Investigating the economic and environmental impacts of a technological shift towards hydrogen-based solutions for steel manufacture in high-renewable electricity mix scenarios for Italy

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Investigating the economic and environmental impacts of a technological shift towards hydrogen-based solutions for steel manufacture in high-renewable electricity mix scenarios for Italy

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Abstract. Steel production is one of the most carbon-intensive industrial sectors, responsible for 8% of European CO2 emissions. While traditional furnaces strongly rely on the consumption of coal or natural gas, potential opportunities for decarbonization stand in the adoption of alternative technologies such as hydrogen-based Direct Reduction Iron (DRI) coupled with Electric Arc Furnaces (EAF). This work focuses on the Italian steel sector and aims at assessing the potential economic and environmental impact of a switch towards such hydrogen-based technology. Three scenarios have been analyzed, all of which are grounded on the common assumption that hydrogen is produced by employing electrolyzers purchasing electricity from the grid. In the first scenario, the share of electricity production from renewable sources (RES) in the national electricity mix coincides with the one in the current Italian situation. The second scenario reflects the national target of 55% of electricity generated by low-carbon technologies. In the last scenario, the RES share in the electricity mix is 100%, meaning steel production plants are fully supplied with green hydrogen. The analysis is carried out by adopting a multi-regional input-output model for sectorial LCA, which allows to highlight the interlinkages of the steel industry with other sectors in different regional areas. The results show that a switch to DRI with EAF technology, coupled with the increase of RES penetration, allows to reduce the CO2 emissions of the Italian steel sector up to 14%, leading to an increase in employment of about 12 thousand units. It is also worth noting that a larger penetration of electricity produced from RES, which are mostly local, would be a significant improvement in terms of energy security of the steel sector, lowering its dependence on foreign fossil resources.

1. Introduction

The steel sector is highly strategic for the global economy due to its interconnections with many other industrial activities; at the same time, due to its strong reliance on fossil fuels, it is highly energy-intensive, and it is commonly included within the so-called “hard-to-abate” sectors. While China is the first steel producer in the world with a share of 53% of the entire market, Italy is placed at the eleventh position with an absolute production of 23 million tonnes (Mton), the second biggest producer in the EU right after Germany (data referring to 2019, pre-pandemic situation) [1]. Keeping a focus on Italy, the steel industry is worth around 60 billion euros and employs 30 thousand direct workers [2]. Its specific carbon footprint has been improving in the last two decades, decreasing by 60%, reaching the value of 0,94 ton CO2 /ton steel in 2018 [3]. The production occurs through two main technologies: the Electric Arc Furnace (EAF) and the Blast Furnace – Basic Oxygen Furnace. The first is used to recycle metal while the other converts iron ores into steel; EAF production represents a virtuous pathway not only because it is an example of circular economy but also because it relies less on coal. In 2019, Italian steel production with EAF represented around 82% of the annual supply, in contrast with the European average where steel production from EAF consists of just 41% [1]. The next years will be critical for what concerns the chance to draw a sustainable development pathway in this specific sector. The European steel industry has shown a strong commitment to act in reducing the environmental impact of the sector, as reported in the "Green Deal for Steel" [4], a document that sets the objectives along with the guidelines to achieve them. Also, the same steel makers have set green initiatives, a possible production option can be represented by the Direct Reduction Iron (DRI) technology, which uses either natural gas or hydrogen as heat source and reducing agent but needs to be coupled with an EAF system [5]. Drawing from all the different possibilities and recent studies on nexus assessment of the iron and steel industry, resumed clearly by Muslemani et al. [6], Devlin and Yang [7] and Kim et al. [8], the purpose of this research is to evaluate the benefits associated with the substitution of the integrated cycle with hydrogen-based DRI technology, which seems one of the most promising, in terms of economic and environmental performance, and how this change is affected by the increase of renewable sources (RES) penetration in the national electricity mix.

To assess this problem, a comparative-static input-output methodology has been adopted, with a specific focus on a backward-forward linkages analysis and, subsequently, the consistency of the results obtained was aligned with the expected outcomes. The authors identified the input-output framework as a novel approach to evaluate the impact of the introduction of hydrogen-based technologies in the Italian steel sector, allowing for an extensive and comprehensive assessment of both environmental and supply-chain implications. The literature review section (section 2), therefore, serves to justify the suitability of the methodology adopted for the study; the theoretical formulation of the methodology is then described in section 3 and applied to the specific case of the Italian steel sector (section 4). A critical discussion of the results is presented in section 5 and final considerations are in section 6.

2. Literature review

The life-cycle-assessment (LCA) method is becoming more and more diffused when dealing with assessing the impact of environmental policies. In recent years various studies adopting LCA instruments based on the input-output analysis, such as the shock analysis and the backward and forward linkages, have been registered in the scientific literature. The strength of this approach is to combine the environmental analysis with economic performance indicators as it is clearly stated by Kecek et al. [9] who quantified the economic effects of renewable technologies deployment in the Croatian economy through an open and closed input-output model. Together with this many other studies in recent literature addressed the issue of quantifying the impact of renewables deployment on national and regional economies by means of input-output analysis (IOA). This is the case of Markaki et al. [10] who performed an analysis on the implication of future investment toward the decarbonization of the electricity sector. A similar analysis is performed by Allan et al. [11] for the case of the Scottish economy, comparing different options for electricity production both conventional and RES. Rocco et al. [12] indeed, adopted an input-output model to perform a shock analysis to evaluate the impact driven by renewable penetration in the electricity sector in Tanzania. Most of these studies although belonging to the energy field do not strictly relate to the interconnection between steel and the energy sector.

Nevertheless, the same kind of analysis can be successfully implemented for any investment in the energy field as can be inferred by the guidelines for broad impacts assessment of power sector projects in developing countries drawn by the International Finance Corporation [13] that refers to input-output multiplier analysis technical notes by Xue et al. [14]. Another relevant contribution in the field belongs to San J. et al. [15] who used the backward and forward linkage approach to identify the key mining sectors in the EU. The present work intends to be inserted into this research field, to propose an application analyzing the interconnections between energy-intensive sectors and the energy sector itself.

For this purpose, the Leontief input-output framework [16] is chosen because of its specific characteristic such as: (i) being able to capture the intersectoral connections, both in terms of final product and intermediate demand at an international scale; (ii) being able to analyze environmental and socio-economic factors, such as pollution, employment and water consumption associated to industrial production processes. (iii) being able to provide compact indicators about sectoral interdependencies.

3. Methods and models

Drawing from considerations coming from the literature review, the use of a standard model based on monetary input-output tables (MIOTs) was considered the best-fitting approach for the purpose of the work. Such tables are widely available and provide multi-regional and multi-sectorial coverage, representing the economic snapshot of a certain region in a determined year. The tables can be interpreted as matrices objects which are described as follows: the intermediate transactions matrix (**Z**), representing the interindustry supply and demand of goods and services; the final demand matrix (**Y**), which characterizes the economic consumption of households as well as the formation of fixed capital and governmental expenditures; the value added matrix (**V**), including the compensation of employees, the consumption of fixed capital and the taxes burdened upon industrial activities, together with their operative surplus; the satellite accounts matrix (**E**), which includes the consumption and/or production of quantities which are outside the national accounting balance: it is the case of, for instance, emissions, water, land and energy consumption. These tables can be used to derive and apply the Leontief model: first, it is important to compute the vector of the endogenous total production X, which represents the total domestic production.

$$\vec{\mathrm{X}} = \mathbf{Z} \cdot \mathrm{i} + \vec{\mathrm{Y}}\mathbf{z} \tag{1}$$

Where i is a column vector composed of unitary values with length equal to the number of rows of the matrix **Z**. The Leontief model relies on the computation of the matrix of technical coefficient (**z**):

$$\mathbf{z} = \mathbf{Z} \cdot \left(\mathbf{I} \cdot \vec{\mathrm{X}}\right)^{-1} \tag{2}$$

From this the Leontief inverse matrix (**w**) can be calculated as:

$$\mathbf{w} = (\mathbf{I} - \mathbf{z})^{-1} \tag{3}$$

In parallel with the Leontief approach, the Ghosh model can be formulated, as necessary to find the so-called *key sectors*. This model relies on two matrixes: the Ghosh coefficient matrix (**g**) and the Ghosh inverse matrix (**G**).

$$\mathbf{g} = \left(\mathbf{I} \cdot \vec{\mathrm{X}}\right)^{-1} \cdot \mathbf{Z} \tag{4}$$

$$\mathbf{G} = (\mathbf{I} - \mathbf{g})^{-1} \tag{5}$$

The comparative static relies on the implementation of shocks: this allows to determine how much a change in final demand level, final demand, or endogenous trade patterns exogenously imposed, causes changes in terms of sectoral output production and therefore value added generation and consequently CO_2 emissions. As previously stated, two very strong hypotheses arise in doing this procedure: the lack of supply-side constraints, and the fixed production technology and consumption mix, except for the shocked one. Given the definition of the Leontief and Ghosh models, it is possible to perform the backward and forward analysis. The total backward linkages are defined as

$$BL(t)_j = \sum_{i=1}^{n} \mathbf{w}_{ij} \tag{6}$$

namely the column sum of the Leontief coefficient matrix. Generally, the backward linkages express the dependence on the interindustry supply of the sector j: the higher it is, the higher the request from other sectors should be to change the production of j of one monetary unit. The forward linkages express the symmetrical opposite concept: how the intermediate demand is activated in all sectors j by the increased production i-th. Similarly to the Backward Linkages, the Total Forward Linkage is defined as

$$FL(t)_i = \sum_{j=1}^{n} \mathbf{g}_{ij} \quad (7)$$

namely the column sum of the Ghosh coefficient matrix. Lastly is important to note that for the sake of feasibility the linkages can be normalized to easily capture the so-called key sectors, which are those with both backward and forward linkages greater than one. By neglecting the diagonal of the matrixes, only the interaction with other sectors is taken into consideration avoiding considering the transactions within the sector itself. The applicability of Leontief and Ghosh models with Backward and Forward linkages is subject to limits, mainly because it is considered that all the matrix coefficients remain constant over time unless they are changed by an external player. However, some efforts have been made to make this approaches suitable also for more dynamic situations, trying to take into account information on how the electricity production mix would evolve over time. This assumption about future technological evolution is the only worthy to be considered for this work, given the limited time span of the analysis. To easily manage the input-output database, a powerful yet simple instrument has been used: MARIO (Multifunctional Analysis of Regions through Input-Output), developed by the Department of Energy of Politecnico di Milano and publicly available on GitHub as an installable Python library [17]. Together with other tools [18]–[20], MARIO stands out as one of the most complete platforms to process all the different types of input-output (IO) tables and provide a framework to implement transparent, automatic, and easily reproducible shock and footprinting analysis. Supply and Use tables are also supported and can be transformed into IO tables employing a built-in function, implementing the transformation models extensively described and adopted in the literature [16], [21].

Furthermore, MARIO allows for smooth handling of database aggregation, modification, and extensions. Finally, productivity and balance tests together with backward-forward linkages analysis and production or consumption-based visualization of results in different scenarios provide IO analysts with basic coding skills with a wide set of instruments.

4. Case study: a technological overview of the steel sector

A possible pathway that could be pursued to decarbonize the Italian steel sector is the substitution of the integrated plants still present on the territory with hydrogen-based DRI systems, combined with EAF. It has been chosen to analyze this solution since, according to Mapelli *et al.* [22], this seems to be the best strategy in terms of tons of carbon dioxide emitted per ton of steel produced, leading to almost carbon-free steel production. The DRI technology has been deployed commercially. Lower investment, and space requirements, together with simpler design operation, make it easier to build and operate a DRI plant [23]. However, DRI furnaces alone are insufficient for the correct production of steel, therefore the steel exiting from a DRI plant should be then sent to an EAF, which could be either in the same location (as assumed in this work) of the furnace or in another site. The DRI plant is composed also of a pelletizer unit, which represents the first stage of the production process: this unit receives iron ore as input and transforms it into an iron pellet by heating the material. The iron pellets are then ready to be sent to DRI Furnace. Here hydrogen is used as a reducing gas, to remove the oxygen present in the iron pellets. The reaction is endothermic. Thermal energy is also needed to preheat the stream of hydrogen entering the furnace. A further step in which the remaining oxygen is mostly removed is required. The EAF offers a response to this necessity. In this stage two main things happen: the hot DRI is completely melted at a temperature of about 1700 °C and furtherly reduced. It is important to highlight that the reduction occurring in the EAF does not involve hydrogen, but carbon oxide deriving from the mixing of oxygen and carbon. It is assumed that 10 kg/tls (tons of liquid steel) of carbon coke are added in the process [23], this is why neither the combined solution hydrogen-based-DRI with EAF can be considered carbon-free. In this work, all thermal inputs are considered obtained from electricity. On the side of hydrogen supply, the amount of hydrogen needed for the production of 1 ton of steel has been estimated at around 0.06 tons [23]: therefore the generation of 1 ton of hydrogen with the available electrolyzers requiring about 50 MWh [23] and 10 m^3 of water [24].

4.1. Technologies comparison

The hydrogen-based DRI with EAF solution does not differ from the integrated cycles only for the higher utilization of electricity and water in the production phase, but also for the different exploitation of carbon. Both the EAF and the integrated cycle require carbon coke, which derives from coal treated in dedicated coke ovens; in this study, it has been assumed that 1.32 tons of coal are required to produce 1 ton of coke [25]. In the integrated cycles, water is used in form of both liquid and vapor in all the processes that constitute the production (coke ovens, sintering plants, Blast Furnaces, Basic Oxygen Furnace). The following table highlights the main differences in the deployment of such resources.

Table 1. Use of resources for steel production ("tls" stands for tons of liquid steel)

	INTEGRATED CYCLE [25]	**H2 DRI + EAF**
Coal [t/tls]	*1,058*	*0,0132 (- 98,75%)*
Electricity [kWh/tls]	*201,147*	*3 940 (+ 1 860%)*[23]
Water [m3=t/tls]	*0,484*	*0,600 (+ 24%)*

It can be noticed that the electricity utilization by DRI with EAF is mainly due to hydrogen production (76%). A clarification about the water consumption in the two different plants must be done. In both cases, only the water consumed within the plant is considered, excluding the water consumption necessary for the extraction of coal and iron ore. In this study, the electrolysers dedicated to hydrogen production are considered to be part of the plant, contributing to the counting of the water deployment.

4.2. Shock implementation

Three shocks are implemented modifying the data referred to the year 2019. Such data are provided by the Exiobase database v.3.8 [26]. Both databases and input data are handled by adopting MARIO. All the shocks model the complete substitution of the integrated cycles present in Italy, with a specific output of 4,207 Mton of crude steel [8], with hydrogen-based DRI with EAF. Assuming the absence of economies of scale, the investment costs would be divided as follows.

Each shock is characterized by changing the electricity mix which feeds the plant operations. What is modified is the share of renewable sources in the national consumption mix.

Table 2. Investment costs for the new technology. Source: *ecoclimate.org*

Type of unit	***Investment cost [€/ton]***
Total to move to DRI with EAF	312
Total to move to hydrogen-based DRI	1 062,5
TOTAL	1 375

- The first electricity production mix considered is the current one. This first case will be referred to as Tech-switch 2019 (TS_{2019})
- The second electricity production mix is characterized in line with the target for 2030 set by the government, therefore it is characterized by 55% of renewable generation. This second case will be referred to as Tech-switch 2030 (TS_{2030})
- The third electricity production mix is characterized by a 100% penetration of renewables. This second case will be referred to as Tech-switch Full-RES ($TS_{fullRES}$)

More in detail, capital expenditures (CAPEX, annualized assuming a lifetime of 20 years) are firstly considered as additional final demand (**Y**) from technological components suppliers. Secondly, the accounting of exogenous resources production and emissions production are modified. In particular, the values of specific water consumption and emissions were changed with a percentage variation for the steel production sector. Lastly, the endogenous transaction matrix (**z**) is changed considering the new value of electricity which feeds the primary metal sector, as well as the new value of coal requested by the new technology. These variations are related to the change in technology in steel production. To show how the final results are correlated with the differences in the electricity mix, further modifications in the matrix endogenous transaction matrix (**z**) were necessary: the renewable and non-renewable sectors both of Italy and the rest of the European Union countries are varied in order to reach the target share of renewable electricity going into the metal sector (55% before and 100% then).

5. Results

In **Figure 1**, the variations of CO_2 emissions and water consumption along the different scenarios analyzed are reported: it can be seen that the change in technology leads to a decrease in CO_2 emissions both at the national and the global level; the benefits would be even bigger if the technological switch were coupled with a higher penetration of renewable sources in the Italian electricity mix.

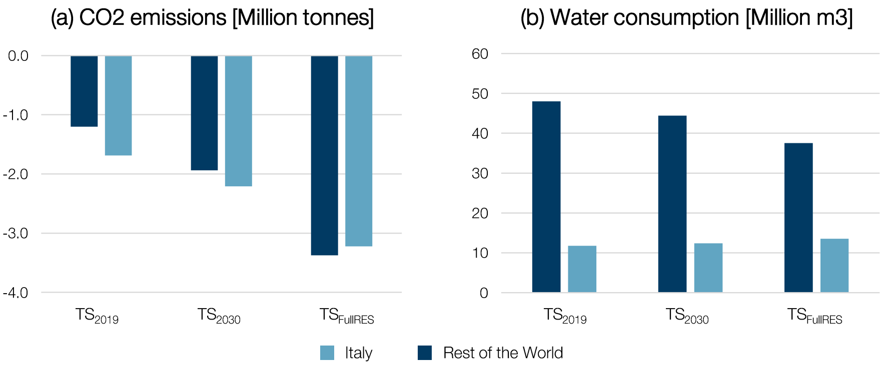

Figure 1. CO_2 emissions (a) and water consumption (b) variations by region and scenario.

In the best case ($TS_{FullRES}$), the annual emissions avoided at the global level would be 3,37 Mton which is equal to 14% of the 2018 emissions of the Italian steel production sector. Concerning water consumption, the value is higher in all the scenarios analyzed with respect to the base case. Considering global consumption, it is possible to notice that the increase in renewable share for electricity production tends to counterbalance the additional requirements of water for electrolyzers. This is due to the savings of water from fossil fuel mining and refinery processes. This reduction cannot be seen from results concerning the Italian national scale where there are no relevant mining activities. Regarding the employment index, it is obtained an increase of about 12 thousand workers new with the technological switch employed mainly in the additional electricity required. This compensates for the reduction of labor that would have occurred by the adoption of the DRI with EAF plants which require fewer workers than traditional plants. It is important to highlight that with the increase in renewable penetration the growth of labor is less pronounced since the renewable sector is less labor-intensive than traditional one.

With reference to **Figure 2**, looking at the national iron and steel sector, it can be seen that the forward linkages remain constant, while its backward linkages increase, mainly due to the much larger dependency on the electricity supply; this might be apparently a negative aspect, but the fact that the sector is way less reliant on carbon products coming from extra-European Union countries could guarantee more stability for the national steel industry. It is important to highlight that, with the increasing of RES penetration, the backward linkages of the sector decrease because RES allows to exploit the local natural resources within the country's borders. The opposite situation characterizes the Italian coal refinery sector, which maintains constant its Backward Linkages, while its Forward Linkages decrease due to the relevant reduction in the request for carbon coke by the Italian steel industry. Concerning the electricity sectors, both renewable and non-renewable, the technological switch causes growth in their Forward Linkages, due to the higher dependence on electricity by the new steel plants. The higher renewable penetration has two opposite effects on the Forward Linkages of the two sectors: the renewable one shows an increase in forward linkages, while in the non-renewable one the inverse occurs. Both sectors' supply chains do not change, so their Backward Linkages.

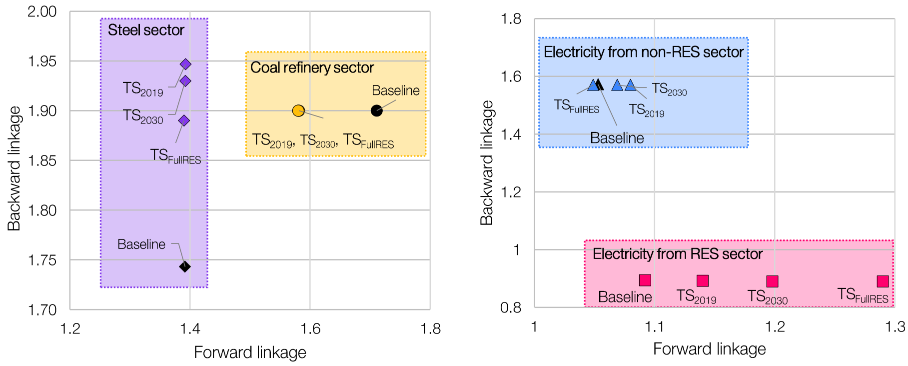

Figure 2. Backward and Forward linkages of Italian selected sectors in each shock. On the left-hand side (a) linkages for steel and coal refinery sectors. On the right-hand side (b), linkages of Electricity from renewables and non-renewables sectors are shown. Please, note the charts have different scales.

6. Conclusions

Decarbonization of the steel sector is pivotal to reach sustainable development; a possible solution valuable for policymakers is one that is both environmentally and economically viable.

The steel sector plays a key role in the global economy, but at the same time, due to its strong exploitation of fossil fuels, its environmental impact is quite big. For these reasons, it is fundamental to implement policies to lead the Italian (and European) steel sector toward a carbon-neutral future, without economic damage. Drawing from all these different possibilities, one of the possible instruments helpful to evaluate the benefits of a policy, at least at the preliminary stages, is the IOA which this paper, under some specific assumptions, proves reliable enough. In this framework is shown that the complete substitution of the existing Italian integrated cycle plants with hydrogen-based DRI with EAF leads to positive effects in terms of carbon dioxide emissions, local pollutants, and socio-economic aspects such as a higher employment index. The only immediate drawback of this substitution is increased water consumption, which can be mitigated by implementing the quality of electricity generation. The overall increase in backward linkages of the Italian steel sector due to the technological switch should be seen as a necessary step in order to reduce GHG emissions, as well as the dependence on Extra-EU countries; the higher use of renewable could in part mitigate this increase.

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