policy trends [14]. The major enabler, which the Commission proposes in order to enforce these principles, is the encouragement and further development of a circular economy, based on reduction, reuse, recycling, and recovery of waste.

A recent paper from J.P. Birat discusses some of these issues, proposing an analysis of what the concept means from the standpoint of materials stakeholders [15] while a EUROFER publish the point of view of steel industry on The Parliament Magazine [16].

In order to improve resource efficiency within its production cycle and in the whole society, the European steel industry is already applying Process integration (PI) [17] for integrating technologies which enhance the use as resources of by-products, discharged water and off-gases at overall plant level. For instance in [18] a PI solution has been explored to improve the exploitation of process off-gases while reducing the CO_2 emissions, in [19] PI-based solutions for recovery of steel scrap through environmental-friendly technologies are investigates. In [20] PI is applied to optimal design of industrial waters management, while in [21] PI-based solutions are analyzed aimed at the recovery and reuse of low temperature heat.

However there is indeed an increasing demand for industrial ecology solution and synergies between industries, cities and communities, as well as for a reinforcement of reuse and recycling. Industrial ecology is a multidisciplinary research field which investigates the material and energy flows within industrial systems often to the aim of analyzing (and possibly reducing) the impacts that industrial activities have on the environment, due to the exploitation of natural resources and the generation and disposal of wastes. According to [22] the term “industrial ecology” derives from and analogy with natural systems that should be used to help to understand how to design sustainable industrial systems. Industrial ecology thus can represent a further step toward a true cross-sectoral and global approach to the problem.

The idea of resource preservation by increasing energy and material efficiency includes the recycling of steel in particular and recycling of the all the large volume of by-products generated by the steel sector both inside and outside the steel production cycle. Steel has been recycled at a high level estimated around 85%. Steel mills are moving towards "zero residues" (zero waste) in a credible way: their energy use is one of the most efficient among Energy Intensive Industries (EII). The steel sector is committed to progress further and to imagine solutions for turning into an even leaner sector. Furthermore, transversal, through-process issues are essential to acknowledge in a holistic approach, as well as the quick integration of new technologies developed outside of the sector and cooperation with other economic players.

However, such as pointed out in [15], large amounts of research were conducted to develop concept into viable industrial solutions, but the death rate was enormous due to low return on investment and/or high operating costs. Thus a system of subsidies would have had to be implemented, like it is done for renewable energy and many other examples. There are many examples of processes in the metal sector, where industrial ecology principles have been applied, sometimes before that discipline was invented, such as, for instance, the use of Blast furnace slag for cement making as a clinker substitute, or of slag for road construction, or of EAF dust as a feedstock for the zinc industry mainly through the Waelz process. How large this part of residue handling actually is in a sector like steel is demonstrated by the material efficiency indicator of the WorldSteel Association which is at the level of 98% [23].

5. Moving smoothly into a closed loop economy

Steel is correctly stated to be the most recycled material in the world and this is often interpreted to mean that steel is part of a closed-loop economy. This is a subtle and complex concept, as an economy can be close-looped for some material and not for others and it can be partially or totally closed (namely the term “closed” can be interpreted in a weak and strong meaning). Steel today is indeed part of a partial closed-loop economy related to the generation and reuse of scrap but also to the reuse of steel without re-melting it, as is commonly practiced for rails or pile sheets.

This practice will be as essential in the future, as it was essential in the past. The steel sector is organized with specialized steelworks, where the production cycle is based on the Electric Arc Furnace (EAF), where the steel scrap is melted to produce new steel products. Moreover, the collection of scrap and its treatment to turn it into a true secondary raw material is mostly a profitable, value-creating business: this is actually why steel is recycled to such a high level. In the future, the fraction of scrap vs iron ore is expected to increase, as the steel produced in the past and especially since the explosion of production, which has taken place since 2000, will be coming back in the economy as scrap. This will raise delicate issues of adjusting the balance between integrated and scrap process routes, for instance in China, which has invested heavily in integrated mills.

This fact will also generate the need for new technologies to sort scrap more effectively and to purify it after sorting, as well as for taking care of the environmental aspects related to recovery and pre-

Copyright © 2015, Infonomics Society

treatment of scrap [19]. In fact, although the EAF-based steel production route shows important environmental advantages, being less energy intensive (and less CO_2 insensitive), the limited availability of scrap means that not all steel demand can be met by recycling. This means that it is not interchangeable but complimentary to the production cycle that produces steel by melting virgin materials (mainly iron ore and carbon) in the Blast Furnace (BF), i.e. the so-called "BF route". The major limitation in steel recycling is represented by tramp elements which can concentrate in the iron and decrease its properties; therefore there are some steel qualities and products that currently can only be produced through the BF route and secondary resources containing high amounts of impurity elements can only be used for lower qualities of steel. Different types of scrap or scrap and virgin ore can be mixed in order to achieve the required specifications making possible to obtain a virtually closed cycle without a drop of quality. However, it has to be pointed out that all tramp elements are irreversibly fed to the iron cycle. As global recycling rates will further increase (up to 80%) the issue of tramp elements will become more important in the future and need to be addressed by the research in the steel field in order promote resource efficiency at global level, which also encompass an efficient exploitation of available secondary raw material.

Finally it must be underlined that the technologies fostering the reuse of the by-products generated by the steel production cycle in other industrial sectors or activities are also an integral part of this effort toward a closed-loop economy. Some examples are still available (see for instance [25]) but the application of Industrial ecology solutions, such as already mentioned in the Sec. 4 needs to be further investigated.

6. Synergies with neighboring communities

The Steel sector is immersed in the economy and society, in various ways: the value chain and the life-cycle dimensions have already been stressed, but various other synergies are at play and operate in a cross-sectorial manner. A steel mill is at the center of a huge logistical hub, where more than 10 tons of matter and scores of energy are handled, transformed, exchanged and sometimes dissipated or landfilled per ton of steel. This puts large demands on logistics, which ought to be considered as a resource akin to raw materials, except that it is a more abstract one, based on seaways, harbors, rail tracks, roads and bridges on the one hand and on ships, cranes, trains and trucks on the other hand.

The steelworks are also connected with other economic sectors and with local communities in a horizontal manner, i.e. not through the logics of the value chain but with that of industrial ecology. Indeed, waste heat and residues can be used elsewhere and the steelworks itself can, in principle, use those of neighboring industrial sites. This is usually a mesoscale effect, as opposed to the macro-scale of international trade. This field is not virgin, as supplying heat to city districts has been practiced for decades (some interesting examples are depicted in [25-26]). Similarly, much of blast furnace slag is used as raw material for the cement industry, the rest being turned into roadbed material. The expectation today is that more can be done in the future to save energy and raw materials globally, across value chains, thus increasing energy and material savings.

The cooperation with other industrial sectors, such as illustrated in Figure 5, has a large potential to promote the reuse of by-products (slag, dust and sludge) as secondary raw materials. It can also recover valuable metals (e.g. zinc, tin, major alloying elements present in steels and iron from non-ferrous metallurgy residues).

Figure 5. Cross-sectorial approach to foster by-products reuse.

These are beneficial for reducing the environmental footprint of steel production and improving competitiveness. Process Integration is an important means to implement industrial symbiosis by promoting resource efficiency: The European steel industry through the Research Fund for Coal and Steel (RFCS) is promoting pilot projects exploring this direction, such as the following projects

- "Development of tools for reduction of energy demand and CO_2-emissions within the iron and steel industry based on energy register, CO_2-monitoringand waste heat power generation" (ENCOP) [18];
- "Processes and technologies for environmentally friendly recovery and treatment of scrap" PROTECT [19];
- "Efficient use of resources in steel plants through process integration" REFFIPLANT [20, 27-28];

Such a cross-sectoral approach can be extended to improve efficient management and reuse of secondary but fundamental resources, such as water and off-gas.

Copyright © 2015, Infonomics Society

The European Steel sector has been a founding stakeholder of the European Public Private Partnership (PPP) named SPIRE (Sustainable Process Industry through Resource and Energy efficiency). The SPIRE association developed its own roadmap [29], which includes also concepts and principles that were already present in the ESTEP roadmap.

7. Overcoming current Life Cycle Assessment

LCA is nowadays a consolidated and widely exploited technique to assess environmental impacts associated with all the stages of the life of a product from cradle to grave [30].

The present most common kind of LCA is named *attributional LCA*. A different method, describing more closely how the real world operates, is the so-called *consequential LCA*, but it is still rarely used. More forward looking methodologies are being developed, such as *foresight LCA*, *dynamic LCA*, *social LCA*, *Life Cycle Costing (LCC)*, introduction of end-of-life and recycling into LCA [5].

Nonetheless there are important areas where LCA is not yet properly used or not adopted at all: This is, for instance, the case of EU rules and regulations for cars, which favor a concept called "recycled content" rather than a recycling ratio. Another example is provided by the use of tail pipe emissions to rank the performance of commercial vehicles, without considering the life cycle emissions instead. As a consequence, the importance of light weighting is overestimated, which is not always a worthy objective when pursuing low Green House Gases emissions. Moreover, this fact gives a predominant importance to climate change without considering other issues and may thus be creating difficulties elsewhere.

Life Cycle Thinking (LCT), the approach behind LCA, is worldwide recognized as beneficial to society and the European steel industry wishes to promote it. However the present methodology is still not perfect and other methodologies are needed to complement it.

To move away from the micro-economic description of the economy related to choosing the functional unit as the central concept of LCA, one should open the scope to macro-economic thinking with Material Flow Analysis (MFA) [30] or Energy Flow Analysis, which lie at the core of the analysis of recycling, a major issue for steel and metals in general and many other materials

This might be insufficient to deal with the main open issues and challenges: thus, more ambitious methodologies, going beyond LCA and MFA have to be developed, or, rather, their development has to be further encouraged. In the steel and structural material sectors, this corresponds to the SOVAMAT initiative [32], which puts forward the concept of "social value", which is close to a more holistic definition of sustainability. The LCA Community is exploring the idea of functionality, beyond that of functional unit, etc. The steel sector needs to be at the forefront of methodological innovation in this area, in order to create a dynamics that would open up to interdisciplinary cooperation, from sociology, socio-economics to scientific ecology by encompassing the various communities of LCA, MFA, economic global modelers, etc.

In order to overcome the current limitations of LCA in the context of process industry, the European Research Framework Program Horizon 2020 (H2020) is currently supporting the following three international research projects running under the umbrella of SPIRE:

1. *STYLE - Sustainability Toolkit for Easy Life Cycle Evaluation* aims at developing a practical toolkit to be used by EU projects and industry in order to assess the value of new technologies and process modifications focused on improving resource and energy efficiency.
2. *MEASURE - Harmonised cross-sectorial sustainability assessment in the European process industries*, aims at developing a roadmap providing recommendations for standards and best-practice methods and tools for life cycle-based evaluation approaches in process industries and sustainable process design.
3. *SAMT - Sustainability assessment methods and tools to support decision-making in the process industries* aims at reviewing and making recommendations on the most suitable methods to evaluate sustainability in the process industry, focusing especially on energy and resource efficiency.

The three projects are linked with each other and several steel industries are partners of the first two above-listed project, by thus accomplishing part of the actions planned in the ESTEP's SRA.

8. Future research directions

The ESTEP is committed to stimulate the research in the steel field in order to provide the European steel industry with all the suitable means to face the future challenges at technological, economical and societal levels. This will lead also to gradually broadening the dimension and scope of the investigations and to enlarge the number of potential partners in the research activities. While in the past (roughly until the end of the nineties) the research was focused mostly on mitigation of the environmental risk at the specific site level, current short term research activities are addressed toward the reduction of the environmental impact of the

Copyright © 2015, Infonomics Society

production cycle in both the surrounding areas and in general at a wider level. Resource efficiency lies in this dimension but it is also a far more global topic. In fact, as depicted in the previous section, the global perspective for an effective resource efficiency strategy must be related to the profitable steel production, competitiveness of European steel industry and creation of new jobs opportunities. The real target for medium-long term research activities and initiatives is aimed at decreasing the "social footprint" of the steel industry targeting at high level technical challengers:

- maintaining continuous improvement in product performance: e.g. high strength - development of both new products and the capability to make them
- Extend service life – through new product development and use of more efficient coatings, the recycling of coatings, closing the loop within manufacturing
- Education and communication – influencing public perceptions of steel in general, also for customers and markets
- Product data tracking, maintaining steel identity (source/batch/history information) through manufacture, supply chain, use and EOL
- Increase re-use – demonstrate the benefits with new business models (technology)
- Improving carbon and energy efficiency of steel plant operation
- Improving process yield and through supply chain yield – new process routes such as additive manufacturing, or optimize products to meet supply chain
- Best use of information technology to balance supply and demand – operational plant IT systems, stock control, flexible manufacturing, response and delivery times
- Using LCA/SATs to demonstrate value of steel in circular economy against alternative materials – social aspects such as flood defense, affordable housing, and agriculture and food production

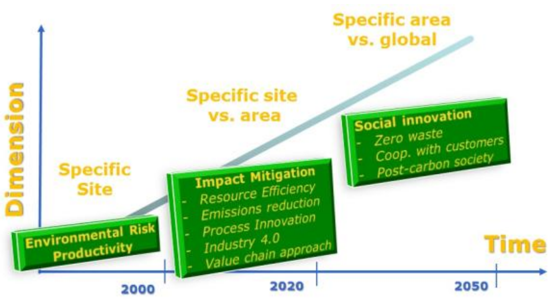

Figure 6. Foreseen dimension and time evolution of the R&D activities

In this frame the cross-sectorial approach and the cooperation with society and stakeholders is also essential. The above-depicted foreseen evolution is summarized in Figure 6.

9. Conclusions

The paper presented an analysis of the ESTEP's SRA concerning the topics which are directly related to resource efficiency. The SRA vision is one of smooth cooperation between the anthroposphere and the bio/ecosphere and to enforce a balanced respect for both. This raises challenges that the sector faces in terms of R&I in relation to sustainable steel production. The focus is on reducing the environmental footprint of steel production and steel solutions by reducing resource consumption, fostering the use of secondary raw materials and thus accelerating the move towards a more closed-loop economy, as well as by implementing energy efficiency, saving exergy, implementing process integration and eco-design approaches.

Environmental topics, constraints and commitments that have long been considered as external to the economy, business and metallurgy, are no more simple boundary conditions expressed by bother-some regulations, but an integral part of an holistic system, where nature and society, geo-, bio and anthropospheres interact at a complex level.

Holistic, transverse, cross-cultural and cross-sector approaches are the standard ways to move forward. Steel is not starting from a clean slate, as these issues have been embedded in its practice and culture for a long time (recycling, energy efficiency, zero waste, carbon-lean steel production processes, steel as an enabler of a leaner economy, etc.), but the pace of change should not slacken and it might even have to accelerate, as the world is becoming ever more populated, more compact and more demanding.

10. References

[1] Strategic Research Agenda: a vision for the future of the steel sector," March 2013, available at: ftp://ftp.cordis.europa.eu/pub/estep/docs/sra-052013-en.pdf.

[2] "World Steel in Figures 2015", WorldSteel Association https://www.worldsteel.org/publications/bookshop/product-details.~World-Steel-in-Figures2015~PRODUCT~World-Steel-in-Figures-2015~.html (May 2015).

[3] J.-P. Birat, "Steel and humanity's grand challenges," Materiaux et Techniques, vol. 103(5), 2015.

[4] J.-P. Birat, V. Colla, E. Malfa, and J.S. Thomas, "The European Steel Technology Platform's Strategic Research Agenda vision for the sustainable steel production 2030s," 14th IAEE European Energy Conference on Sustainable Energy Policy and Strategies for Europe, October 2014.

Copyright © 2015, Infonomics Society

[5] J.-P. Birat, V. Colla, E. Malfa, and J.S. Thomas, “SUSTAINABLE steel production for the 2030s: The vision of the European Steel Technology Platform's Strategic Research Agenda (ESTEP's SRA,” Technical Proceedings of the 2014 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2014, vol. 3, pp. 238-241, 2014.

[6] C. Pietrosanti, V. Colla, H. Peters: "Integrated Intelligent Manufacturing and Optimization: the hen and the egg", Proc. 2nd European Steel Technology and Application Days ESTAD 2015, Dusseldorf (Germany), June 15-19 2015.

[7] J.-P. Birat, “Life-cycle assessment, resource efficiency and recycling” Metallurgical Research and Technology, vol. 112(2), 2015.

[8] ODYSEE-MURE “Synthesis: Energy Efficiency Trends and Policies Lessons from the ODYSSEE MURE project” (September 2015), available at http://www.odyssee-mure.eu/publications/br/energy-efficiency-trends-policies-in-europe.html

[9] EUROFER: “Steel and the circular economy”, http://www.eurofer.org/News%26Media/PublicationsLinksList/20151016_CircularEconomyA4.pdf (16 October 2015)

[10] L. Horvath et al., “Energy Use in the Steel Industry,” World Steel association, 2014.

[11] B. de Lamberterie et al., “Steel production - energy efficiency working group Final report”, ESTEP report, ftp://ftp.cordis.europa.eu/pub/estep/docs/wg7-final-report.pdf (20 October 2015)

[12] http://www.ulcos.org/en/about_ulcos/home.php, (Access date: 2 May 2014).

[13] ec.europa.eu/eip/raw-materials/en, (Access date: 22 July 2014).

[14] European Commission, “Towards a circular economy: A zero waste program for Europe”, COM 398 final, Brussels, 2.7.2014, available at http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A5 2014DC0398

[15] J.P Birat, “Life-cycle assessment, resource efficiency and recycling,” Metall. Res. Technol. 112, 206 (2015)

[16] https://www.theparliamentmagazine.eu/articles/magazines/eurofer-supplement-september-2015

[17] J.J. Klemeš et al., “Recent developments in advanced process integration: Learning the lessons from industrial implementations,” Applied Mechanics and Materials, vol. 625, pp. 454-457, 2014.

[18] G.F. Porzio et al.: “Process integration in energy and carbon intensive industries: An example of exploitation of optimization techniques and decision support,” Applied Thermal Engineering, vol. 70(2), pp. 1148-1155, September 2014.

[19] G.F. Porzio et al., “Process integration analysis and some economic-environmental implications for an innovative environmentally friendly recovery and pre-treatment of steel scrap,” Applied Energy, vol. 161, pp. 656-672, 2016.

[20] G.F. Porzio, E. Alcamisi, I. Matino, and V. Colla, “An integrated approach for industrial water systems optimal design,” Technical Proceedings of the 2014 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2014, vol. 3, pp. 529-532, June 2014.

[21] C. Wang et al., “Techno-economic assessment of recovery and reuse of low temperature heat (T<350°C) in the steel industry by means of process integration,” Energy Procedia, vol. 61, pp. 2188-2191, 2014.

[22] R.A. Frosch, and N.E. Gallopoulos, “Strategies for Manufacturing,” Scientific American vol. 261(3), pp. 144–152, 1989.

[23] WorldSteel Association, “Sustainable Steel: Policy and Indicators 2013” (8 October 2013) available at https://www.worldsteel.org/publications/bookshop/product-details.~Sustainable-steel--Policy-and-indicators-2013~PRODUCT~Sustainable-steel~.html

[24] T.A. Branca et al. “Investigation of (BOF) Converter slag use for agriculture in europe,” Metallurgical Research and Technology, vol. 111(3), pp. 155-167, 2014.

[25] C.-E. Grip, “Steel and sustainability: Scandinavian perspective,” Ironmaking and Steelmaking, vol. 32(3), pp. 235-241, 2005.

[26] A. Villar, J. Parrondo, and J.J. Arribas, “District heating from industrial surplus heat in Avilés (Spain)”, Environmental Progress and Sustainable Energy, vol. 33(4), pp. 1380-1388, 2014.

[27] E. Alcamisi et al., “Process integration solutions for water networks in integrated steel making plants,” Chemical Engineering Transactions, vol. 45, pp. 37-42, October 2015.

[28] A. Wedholm, M. Brämming, and D. Olofsson. “Activities for material resource efficiency at MEROX north”, 1st International Process Integration Forum for the Steel Industry 2014, Luleå, Sweden, June 2014.

[29] A.SPIRE aisbl. SPIRE Roadmap: Sustainable Process Industry through Resource and Energy Efficiency, http://www.spire2030.eu/uploads/Modules/Publications/spire-roadmap_december_2013_pbp.pdf (25 October 2013).

[30] “Defining Life Cycle Assessment (LCA).” US Environmental Protection Agency. 17 October 2010.

[31] P.H. Brunner, and H. Rechberger. Practical Handbook of Material Flow Analysis. Lewis Publishers, New York. 2004.

[32] www.sovamat.org, (Access date: 11 October 2013).

Copyright © 2015, Infonomics Society