

## The impact of decarbonising the iron and steel industry on European power and hydrogen systems

Boldrini, Annika; Koolen, Derck; Crijns-Graus, Wina; van den Broek, Machteld

**DOI**

[10.1016/j.apenergy.2024.122902](https://doi.org/10.1016/j.apenergy.2024.122902)

**Publication date**

2024

**Document Version**

Final published version

**Published in**

Applied Energy

**Citation (APA)**

Boldrini, A., Koolen, D., Crijns-Graus, W., & van den Broek, M. (2024). The impact of decarbonising the iron and steel industry on European power and hydrogen systems. *Applied Energy*, 361, Article 122902. <https://doi.org/10.1016/j.apenergy.2024.122902>

**Important note**

To cite this publication, please use the final published version (if applicable). Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.



# The impact of decarbonising the iron and steel industry on European power and hydrogen systems

Annika Boldrini <sup>a,c</sup>, Derck Koolen <sup>b,d,\*</sup>, Wina Crijns-Graus <sup>c</sup>, Machteld van den Broek <sup>e</sup>

<sup>a</sup> European Commission, Joint Research Centre, Directorate for Energy, Transport and Climate, Petten, The Netherlands

<sup>b</sup> European Commission, DG Energy, Brussels, Belgium

<sup>c</sup> Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands

<sup>d</sup> School of Economics, Utrecht University, Utrecht, The Netherlands

<sup>e</sup> Faculty of Technology, Policy and Management, Technical University Delft, Delft, The Netherlands

## ARTICLE INFO

### Keywords:

Power systems  
Hydrogen  
Iron and steel industry  
Decarbonisation  
Energy policy

## ABSTRACT

The transition of the European iron and steel industry (ISI) towards low-carbon manufacturing is crucial for the European Union (EU)'s 2050 climate neutrality objective. One emerging solution is electrification by using hydrogen (H<sub>2</sub>) as iron ore reductant, which increases specific electricity use per tonne of steel up to 35 times compared to the conventional, most adopted coal-based technology. This study develops three scenarios, encompassing a moderate to an accelerated ISI transition, to evaluate the impact of the ISI decarbonisation on the power system CO<sub>2</sub> emissions, generation mix and volume, and marginal prices in 2030. The study first estimates future electricity and H<sub>2</sub> demand by considering country-specific technologies deployment and energy intensities. Then, these estimates serves as input to the model METIS to simulate European power system operations through a unit commitment and economic dispatch problem. The study shows that the power system can accommodate a transition of the ISI that substitutes 28% of the coal-based production with low carbon technologies, mainly based on H<sub>2</sub>. This leads to a 25% reduction in direct CO<sub>2</sub> emissions and a demand increase of 20 TWh of electricity and 40 TWh<sub>HHV</sub> of H<sub>2</sub>. Furthermore, a 50% reduction in indirect power system emissions is achieved, compared to 2018, thanks to the substantial renewable power capacity deployment foreseen in the coming years. The study also demonstrates that a reduction of indirect CO<sub>2</sub> emissions by over 85% can be achieved by deploying 1.2 and 2.7 GW of renewable power generators, and 200 and 400 MW of electrolyser capacity for each million tonne of steel produced annually with low-carbon technologies. Additional renewable capacity that ensures green steel production is also key to maintaining stable electricity prices.

## 1. Introduction

The transition of the power sector is widely regarded as a cornerstone pillar to achieve the ambition of the European Union (EU) to become climate neutral by 2050 [2]. Where most of the EU's energy demand is today met by using fossil fuels, the electrification of the industry, buildings and transport sectors in combination with an increased scaling- and speeding-up of renewable energy in the power sector reduces dependence on foreign energy sources and energy-related greenhouse gas (GHG) emissions. A full decarbonisation of all energy sectors will put the power sector at the centre of the EU energy system, generating and channelling renewable energy into

high-emitting sectors like buildings, transport and mainly the industrial sector.

In 2021, the industrial sector was responsible for nearly 21% of carbon dioxide (CO<sub>2</sub>) emissions in the EU [3], with almost a quarter deriving from the iron and steel industry (ISI). On average, direct<sup>1</sup> CO<sub>2</sub> emissions from steel manufacturing amounts to one tonne of CO<sub>2</sub> per tonne of steel ( $t_{CO_2}/t_{STEEL}$ ) and indirect<sup>2</sup> emissions to another hundred kilograms, mainly attributable to grid-electricity [4,5]. Emissions in the sector are usually considered hard-to-abate, mainly due to the high heat requirements, using carbon as a process input, as well as low profit margins, high capital intensity, long asset life,

\* Corresponding author.

E-mail address: [derck.koolen@ec.europa.eu](mailto:derck.koolen@ec.europa.eu) (D. Koolen).

<sup>1</sup> Scope 1 following the definition of the GHG protocol: emissions from sources that are owned or controlled by the reporting entity [1].

<sup>2</sup> Scope 2 following the definition of the GHG protocol: emissions from acquired electricity, steam, heat and cooling [1].

**Nomenclature****Abbreviations**

CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture Utilisation and/or Storage
EAF	Electric Arc Furnace
EU	European Union
GHG	Greenhouse Gas
HHV	Higher Heating Value
ISI	Iron and Steel
MOE	Molten Oxide Electrolysis
MS	Member State
NA	Not Available
NG	Natural Gas
OCGT	Open Cycle Gas Turbine
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
SMR	Steam Methane Reforming
UCED	Unit Commitment and Economic Dispatch

**Country abbreviations**

AT	Austria
BA	Bosnia and Herzegovina
BE	Belgium
BG	Bulgaria
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GB	Great Britain
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxemburg
LV	Latvia
ME	Montenegro
MK	Macedonia
MT	Malta
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania

RS	Serbia
SE	Sweden
SI	Slovenia
SK	Slovakia

**Other symbols**

CO <sub>2</sub>	Carbon Dioxide
H <sub>2</sub>	Hydrogen

**Production technologies**

BF-BOF	Blast Furnace with Basic Oxygen Furnace
BF-BOF-CCUS	Blast Furnace with Basic Oxygen Furnace with Carbon Capture Utilisation and/or Storage
DRI-EAF	Direct Reduction of Iron with Electric Arc Furnace
H <sub>2</sub> -DRI-EAF	Hydrogen-based Direct Reduction of Iron with Electric Arc Furnace
scrap-EAF	Scrap processing in Electric Arc Furnaces

Tracker database [8], which records global announcements of low-carbon steelmaking projects, highlights a large interest of European steel-makers for technologies that use hydrogen (H<sub>2</sub>) for the reduction of iron ore, instead of carbon. While offering great potential benefits in reducing ISI's process emissions, the H<sub>2</sub>-based core processes typically consume eight times more electricity compared to traditional coal-based production methods, without taking into account the use of electrolytic H<sub>2</sub> thus primarily driven by the utilisation of electric arc furnaces (EAFs) for the steel-making process [9]. The use of electrolytic H<sub>2</sub> raises this ratio by a factor of four [9]. As of March 2022, the Green Steel Tracker had recorded 13 European projects set to transform the production processes from coal-based to electricity- or electrolytic H<sub>2</sub>-based by 2030. Although uncertainties remain in regard of the approach and timeline, the potential substantial increase in electricity demand in the short-term can significantly impact power system operations and dynamics considering that, in 2018, the ISI was responsible for about 7% of the European final energy demand [10]. For example, it could result in an overall rise of indirect CO<sub>2</sub> emissions if fossil-based power plants are needed to meet the additional electricity demand by electrified industrial processes.

Earlier studies assessed how decarbonising the ISI affects power system investments and operations in the long-term, mostly 2050. Lechtenböhrer et al. [11] found through a *what-if* analysis that full electrification of steel, cement, glass, lime, petrochemicals, chlorine and ammonia production could increase European electricity demand by over 1500 TWh<sup>3</sup>, of which 1200 TWh designated for producing electrolytic H<sub>2</sub> and synthetic fuels. Achieving this level of electrification requires investment in generation capacities and flexibility options such as storage, dispatchable generators and flexible consumers. Toktarova et al. [12] focus on optimal system investments, operations and spatial allocation of steel plants in 2050 through a unit commitment and economic dispatch (UCED) model in the context of the North European power system. The authors assess the interaction between a decarbonised H<sub>2</sub>-based ISI and the 2050 electricity system, finding that an increase of steel electricity demand of 11% (or 183 TWh) can mainly be met by increasing outputs from wind and solar power, provided there is an excess of flexible technologies available such as electrolyzers. Within the same geographical scope, Göransson et al. [13] employed a cost-minimising electricity system investment model with 3-hour resolution

and trade challenges [6]. While various technologies may help producers in increasing energy efficiencies and cutting CO<sub>2</sub> emissions, a deep decarbonisation of the sector is expected to rely on new technologies [7]. Many major European steel-makers have announced or started the construction or operations of pilot, demonstration or full-scale plants for low-carbon manufacturing of steel. The Green Steel

<sup>3</sup> The EU generated almost 2800 TWh of electricity in 2021 [10].

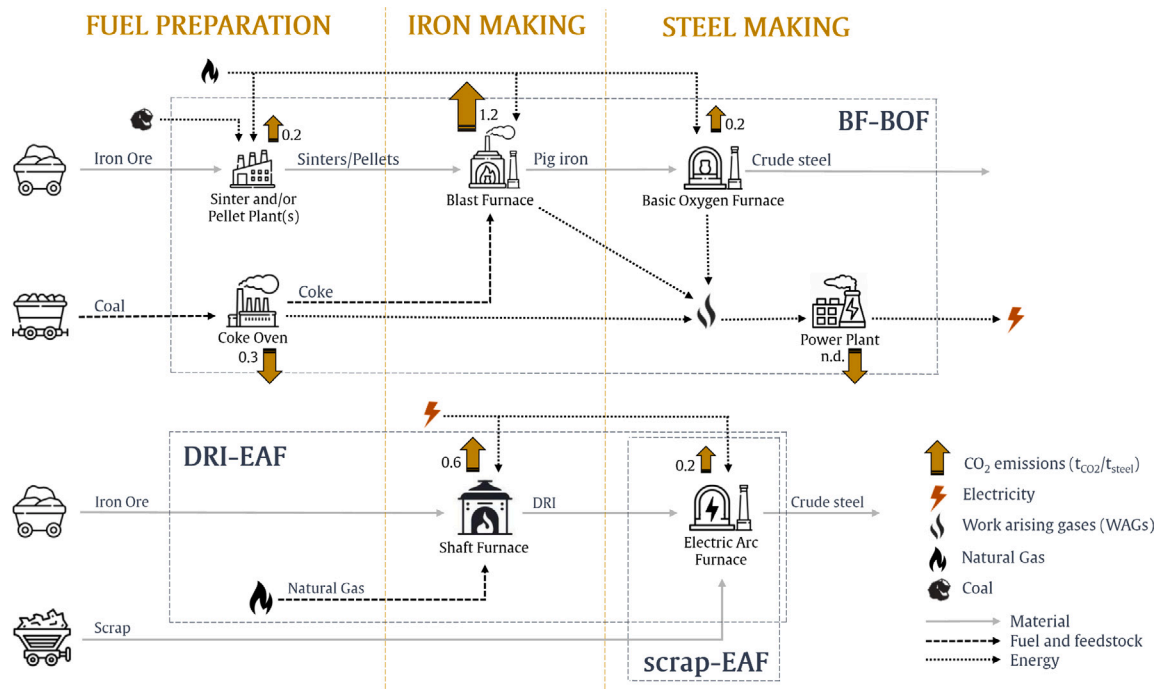


Fig. 1. Present-day production routes used in the EU, showing the most relevant production processes, material and energy input/output, and average European CO<sub>2</sub> emission per process [9]. In the BF-BOF route, the CO<sub>2</sub> emissions reported correspond to the total CO<sub>2</sub> produced per tonne of steel at the designated plant. However, these emissions are mostly released at the power plant where the carbon-rich WAGs are combusted.

to assess the costs benefits of flexible consumption by the iron and steel, passenger vehicle and residential heat supply sectors. The authors performed the analysis for 2030, 2040 and 2050 but assuming the H<sub>2</sub> demand of the ISI null in 2030. Meanwhile, Arens et al. [14] assessed the short-term readiness of steel producing global regions to low-carbon manufacturing by developing a set of indicators that take into account future steel production targets and renewable energy strategies.

In summary, previous studies have either targeted the long-term transition of the ISI through high temporal resolution UCED models operating with large shares of renewable power capacities, or examined the short-term transition of the ISI without conducting modelling analysis or considering H<sub>2</sub> demand for steel, thus without the updated decarbonisation targets of European steel manufacturers. The interest of steel-makers in electrified solutions has increased in recent years thanks to more stringent decarbonisation targets set by the EU [3]. Consequently, the demand for electricity and H<sub>2</sub> by the ISI is likely to experience a significant increase by 2030. However, this rapid surge in electricity demand poses additional challenges for the transitioning power sector, still focusing on expanding and integrating renewable power generation. While the accelerated electrification of the ISI leads to reduced emissions within the industry, it also risks to be counter effective if not properly supported by an expansion of renewable power supply. If the electricity and electrolytic H<sub>2</sub> demand is met by grid-electricity mainly generated by fossil-based sources, it could result in an increase in indirect CO<sub>2</sub> emissions.

In this paper we study the short-term decarbonisation of the European ISI and the effect on the power system through high-temporal resolution modelling, by answering to the following research question: *how does the short-term transition to a low-carbon ISI affect the European power system operations and its CO<sub>2</sub> emissions?* The study aims at answering this question with two primary objectives that cover existing research gaps:

- developing scenarios for the decarbonisation of the ISI that take into account recent projects development documented by the Green Steel Tracker [8] and define 2030 energy demand and direct CO<sub>2</sub> emissions reduction.

- performing high temporal resolution power system modelling in 2030, with various level of decarbonisation of the ISI to evaluate the impact on net CO<sub>2</sub> emissions, energy generation and marginal electricity prices.

The first point is addressed in Section 2, which presents an overview of the current structure of the European ISI, projects documented by the Green Steel Tracker, assumptions for scenario development and for deriving the energy intensities and specific CO<sub>2</sub> emissions of steel-making technologies. The second point is tackled in Section 3 and Section 4. Section 3 presents the modelling methods and Section 4 the results obtained from the modelling. Discussion and conclusions are reported in Section 5 and Section 6, respectively.

## 2. Steel decarbonisation pathways in the EU

In 2018, the European steel production of about 160 Mt was mainly manufactured following two different options, i.e., primary or secondary production. About 58% of steel was manufactured via primary routes – i.e., production from raw materials – while the other 42% by recycling steel. Fig. 1 provides a simplified representation of the production processes of the main manufacturing technologies used in the EU. Over 57% of European steel is made by the blast furnace with basic oxygen furnace technology (BF-BOF) that uses coal as main energy input. The iron making process occurs in the blast furnaces, where iron ore is reduced to pig iron using coke – i.e., a coal derivative – as heat source and reductant. This process is responsible for over 50% of the total CO<sub>2</sub> emissions of the BF-BOF production route, which, with its 1.8 t<sub>CO2</sub>/t<sub>STEEL</sub>, is the most CO<sub>2</sub> intensive technology for steel production [5]. Less than 1% of the European steel is produced by the direct reduction of iron and electric arc furnace technology (DRI-EAF). This production route emits on average 0.9 t<sub>CO2</sub>/t<sub>STEEL</sub>, half of the BF-BOF route, thanks to the natural gas-based reduction of iron ore and the electric-based steel-making process [4]. The remaining 42% of European steel is produced by the processing of recycled scrap steel in electric arc furnaces (scrap-EAF) [5]. Although this route is largely

electrified, direct emissions are still about  $0.1 t_{\text{CO}_2}/t_{\text{STEEL}}$  due to small amounts of natural gas or coal injected to provide additional heat [5].

A straightforward solution to reduce the CO<sub>2</sub> emissions of the ISI is to replace primary production by secondary production. The introduction of a more circular economy, as foreseen by the Green Deal, favours higher secondary production from recycled material [15]. The scrap-EAF route is however constrained by the availability of high quality scrap, essential for the quality of the final product [5,16]. Regarding new technologies for the primary production of steel, various low-carbon solutions exist at different stages of development and varying decarbonisation potential. For instance, the CO<sub>2</sub> produced in the different sub-plants of the BF-BOF route can be captured for storage and/or the carbon used for other chemical processes [17]. Various CO<sub>2</sub> capture utilisation and storage (CCUS) technologies exist that can be retrofitted to the various sub-plants and result in a steel plant decarbonisation potential from 35% to 90% [5]. The higher end of the reduction potential is for the HIsarna technology, a coal-based smelting reduction technology that processes iron ore directly into pig iron, avoiding sinter, pellet and coke making, and thus reducing the overall energy consumption by 20% compared to the BF-BOF technology. Electricity consumption of HIsarna remains similar to the integrated route [18]. The gas emitted by HIsarna has a purer and easier to capture CO<sub>2</sub> stream, allowing a decarbonisation potential of up to 90% [5]. While production costs are estimated to be only 9% to 16% higher than the integrated route, HIsarna developer Tata Steel IJmuiden has announced in 2021 the plan of pursuing another low-carbon alternative, suggesting that the HIsarna technology may not be deemed a viable solution for the plant [5].

Other more revolutionary solutions for primary steel-making can reach decarbonisation levels from 85% to 98% compared to the BF-BOF route: electrolytic processes and smelting reduction of iron ore using H<sub>2</sub> plasma have high efficiencies and no fossil fuel utilisation as they are directly or indirectly fuelled by electricity [19]. The H<sub>2</sub>-based direct reduction of iron technology (H<sub>2</sub>-DRI-EAF) Hydrogen-based Direct Reduction of Iron with Electric Arc Furnace) uses H<sub>2</sub> as fuel and feed-stock for the iron ore reduction in the shaft furnace, instead of natural gas [5]. The natural gas-based DRI-EAF has already electricity consumption eight times higher than the BF-BOF route. If fully fed by electrolytic H<sub>2</sub>, the H<sub>2</sub>-DRI-EAF route could experience a growth in electricity demand by over four times compared to the DRI-EAF route, that is 35 times compared to the BF-BOF route [9]. In the short-term future, production costs are estimated 10% to 60% higher than those for the BF-BOF technology, with significant uncertainty stemming from H<sub>2</sub> cost [5]. However, with H<sub>2</sub> priced at 1 €/kg, one analysis estimates that by 2050 steel production using the H-DRI-EAF technology could be more cost-effective than the BF-BOF technology. Despite uncertainties in future H<sub>2</sub> costs, the H<sub>2</sub>-DRI-EAF technology has, in recent years, gained the attention of many European steelmakers with major companies announcing associated investments over the coming decade [8].

Based on the developments in the European ISI, we build three different steel decarbonisation pathways for the EU to simulate ISI electricity and H<sub>2</sub> demand in 2030. We first estimate present-day energy intensities at EU member state (MS) level per production route (Section 2.1). Then, three steel scenarios are developed to reflect different rates of deployment of low-carbon steel making technologies by 2030, mainly through brownfield development of the existing stock in each MS (Section 2.2). The electricity and H<sub>2</sub> demand for steel production in 2030 is then calculated for the scenarios by using energy intensities derived in Section 2.1 for current operational technologies and estimations from literature for the new low-carbon technologies (Section 2.3).

## 2.1. Present-day energy demand of the iron and steel industry

In this paper, we estimate energy intensities per energy carrier and per production route of the ISI at EU MS-level. This allows us to project the energy use of the future ISI at a highly granular level, rather than using EU aggregates, and represent actual differences of the various MSs. As such, we analyse the effect of the decarbonisation of the ISI on EU energy systems with more precision, and model an accurate representation of physical energy flows and trade between MSs.

The energy intensities per energy carrier and per production route, derived at MS-level, are based on the IEA extended World energy balances [20]. These provide statistical data of all energy sources produced, traded, transformed and consumed on a country scale for an indicated reference year. The approach follows the methodology developed by Koolen and Vidovic [4], who estimate GHG efficiencies of the global ISI at national level. This study revisits their model to estimate energy use at MS level per iron and steel production route, for the routes presented in Fig. 1.

We denote a single energy carrier<sup>4</sup> as  $c$  and a single energy flow<sup>5</sup> as  $f$ , and the total energy demand  $E^T$  of the ISI of a country as follows:

$$E^T = \sum_c \sum_f E_{c,f} \quad (1)$$

whereby  $E_{c,f}$  represents in TJ the energy involved for energy carrier<sup>6</sup>  $c$  relevant to energy flow  $f$ .

While disaggregating  $E^T$  to energy intensities on production route level would suffice for the scenarios building purpose in this paper, we estimate energy intensities at process level in order to account for energy allocated to the imports and exports of intermediate products. In order to establish these trade balances, of both intermediate products and crude steel volumes per production route, we rely on the following datasets:

- IEA World energy statistics on production and trade of coal [20]: data source containing information on production, imports and exports of cokes. Used for the analysis on energy intensity of the intermediate product coke.
- UN Comtrade imports and exports of iron ore and concentrates [21]: data on imports and exports of agglomerated iron ores & concentrates (excl. roasted iron pyrites). Used for analysis on energy intensity of the intermediate product pellets. Where data on quantity (tonne) is missing, estimates are based on trade values (USD).

<sup>4</sup> While the energy balances report a multitude of energy carriers (66 in total), with the categories of solid fossil fuels and manufactured gases of significant importance to the current ISI, our main carriers of interest for this study are electricity and H<sub>2</sub>.

<sup>5</sup> In terms of energy flows, extended world energy balances detail the flow of energy in three main blocks: Supply, Transformation and Own Energy Use, and Final Energy Consumption. The latter block has a specific energy flow related to the ISI, used in this study. Within the block of Transformation and Own Energy Use, specific energy flow information is available on the coke ovens and blast furnaces for both the transformation of energy and own energy use of these facilities. This allows for a specific allocation of energy to both processes within the scope of this study. Furthermore, this middle block lists energy flows for auto-production of heat & electricity, indicating the transformation of energy for use within the own installation boundaries, as well as the main production of heat & electricity. Both of these energy flows are of interest with regard to the waste gas energy carriers of the iron and steel industry, notably coke oven gas, blast furnace gas and other recovered gases.

<sup>6</sup> Energy carriers  $c$  range over all 48 energy carriers under consideration in the energy balances for the Transformation and own energy use of the coke oven and blast furnace energy flows as well as the final energy consumption for the iron and steel energy flow. For the auto-production and main production of electricity and heat energy flows in the transformation and own energy use category, the relevant energy carriers  $P_i$  range consists of three waste gas categories.

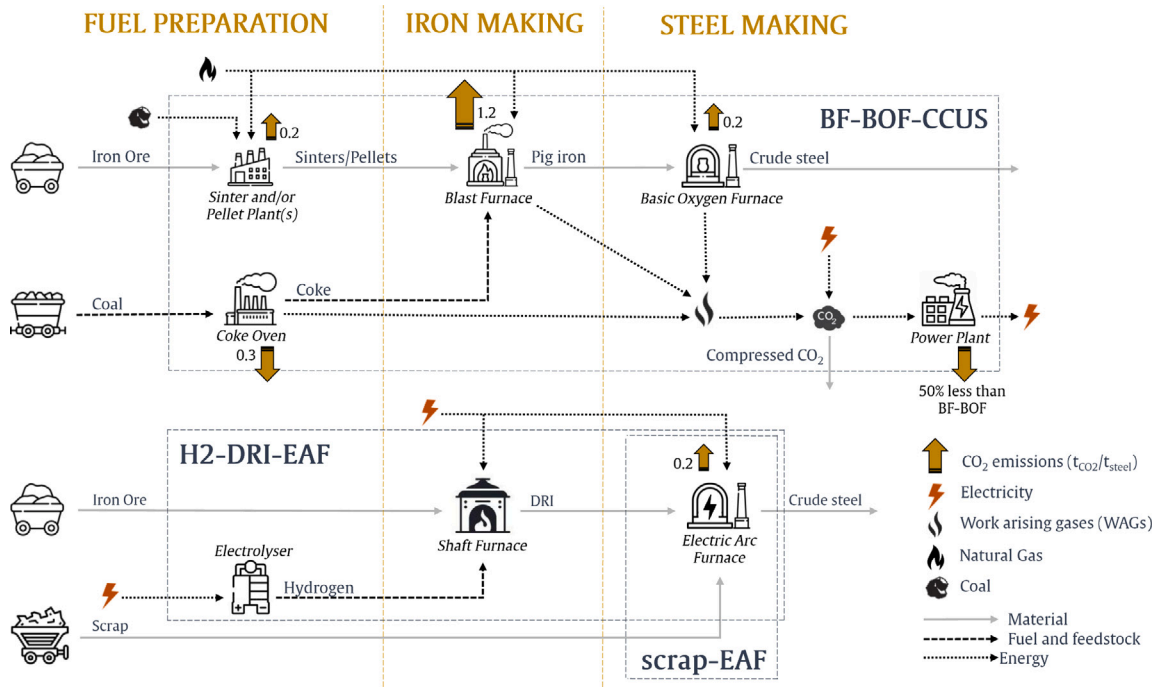


Fig. 2. Emerging production routes included in the study, showing the most relevant production processes, material and energy input/output, and CO<sub>2</sub> emission per process [9]. In the BF-BOF-CCUS route, the CO<sub>2</sub> emissions reported correspond to the total CO<sub>2</sub> produced per tonne of steel at the designated plant. However, the non-captured share is released at the power plant where the carbon-rich WAGs are combusted.

- Worldsteel production volumes of steel and related products [22]: production volumes via primary and secondary route, for analysis on energy intensities of the respective production routes; and production volumes of pig iron from the integrated route and sponge iron from the DRI process, for the analysis on energy intensities of the respective intermediate product.

The estimated production volumes per process step  $V_s$  together with energy and mass process balances of the ISI serve as input for the allocation of energy to production routes and process steps. We base our analysis on the energy process and mass balances by Moya et al. [23] and Pardo et al. [24], which report net energy intensities per process step for the main energy carriers in the ISI, to calculate volume weighted energy intensities per process step and per MS. We thereby only apply the process balances in a relative manner, in order to verify that total energy demand of all process steps corresponds to the demand as reported in the aggregated statistics of the extended world energy balances. This approach allows to estimate the energy  $E^S$  at process level  $S$  by:

$$E^S = \sum_c [\gamma_{S,c} \cdot \sum_j E_{c,f}] \quad \forall S \in PS \quad (2)$$

where  $PS$  represents the group of all process steps for all production routes together, and  $\gamma_{S,c}$  represents, as ratio, the national volume weighted energy use of the respective process step per energy carrier:

$$\gamma_{S,c} = \frac{V_S \cdot EPB_{S,c'}}{\sum_S V_S \cdot EPB_{S,c'}} \quad (3)$$

where  $V_S$  represents the production volume per process step in tonne and  $EPB_{S,c'}$  the energy use for the respective energy process step  $S$  and energy carrier  $c$  in the energy process balance in TJ/tonne.

We consider seven different processes involved in the production of crude steel: coke plant, sinter plant, pellet plant, the blast furnace, the basic oxygen furnace, DRI-EAF and EAF. Where the latter two also represent the entire production routes, the integrated route combines, in order, the first five process steps. Additionally, the final process step represent the relative amount of energy use for finalisation processes in

the ISI, relying on the JRC-IDEES database [25]. Based on the detailed split of iron and steel energy consumption by sub-sector in the EU in this database,<sup>7</sup> it allows to estimate the energy use for the refining and rolling processes and product finishing categories per energy carrier and production route in a similar relative manner.

In order to derive the energy use per energy carrier per production route, we estimate the volume of intermediate product required to satisfy the demand for crude steel produced via the respective production route:

$$E^R = \sum_S \frac{V_{S,r}}{V_S} \cdot E^S \quad (4)$$

whereby  $E^R$  represents the energy use of the production route, and  $V_{S,r}$  the mass of the intermediate product in the process step  $S$  needed as input for the production of crude steel in production route  $R$ .

Table A.5 reports the energy intensities per energy carrier and present-day production routes for electricity, hydrogen and natural gas. These values are corrected to include a shift towards direct electrification for finalisation processes, as discussed in the following section.

## 2.2. Steel production pathways in 2030

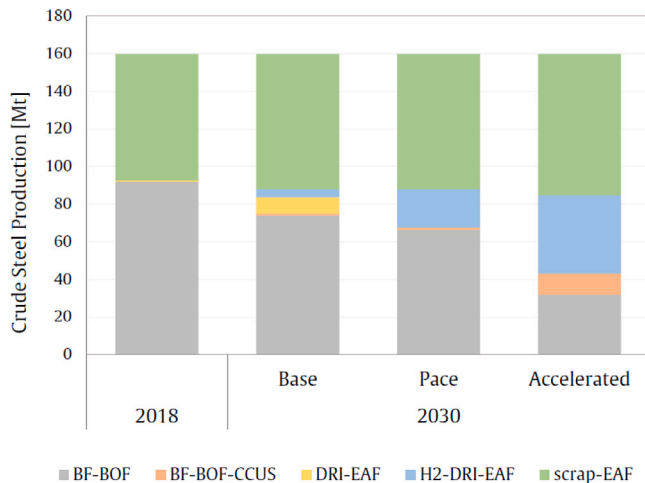
This study identifies various decarbonisation pathways for the ISI in 2030 that are reflected by the steel scenarios. From the energy demand calculated for these scenarios, we build the analysis on the European energy system through modelling while comparing or calibrating the steel scenarios to the following two EU policy scenarios for 2030:

- Reference** is a scenario reflecting a conservative decarbonisation pathway foreseen by the POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment) Central Scenario. The reference POTEnCIA describes the evolution of the energy system of the EU by MS with the assumption that no further

<sup>7</sup> This includes ‘Steel: Furnaces, Refining and Rolling’ – thermal and electric – ‘Steel: Products finishing’ – thermal, steam and electric’.

**Table 1**  
Assumptions applied to develop the steel scenarios for 2030.

Scenarios	Share of secondary production	Deployment of low-carbon primary route	Fuel shift	Fuel for DRI
<i>Base</i>	45%	Reflecting operating pilots and approved projects [8], see Table A.7	33% of natural gas used for finalisation processes shifts to electricity	Natural gas and H <sub>2</sub>
<i>Pace</i>	45%	Reflecting all announced projects [8], see Table A.7	33% of natural gas used for finalisation processes shifts to electricity	All H <sub>2</sub>
<i>Accelerated</i>	47%	Reflecting the refurbishment needs of existing blast furnaces [26] assuming 25 years of lifetime [27] and CCUS projects applied to BF-BOF with timeframe beyond 2030	33% of natural gas used for finalisation processes shifts to electricity	All H <sub>2</sub>



**Fig. 3.** EU steel production by technology in 2018 and in 2030 as foreseen by the steel scenarios.

policies are introduced beyond 2017 and it is often used as benchmark to assess the impact of alternative energy and climate policies [25]. The *Reference* scenario is only used in this study for benchmarking purposes.

- **MIX-H2** is one of the scenarios developed for the fit-for-55 policy proposals by the European Commission, serving as a common analytical tool for impact assessments of various policies within the context of the European Green Deal [28]. The MIX-H2 scenario builds on top of the MIX scenario, one of the three core policy scenarios, which achieves a net 55% reduction of greenhouse gases and a share of 38%–40% renewable energy sources in gross final energy consumption by 2030. The MIX-H2 scenario builds on the MIX scenario by relying on a higher uptake of H<sub>2</sub> in final energy demand, which implies a considerable increase of electrolyser capacity (40 GW in the EU by 2030), aligned with the objectives of the Hydrogen strategy [29]. Because the MIX-H2 scenario serves as the overarching context that defines all energy system parameters for the modelling, excluding for the ISI, we rely on it to fine-tune the steel scenarios. Details on this calibration process are reported later in the section.

The steel scenarios are defined by the extent to which low-carbon steel technologies replace existing BF-BOF capacity, the most widely adopted polluting primary production route. The replacing technologies are among those with the most likely deployment in the next decade based on technology readiness level and decarbonisation strategies declared by European steel-makers, as recorded by the Green Steel Tracker as of March 2022 [8]. These projects are reported in Table A.7. Projects aiming at being operating by 2030 include natural gas-based

DRI-EAF, H<sub>2</sub>-DRI-EAF and DMX absorption carbon capture technology applied to blast furnaces' gases (BF-BOF-CCUS) [30,31]. Fig. 2 shows the material, energy and carbon flows for the two emerging technologies included in this study: H<sub>2</sub>-DRI-EAF and BF-BOF-CCUS.

As many of the announcements are non-binding, the advancement of these projects have a certain degree of uncertainties that is reflected in our three scenarios. *Base* scenario includes projects that are currently operating, whose construction has started or has been approved. *Pace* scenario includes all announced projects, thus also more uncertain ones. Some of these projects for steel-making through DRI foresee the initial use of natural gas as energy source before an affordable H<sub>2</sub> supply is ensured. In *Base*, it is assumed that these projects will use natural gas in 2030 while in *Pace* all DRI is manufactured using H<sub>2</sub>. *Pace* presents a similar demand of H<sub>2</sub> for steel production as the MIX-H2 scenario, suggesting a similar level of production using the H<sub>2</sub>-DRI-EAF route. The third scenario, *Accelerated*, is a more ambitious scenario developed with the aim to assess the ability of the power system to cope with an accelerated decarbonisation of the ISI. Therefore, it foresees that all the blast furnaces that require refurbishment before 2030 are replaced by H<sub>2</sub>-DRI-EAF capacity. This projection is based on the age of the existing stock and refurbishments recorded by Eurofer [26] and takes into account an extended operational lifespan through refurbishment of 25 years [27]. For all scenarios, we assume steel production volumes to remain stable compared to 2018,<sup>8</sup> and the share of recycled steel for secondary steel production to only slightly increase from 42% in 2018 to 45% or 47% in 2030, depending on the scenario.<sup>9</sup> We finally assume a partial fuel shift for heat supply from natural gas to electricity for finalisation processes. *Pace* presents a very similar demand to MIX-H2 for H<sub>2</sub>, suggesting a comparable volume of steel produced via the H<sub>2</sub>-DRI-EAF technology. Therefore, we calibrate *Pace* with MIX-H2 by aligning not only H<sub>2</sub> demand, but also natural gas and electricity consumption. This calibration ensures that one the steel scenarios closely mirrors the ISI as foreseen by the MIX-H2, while providing a more detailed representation of the sector. The alignment results in a substitution by electricity of 33% of the natural gas use for finalisation processes, which is in line with published literature [35]. This assumption is extended to the other steel scenarios. Table 1 summarises the assumptions applied, Fig. 3 shows the resulting steel production by technology in each scenarios, compared to 2018.

<sup>8</sup> Literature that takes into account global iron and steel market development have large discordance on European steel production levels in 2030. Scenarios foresee steel production variation in the range of -25% and +14% compared to 2018 [32–34]

<sup>9</sup> The share of manufacturing performed via the secondary (recycling) route is, similarly to production levels, highly influenced by global markets. Pardo et al. [24] mentioned in 2012 that 47% is a plausible share of secondary production in the EU by 2030. However, given that the current share of 42% is still comparable to years previous to 2012, we consider 47% of secondary production as an ambitious scenario that foresees enhanced circularity.

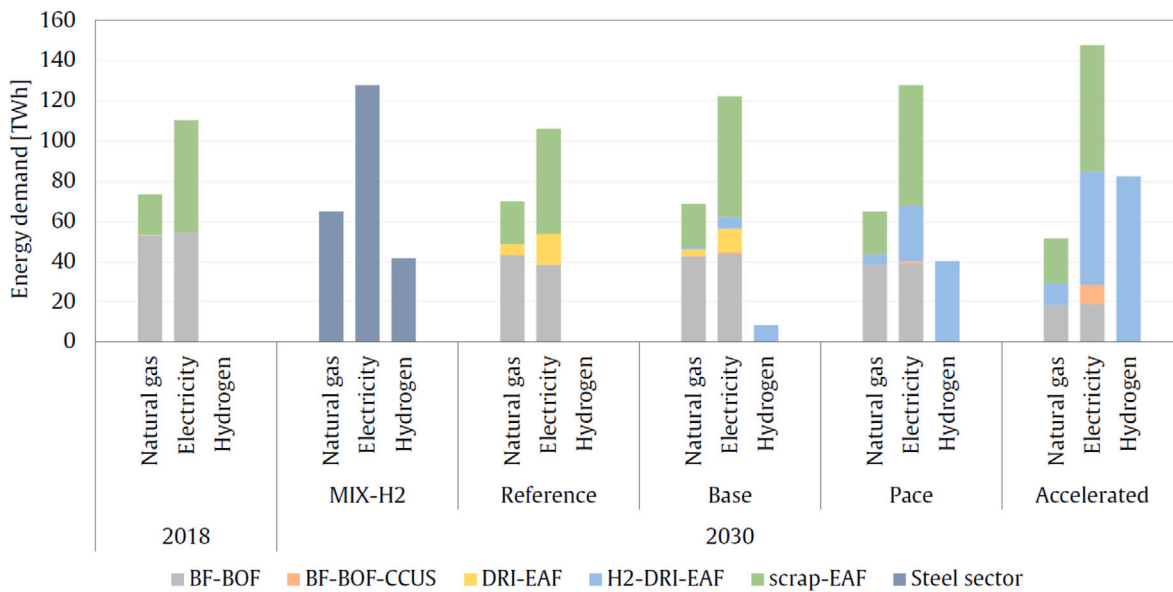


Fig. 4. Energy demand of the European ISI in 2018, MIX-H2, Reference and the steel scenarios. MIX-H2 is shown without differentiation among production route because the information is not available. Energy demand for natural gas and hydrogen is expressed in higher heating value (HHV).

Table 2

Overview of sub-scenarios differentiated by (i) generation capacities as foreseen by the MIX-H2 – i.e., UCED problem – and with capacity expansion – i.e., UCED problem with capacity expansion – and (ii) low and high natural gas and H<sub>2</sub> other supply prices. All other parameters of the energy system are retrieved from the 2030 MIX-H2 scenario [28].

2030 MIX-H2		(ii) Low prices	(ii) High prices
(i)	UCED problem	Reference Base Pace Accelerated	Reference_high Base_high Pace_high Accelerated_high
(i)	UCED problem with capacity expansion	Reference_EXP Base_EXP Pace_EXP Accelerated_EXP	Reference_high_EXP Base_high_EXP Pace_high_EXP Accelerated_high_EXP

### 2.3. Electricity and hydrogen demand for steel in 2030

We calculate the annual electricity and H<sub>2</sub> demand per MS to feed into our simulations from the steel production scenarios. For the current production technologies that are still operational in 2030, energy demand is calculated based on the energy intensities retrieved in Section 2.1. We assume that no energy efficiency improvements occur for these processes because many European steelmakers have in recent years already reached efficiencies close to optimal levels in order to reduce energy costs [16]. Regarding new steel-making technologies, we apply the following assumptions:

- **H<sub>2</sub>-DRI-EAF:** DRI-making in the shaft furnace is fuelled by 95% H<sub>2</sub> and 5% natural gas [5]. All other production steps remain the same as for the DRI-EAF route.
- **BF-BOF-CCUS:** carbon capture increases electricity consumption by 0.97 GJ/t<sub>STEEL</sub> compared to BF-BOF [36], based on a 50% CO<sub>2</sub> capture rate [5]. The relatively low capture rate takes into account that only the blast furnaces are retrofitted with the carbon capture technology. CO<sub>2</sub> emissions from other sources are assumed unchanged. All other production steps remain the same as for the BF-BOF route.

Table A.5 reports the resulting energy intensities for these new steel-making technologies together with currently operating ones.

Fig. 4 shows the resulting electricity, H<sub>2</sub> and natural gas demand of the steel scenarios together with 2018, Reference and MIX-H2 energy

demand. Compared to 2018, Base foresees an increment of electricity and H<sub>2</sub> demand of about 11 and 8 TWh<sub>HHV</sub>, respectively. Pace foresees a sharp increase in H<sub>2</sub> demand, almost five times larger than in Base and a 5% increase of electricity demand compared to Base. Accelerated further stretches the electricity demand by 15% and more than doubles the H<sub>2</sub> demand compared to Pace. If H<sub>2</sub> is produced via electrolysis, power demand further increases in all scenarios.

### 3. Modelling the EU power and hydrogen system of 2030

We use the METIS model to simulate the effect of the decarbonisation of the ISI under the three steel scenarios on EU power system dynamics and H<sub>2</sub> supply. METIS is a mathematical model simulating the electricity system operations at MS-level through a UCED problem. METIS optimises the operations of the system assets at each hour of a given year using data on installed capacities and commodity price costs to minimise the overall system costs while maintaining the supply/demand equilibrium at each node. Furthermore, it optimises the level of H<sub>2</sub> supplied by electrolysis. It can also run a capacity expansion optimisation problem, performing a joint optimisation of generation, storage and transmission capacities, starting from the existing stock, and their hourly optimal dispatch. The optimisation problem is solved using a rolling horizon approach. Sakellaris et al. [37] and Bardet et al. [35] report more information on the model optimisation. We simulate the effect of the steel scenarios in a 2030 MIX-H2 context in METIS, building on the METIS model context development by De



**Table 3**

European average fuel prices and CO<sub>2</sub> emission price. *Low* prices are retrieved from the 2030 MIX-H2 scenario [28].

	Unit	Low prices	High prices
Natural gas	€/MWh <sub>HHV</sub>	29.8	178.9
Coal	€/MWh <sub>HHV</sub>	9.5	
Lignite	€/MWh <sub>HHV</sub>	3.4	
Biomass	€/MWh <sub>HHV</sub>	36.6	
H <sub>2</sub> other supply	€/MWh <sub>HHV</sub>	59.0	257.8
CO <sub>2</sub> emissions	€/tCO <sub>2</sub>	48.0	

Felice [28]. We briefly revisit the main input parameters for the model in interest of this work here – i.e., ISI energy demand. For a full description of the model we refer to their work [38].

Starting from the energy demand profiles per carrier foreseen by the MIX-H2 scenario, we detract the ISI demand as foreseen by MIX-H2 in order to derive *rest demand*. Rest demand represents the demand of all sectors except ISI. The steel scenarios are modelled in METIS by adding the respective ISI energy demand to rest demand. ISI annual demand is disaggregated to an hourly granularity to feed into the model's temporal resolution. We assume a constant H<sub>2</sub> demand profile for the ISI throughout the year due to a lack of more detailed information and given that this assumption mainly affects the utilisation of H<sub>2</sub> storage. Electricity demand profile for ISI is disaggregated to an hourly resolution profile following the production- and country-specific profiles provided by the Hotmaps database [39]. These profiles are characterised by monthly variations and off-peak hours during weekends and nights.

We define a set of sub-scenarios to run sensitivity analyses on the following parameters: (i) the availability of renewable electricity generation and electrolyser capacity, which preliminary results have shown to be critical factors in delivering cost-effective renewable energy supply; and (ii) the prices of natural gas and H<sub>2</sub> for supply other than electrolysis, to reflect the price sensitivities of these carriers<sup>10</sup> observed in recent years in the European energy markets [40]. Table 2 reports an overview of all sub-scenarios. Following criteria (i), the capacity expansion in addition to the capacities foreseen by the MIX-H2 scenario, reported in Table B.8, enables the investigation of factors affecting the optimal level of green steel in the different scenarios. This means that the capacity expansion optimises the share of demand for electricity and H<sub>2</sub> from our steel scenarios that is met by renewable electricity only, generated by additionally deployed renewable generation and electrolyser capacity. The price variation following criteria (ii) allows an evaluation of the increase in local electrolytic H<sub>2</sub> production in relation to varying fuel prices. In the high prices sub-scenarios, we use the prices multiplied by factor six as a upper price limit to revoke the European Energy crisis started in 2021 and aggravated in 2022 by the war in Ukraine, with the factor six representing the price increase reached in July 2022 [41]. We adjust the prices of H<sub>2</sub> other supply accordingly (see Table 3).<sup>11</sup>

Finally, the CO<sub>2</sub> emissions generated by the power system to supply the ISI demand of the steel scenarios are compared to the direct CO<sub>2</sub> emissions reduction. To calculate annual direct emissions in 2030 we use MS-specific CO<sub>2</sub> emissions intensities based on Koolen and Vidovic [4], whose method has been adapted for this study to calculate

<sup>10</sup> H<sub>2</sub> is currently mainly produced from natural gas in the EU.

<sup>11</sup> We assume the price of H<sub>2</sub> other supply as if produced via steam methane reforming (SMR) because this process is already applied to natural gas when used in the DRI-EAF technology for steel making. We apply a large range of costs in the sub-scenarios that could hypothetically include several ways of H<sub>2</sub> supply and CO<sub>2</sub> price – e.g., blue H<sub>2</sub> or imports from extra-EU countries – hence the parameter is referred to as H<sub>2</sub> other supply. Accordingly, a natural gas price increase by six times equals a increase of the H<sub>2</sub> price by 4.4 taking into account fix and variable operating costs of the SMR process.

**Table 4**

System costs for all Reference scenarios. System costs include operational power system costs and annualised investment of the additional renewable and electrolyser capacities, where applicable, compared to the respective Reference scenarios.

Scenarios	System costs [B€]
Reference	97.15
Reference_high	152.23
Reference_EXP	77.10
Reference_high_EXP	105.96

energy intensities in Section 2.1, and EU averages for new technologies. The values applied to each technologies and country are reported in Table A.6.

## 4. Results

### 4.1. Electricity and hydrogen system indicators

We present the results of the METIS modelling exercise assessing power system dynamics under various levels of decarbonisation of the ISI. Fig. 5(a) shows that the steel scenarios increase EU power generation by less than 1% compared to *Reference*, partly due to the limited growth in electrolytic H<sub>2</sub> production depicted in Fig. 5(b). Specifically, H<sub>2</sub> supply for the ISI increases by over 60% in *Accelerated* compared to *Reference*, met by only a 14% increase of electrolytic H<sub>2</sub> and 72% of *other supply*. Furthermore, the energy stored in the form of H<sub>2</sub> decreases from *Reference* to *Accelerated*. This decline is attributed to the higher demand profile of *Accelerated*, which leads to increased direct consumption of electrolytic hydrogen, mainly produced during periods of low electricity prices and high renewable power generation. As steel demand is distributed unevenly among MSs, the country-level impact greatly varies. In eight MSs, demand for electricity and H<sub>2</sub> increase respectively by 5% and 40% or higher, as shown in Fig. 6. It is worth noting that some EU MSs are not steel producers, and only 15 of them are involved in primary iron and steel production. Additionally, there are no decarbonisation plans in four of these primary producer MSs. This explains the H<sub>2</sub> demand for ISI spread over 11 MSs, as shown in Fig. 6. The following subsections report the results of the sub-scenarios with high prices and capacity expansion, in Sections 4.1.1 and 4.1.2, respectively.

#### 4.1.1. Increasing natural gas prices

The operations of the European power and H<sub>2</sub> systems in *Reference* and *Reference\_high* are shown in Figs. B.13–B.16. Electricity generation is disaggregated by country and technology to highlight variations of power and H<sub>2</sub> production with high fuel prices. The variations for *Reference\_high* compared to *Reference* are shown in patterned colours. In *Reference\_high*, decreasing power generation by the combined cycle gas turbines (CCGT) fleet in Germany, Italy and the Netherlands is mainly compensated by the coal and lignite fleet in Czechia, Germany, Poland, and imported from Serbia. The increased power generated by some technologies is not only due to lower utilisation of natural gas, but also by the increased production of hydrogen via electrolysis, due to the price rise of H<sub>2</sub> other supply.

Fig. 7 shows that, when dealing with higher prices for natural gas and H<sub>2</sub> other supply, the power system generates up to 60 TWh of additional power in *Accelerated\_high* compared to *Reference\_high*, shown in B.14, that is a 1.5% increase against 1.0% in the *low prices* scenarios. The additional electricity production feeds the process of electrolysis and it is mainly produced by fossil-based sources and to a lower extent by nuclear. Among *low prices* and *high prices* scenarios, the technologies producing the additional electricity are comparable, but with a larger increase of coal, lignite and oil utilisation in *high prices* scenarios. H<sub>2</sub> demand increases by 84 TWh<sub>HHV</sub> Tera in *Accelerated\_high* compared to *Reference\_high*, of which 72% is supplied by non-electrolytic H<sub>2</sub>–

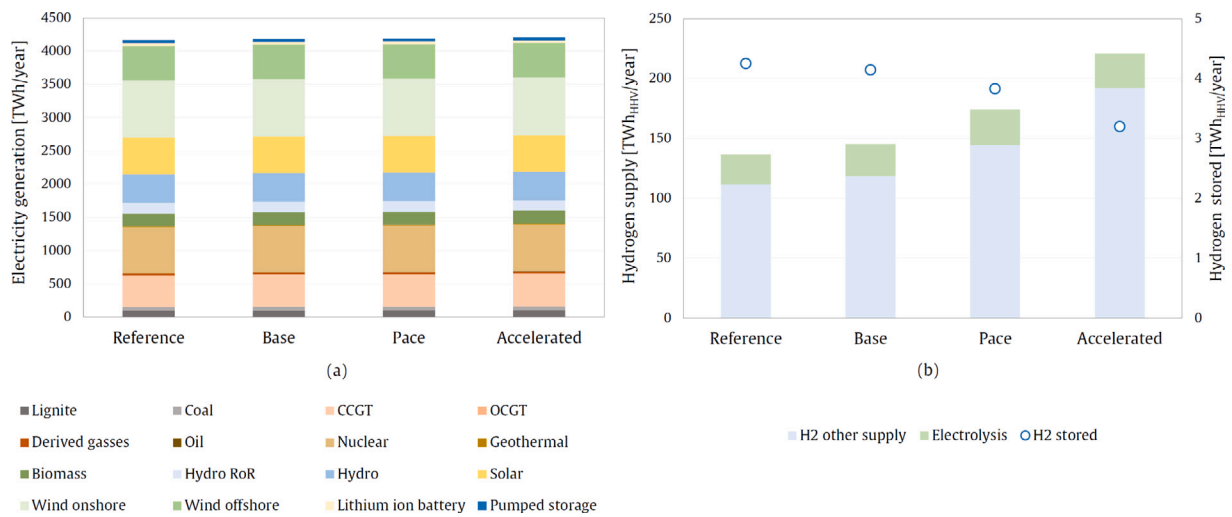


Fig. 5. Results of UCED problem with low prices for 2030. (a) the total power generation by technology in the EU27 and neighbouring countries (BA, CH, GB, ME, MK, NO, RS). (b) H<sub>2</sub> supply and H<sub>2</sub> storage in the EU27 <sup>12</sup>.

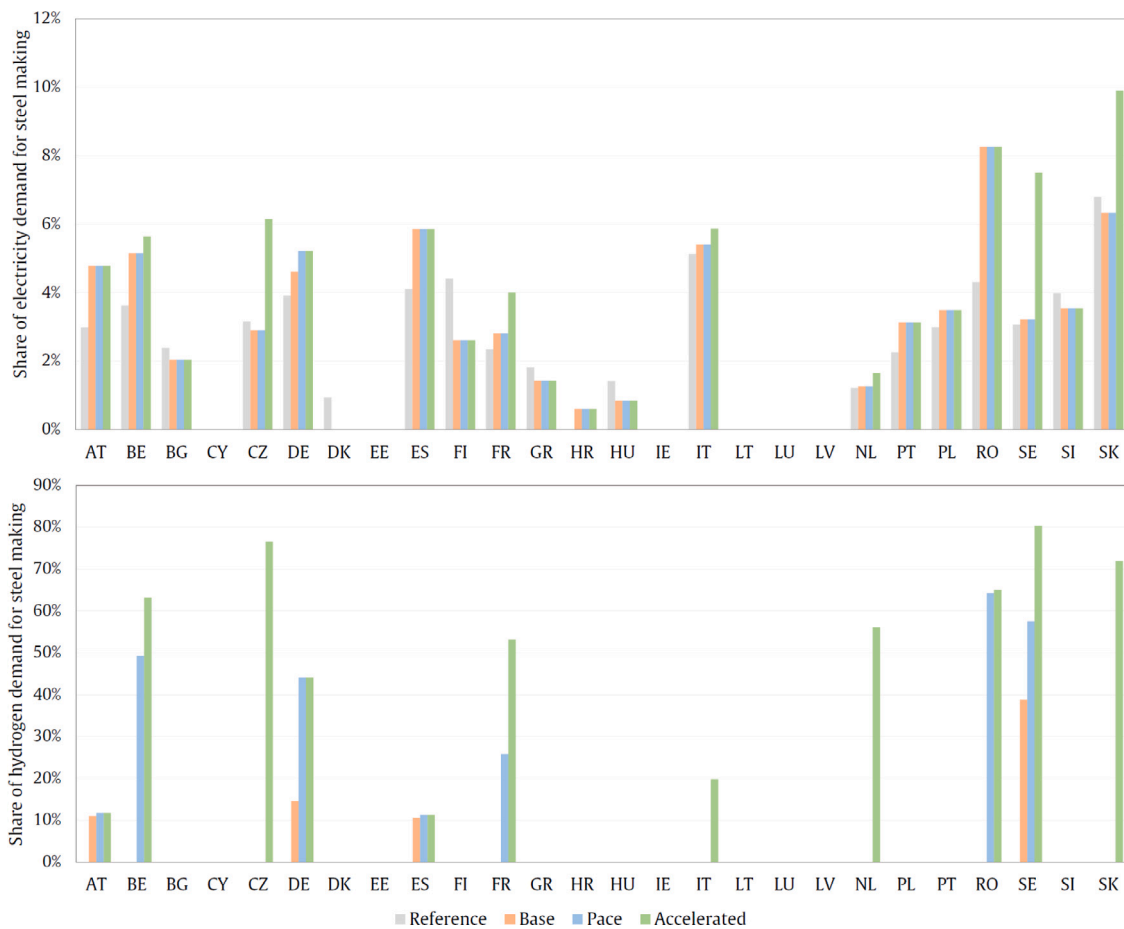


Fig. 6. Share of electricity and H<sub>2</sub> demand for steel-making in total demand per MS and scenario.

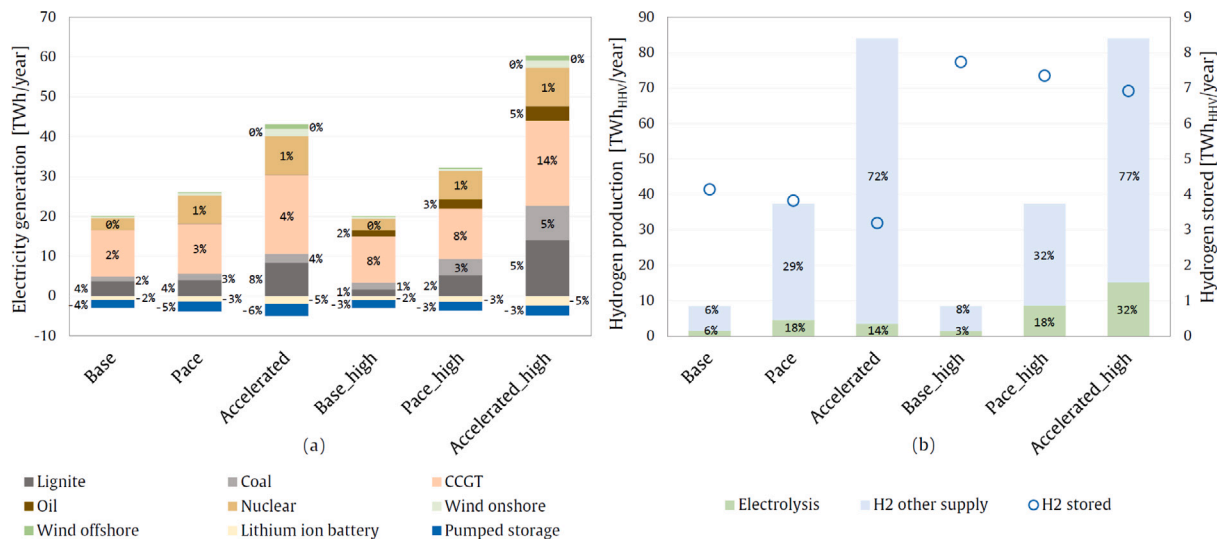


Fig. 7. Additional power (a) and H<sub>2</sub> (b) production in the EU<sup>12</sup> compared to Reference and Reference<sub>high</sub>, with low and high prices respectively and with renewable power and electrolyser capacities as foreseen by MIX-H2, see Table B.8. Percentage values report production variations of a specific technology compared to Reference and Reference<sub>high</sub>, respectively. The yearly energy stored via H<sub>2</sub> is shown on the secondary vertical axis in (b).

i.e., H<sub>2</sub> other supply. Nonetheless, electrolytic H<sub>2</sub> production more than doubles in Accelerated<sub>high</sub> compared to Accelerated scenario. It is worth noting from Fig. 7 that Pace foresees a larger absolute production of electrolytic H<sub>2</sub> than Accelerated because electricity demand for the manufacturing processes, i.e., not for electrolysis, largely increases for Accelerated compared to Pace. Therefore, the power generated is redirected from electrolysis to the manufacturing processes, inducing the cost-effective use of more non-electrolytic H<sub>2</sub>. Overall, it can be concluded that high fuel prices only slightly stimulate electrolytic H<sub>2</sub> production, and that this additional production is mainly provided by fossil-based power generators, whose CO<sub>2</sub> emissions are presented later in the study.

#### 4.1.2. Renewable capacity expansion

Fig. 8 presents the outcome of the steel scenarios when utilising the METIS capacity expansion feature for renewable and electrolysers, as opposite to the previous scenarios, where the UCED was simulated using the capacity per technology as foreseen by the MIX-H2 scenario. Fig. 8(a) shows the renewable power capacity installed and the electricity produced as additional capacity or energy, compared to Reference and Reference<sub>high</sub>. 17 to 35 GW of renewable power capacity is installed for the low prices scenarios, while 40 to 112 GW for the high prices scenarios. Germany, Italy, Spain, France and Belgium are, in order, the countries with the highest capacity deployment and together amount to 80% of total deployment. The deployed renewable capacity supplies the following shares of steel energy demand, as direct electricity or for electrolysis: 29%, 36%, 38% and 34% for Reference<sub>EXP</sub>, Base<sub>EXP</sub>, Pace<sub>EXP</sub> and Accelerated<sub>EXP</sub> and 63%, 80%, 87% and 93% for Reference<sub>high</sub><sub>EXP</sub>, Base<sub>high</sub><sub>EXP</sub>, Pace<sub>high</sub><sub>EXP</sub> and Accelerated<sub>high</sub><sub>EXP</sub>, respectively. The remaining demand is supplied

<sup>12</sup> EU will henceforth be used to refer to EU27 and neighbouring countries for the power system, and EU for the H<sub>2</sub> system. It is assumed that neighbouring countries do not have a H<sub>2</sub> demand and that there is no relevant hydrogen cross-border infrastructure in 2030. Therefore, neighbouring countries are irrelevant and excluded from the analysis of the H<sub>2</sub> system.

by grid-electricity. Among the low prices scenarios, Pace<sub>EXP</sub> has the highest share of renewably generated electricity, indicating the best trade-off between the cost of deploying renewable capacity and additional generation by existing capacities. With high prices, the cost of this additional generation increases, driving the large renewable deployment of Accelerated<sub>high</sub><sub>EXP</sub>. Another driver to the scale of the renewable deployment in the high prices scenarios is the share of H<sub>2</sub> supplied via electrolysis, respectively 93%, 92% and 91% in Base<sub>high</sub><sub>EXP</sub>, Pace<sub>high</sub><sub>EXP</sub> and Accelerated<sub>high</sub><sub>EXP</sub>, as shown in Fig. 8(b). Larger deployment of electrolysers is foreseen by the high prices scenarios, respectively 1.5, 2.8 and 3.2 times in Base<sub>high</sub><sub>EXP</sub>, Pace<sub>high</sub><sub>EXP</sub> and Accelerated<sub>high</sub><sub>EXP</sub> compared to the low prices corresponding scenarios. Nonetheless, the production of electrolytic H<sub>2</sub> is 1.8, 3.2 and 4.3 times higher, indicating that in the higher prices scenarios electrolysers have higher capacity factors. Fig. 9 shows that, in low prices scenarios, solar capacity is deployed the most because it is the cheapest technology. Solar capacity has, on average, lower capacity factor than wind capacity, thus requiring larger electrolyser capacities to maintain the same H<sub>2</sub> production. The higher fuel prices drive the installation of larger wind capacities. An exception is Sweden, where the share of wind capacity installed is between 67% and 100% for all scenarios, resulting in overall higher electrolysers capacity factors compared to other countries.

#### 4.2. Direct and indirect CO<sub>2</sub> emissions

This section explores the trade-off between reducing direct ISI CO<sub>2</sub> emissions through electricity-intensive technologies and the variation in indirect CO<sub>2</sub> emissions from the power system, alongside considerations of system costs. Fig. 10 shows the total CO<sub>2</sub> emissions for all sub-scenarios and for 2018, and the power system costs variation compared to Reference. As the full range of options to supply H<sub>2</sub> was not taken into account in this study, Fig. 10 displays in patterned grey the CO<sub>2</sub> emission as if H<sub>2</sub> were supplied via SMR. Plausible alternatives such as SMR with CCUS or imported green H<sub>2</sub> would result in lower or zero H<sub>2</sub> emissions, falling within the range of the patterned grey stacked column.

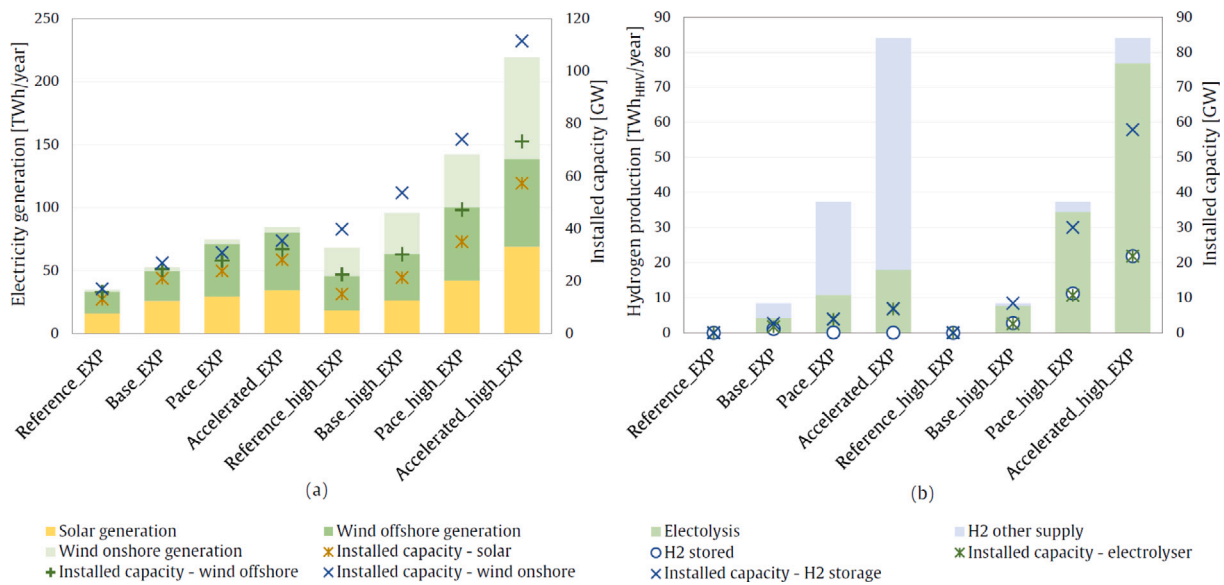


Fig. 8. Additional power (a) and H<sub>2</sub> (b) production, and additional generation capacities in the EU<sup>12</sup> with low and high prices and with renewable capacity expansion, compared to *Reference* and *Reference\_high*, respectively, when optimised without the METIS feature of capacity expansion. In(b), H<sub>2</sub> stored refers to the primary vertical axis – H<sub>2</sub> production [TWh<sub>HHV</sub>/year]. In (a) and (b) cumulative capacity installed are shown on secondary vertical axes.

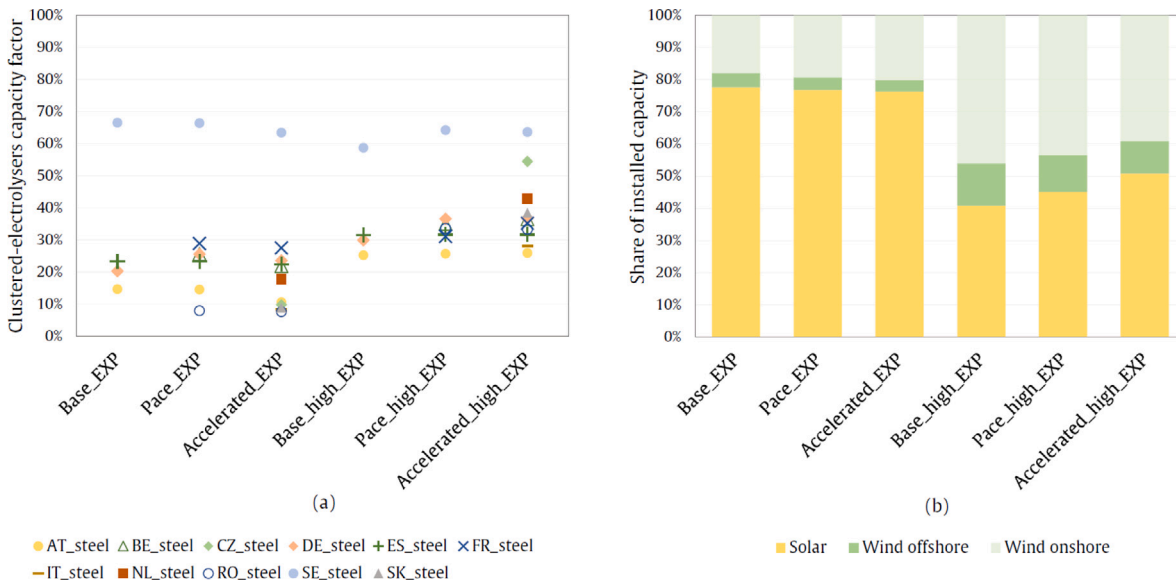
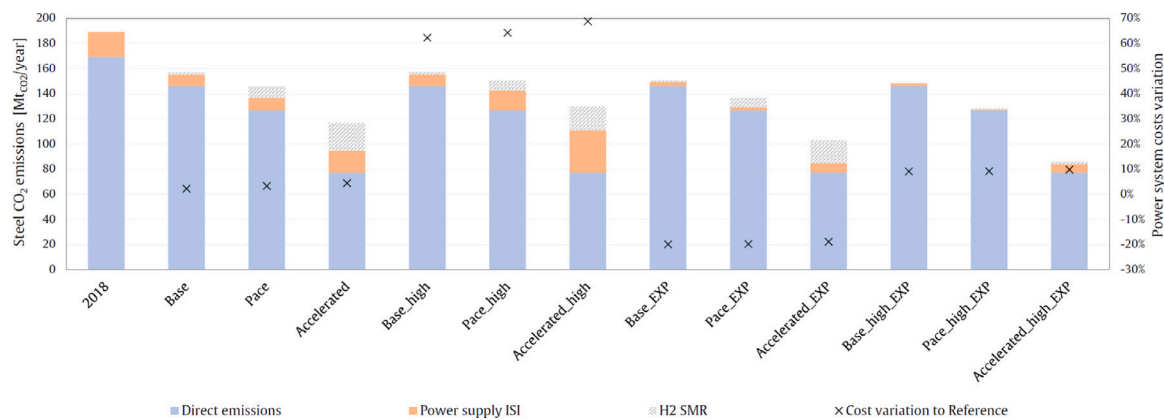


Fig. 9. (a) Capacity factors of electrolyzers by country and (b) share of installed renewable capacities by technology.

All scenarios foresee an overall reduction in CO<sub>2</sub> emissions compared to 2018, primarily due to direct emissions reductions of 14%, 25% and 54% in *Base*, *Pace* and *Accelerated*, respectively. Without the expansion of renewable capacity, indirect CO<sub>2</sub> emissions increase with the growth of electricity demand, as from *Base* to *Accelerated*, because more electricity is generated by fossil-fed power plants. Nonetheless, the level of indirect CO<sub>2</sub> emissions allocated to the ISI remains below 2018 values due to additional deployment of renewable power generators foreseen in the MIX-H2 scenario by 2030. High natural gas and H<sub>2</sub>

*other supply* prices in *\_high* scenarios leads to a larger use of coal- and lignite-based power plants instead of gas-based, resulting in indirect CO<sub>2</sub> emissions being almost 70% higher in 2030 than in 2018. Five MS are responsible for 74% of total EU indirect CO<sub>2</sub> emissions. These are, in order of contribution, Poland, Germany, Italy, Czech Republic and Romania. By contrast, the dedicated capacity expansion of *\_EXP* scenarios leads to significant reductions in indirect CO<sub>2</sub> emissions with peaks reaching up to 96% emissions cuts in *Pace\_high\_EXP* compared to 2018.



**Fig. 10.** Direct and indirect CO<sub>2</sub> emission in the EU<sup>12</sup> of steel scenarios compared to 2018, with and without capacity expansion. The secondary axis reports the variation of operational power system costs and annualised investment of the additional renewable and electrolyser capacities deployed in the capacity expansion scenarios, compared to *Reference* (97 B€).

Regarding system costs variations, Fig. 10 indicates that allowing capacity expansion results in a maximum increase of 10% in *Accelerated\_high\_EXP* compared to 2018, in contrast to the nearly 70% increase in *Accelerated\_high*. This trend is reflected in Fig. 11(a), showing marginal electricity costs per scenario, where the expansion of renewable capacity prevents a rise in costs, even under high demand scenarios such as *Accelerated\_EXP*. Fig. 11(b) indicates that system costs increase within the range of 0.3 to 73.4 €/t<sub>STEEL</sub> for all scenarios compared to their respective Reference scenario, whose system costs are reported in Table 4. The *high* scenarios experience the most substantial increase and the largest cost difference among scenarios, even with the most limited CO<sub>2</sub> emission reduction variation among the sets of scenarios (0.2 t<sub>CO<sub>2</sub></sub>/t<sub>STEEL</sub>). In contrast, the high prices of the *high\_EXP* scenarios drive renewable deployment to the extent that additional system costs are under 5 €/t<sub>STEEL</sub> for all scenarios, and 0.3 €/t<sub>STEEL</sub> for *Pace\_high\_EXP*. The costs variation remains between 5 to 27 €/t<sub>STEEL</sub> for scenarios without high prices and, by expanding renewable capacity, system costs can be reduced by 8 to 16 €/t<sub>STEEL</sub> while simultaneously reducing CO<sub>2</sub> emissions, as shown by the difference between the blue and the green trend-line. Overall, these variations are between 0.1% to 21% of steel production costs if this is within 350 to 750 €/t<sub>STEEL</sub>. This range encompasses mature technologies such as BF-BOF to more expensive emerging technologies [42].

## 5. Discussion

This study assesses the results' robustness by conducting sensitivities analysis that involve varying fuel prices, and renewable and electrolyser capacities. Nonetheless, the study presents limitations arising from the uncertainty encompassing numerous parameters related to the future of the European ISI. For instance, the study assumes constant production levels in 2030 compared to 2018. In practice, a decrease in production is plausible, as cost disadvantages of European steel-makers compared to offshore alternatives increases the likelihood of relocation [43]. Furthermore, this study assumes the replacement of existing plants with low-carbon technologies of the same size, but the development of new, non-mature technologies is more likely to be at smaller scale. Similarly to the above-mentioned assumption, this could lead to a reduction of European steel production unless a larger number of smaller steel plants are constructed. This reduced operational capacity would have smaller impact on the power system, ultimately

resulting in lower CO<sub>2</sub> emissions. Furthermore, technologies included in the steel scenarios are limited to H<sub>2</sub>-DRI and BF-BOF-CCUS, with only a modest increase in the use of recycled steel (scrap-EAF). Promoting circularity in the ISI could partly decrease the deployment of new primary technology, thus decreasing system impact and CO<sub>2</sub> emissions. However, the use of recycled steel is limited by the availability of high quality scrap [5]. This is a globally traded commodity thus constrained by global supply. The share of steel manufactured via the secondary route greatly varies around the World. It is 24% globally and reaches 69% in the USA [7]. No study is found suggesting a sharp increase of secondary production in the EU in the near future.

Regarding primary steel-making, other emerging technologies that the ones included in the steel scenarios may become relevant in the coming years and could be adopted by European steel-makers. For example, Boston Metal expects commercial deployment of the molten oxide electrolysis (MOE) technology by 2026 in the USA [44], but with no involvement from any European producer. Electrowinning technologies are expected to consume between 2.5 and 3.7 MWh<sub>EL</sub>/t<sub>STEEL</sub> [5, 45], making them slightly more efficient than the H<sub>2</sub>-DRI-EAF route. However, electricity needs to be consumed directly while, in the H<sub>2</sub>-based technology, three quarters of the electricity is used for producing electrolytic H<sub>2</sub>, which can be stored providing options for flexible consumption. Regarding the calculation of energy intensities, it must be acknowledged that energy requirements for steel finalisation processes can vary significantly depending on production method and final steel application. We consider the general assumption about the energy savings valid in the context of steel production at the European scale, recognising that these may vary by technology, steel application and country.

Examining our results in a broader context, *Accelerated\_high\_EXP* and *Pace\_high\_EXP* allocate 20 GW and 10 GW of electrolyser capacity to steel-making, which correspond to half and a quarter of total electrolyser capacity foreseen by MIX-H2 in 2030, respectively. With low gas prices, these numbers reduce to 9 GW and 4 GW for *Accelerated* and *Pace*. *Pace*, which is in line with MIX-H2, foresees 10% of the total MIX-H2 electrolyser capacity allocated to supply the ISI. While this seems reasonable given that the ISI is one of the sectors with the highest demand, it is worth noting that lower capacities could suffice if operating at higher capacity factors than as calculated by the model – i.e., in the range of 20%–39% as shown in Fig. 12. For example, supplying wind-generated electricity instead of solar- to electrolyzers

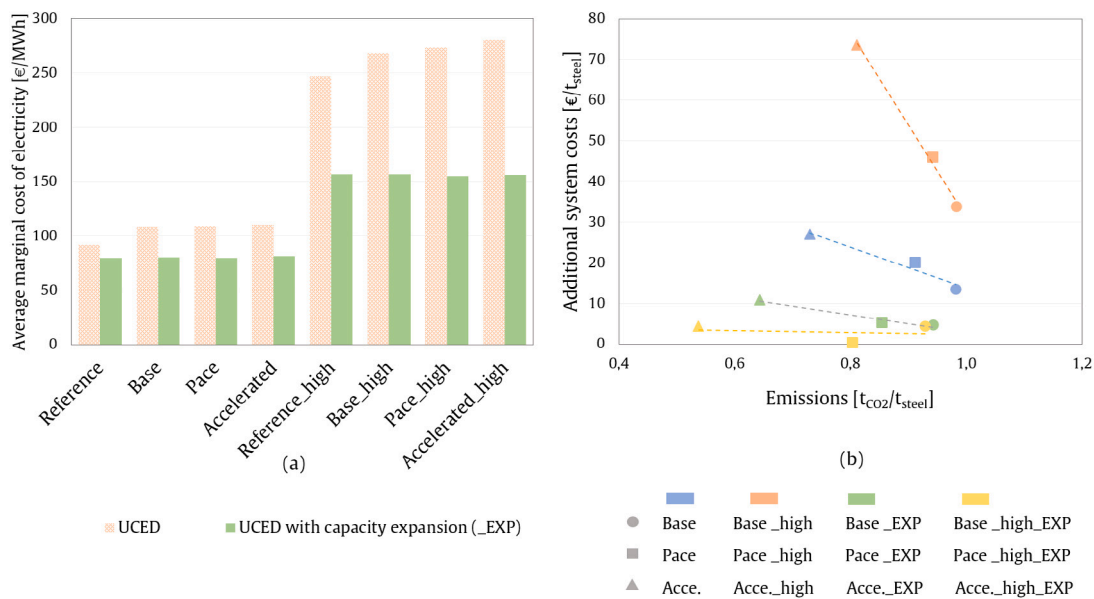


Fig. 11. (a) Marginal cost of electricity per scenario, average of all countries and hours of the year, and (b) system costs, as additional to Reference, per unit of steel produced plotted against the average direct and indirect CO<sub>2</sub> emissions per scenario. For comparison, the production of one tonne of steel in the EU in 2018 was responsible on average for 1.2 tonne of CO<sub>2</sub>.

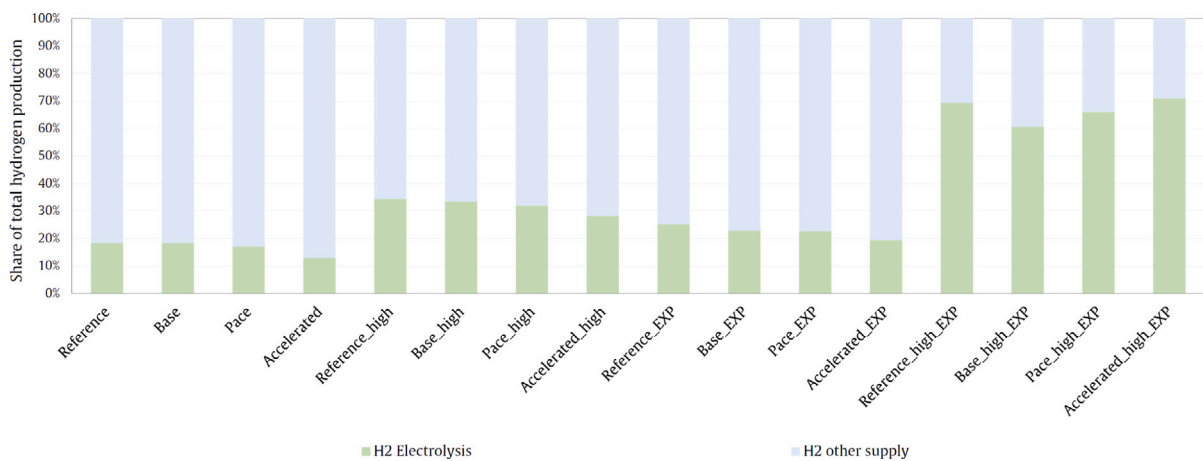


Fig. 12. Share of total EU H<sub>2</sub> method of supply or production.

leads to higher capacity factors. Results show that in Sweden, where almost no solar capacity is installed, the electrolyzers run at 60%–70% capacity factors, mainly supplied by wind and nuclear generated power.

Overall, our results show a larger deployment of renewable and electrolyser capacity, compared to the MIX-H2 scenario, to ensure the cost-effective supply of renewable H<sub>2</sub> and electricity to steel-makers, while avoiding an increase in indirect CO<sub>2</sub> emissions. This expansion of variable renewable capacity should be accompanied by an increase of flexibility by the power system, in the form of dispatchable power generators, storage, increased interconnections or flexible demand. While electrolysis can flexibly absorb excess power generation, a shortage of renewable electricity entails increasing generation by dispatchable

plants, which comes at additional starting costs and lower efficiencies. The former are captured by the system operating costs calculated by the model and shown in Fig. 10, but the lower power plant efficiencies are not included, leading to higher indirect CO<sub>2</sub> emissions and ramping costs than the results computed by METIS. Furthermore, the hourly resolution of the model might result in an underestimation of system flexibility requirements, especially if they occur on a timescale below an hour. Finally, if capacity expansion were permitted for technologies beyond wind, solar power and electrolyzers, the optimal energy system configuration might have included higher capacities of flexible alternatives such as electric storage or interconnections.

Since the energy crisis there has been a stronger push by the EU to move away from the dependency on foreign countries for natural gas by increasing the renewable energy targets and H<sub>2</sub> production and import. In line with our results, the REPower EU plan foresees 45% renewable energy in the final consumption and an increase of 15 Mt of renewable H<sub>2</sub> compared to MIX-H2, of which 5 Mt domestically produced and 10 Mt imported [46]. The price applied for H<sub>2</sub> *other supply* – e.g., imported, produced as grey or blue H<sub>2</sub> – is between 2 and 10 €/kg<sub>H<sub>2</sub></sub>, which is in line with the price of green H<sub>2</sub> expected by currently developing H<sub>2</sub> hubs around the world [47]. Therefore, the study provides realistic insights into the competitiveness of future locally produced H<sub>2</sub>. Fig. 12 shows that, with low H<sub>2</sub> *other supply* prices, the cost-effectiveness of deploying renewable and electrolyser capacity is limited and the share of H<sub>2</sub> *other supply* remains over 75% in all scenarios. Instead, with high prices the share of H<sub>2</sub> *other supply* lowers to under 40% with capacity expansion, enhancing the cost-effectiveness of locally produced electrolytic H<sub>2</sub>.

## 6. Conclusion

The iron and steel industry (ISI) is currently a highly energy intensive and CO<sub>2</sub> emitting sector. Decarbonising the ISI involves the application of direct or indirect electrification technologies. As part of the ISI energy input electrifies, the impact on the power system becomes more pronounced. Many steel manufacturer plan to start the operation of new low-carbon technologies, such as H<sub>2</sub>-based direct reduction of iron (H<sub>2</sub>-DRI-EAF) by 2030. At this point in time, the power sector will not have fully transitioned to a low-carbon system. This study aims at assessing the consequences of a short-term increase of ISI electricity demand by developing nine scenarios that reflect various levels of decarbonisation, fuel prices, and renewable power and electrolyser capacities. Through modelling, this work evaluates the impact of the transformation of the ISI in 2030 on the European power and H<sub>2</sub> system in terms of generating technologies, marginal prices and CO<sub>2</sub> emissions.

The findings of this study indicate that the European power system, as foreseen by the MIX-H2 scenario for 2030, is capable of accommodating an advanced transition of the ISI, represented by our *Pace* scenario. In the *Pace* scenario, the ISI achieves a direct CO<sub>2</sub> emissions reduction of 25% compared to 2018, thanks to the adoption of electrified processes that increase electricity and H<sub>2</sub> demand, respectively, by 17 TWh and 40 TWh<sub>HHV</sub> at EU-level. Nonetheless, indirect CO<sub>2</sub> emissions decrease by one-third to one-half compared to 2018, considering a range of fuel prices, despite the 16% increase in electricity demand. Electrolytic H<sub>2</sub> supply remains below 25% of demand, even when the price of alternative supplies – e.g., import, produced by steam methane reforming (SMR) – reaches 10 €/kg<sub>H<sub>2</sub></sub>. Although this study does not deal with a detailed assessment of the indirect CO<sub>2</sub> emissions from alternative H<sub>2</sub> supplies, it must be noted that if the over 75% of H<sub>2</sub> demand were met through SMR without carbon capture, the total indirect emissions would increase by 5% compared to 2018 levels. On the other hand, an *Accelerated* transition of the European ISI, which results in a substantial 54% reduction of CO<sub>2</sub> direct emissions, can cause an increment of indirect emissions up to 69%. This increase occurs because the additional demand is mainly met by fossil-based power plants. The major contributors to indirect CO<sub>2</sub> emissions are Poland, Germany, Italy, Czech Republic and Romania.

The study further demonstrates that a drastic reduction of indirect CO<sub>2</sub> emissions can be realised by combining the installation of dedicated renewable capacity alongside the transformation of the ISI. In the *Pace* scenario, 30 and 70 GW of renewable power generators, and 5 and 10 GW of electrolysers are installed with *low* and *high* fuel prices, respectively, mainly in Germany, Italy, Spain, France and Belgium. That entails that a reduction of indirect CO<sub>2</sub> emissions of 85% or higher, together with 25% reduction of direct CO<sub>2</sub> emissions compared to 2018, can be achieved by deploying 1.2 to 2.7 GW of renewable power generators, and 200 to 400 MW of electrolysers for each million tonne of steel produced annually with low-carbon technologies, with *low* and *high* fuel prices, respectively. This approach of expanding the ISI-dedicated renewable capacity also contributes to keeping marginal prices of electricity stable, even when facing a large increase in electricity demand. This is in contrast to scenarios with limited renewable capacity, where marginal electricity prices increase by 10%–20%.

Establishing a cost-effective and low-carbon H<sub>2</sub> supply is crucial to decarbonise the ISI and to facilitate the competitiveness of European steel-makers on the global market. Additional renewable capacity that ensures green steel production is key to avoid CO<sub>2</sub> emissions spill-over and maintaining stable electricity prices. Renewable energy for steel-making purposes could be ensured through contracts such as power purchase agreements or energy cooperations, as long as these entails additionality of renewable energy. A collaborative and integrated approach among power, H<sub>2</sub> and steel sectors is essential for a cost-effective and efficient system transformation to net-zero. Such integrated systems can unlock new opportunities such as flexible consumption. Further research should focus on researching such systems by, for example, assessing the role of new large electricity consumers such as the steel sector in providing flexibility to the power system through demand response. These strategies can help industrial consumers in decreasing their energy bills and the power sector in cost-effectively integrating higher shares of variable renewable energy.

## CRedit authorship contribution statement

**Annika Boldrini:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Derck Koolen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Wina Crijns-Graus:** Validation, Supervision. **Machteld van den Broek:** Validation, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A. Derivation of steel scenarios, their energy demand and CO<sub>2</sub> emissions

Tables A.5–A.7 report derived energy intensities of steel-making technologies, direct CO<sub>2</sub> emissions intensities and projects for low-carbon steel-making in the EU.

**Table A.5**

Derived energy intensities of steel-making technologies in 2030 for natural gas (NG), electricity (EL) and hydrogen (H<sub>2</sub>), for all member states (MSs) that are steel producers and EU average. MSs that only employ secondary production present energy intensities for the secondary route alone (scrap-EAF) and viceversa. Natural gas consumption for the carbon capture system is not calculated as not relevant for the modelling input, thus NG consumption in BF-BOF-CCUS is assumed to remain the same as in BF-BOF.

GJ/t <sub>STEEL</sub>	Present-day technologies									New technologies					
	BF-BOF			DRI-EAF			Scrap-EAF			BF-BOF-CCUS			H <sub>2</sub> -DRI-EAF		
	NG	EL	H <sub>2</sub>	NG	EL	H <sub>2</sub>	NG	EL	H <sub>2</sub>	NG	EL	H <sub>2</sub>	NG	EL	H <sub>2</sub>
EU	2.08	2.13	–	10.55	4.89	–	1.07	3.00	–	2.08	3.10	–	0.92	4.89	7.13
AT	2.62	1.82	–	10.56	3.43	–	1.32	1.97	–	2.62	2.79	–	0.93	3.43	7.13
BE	2.48	1.85	–	10.53	4.12	–	1.42	2.44	–	2.48	2.82	–	0.91	4.12	7.13
BG	–	–	–	–	–	–	3.04	4.11	–	–	–	–	–	–	–
CZ	1.13	1.45	–	10.40	4.81	–	0.88	3.06	–	1.13	2.42	–	0.77	4.81	7.13
DE	1.89	2.11	–	10.55	4.73	–	1.08	2.90	–	1.89	3.08	–	0.92	4.73	7.13
ES	2.66	3.86	–	10.38	6.97	–	0.98	4.51	–	2.66	4.83	–	0.75	6.97	7.13
FI	0.27	1.60	–	10.01	5.10	–	0.23	3.76	–	0.27	2.57	–	0.39	5.10	7.13
FR	1.68	2.09	–	10.49	5.67	–	1.17	3.62	–	1.68	3.06	–	0.86	5.67	7.13
GR	–	–	–	–	–	–	0.61	2.39	–	–	–	–	–	–	–
HR	–	–	–	–	–	–	0.86	3.61	–	–	–	–	–	–	–
HU	2.46	0.67	–	10.64	3.21	–	1.07	1.80	–	2.46	1.64	–	1.01	3.21	7.13
IT	3.39	2.23	–	10.62	4.50	–	1.51	2.81	–	3.39	3.20	–	1.00	4.50	7.13
LU	–	–	–	–	–	–	2.12	2.14	–	–	–	–	–	–	–
NL	1.38	1.30	–	10.55	1.89	–	–	–	–	1.38	2.27	–	0.92	1.89	7.13
PL	2.20	2.44	–	10.47	4.60	–	1.32	2.82	–	2.20	3.41	–	0.84	4.60	7.13
PT	–	–	–	–	–	–	0.73	2.90	–	–	–	–	–	–	–
RO	1.54	2.38	–	10.05	7.66	–	1.34	4.40	–	1.54	3.35	–	0.43	7.66	7.13
SK	1.20	1.47	–	10.63	5.48	–	1.01	3.48	–	1.20	2.44	–	1.01	5.48	7.13
SI	–	–	–	–	–	–	4.27	3.53	–	–	–	–	–	–	–
SE	0.44	3.94	–	10.13	4.52	–	0.17	2.67	–	0.44	4.91	–	0.51	4.52	7.13

**Table A.6**

Direct CO<sub>2</sub> emissions intensities per EU steel manufacturing countries and technology. BF-BOF and scrap-EAF are retrieved from Koolen and Vidovic [4]. For DRI-EAF and H<sub>2</sub>-DRI-EAF EU averages are used because of their limited capacities deployed today. BF-BOF-CCUS is assumed to capture 50% of total BF-BOF CO<sub>2</sub> emissions [5].

t <sub>CO<sub>2</sub></sub> /t <sub>STEEL</sub>	Present-day technologies			New technologies	
	BF-BOF	DRI-EAF	Scrap-EAF	BF-BOF-CCUS	H <sub>2</sub> -DRI-EAF
EU	1.78	0.89	0.08	0.89	0.09
AT	1.27	0.89	0.08	0.63	0.09
BE	1.90	0.89	0.11	0.95	0.09
BG	–	–	0.15	–	–
CZ	1.96	0.89	0.05	0.98	0.09
DE	1.55	0.89	0.14	0.78	0.09
ES	1.57	0.89	0.07	0.79	0.09
FI	1.68	0.89	0.03	0.84	0.09
FR	1.83	0.89	0.08	0.92	0.09
GR	–	–	0.04	–	–
HR	–	–	0.13	–	–
HU	2.02	0.89	0.04	1.01	0.09
IT	1.55	0.89	0.09	0.77	0.09
LU	–	–	0.12	–	–
NL	1.76	0.89	–	0.88	0.09
PL	3.31	0.89	0.09	1.66	0.09
PT	–	–	0.05	–	–
RO	1.30	0.89	0.19	0.65	0.09
SK	1.95	0.89	0.06	0.98	0.09
SI	–	–	0.25	–	–
SE	1.94	0.89	0.02	0.79	0.09



**Table A.7**

Projects for the decarbonisation of steel production in the EU, as recorded by the Green Steel Tracker in March 2022 [8]. NA: not available; MoU: memorandum of understanding.

Project name	Company	Location	Project scale	Technology	Project status	Year online	Capacity [Mt <sub>STEEL</sub> ]
H2Steel	Thyssenkrupp	Duisburg (DE)	Full scale	H <sub>2</sub> -DRI-EAF	Announcement	2025/2030 <sup>a</sup>	0.4/1.2 <sup>a</sup>
SALCOS	Salzgitter	Salzgitter (DE)	Full scale	Electrolyser, H <sub>2</sub> -DRI-EAF	Construction started	NA	1.0
Steel4Future	ArcelorMittal	Bremen (DE)	Full scale	DRI-EAF → H <sub>2</sub> -DRI-EAF	MoU signed	2026	1.75 <sup>b</sup>
Steel4Future	ArcelorMittal	Eisenhüttenstadt (DE)	Pilot	H <sub>2</sub> -DRI-EAF	MoU signed	2026	1.75 <sup>b</sup>
NA	ArcelorMittal	Dunkirk (FR)	Full scale	H <sub>2</sub> -DRI-EAF	MoU signed	2027	2.00
NA	ArcelorMittal	Ghent (BE)	Full scale	DRI-EAF → H <sub>2</sub> -DRI-EAF	Letter of intent signed	2030	2.50
NA	ArcelorMittal	Gijon (ES)	Full scale	H <sub>2</sub> -DRI-EAF	MoU signed	2025	1.10
HYFOR	Voestalpine	Donawitz (AT)	Pilot	H <sub>2</sub> -DRI-EAF	Operational	2021	0.25
Hybrit	SSAB	Luleå (SE)	Pilot/Demo <sup>a</sup>	Electrolyser, H <sub>2</sub> -DRI- EAF	Pilot plant operational	2021/2026 <sup>a</sup>	0.25/NA <sup>a</sup>
Liberty Steel	NA	Galati (RO)	Full scale	DRI-EAF → H <sub>2</sub> -DRI-EAF	MoU signed	2024	4.00
H2 Green Steel	H2 Green Steel	Svartbyn (SE)	Full scale	Electrolyser, H <sub>2</sub> - DRI-EAF	Announcement	2030	5.00
HYBRIT	SSAB	Gallivare (SE)	full scale	Electrolyser, H <sub>2</sub> - DRI- EAF	NA	2026/2030 <sup>a</sup>	1.30/2.70 <sup>a</sup>
H2Hamburg	ArcelorMittal	Hamburg (DE)	Demo	DRI-EAF → H <sub>2</sub> -DRI-EAF	Plant design commissioned	2024	0.1
3D project	ArcelorMittal	Dunkirk (FR)	Demo/ Full scale <sup>a</sup>	BF-BOF-CCUS	Construction started	2025/2035 <sup>a</sup>	1.0/10.0 <sup>a</sup>

Notes: <sup>a</sup> the latter refers to an expansion foreseen; <sup>b</sup> ArcelorMittal plans a combined capacity of 3.5 [Mt<sub>STEEL</sub>] between Bremen and Eisenhüttenstadt plants.

## Appendix B. Modelling assumptions and results

Table B.8 reports the power generation capacities as foreseen by the MIX-H2 scenarios, Figs. B.13–B.16 report the power and hydrogen generation in *Reference* and *Reference\_high* scenarios.

**Table B.8**Capacities installed of EU power generation technologies in MIX-H2 2030 [28]. These are the capacities installed for all non-*EXP* scenarios. Additional capacities installed in Fig. 8 are in comparison to the capacities in this table.

Generation technologies	Installed capacities GW <sub>EL</sub>
Coal subcritical	15.0
Coal (ultra)supercritical	14.4
Lignite subcritical	29.2
Lignite supercritical	13.2
CCGT	164.8
CCGT CHP	19.3
Derived gases	6.9
OCGT	4.92
Oil Subcritical	14.23
Nuclear	102.2
Biomass	53.4
Geothermal	1.8
Hydro	122.2
Hydro RoR	48.1
Solar fleet	452.0
Wind onshore	427.5
Wind offshore	117.0

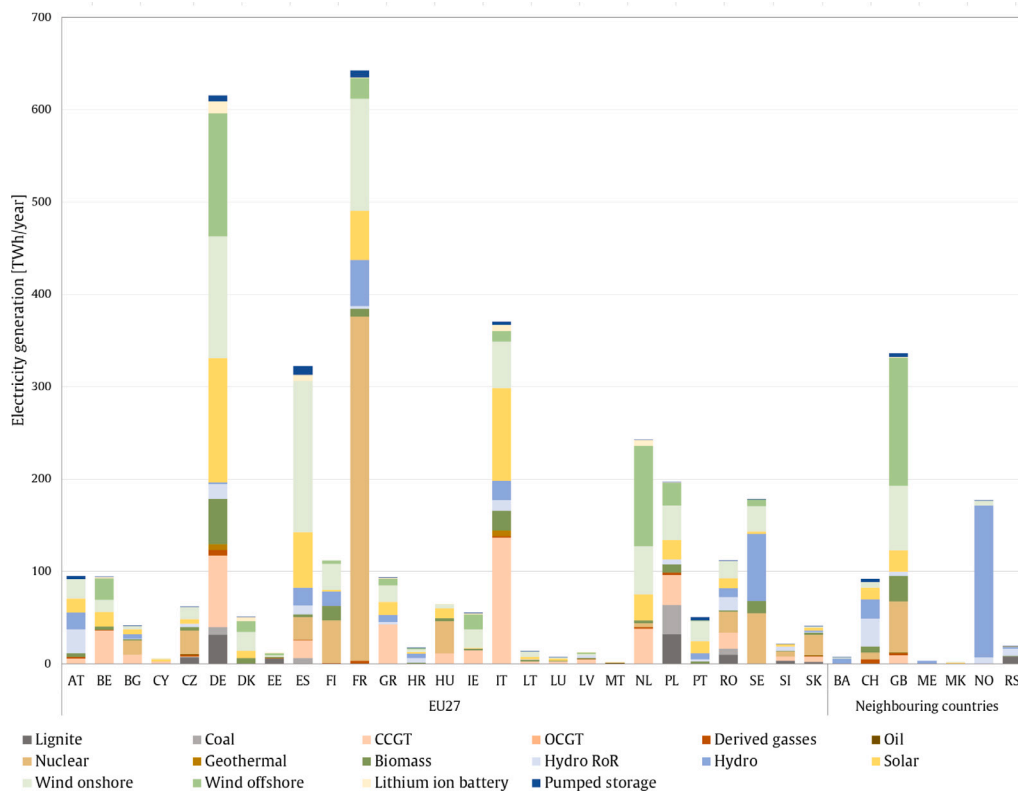


Fig. B.13. Total electricity generated by technology and EU<sup>12</sup> country in *Reference* scenario.

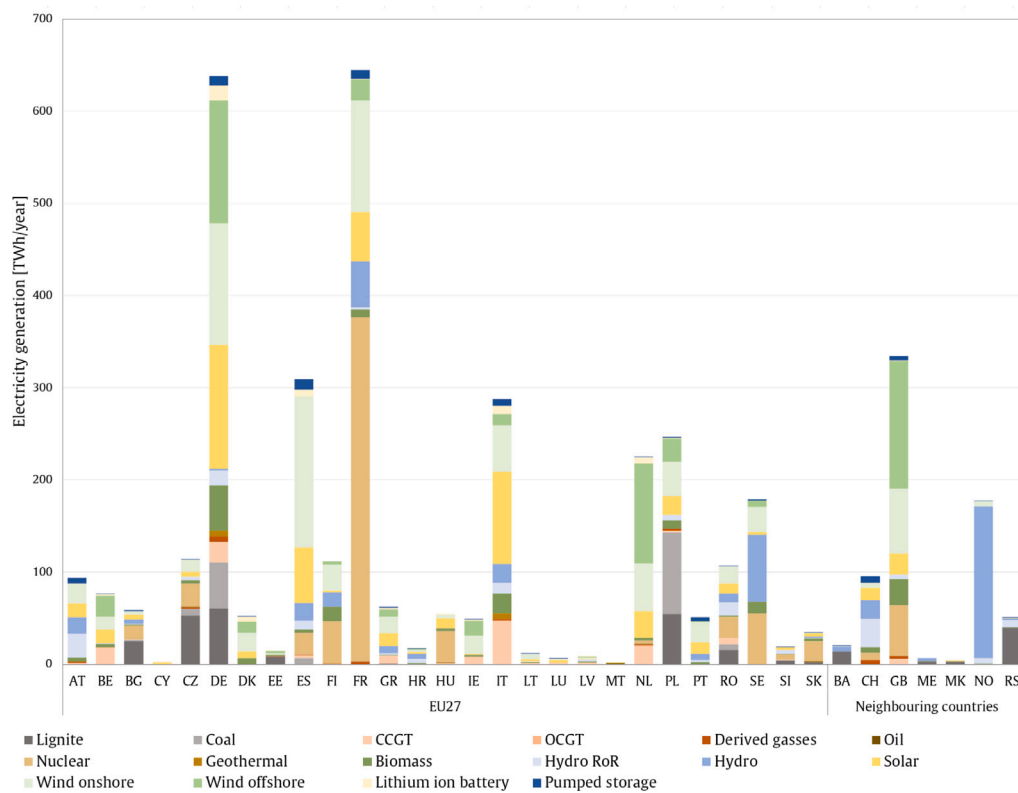


Fig. B.14. Total electricity generated by technology and EU<sup>12</sup> country in *Reference\_high* scenario.

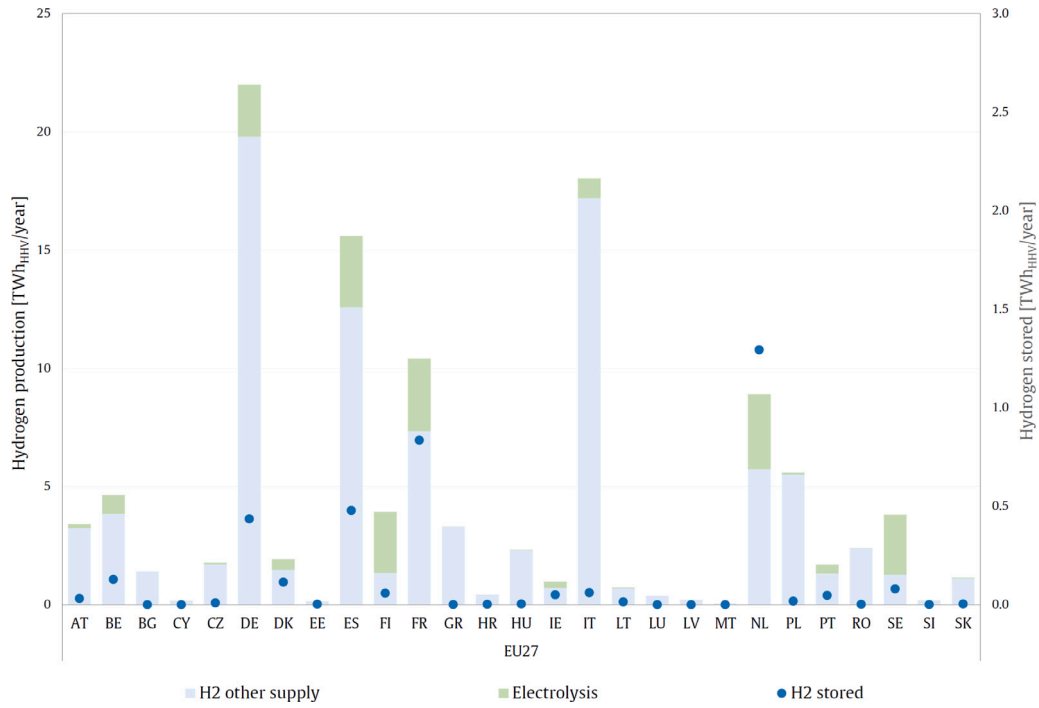


Fig. B.15. Total hydrogen generated by technology and EU<sup>12</sup> country in Reference scenario.

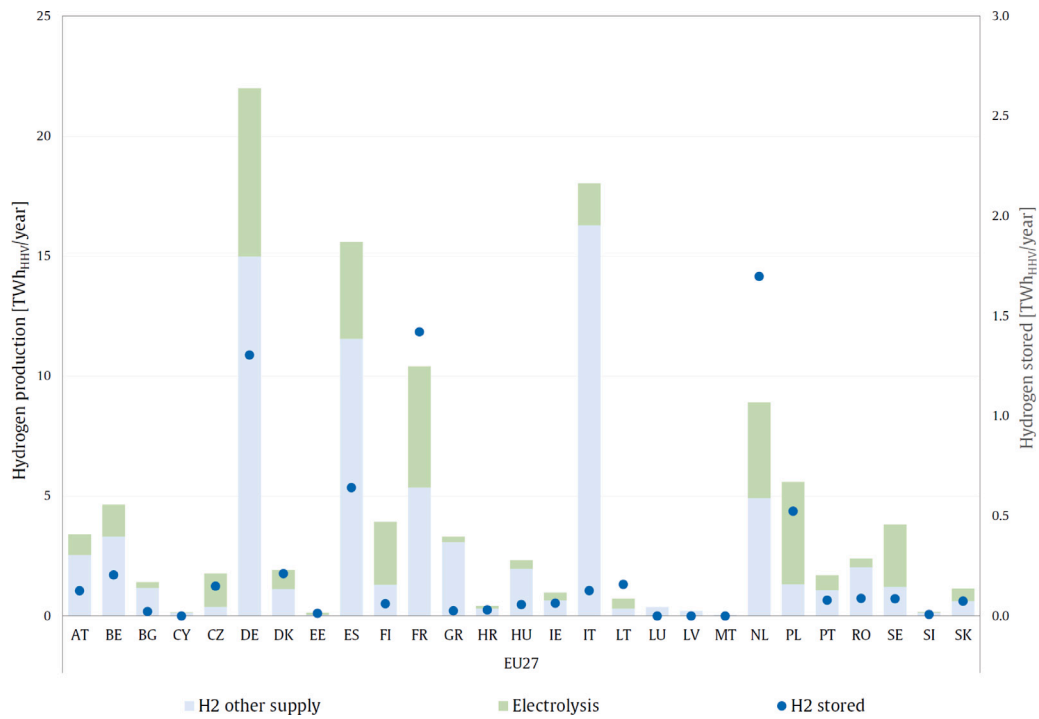


Fig. B.16. Total hydrogen generated by technology and EU<sup>12</sup> country in Reference\_high scenario.

## References

- [1] Greenhouse gas protocol. 2023, URL <https://ghgprotocol.org/>. Last [Accessed 31 March 2023].
- [2] Peng K, Feng K, Chen B, Shan Y, Zhang N, Wang P, et al. The global power sector's low-carbon transition may enhance sustainable development goal achievement. *Nat Commun* 2023;14(1):1–14. <http://dx.doi.org/10.1038/s41467-023-38987-4>.
- [3] Tiseo I. Carbon dioxide emissions from fossil fuel combustion in Europe in 2021, by sector. 2023, Statista. URL <https://www.statista.com/statistics/206115/total-oecd-europe-carbon-dioxide-emissions-by-sector/>.
- [4] Koolen D, Vidovic D. Greenhouse gas intensity of the EU steel industry and its trading partners. Tech. Rep., Publications Office of the European Union; 2022, <http://dx.doi.org/10.2760/170198>.
- [5] Somers J. Technologies to decarbonise the EU steel industry. Tech. Rep., Publications Office of the European Union; 2022, <http://dx.doi.org/10.2760/069150>.
- [6] Kim J, Sovacool BK, Bazilian M, Griffiths S, Lee J, Yang M, et al. Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Res Soc Sci* 2022;89:2214–6296. <http://dx.doi.org/10.1016/j.erss.2022.102565>.
- [7] Fan Z, Friedmann SJ. Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule* 2021. <http://dx.doi.org/10.1016/j.joule.2021.02.018>.
- [8] Leadership group for industry transition (LEADIT). Green steel tracker. 2022, URL <https://www.industrytransition.org/green-steel-tracker/>. Last [Accessed 15 March 2022].
- [9] Boldrini A, Koolen D, Crijns-Graus W, van den Broek M, Worrell E. The demand response potential in a decarbonising iron and steel industry: A review of flexible steelmaking. 2023, <http://dx.doi.org/10.2139/SSRN.4472250>, [Preprint].
- [10] Eurostat. Data browser. 2023, URL [https://ec.europa.eu/eurostat/databrowser/view/TEN00123/default/table?lang=en&category=nrg.nrg\\_quant.nrg\\_quant.nrg\\_bal](https://ec.europa.eu/eurostat/databrowser/view/TEN00123/default/table?lang=en&category=nrg.nrg_quant.nrg_quant.nrg_bal).
- [11] Lechtenböhmer S, Nilsson LJ, Åhman M, Schneider C. Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy* 2016;115:1623–31. <http://dx.doi.org/10.1016/j.energy.2016.07.110>.
- [12] Toktarova A, Walter V, Göransson L, Johnsson F. Interaction between electrified steel production and the north European electricity system. *Appl Energy* 2022;310(November 2021). <http://dx.doi.org/10.1016/j.apenergy.2022.118584>.
- [13] Göransson L, Lehtveer M, Nyholm E, Taljegard M, Walter V. The benefit of collaboration in the North European electricity system transition—System and sector perspectives. *Energies* 2019;12(24):4648. <http://dx.doi.org/10.3390/EN12244648>.
- [14] Arens M, Åhman M, Vogl V. Which countries are prepared to green their coal-based steel industry with electricity? - Reviewing climate and energy policy as well as the implementation of renewable electricity. *Renew Sustain Energy Rev* 2021;143:110938. <http://dx.doi.org/10.1016/j.rser.2021.110938>.
- [15] European Commission. 2050 Long-term strategy. 2022, URL [https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy\\_en](https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en). Last [Accessed 16 August 2022].
- [16] Somers J, Moya J. Decarbonisation of industrial heat: The iron and steel sector. Tech. Rep. (5). European Commission - Joint Research Centre; 2020.
- [17] Baena-Moreno FM, Rodríguez-Galán M, Vega F, Alonso-Fariñas B, Vilches Arenas LF, Navarrete B. Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, A: Recov, Utilizat, Environ Effects* 2018;41(12):1403–33. <http://dx.doi.org/10.1080/15567036.2018.1548518>, URL <https://www.tandfonline.com/doi/abs/10.1080/15567036.2018.1548518>.
- [18] West K. Technology factsheet: Hisarna with CCS. Tech. Rep., 2020, URL [https://energy.nl/wp-content/uploads/hisarna-ccs-technology-factsheet\\_080920-7.pdf](https://energy.nl/wp-content/uploads/hisarna-ccs-technology-factsheet_080920-7.pdf).
- [19] Cavaliere P. Electrolysis of Iron Ores: Most Efficient Technologies for Greenhouse Emissions Abatement. *Clean Ironmak Steelmak Process* 2019;555–76. <http://dx.doi.org/10.1007/978-3-030-21209-410>.
- [20] International Energy Agency (IEA). Extended world energy balances. IEA World Energy Statistics and Balances; 2021, <http://dx.doi.org/10.1787/enestats-data-en>.
- [21] UN Comtrade. UN comtrade database. 2021, URL <https://comtrade.un.org/data>.
- [22] Worldsteel. Steel statistical yearbook 2020. Worldsteel Association, URL <https://worldsteel.org/>.
- [23] Moya JA, Pardo N. The potential for improvements in energy efficiency and CO<sub>2</sub> emissions in the EU27 iron and steel industry under different payback periods. *J Clean Prod* 2013;52:71–83. <http://dx.doi.org/10.1016/j.jclepro.2013.02.028>.
- [24] Pardo N, Moya JA, Vatopoulos K. Prospective scenarios on energy efficiency and CO<sub>2</sub> emissions in the European Iron and Steel industry. In: *Energy*. Vol. 54, Publications Office of the European Union, 2012; 2012, <http://dx.doi.org/10.1016/j.energy.2013.03.015>, EUR 25543.
- [25] Mantzos L, Matei N-A, Mulholland E, Rózsai M, Tamba M, Wiesenthal T. JRC-IDEES 2015. European Commission, Joint Research Centre (JRC); 2018, <http://dx.doi.org/10.2905/JRC-10110-10001>.
- [26] Eurofer. European steel in figures - covering 2011–2020. The European Steel Association; 2020, arXiv:1011.1669. URL <https://www.eurofer.eu/assets/Uploads/European-Steel-in-Figures-2020.pdf>. Last [Accessed 20 March 2023].
- [27] ArcelorMittal. Blast furnace relining has commenced. 2023, URL <https://belgium.arcelormittal.com/en/blast-furnace-relining/>. Last [Accessed 20 August 2023].
- [28] De Felice M. Fit for 55 MIX scenario 2030 (JRC-FF55-MIX-2030) - input data for METIS context. European Commission, Joint Research Centre (JRC); 2022, <http://data.europa.eu/89h/d4d59b89-89f7-4275-801a-45ea8957e973>.
- [29] European Commission. A hydrogen strategy for a climate-neutral Europe. 2020, URL <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301>. Last [Accessed 20 August 2023].
- [30] Axens. A breakthrough demixing solvent for post combustion CO<sub>2</sub> capture the key role of CCS in emissions reductions. 2022, URL <https://3d-ccus.com>. Last [Accessed 20 August 2023].
- [31] Lacroix M, Broutin P, Lethier S, Nevicato D, Petetin B, De Coninck E, et al. DMX Demonstration in Dunkirk: 3D Project granted by H2020: scope and objectives. 2023, URL <https://3d-ccus.com/wp-content/uploads/2020/02/TCCS-10-3D-Project.pdf>. Last [Accessed 20 August 2023].
- [32] Material Economics. Industrial transformation 2050 - pathways to net-zero emissions from EU heavy industry. Tech. Rep., 2019, URL <https://materialeconomics.com/publications/publication/industrial-transformation-2050>.
- [33] Agora. Breakthrough strategies for industry in Europe breakthrough strategies for climate-neutral industry in Europe. Tech. Rep., 2021, URL <https://www.agora-energiewende.de/en/publications/breakthrough-strategies-for-climate-neutral-industry-in-europe-study/>.
- [34] Bataille C, Stiebert S, Li F. Global facility level net-zero steel pathways: technical report on the first scenarios of the Net-zero Steel Project. Tech. Rep., IDDR; 2021, URL <http://netzerosteel.org>.
- [35] Bardet R, Bossavy A, Chammas M, Fournié L, Khallouf P, Texier B. METIS technical note T2 - METIS power market models. In: METIS technical notes. (October). Publication Office of the European Union; 2016.
- [36] Jackson S, Brodal E. A comparison of the energy consumption for CO<sub>2</sub> compression process alternatives. IOP Conf Ser: Earth Environ Sci 2018;167(1). <http://dx.doi.org/10.1088/1755-1315/167/1/012031>.
- [37] Sakellaris K, Canton J, Zafeiratou E, Fournié L. METIS - An energy modelling tool to support transparent policy making. *Energy Strategy Rev* 2018;22(August):127–35. <http://dx.doi.org/10.1016/j.esr.2018.08.013>.
- [38] De Felice M. Creating a METIS model for Fit for 55 scenarios. Tech. Rep., European Commission, Joint Research Centre (JRC); 2022, URL <https://joint-research-centre.ec.europa.eu>.
- [39] The Hotmaps Team. Hotmaps. 2023, URL <https://gitlab.com/hotmaps>. Last [Accessed 25 April 2023].
- [40] Gasparella A, Koolen D, Zucker A. The merit order and price setting dynamics in European electricity markets. Tech. Rep., European Commission, Petten; 2023, JRC134300.
- [41] McKinsey and Company. Safeguarding green steel in Europe: Facing the natural-gas challenge. 2022, URL <https://www.mckinsey.com/industries/metals-and-mining/our-insights/safeguarding-green-steel-in-europe-facing-the-natural-gas-challenge>. Last [Accessed 30 January 2023].
- [42] IEA. Simplified levelised cost of competing low-carbon technologies in steel production. 2020, URL <https://www.iea.org/data-and-statistics/charts/simplified-levelised-cost-of-competing-low-carbon-technologies-in-steel-production>. Last [Accessed 23 January 2024].
- [43] Vögele S, Grajewski M, Govorukha K, Rübbecke D. Challenges for the European steel industry: Analysis, possible consequences and impacts on sustainable development. *Appl Energy* 2020;264:114633. <http://dx.doi.org/10.1016/J.APENERGY.2020.114633>.
- [44] Metal B. Boston metal fact sheet. Tech. Rep., 2023, URL <https://www.bostonmetal.com/wp-content/uploads/2023/09/Boston-Metal-FactSheet-20230920.pdf>. Last [Accessed 30 January 2023].
- [45] Allanore A. Features and challenges of molten oxide electrolytes for metal extraction. *J Electrochem Soc* 2015;162(1):13–22. <http://dx.doi.org/10.1149/2.0451501jes>.
- [46] Koolen D, De Felice M, Busch S. Flexibility requirements and the role of storage in future European power systems: A 2030 and 2050 modelling assessment with METIS. Tech. Rep., Publications Office of the European Union; 2022, <http://dx.doi.org/10.2760/384443>.
- [47] Clean Hydrogen Partnership, Mission Innovation. Hydrogen cost and sales prices. 2023, URL <https://h2v.eu/analysis/statistics/financing/hydrogen-cost-and-sales-prices>. Last [Accessed 15 July 2023].