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

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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_2) 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_2 emissions, generation mix and volume, and marginal prices in 2030. The study first estimates future electricity and H_2 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_2. This leads to a 25% reduction in direct CO_2 emissions and a demand increase of 20 TWh of electricity and 40 TWh_{HHV} of H_2. 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_2 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_2) emissions in the EU [3], with almost a quarter deriving from the iron and steel industry (ISI). On average, direct[1] CO_2 emissions from steel manufacturing amounts to one tonne of CO_2 per tonne of steel (t_{CO_2}/t_{STEEL}) and indirect[2] 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,

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[1] Scope 1 following the definition of the GHG protocol: emissions from sources that are owned or controlled by the reporting entity [1].
[2] Scope 2 following the definition of the GHG protocol: emissions from acquired electricity, steam, heat and cooling [1].

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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_2	Carbon Dioxide
H_2	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_2-DRI-EAF	Hydrogen-based Direct Reduction of Iron with Electric Arc Furnace
scrap-EAF	Scrap processing in Electric Arc Furnaces

and trade challenges [6]. While various technologies may help producers in increasing energy efficiencies and cutting CO_2 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 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_2) for the reduction of iron ore, instead of carbon. While offering great potential benefits in reducing ISI's process emissions, the H_2-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_2 thus primarily driven by the utilisation of electric arc furnaces (EAFs) for the steel-making process [9]. The use of electrolytic H_2 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_2-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_2 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. Lechtenböhmer 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[3], of which 1200 TWh designated for producing electrolytic H_2 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_2-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 electrolysers. Within the same geographical scope, Göransson et al. [13] employed a cost-minimising electricity system investment model with 3-hour resolution

[3] The EU generated almost 2800 TWh of electricity in 2021 [10].

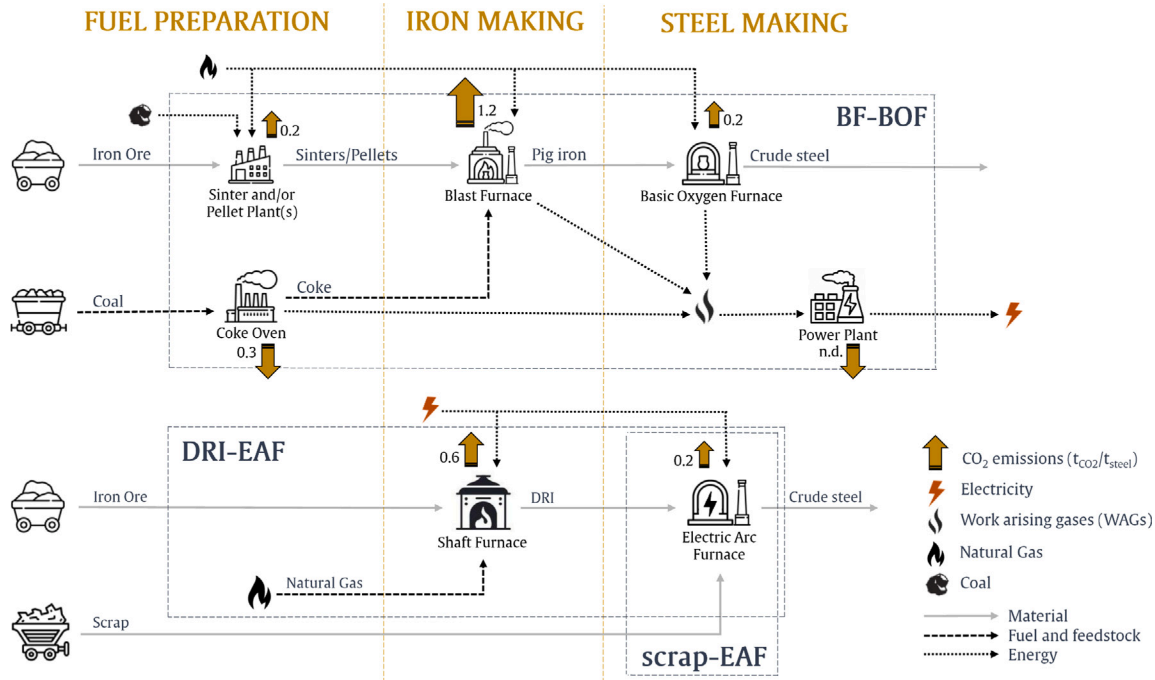

Fig. 1. Present-day production routes used in the EU, showing the most relevant production processes, material and energy input/output, and average European CO_2 emission per process [9]. In the BF-BOF route, the CO_2 emissions reported correspond to the total CO_2 produced per tonne of steel at the 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_2 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_2 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_2 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_2 demand is met by grid-electricity mainly generated by fossil-based sources, it could result in an increase in indirect CO_2 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_2 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_2 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_2 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_2 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_2 emissions of the BF-BOF production route, which, with its 1.8 t_{CO_2}/t_{STEEL}, is the most CO_2 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_{CO_2}/t_{STEEL}, 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_{CO_2}/t_{STEEL} due to small amounts of natural gas or coal injected to provide additional heat [5].

A straightforward solution to reduce the CO_2 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_2 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_2 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_2 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_2 plasma have high efficiencies and no fossil fuel utilisation as they are directly or indirectly fuelled by electricity [19]. The H_2-based direct reduction of iron technology (H_2-DRI-EAF) Hydrogen-based Direct Reduction of Iron with Electric Arc Furnace) uses H_2 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_2, the H_2-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_2 cost [5]. However, with H_2 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_2 costs, the H_2-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_2 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_2 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[4] as c and a single energy flow[5] 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[6] 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).

[4] 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_2.

[5] 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.

[6] 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.

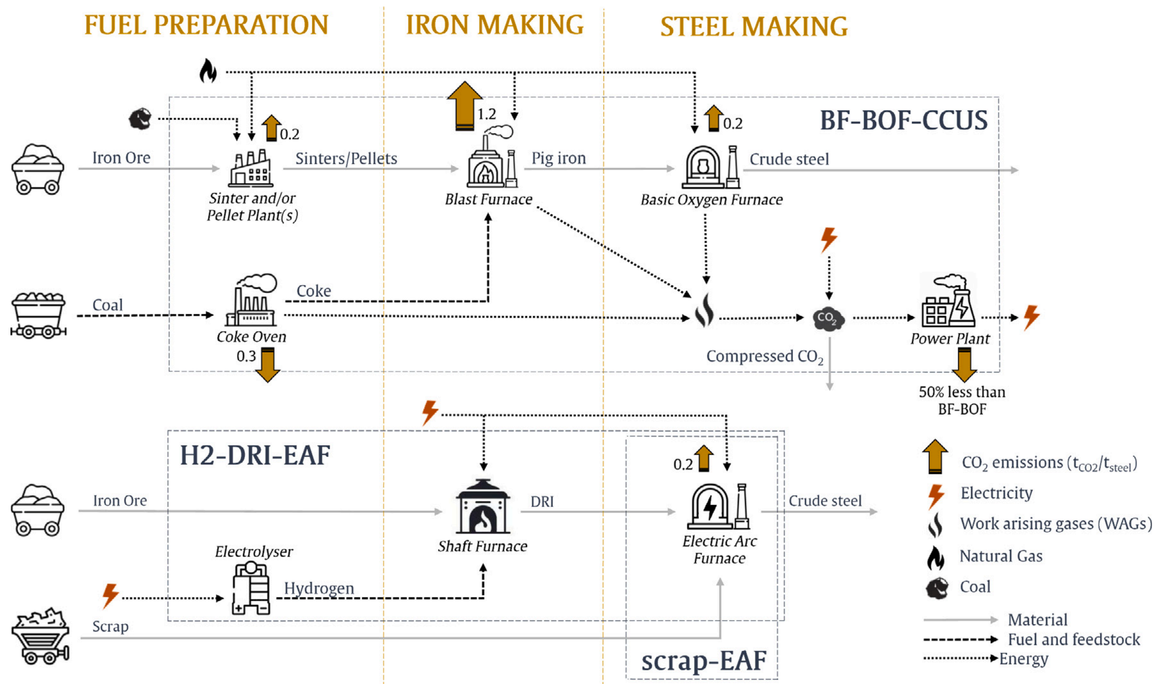

Fig. 2. Emerging production routes included in the study, showing the most relevant production processes, material and energy input/output, and CO_2 emission per process [9]. In the BF-BOF-CCUS route, the CO_2 emissions reported correspond to the total CO_2 produced per tonne of steel at the designated 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:

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

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:

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

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/ktonne.

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,[7] 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:

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

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

[7] 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
Base	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_2
Pace	45%	Reflecting all announced projects [8], see Table A.7	33% of natural gas used for finalisation processes shifts to electricit	All H_2
Accelerated	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_2

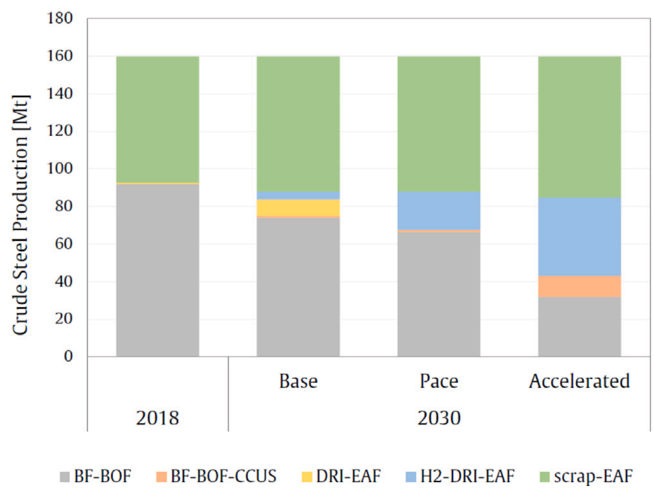

Fig. 3. EU steel production by technology in 2018 and in 2030 as foreseen by the steel scenarios.

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_2 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_2-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_2-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_2 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_2. *Pace* presents a similar demand of H_2 for steel production as the MIX-H2 scenario, suggesting a similar level of production using the H_2-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_2-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,[8] 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.[9] 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_2, suggesting a comparable volume of steel produced via the H_2-DRI-EAF technology. Therefore, we calibrate *Pace* with MIX-H2 by aligning not only H_2 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.

[8] 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]

[9] 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.

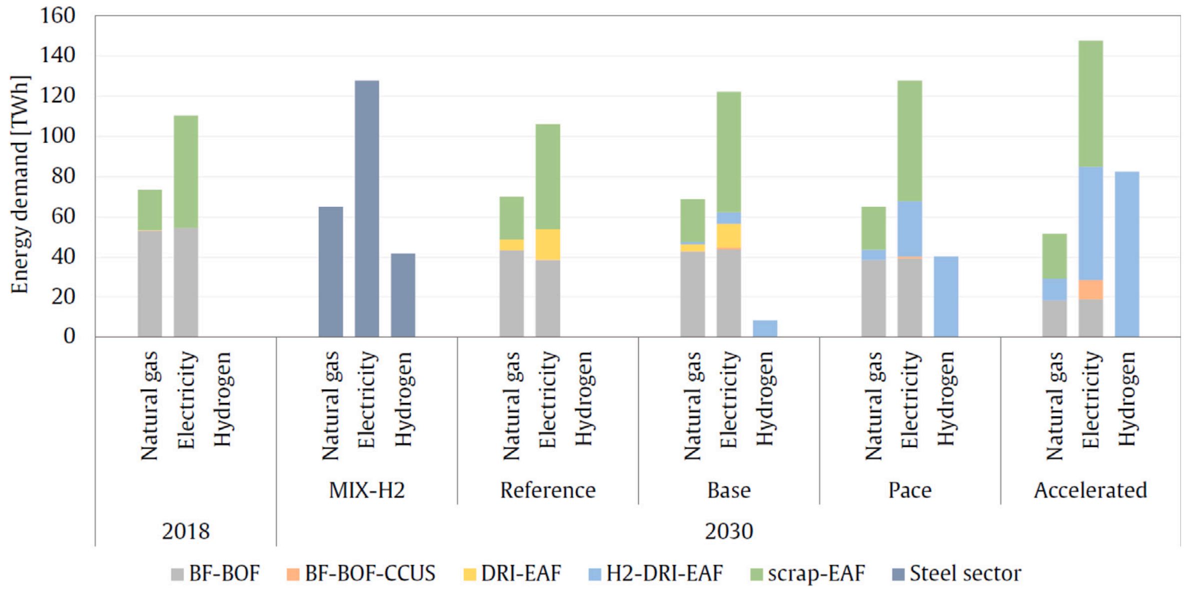

Fig. 4. Energy demand of the European ISI in 2018, MIX-H2, Reference and the steel scenarios. MIX-H2 is shown without differentiation among production route because the information is not available. Energy demand for natural gas and hydrogen is expresses in higher heating value (HHV).

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_2 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_2 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_2-DRI-EAF**: DRI-making in the shaft furnace is fuelled by 95% H_2 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_{STEEL} compared to BF-BOF [36], based on a 50% CO_2 capture rate [5]. The relatively low capture rate takes into account that only the blast furnaces are retrofitted with the carbon capture technology. CO_2 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_2 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_2 demand of about 11 and 8 TWh_{HHV}, respectively. *Pace* foresees a sharp increase in H_2 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_2 demand compared to *Pace*. If H_2 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_2 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_2 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_2 emission price. *Low* prices are retrieved from the 2030 MIX-H2 scenario [28].

	Unit	Low prices	High prices
Natural gas	€/MWh_{HHV}	29.8	178.9
Coal	€/MWh_{HHV}	9.5	
Lignite	€/MWh_{HHV}	3.4	
Biomass	€/MWh_{HHV}	36.6	
H_2 other supply	€/MWh_{HHV}	59.0	257.8
CO_2 emissions	€/t_{CO_2}	48.0	

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

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 forseen 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_2 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_2 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_2 for supply other than electrolysis, to reflect the price sensitivities of these carriers[10] 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_2 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_2 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_2 other supply* accordingly (see Table 3).[11]

Finally, the CO_2 emissions generated by the power system to supply the ISI demand of the steel scenarios are compared to the direct CO_2 emissions reduction. To calculate annual direct emissions in 2030 we use MS-specific CO_2 emissions intensities based on Koolen and Vidovic [4], whose method has been adapted for this study to calculate 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_2 production depicted in Fig. 5(b). Specifically, H_2 supply for the ISI increases by over 60% in *Accelerated* compared to *Reference*, met by only a 14% increase of electrolytic H_2 and 72% of *other supply*. Furthermore, the energy stored in the form of H_2 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_2 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_2 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_2 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_2 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_2 other supply*.

Fig. 7 shows that, when dealing with higher prices for natural gas and *H_2 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_2 demand increases by 84 TWh_{HHV} Tera in *Accelerated_high* compared to *Reference_high*, of which 72% is supplied by non-electrolytic H_2–

[10] H_2 is currently mainly produced from natural gas in the EU.

[11] We assume the price of *H_2 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_2 supply and CO_2 price – e.g., blue H_2 or imports from extra-EU countries – hence the parameter is referred to as *H_2 other supply*. Accordingly, a natural gas price increase by six times equals a increase of the H_2 price by 4.4 taking into account fix and variable operating costs of the SMR process.

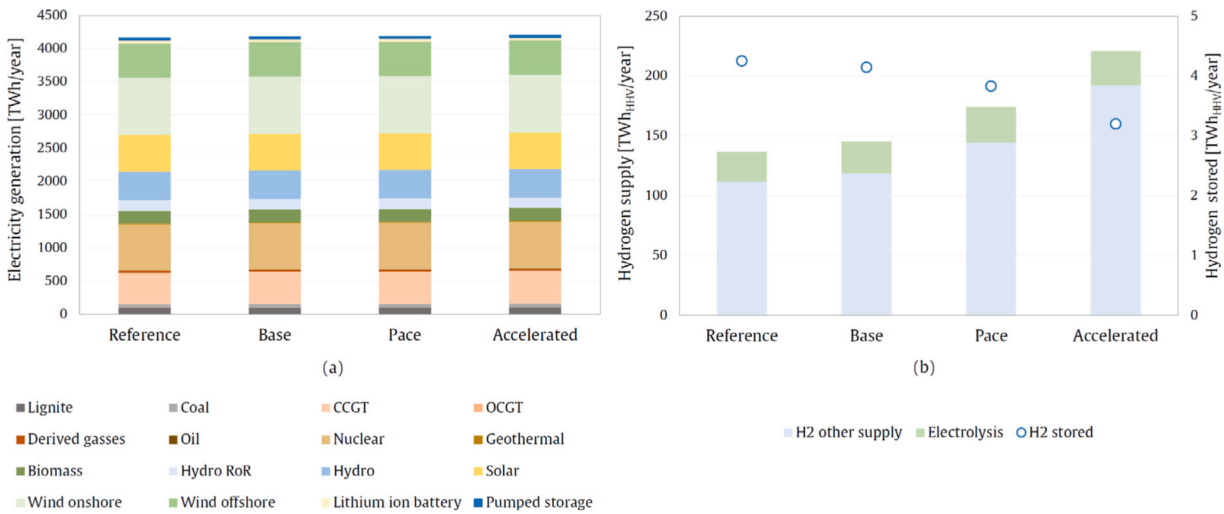

Fig. 5. Results of UCED problem with low prices for 2030. (a) the total power generation by technology in the EU27 and neighbouring countries (BA, CH, GB, ME, MK, NO, RS). (b) H_2 supply and H_2 storage in the EU27 [12].

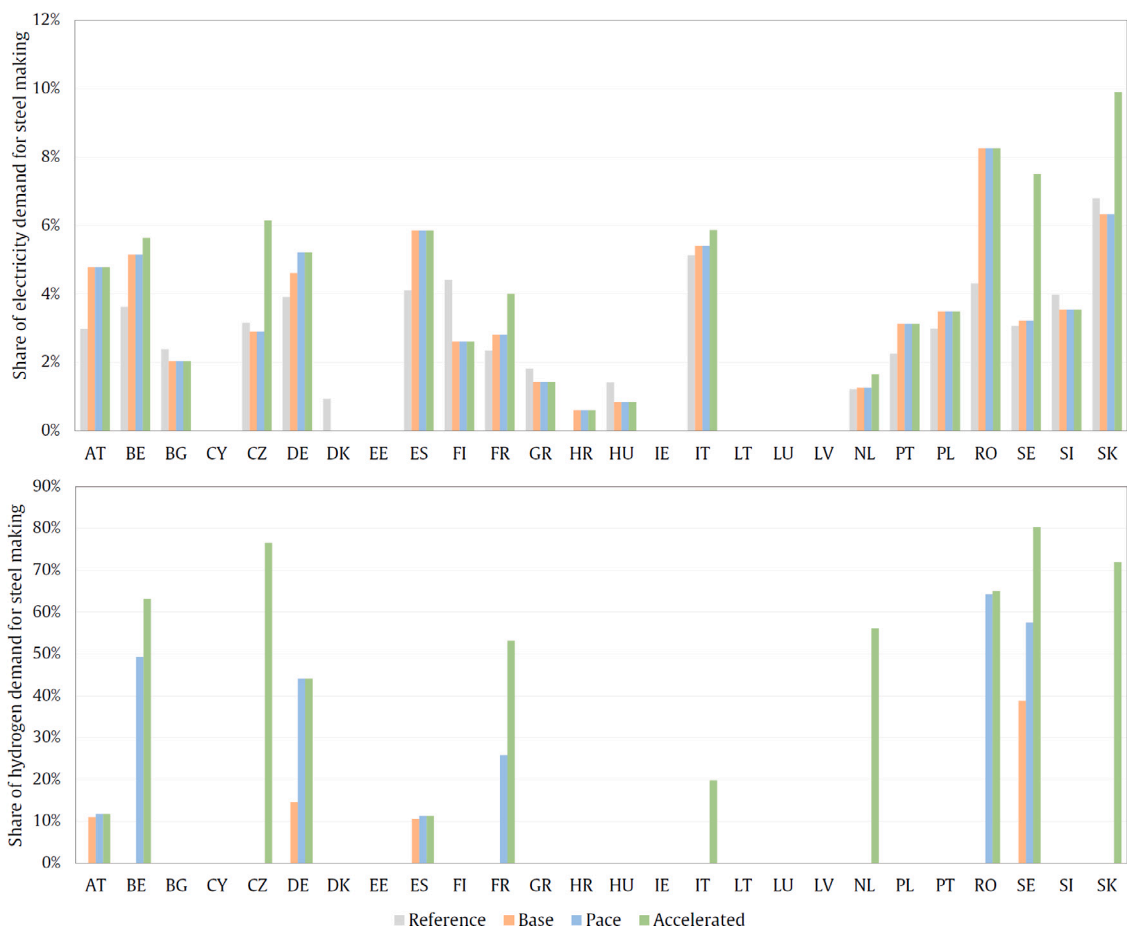

Fig. 6. Share of electricity and H_2 demand for steel-making in total demand per MS and scenario.

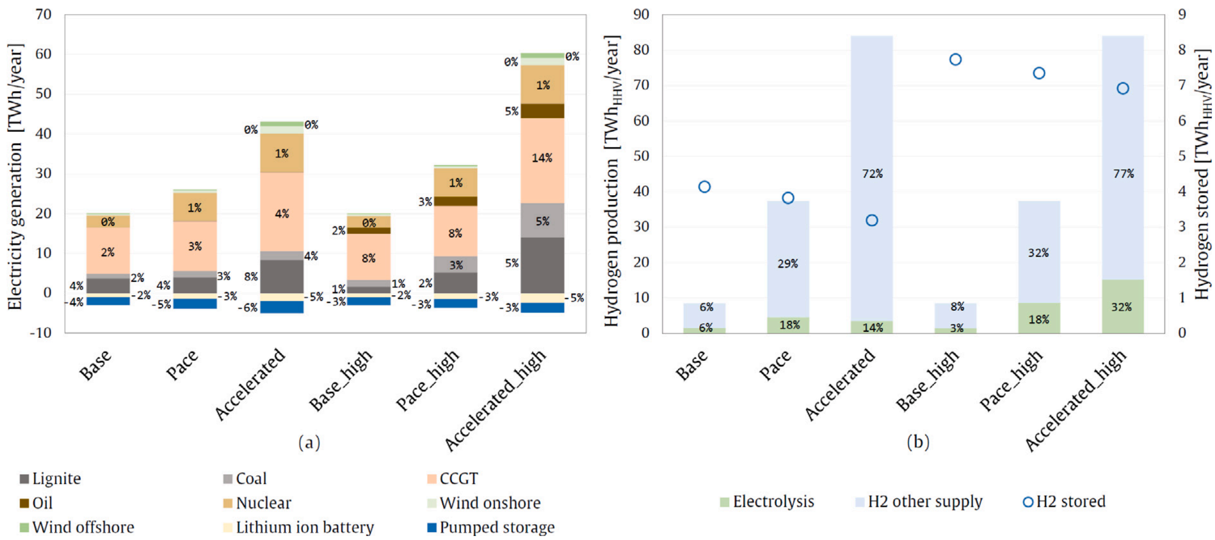

Fig. 7. Additional power (a) and H_2 (b) production in the EU[12] compared to *Reference* and *Reference_high*, with low and high prices respectively and with renewable power and electrolyser capacities as foreseen by MIX-H2, see Table B.8. Percentage values report production variations of a specific technology compared to *Reference* and *Reference_high*, respectively. The yearly energy stored via H_2 is shown on the secondary vertical axis in(b).

i.e., *H_2 other supply*. Nonetheless, electrolytic H_2 production more than doubles in *Accelerated_high* compared to *Accelerated* scenario. It is worth noting from Fig. 7 that *Pace* foresees a larger absolute production of electrolytic H_2 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_2. Overall, it can be concluded that high fuel prices only slightly stimulate electrolytic H_2 production, and that this additional production is mainly provided by fossil-based power generators, whose CO_2 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_high*. 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_EXP*, *Base_EXP*, *Pace_EXP* and *Accelerated_EXP* and 63%, 80%, 87% and 93% for *Reference_high_EXP*, *Base_high_EXP*, *Pace_high_EXP* and *Accelerated_high_EXP*, respectively. The remaining demand is supplied by grid-electricity. Among the *low prices* scenarios, *Pace_EXP* 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_high_EXP*. Another driver to the scale of the renewable deployment in the high prices scenarios is the share of H_2 supplied via electrolysis, respectively 93%, 92% and 91% in *Base_high_EXP*, *Pace_high_EXP* and *Accelerated_high_EXP*, 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_high_EXP*, *Pace_high_EXP* and *Accelerated_high_EXP* compared to the *low prices* corresponding scenarios. Nonetheless, the production of electrolytic H_2 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_2 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_2 emissions

This section explores the trade-off between reducing direct ISI CO_2 emissions through electricity-intensive technologies and the variation in indirect CO_2 emissions from the power system, alongside considerations of system costs. Fig. 10 shows the total CO_2 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_2 was not taken into account in this study, Fig. 10 displays in patterned grey the CO_2 emission as if H_2 were supplied via SMR. Plausible alternatives such as SMR with CCUS or imported green H_2 would result in lower or zero H_2 emissions, falling within the range of the patterned grey stacked column.

[12] *EU* will henceforth be used to refer to EU27 and neighbouring countries for the power system, and EU for the H_2 system. It is assumed that neighbouring countries do not have a H_2 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_2 system.

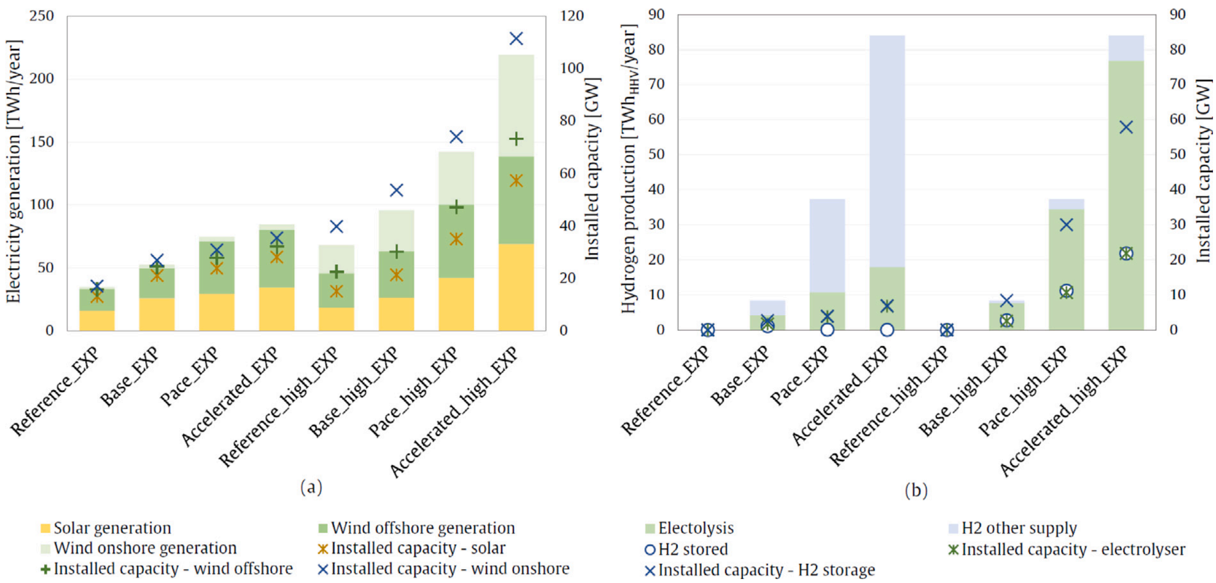

Fig. 8. Additional power (a) and H_2 (b) production, and additional generation capacities in the EU[12] with low and high prices and with renewable capacity expansion, compared to *Reference* and *Reference_high*, respectively, when optimised without the METIS feature of capacity expansion. In(b), H_2 stored refers to the primary vertical axis – H_2 production [TWh_{HHV}/year]. In (a) and (b) cumulative capacity installed are shown on secondary vertical axes.

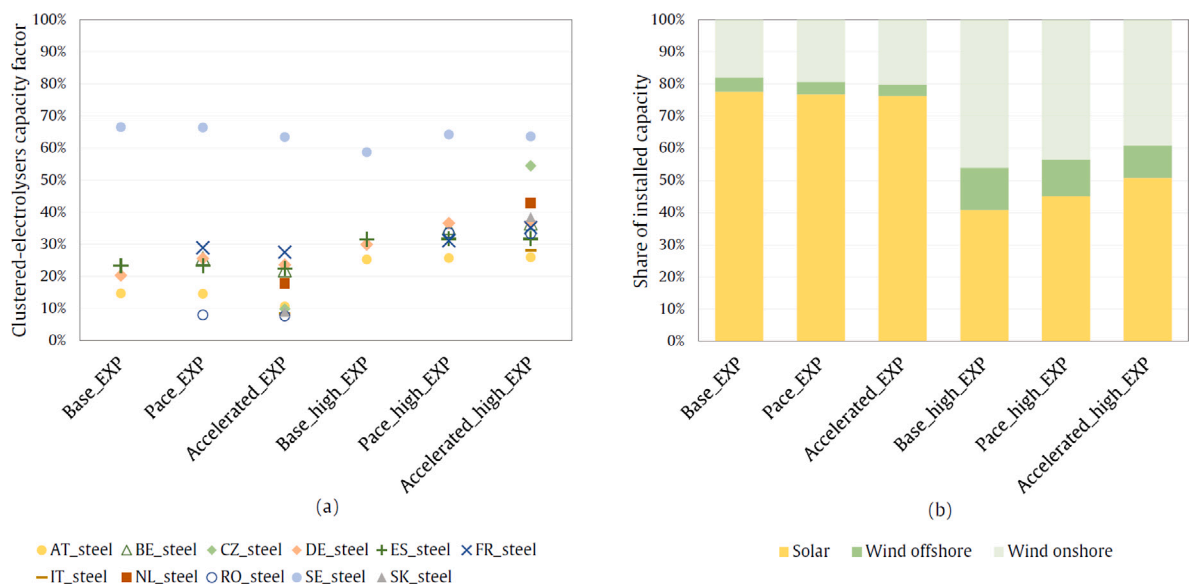

Fig. 9. (a) Capacity factors of electrolysers by country and(b) share of installed renewable capacities by technology.

All scenarios foresee an overall reduction in CO_2 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_2 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_2 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_2 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_2 emissions being almost 70% higher in 2030 than in 2018. Five MS are responsible for 74% of total EU indirect CO_2 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_2 emissions with peaks reaching up to 96% emissions cuts in *Pace_high_EXP* compared to 2018.

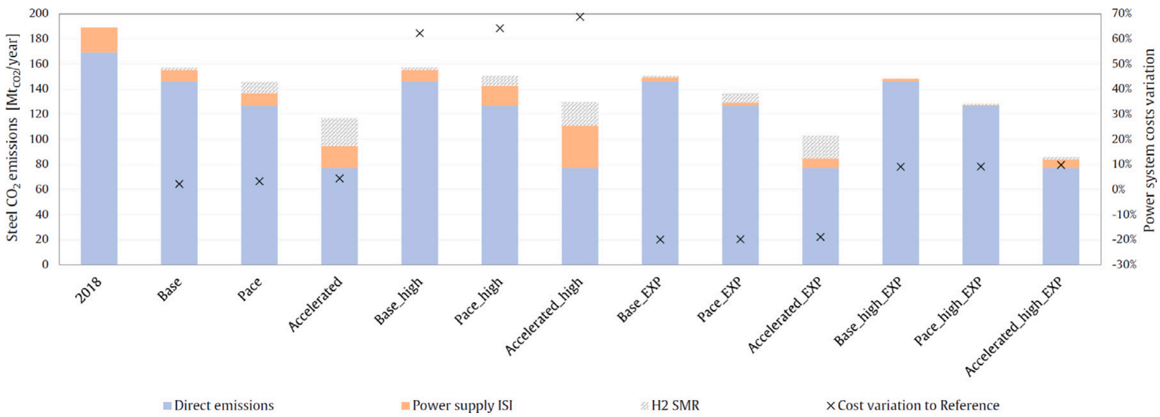

Fig. 10. Direct and indirect CO_2 emission in the EU[12] of steel scenarios compared to 2018, with and without capacity expansion. The secondary axis reports the variation of operational power system costs and annualised investment of the additional renewable and electrolyser capacities deployed in the 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_{STEEL} 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_2 emission reduction variation among the sets of scenarios (0.2 t_{CO_2}/t_{STEEL}). In contrast, the high prices of the *_high_EXP* scenarios drive renewable deployment to the extent that additional system costs are under 5 €/t_{STEEL} for all scenarios, and 0.3 €/t_{STEEL} for *Pace_high_EXP*. The costs variation remains between 5 to 27 €/t_{STEEL} for scenarios without high prices and, by expanding renewable capacity, system costs can be reduced by 8 to 16 €/t_{STEEL} while simultaneously reducing CO_2 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_{STEEL}. 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_2 emissions. Furthermore, technologies included in the steel scenarios are limited to H_2-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_2 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_{EL}/t_{STEEL} [5, 45], making them slightly more efficient than the H_2-DRI-EAF route. However, electricity needs to be consumed directly while, in the H_2-based technology, three quarters of the electricity is used for producing electrolytic H_2, 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 electrolysers

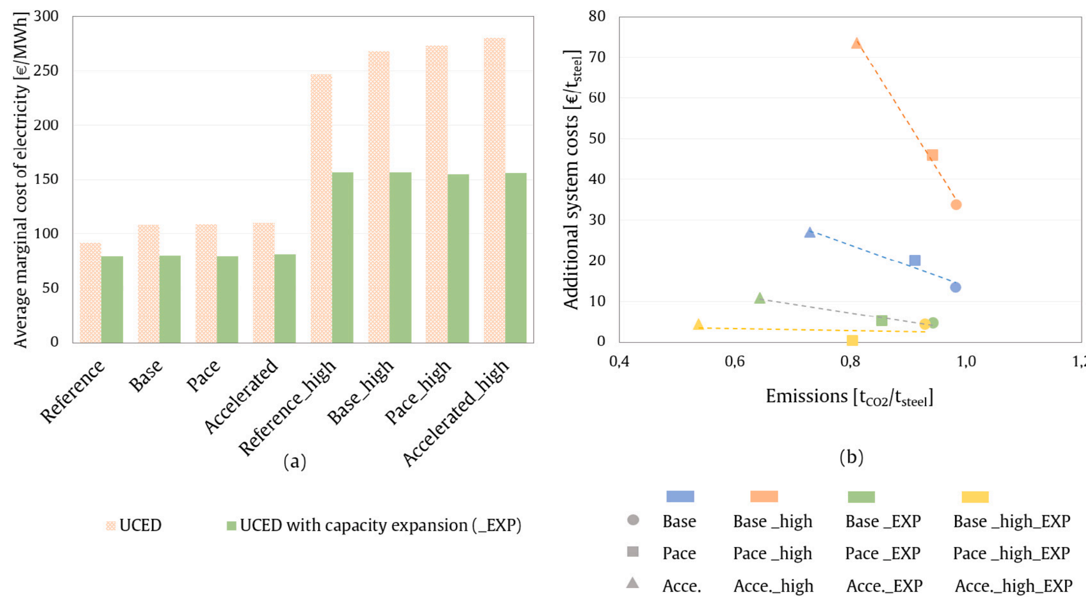

Fig. 11. (*a*) Marginal cost of electricity per scenario, average of all countries and hours of the year, and (*b*) system costs, as additional to Reference, per unit of steel produced plotted against the average direct and indirect CO_2 emissions per scenario. For comparison, the production of one tonne of steel in the EU in 2018 was responsible on average for 1.2 tonne of CO_2.

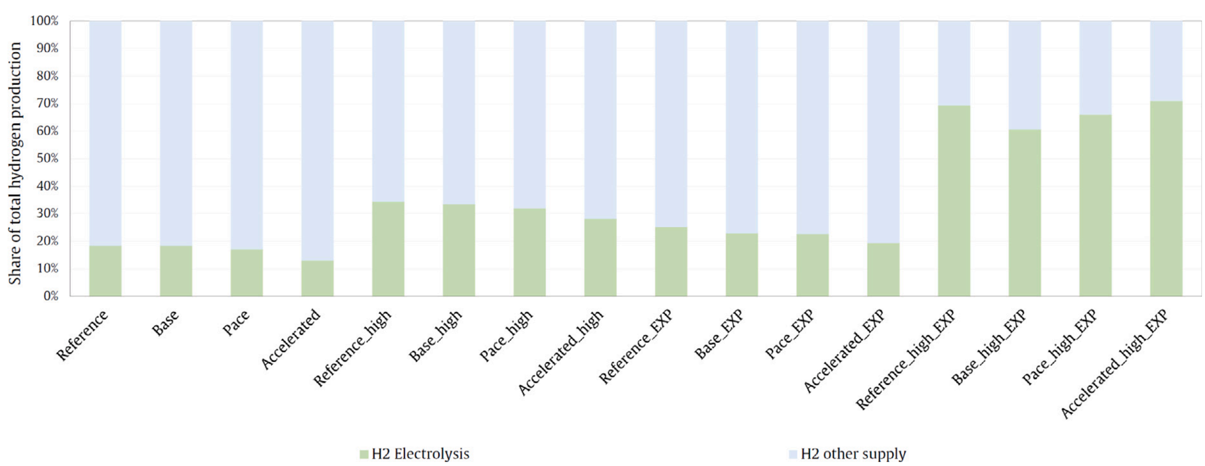

Fig. 12. Share of total EU H_2 method of supply or production.

leads to higher capacity factors. Results show that in Sweden, where almost no solar capacity is installed, the electrolysers 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_2 and electricity to steel-makers, while avoiding an increase in indirect CO_2 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_2 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 electrolysers, 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_2 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_2 compared to MIX-H2, of which 5 Mt domestically produced and 10 Mt imported [46]. The price applied for H_2 *other supply* – e.g., imported, produced as grey or blue H_2– is between 2 and 10 €/kg_{H_2}, which is in line with the price of green H_2 expected by currently developing H_2 hubs around the world [47]. Therefore, the study provides realistic insights into the competitiveness of future locally produced H_2. Fig. 12 shows that, with low H_2 *other supply* prices, the cost-effectiveness of deploying renewable and electrolyser capacity is limited and the share of H_2 *other supply* remains over 75% in all scenarios. Instead, with high prices the share of H_2 *other supply* lowers to under 40% with capacity expansion, enhancing the cost-effectiveness of locally produced electrolytic H_2.

6. Conclusion

The iron and steel industry (ISI) is currently a highly energy intensive and CO_2 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_2-based direct reduction of iron (H_2-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_2 system in terms of generating technologies, marginal prices and CO_2 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_2 emissions reduction of 25% compared to 2018, thanks to the adoption of electrified processes that increase electricity and H_2 demand, respectively, by 17 TWh and 40 TWh_{HHV} at EU-level. Nonetheless, indirect CO_2 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_2 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_{H_2}. Although this study does not deal with a detailed assessment of the indirect CO_2 emissions from alternative H_2 supplies, it must be noted that if the over 75% of H_2 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_2 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_2 emissions are Poland, Germany, Italy, Czech Republic and Romania.

The study further demonstrates that a drastic reduction of indirect CO_2 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_2 emissions of 85% or higher, together with 25% reduction of direct CO_2 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_2 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_2 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_2 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_2 emissions

Tables A.5–A.7 report derived energy intensities of steel-making technologies, direct CO_2 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_2), 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_{STEEL}	Present-day technologies									New technologies					
	BF-BOF			DRI-EAF			Scrap-EAF			BF-BOF-CCUS			H_2-DRI-EAF		
	NG	EL	H_2	NG	EL	H_2	NG	EL	H_2	NG	EL	H_2	NG	EL	H_2
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_2 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_2-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_2 emissions [5].

t_{CO_2}/t_{STEEL}	Present-day technologies			New technologies	
	BF-BOF	DRI-EAF	Scrap-EAF	BF-BOF-CCUS	H_2-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_{STEEL}]
H2Steel	Thyssenkrupp	Duisburg (DE)	Full scale	H_2-DRI-EAF	Announcement	2025/2030[a]	0.4/1.2[a]
SALCOS	Salzgitter	Salzgitter (DE)	Full scale	Electrolyser, H_2-DRI-EAF	Construction started	NA	1.0
Steel4Future	ArcelorMittal	Bremen (DE)	Full scale	DRI-EAF → H_2-DRI-EAF	MoU signed	2026	1.75[b]
Steel4Future	ArcelorMittal	Eisenhüttenstadt (DE)	Pilot	H_2-DRI-EAF	MoU signed	2026	1.75[b]
NA	ArcelorMittal	Dunkirk (FR)	Full scale	H_2-DRI-EAF	MoU signed	2027	2.00
NA	ArcelorMittal	Ghent (BE)	Full scale	DRI-EAF → H_2-DRI-EAF	Letter of intent signed	2030	2.50
NA	ArcelorMittal	Gijon (ES)	Full scale	H_2-DRI-EAF	MoU signed	2025	1.10
HYFOR	Voestalpine	Donawitz (AT)	Pilot	H_2-DRI-EAF	Operational	2021	0.25
Hybrit	SSAB	Luleå (SE)	Pilot/Demo[a]	Electrolyser, H_2-DRI- EAF	Pilot plant operational	2021/2026[a]	0.25/NA[a]
Liberty Steel	NA	Galati (RO)	Full scale	DRI-EAF → H_2-DRI-EAF	MoU signed	2024	4.00
H2 Green Steel	H2 Green Steel	Svartbyn (SE)	Full scale	Electrolyser, H_2- DRI-EAF	Announcement	2030	5.00
HYBRIT	SSAB	Gallivare (SE)	full scale	Electrolyser, H_2- DRI- EAF	NA	2026/2030[a]	1.30/2.70[a]
H2Hamburg	ArcelorMittal	Hamburg (DE)	Demo	DRI-EAF → H_2-DRI-EAF	Plant design commissioned	2024	0.1
3D project	ArcelorMittal	Dunkirk (FR)	Demo/ Full scale[a]	BF-BOF-CCUS	Construction started	2025/2035[a]	1.0/10.0[a]

Notes:[a] the latter refers to an expansion foreseen;[b] ArcelorMittal plans a combined capacity of 3.5 [Mt_{STEEL}] 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_{EL}
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

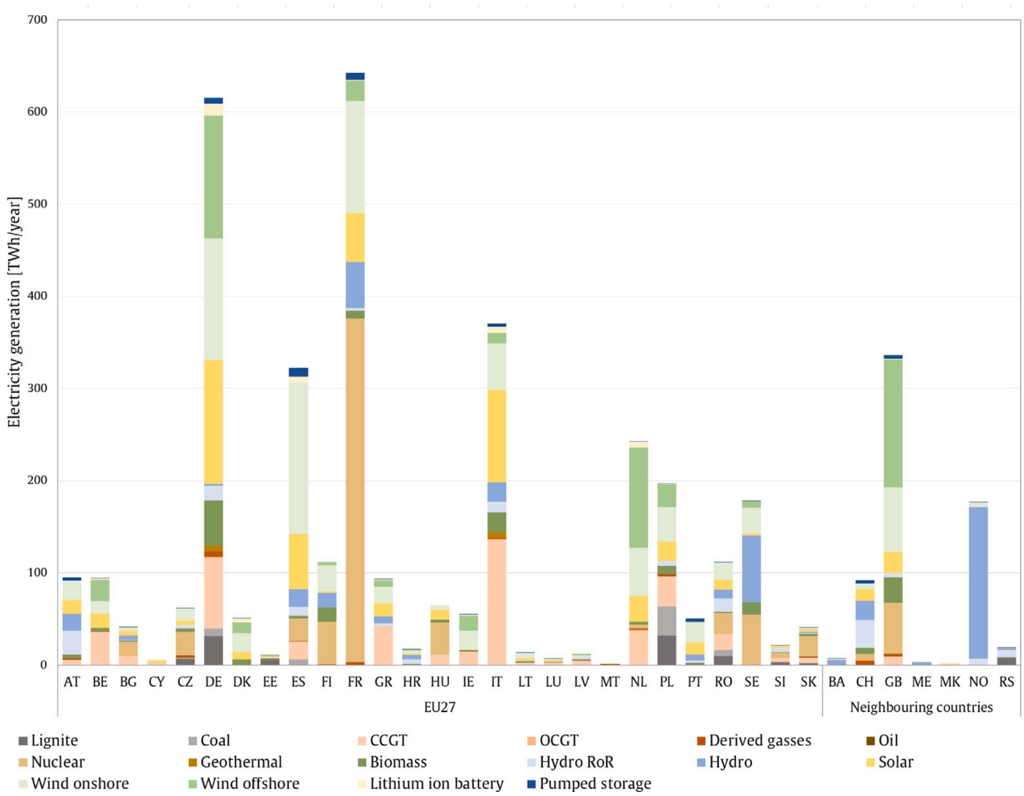

Fig. B.13. Total electricity generated by technology and EU[12] country in *Reference* scenario.

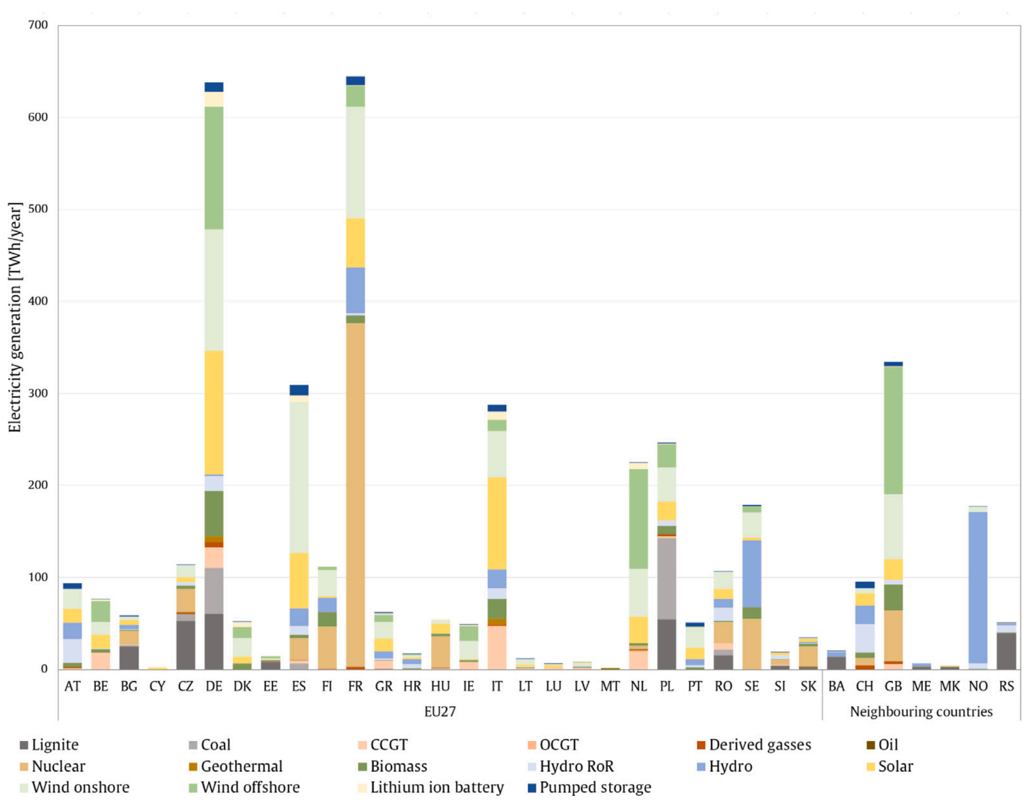

Fig. B.14. Total electricity generated by technology and EU[12] country in *Reference_high* scenario.

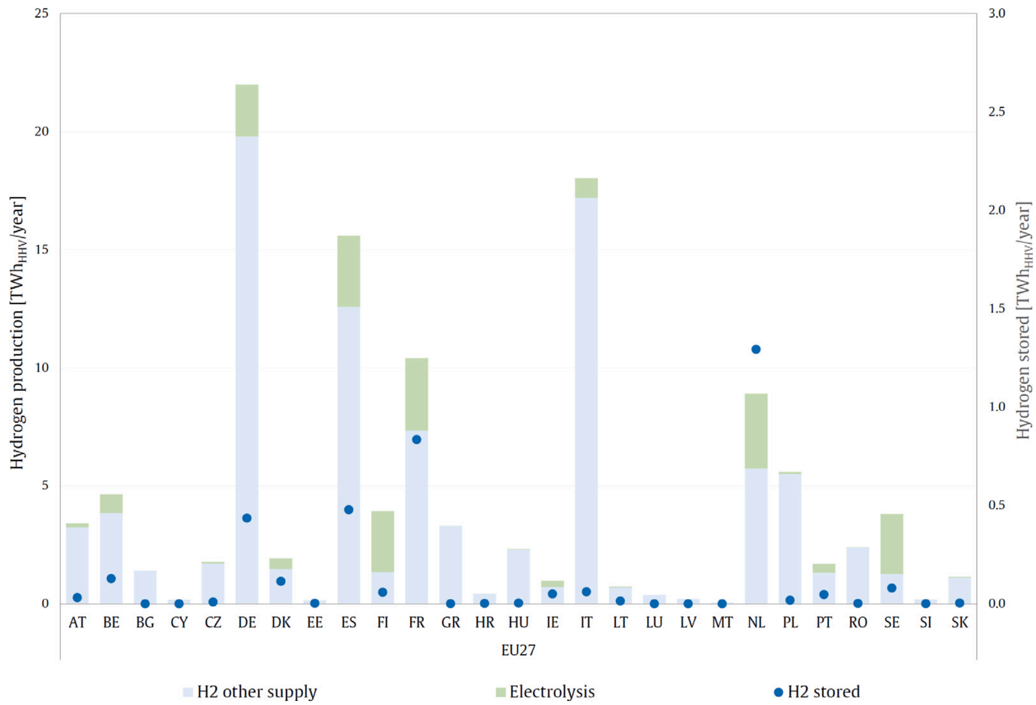

Fig. B.15. Total hydrogen generated by technology and EU[12] country in *Reference* scenario.

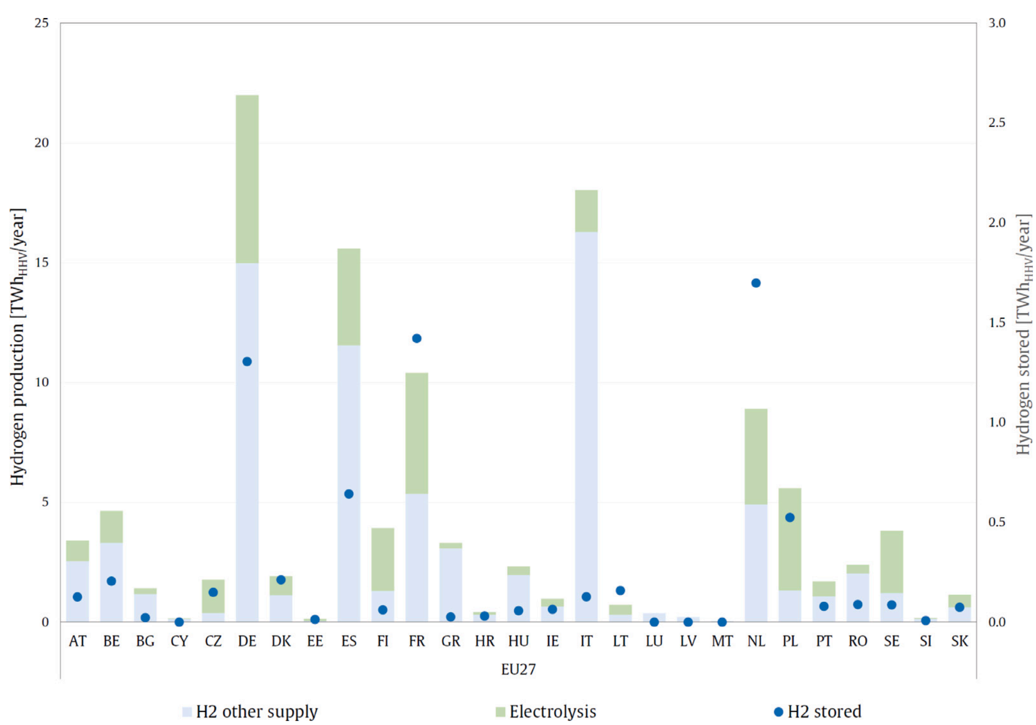

Fig. B.16. Total hydrogen generated by technology and EU[12] country in *Reference_high* scenario.

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