named Ultra Low CO_2 Steel making (ULCOS). Evolution in material consumption patterns deserves a special research agenda which focuses upon the long term evolution of the consuming sectors as major changes in the infrastructure and products that support our many energy 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*", or 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 indicates that 50−75% emissions reduction is needed in industrialized countries. System innovations in energy intensive industries are also of great importance for the Developing Countries in their industrialization period enabling them to leapfrog. Considering the important challenge of "Factor 4", it is hard to comprehend how economies can evolve towards a much less carbon-intensive path.

Any reduction goal compatible with climate stabilization will have considerable effects on economic activities, markets and behaviors. The demand side (in particular buildings and transportation) will be impacted, via their material's 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 is divided into three parts. First, we highlight the different strategies

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for the steel industry to diminish its contribution to global warming. In Section 2, we focus on the possible changes in the trajectory due to the new ULCOS (Ultra Low CO_2 Steel making) breakthrough technologies. In Section 3, we look at the possible contribution of steel in Product Service Systems and dematerialization. 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 and in consumption patterns. While the pea is an important vegetable, symbolically, if not quantitatively or nutritionally for the UK diet, iron and steel is a key component of our current industrial metabolism.

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 stabilize the concentration in the 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 380–400 ppmv and 550 ppm CO_2 equivalent [5] (which means 450 ppmv CO_2 only) in the atmosphere. Such a level of concentration is still subject to uncertainty and new scientific knowledge may become available in the future, especially on the climate sensitivity factor [6]. The German Advisory Council (WBGU) has recommended the stabilization of CO_2 concentration in the atmosphere below 450 ppmv [7]. The most up to date findings published in the IPCC 4th Assessment Report summary stressed the need for global action.

The recent study "GhG Reductions Pathways" [8] looked at options for a future climate change regime. A concentration level of 550 ppm CO_2e 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 severe for industrialized 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 Fig. 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 as a benchmark for the assessment of alternative policy schemes.

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

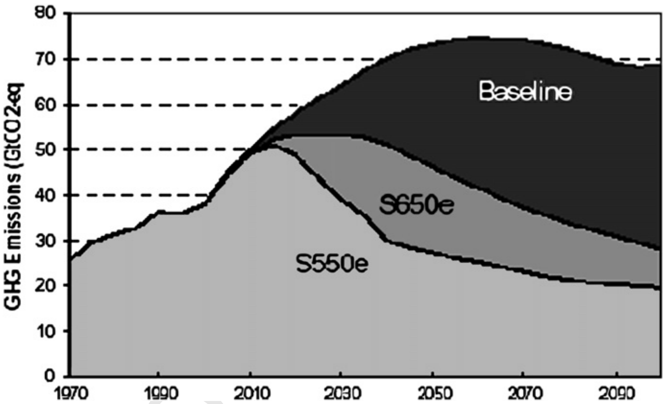


Fig. 1. World emissions profile for different CO_2 concentrations in atmosphere. Source: IMAGE2.2 [8].

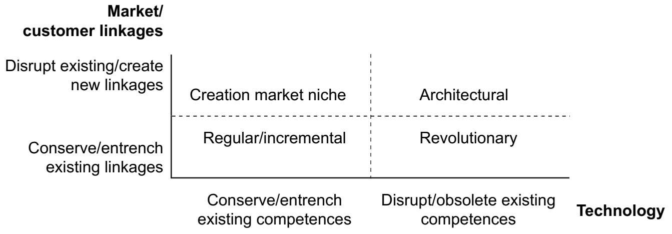
2.2. Linking innovation in production and consumption patterns

A growing literature aims to understand and promote the transformation of the structural characteristics of technological regimes 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/organization, skills (labor, 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 (Fig. 2).

Geels [12] proposes to add the issues at stake in studies on public policies, infrastructures, maintenance networks to



Market/ customer linkages		
Disrupt existing/create new linkages	Creation market niche	Architectural
Conserve/entrench existing linkages	Regular/incremental	Revolutionary
	Conserve/entrench existing competences	Disrupt/obsolete existing competences
		Technology

Fig. 2. Typology of Abernathy and Clark [11].

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define the systems innovation, describing it as an ‘‘AI. writ large’’. The Industrial Transformation Science Plan [13] 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 10–25 years. Fig. 3 illustrates the relation between various response modes, the time scale, and the geographic scale involved.

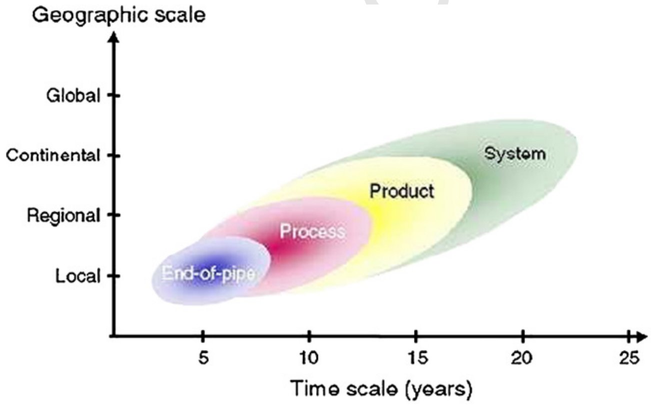
Necessary emission reductions of a Factor 4 or 10 require major technological changes and also that innovation arises out of a more integrated arena. The concept of systems change is proposed as a combination of technical change and societal change.

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 [14].

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 [15] or OECD [16], 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 (Post 2012). Advances in steel making 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. Transition issues in the steel industry

The studies of GhG emissions reduction potentials have traditionally been focusing on energy, mobility and sometimes agriculture system [17]. The question of the measure of inputs of materials has been developed [18,19] and is of particular interest as the composition of this flux reveals the economic structure of a country and may enable us to anticipate the environmental consequences of its development. Then, improvement in material efficiency seems to be a more cost effective way and at least should be favored in parallel with energy system optimization or evolution. Indeed, the MATTER Project (MATerials Technologies for greenhouse 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 [20,21].



Source: Pier Vellinga, 1999

Fig. 3. Societal responses to the issue of environment source [13].

Literature on the environment has identified the need for decoupling environmental impact from economic growth. Lovins' earlier ‘‘Factor 4’’ book argued that numerous technical and organizational opportunities exist for quadrupling resource productivity, enabling a doubling of wealth whilst halving resource use [22]. The ability to realize 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 of decoupling CO_2 and GDP growth are listed in the equation of Fig. 4. Four strategies are listed where ‘‘Transmaterialization’’ implies a recurring industrial transformation in the way that economic societies use materials [23,24]. ‘‘Dematerialisation’’ is a common goal, although its ‘‘automatic’’ happening as GDP increases is challenged.

Emissions associated with the demand for energy-intensive materials (steel, aluminum, cement, etc.) 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.
- by increased recycling or substitution of those materials by less energy-intensive or biomass based materials.

  The central idea of ‘‘industrial ecology’’ is to optimize the flow of materials and energy between different industries and in that way to propose new ‘‘industrial metabolisms’’. Like the Kalundborg case, these loop-closing activities slowly developed over time as firms identified and characterized waste sources, sinks and synergies, for example between cement and steel plants [28]. It derives partly from a desire to see societies internalize these impacts through new models of economic development and conceptualizations of societal ‘progress’. Zero waste and 4R (reuse, remanufacture, recycle and recover) approaches have become common concepts and they are often included in the strategic policy of several companies, who view the environmental issue as a priority as much as

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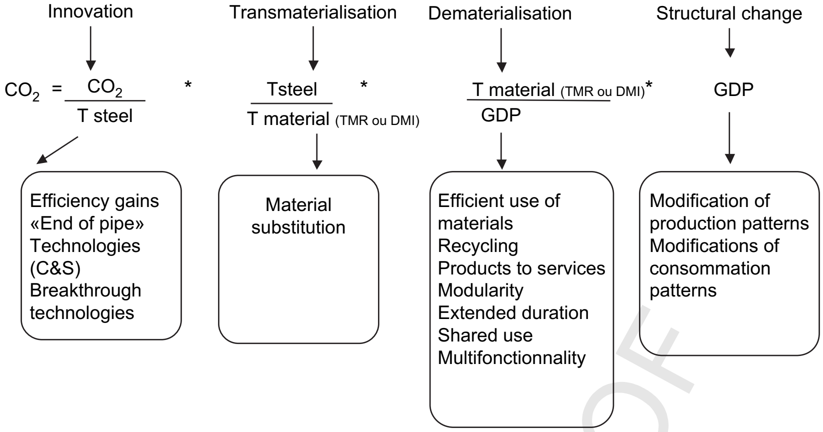

Fig. 4. Decoupling strategies [25]. Adapted from Refs. [26,27].

more traditional aspects concerning productivity, production cost cuts, etc [29,30].

- 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.

- "Process innovation" deals with the radical or incremental innovations that would decrease the CO_2 emissions per tonne of material. Moors et al. [31] proposed a typology to move towards cleaner production in the metal industry.

3. Current technology transitions and the possible future of the ultra low CO_2 steel making (ULCOS) process

We focus on the European steel making industry and other industrialized countries as we suppose that the context of trade, industrial structure, capital but also national demand for steel is different in other countries. Links between industrialization paths, sectoral strategies for leapfrogging are to be treated 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 1970s, 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 [32] resulting in the lock-in in suboptimal technologies because of increasing return to adoption.

This issue has been quite extensively studied in the carbon based energy systems [33]. In the steel industry, Luiten [34] 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 steel making, doing away with the need for reheating and hot rolling mill did not enable them to go "Beyond efficiency" [31].

Smelting reduction is a promising technology which has been intensively studied [35,36]. However, on the short term, the most promising answer to limit GhG emissions is recycling (up to 250 kg of scrap per tonne 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 tonnes of avoided CO_2. Moreover, it does not require drastic revisions of steel making 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 is a momentum for the renewal of this industry. Minimills 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. Limits of the socio-technical system and the ULCOS technologies

In the "book of steel" [37], two industry experts explain that the giant integrated networks have 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 industrialized 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 alternative

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technologies and the development of more radical technologies (ULCOS) which we describe later in this document;

- lacks flexibility and reactivity since the lead time to fulfill an order remains long (30 days would still represent an ambitious objective). Moreover, the capital investments are colossal.

As previously identified, the conflict grew 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 [38].

In parallel, as the momentum grew so that emission reduction was addressed, a European viewpoint on the challenges to the steel industry was given [39,40]. The ultimate objective of the ULCOS project is to achieve a reduction in CO_2 emissions of more than 50% compared to the benchmark ore-based iron and steel making. 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 and Brazil) and at the world level (IISI CO_2 breakthrough program).

Production of steel is energy intensive due to thermodynamic needs of the chemical reaction of iron ore reduction at high temperature by the carbon contained in coal. New concepts for ULCOS technologies are very innovative and involve a reflection on the basis of steel making and a change in the reducing agent as indicated in Fig. 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 sequestrating CO_2 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;
- combinations of all of the above.

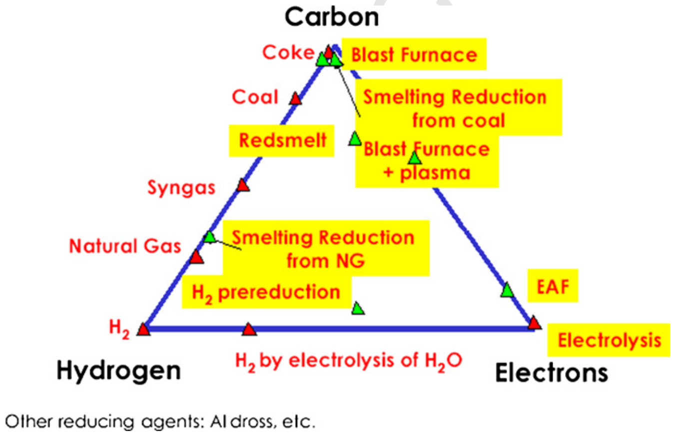

Fig. 5. Conceptual representation of the various ''breakthrough'' steel production routes.

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

3.3. Uncertainties of the technological discontinuity

The emergence of a technological discontinuity will depend on a number of key characteristics, amongst them technological and economic uncertainties. From the technological point of view, the viability of each envisaged technology depends on key uncertainties. First, the Electric Arc Furnace is not the back-stop technology as it is highly sensitive to the carbon-intensity of the electricity used in the process and to the availability and price of scrap. Second, when considering changing 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 pre-reduction processes. However, availability and price are subject to significant changes.
- Availability and price of energy vectors (electricity and hydrogen) as well as acceptability of their production mode (nuclear or not) are highly uncertain.
- Although it is not implemented in the steel industry but has been tested at the pilot plant level, electrolysis could, in principle, be applied in different ways to steel production.

The ULCOS breakthrough technologies will produce different off-gases, by-products and wastes. When available, the complete characterization of the routes will enable optimization of the flows of materials and energy in the plant and potentially with other industries in the same local ''industrial metabolism''. The industrial ecology approach would be needed. Research programs are evaluating the energy and material balances, by process integration techniques, of the integration of industrial sectors (pulp and paper mills, cement kilns, chemical industry and community sector) to use the high temperature heat with better energy efficiency.

From the economic point of view, the evolution of production costs (raw materials, energy, CO_2 price, labor) 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 but will experience learning curves. The theoretical debate on the determinants of the adoption of new technologies is beyond the scope of this paper [41]. Industrial economic theories provide good insights on the conditions of adoption and diffusion of radical innovations under imperfect competition and renewal of the capital cycles. From an empirical point of view, work has been performed using a sectoral equilibrium model of the steel industry, developed at IPTS [42] and linked with the POLES model.

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The steel industry may be one of the first sectors which may experience "*industrial transformation*". Technology could be seen as the entry point of more radical shifts in the socio-technological regime. Indeed, one can envision that the carbon constraint and sectoral trends may induce structural changes in urbanization, transport systems, housing. The main 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 [38].

4. Changing patterns of steel consumption and transitions to PSS

For some time now, on the business side, some companies have positioned themselves as service providers but quite independently from their environmental aspirations. In the first part of the paper, we indicated that the climate protection imperative and energy price trends may change the operating conditions of companies.

It is important that social and technical solutions are developed to enable implementation of climate policies. Therefore, it is important to systematically address the potential contributions 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 to a competitive and sustainable European production system in the period upto 2020. The group developed an integrated view of competitive and sustainable production. This view links production technology, technologies in products 'in use' whether as artifacts and materials, to the socio-technical systems in which they are embedded. It also argues that purposeful change and innovation in socio-technical systems involves 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 [43]. Literature is much more abundant on eco-efficiency (WBCSD) and some best practices are already economically viable.

Sufficiency is based on the notion of moving from selling products (with the material throughput philosophy) to providing performance, managing the material content of products together with their asset value. A growing number of authors are trying to bridge the gap and to deal with the modification in consumption patterns.

The challenges are to help in the construction and implementation of new ways to meet social needs. This empirical research seems to be promising, in particular, to indicate whether dematerialization options could be coherent and compatible with business strategies in the material industry that go beyond eco-efficiency and process optimization. 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.

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 [45]. In the last decade, it has resurfaced and a growing literature deals 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 [46,47].

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

Table 1
Resource efficiency and business strategies in the Service Economy, adapted from Ref. [44]

Increased resource efficiency	Types of business strategies	
	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

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However, the definition of Product Service System is still in construction [48–53]. Innovative products or services can clearly increase resource efficiency without adverse effects on functionality or usefulness. There has been a rapid development of PSS ideas in the utility sector and among chemicals industry but case studies are still few. Few attempts have been made to devise methodologies for developing PSS [54,55]. More research is needed to strengthen the market for PSS and to evaluate 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 [56] input–output models and integrated system assessment models and develop hypothesis on the input coefficients for materials in the GDP and the trends towards absolute or relative dematerialization [57]. 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.

Indeed, the Strategic research Agenda of the European Steel technology Platform established an agenda for the scientific and technical development of steel as a material for 2030. For now, steel is mainly consumed in the transport, packaging and construction sectors and the majority of studies looked at inter-material substitution between materials (steel, aluminum, 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 CO_2 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 substitution between materials and new use of materials. The conceptual framework of transmaterialization implies a recurring industrial transformation in the way that societies use materials. Moreover, the 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 demands in quality and quantity. One could think about the implication of changes in mobility or car-sharing as studied by Meijkamp [58] on the steel or aluminum demand. The use of steel in construction and transport sector will be explored in two sub-programs as stated in the Steel Strategic Research Agenda. 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 consumer's level. In the steel industry, the Business to Business relationship is particularly important. More research from the social sciences is needed on this.

5. Conclusions

The traditional approach in the climate policy arena has been coupled, for too long, with the 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 system innovations via the co-construction of technological breakthroughs. It also calls 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 businesses, 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 [59]. 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.

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