Renewable and Sustainable Energy Reviews 143 (2021) 110938

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

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

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ARTICLE INFO

Keywords:
CO_2 reduction
Paris agreement
Climate neutrality
Renewable energy
International comparison
Carbon lock-in

ABSTRACT

Global steel production is currently dependent on coal and capital-intensive production facilities with long economic lifetimes. While the Paris Agreement means carbon neutrality must be reached globally by 2050–2070, with negative emissions thereafter, coal-based steel production today accounts for around 8% of global energy-related CO_2 emissions. Its production may stabilize or even decline in industrialized countries, but it will increase significantly in the emerging economies. In the past, the focus of CO_2 reduction for steel has been on moderate emissions reductions through energy efficiency measures and on exploring carbon capture and storage. However, as (1) the cost of renewable electricity is declining rapidly, (2) carbon capture and storage has not materialized yet, and (3) and more and more countries set deep emission reduction targets, electricity- and hydrogen-based steelmaking has gathered substantial momentum over the past half-decade. Given the short time frame and the sector's deep carbon lock-in, there is an urgent need to understand the national climate and energy policy as well as the current implementation of low-CO_2 and renewable electricity that would enable a shift from coal-based to electricity-based steelmaking. In this paper, we first identify the countries that are likely to be major steel producers in the future and thus major CO_2-emitters. Then we map medium- and long-term CO_2 reduction and renewable targets as well as the current share of low-CO_2 and renewable electricity by country. Based on these data, we develop a set of indicators that map the readiness of steel-producing countries for a sustainable transition. Our findings show that although binding long-term CO_2 reduction targets are being implemented, medium-term CO_2 reduction do not yet affect coal based steel production. Overall, the global steel industry seems not be on track yet, though differences between steel producing countries are large. Common shortcomings across countries are a lack of access to renewable electricity and a lack of demanding medium-term CO_2 reduction targets. The paper ends with recommendations on how to enable a low-carbon transition of the global steel industry in line with the Paris Agreement.

1. Introduction

The steel sector is heavily dependent on coal as input to the traditional blast-furnace based production process that produces primary steel from iron ore. Today, the sector is responsible for about 8% of all global energy-related CO_2 emissions [1,2]. This share of global emissions will increase due to growing steel production and limited short-term options to reduce emissions, and moreover as at the same time other sectors such as the energy sector or the transport sector are accelerating their decarbonisation that has already begun [3]. Furthermore, the phase-out of blast furnaces is expected to take time as they typically are run in campaigns of 18–23 years between major revisions [4]. Blast furnaces have no strict lifetime limits as they can be refurbished several times. Current blast furnaces can thus still emit large amounts of CO_2 by 2050. The 2015 Paris Agreement, however, asks for global climate neutrality between 2050 and 2070 at the latest and puts a limit to cumulative emissions over this century [5]. This means that also the global steel industry will have to reach for zero emissions by 2050–2070.

If current blast furnaces were allowed to be relined only until 2030 and then would have to be replaced by or equipped with low-carbon steelmaking processes, then the global CO_2 emissions from steel production could reach close to zero CO_2 emissions by 2050. As investment

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https://doi.org/10.1016/j.rser.2021.110938
Received 6 August 2020; Received in revised form 1 February 2021; Accepted 3 March 2021
Available online 24 March 2021
1364-0321/

List of abbreviations:

BAU	business-as-usual
CCS	carbon capture and storage
CCU	carbon capture and utilization
EU-28	European Union 28
INDC	Intended Nationally Determined Contributions
LULUCF	Land use, land use change & forestry
NHB-RES	non-hydro, non-biofuels renewables

decisions, approval procedures and the final construction and commissioning of large new facilities require about 8–10 years, by the very early 2020s companies have to decide on the steel production facility that should run from 2030 onwards. Postponing the last relining of blast furnaces until 2040 would mean that about half of the capacity would still be in operation in 2050, making carbon neutrality of the steel sector almost impossible by mid-century.

However, global primary steel production is even on the verge of a further increase, so new blast furnace capacity will be added to the current stock of blast furnaces. The World Steel Association assumes an increase from currently 1000 Mt to 1400 Mt primary steel by 2050 [6]. In this scenario steel production in China, Japan and South Korea decreases while India and ASEAN countries are increasing their primary steel production [7]. Pauliuk et al. (2013) showed another scenario in which primary steel production decreases to 1000 Mt by 2050 as more and more scrap becomes available [8]. These exemplary forecasts indicate that CO_2 emissions from primary steelmaking might be in the range of 2.0 Gt to 2.8 Gt each year by 2050 if no low-carbon technologies will be applied. Both scenarios are clearly not in line with the Paris Agreement. This reflects the urgent need for a clear pathway to a climate neutral steel production and for accelerating the energy transition of the global steel industry.

The use of coal in the steel industry has a long tradition and the industry is embedded in a system that supports coal against other energy carriers. This carbon lock-in [9] includes sunk costs in both existing production routes and in the supporting of technical infrastructure such as railways, ships and ports for the transport of coal [10,11]. The carbon lock-in is not merely technological, but it also includes supporting institutions like sectoral associations, whole steel ministries, research and development funds, and research institutions as well as political support derived from a long history and co-evolution with society in general. These supporting institutions also include the regulatory framework and policies that for instance exempt coal consumption from certain levies and taxes (e.g., the exemption of industrial coal consumption from the energy tax in Germany) while electricity is higher taxed in some regions (e.g., levies for the support of renewable energies).

Breaking the carbon lock-in of the steel sector requires systemic change and transformative climate and energy policy. Transition pathways of primary steel production that have the potential of reaching close to zero emissions are systemic and involve not only a technological shift but also introduce several changes to the technical and institutional elements surrounding the industry [4]. These include institutional changes such as climate and renewable energy targets and the provision of infrastructure and renewable energy access. System change takes time, especially since this change involves a broader range of actors and changes in infrastructure as well as legal and social institutions [4,12]. However, the steel industry has gone through major technological revolutions before such as the shifts from open hearth to basic oxygen furnace or from bulk casting to continuous casting [12,13]. These shifts were motivated by huge gains in efficiency and product quality. But a transition towards steel production based on electricity would instead be driven by climate policy. "Green" steel has the same material properties as steel produced with coal, but has higher costs, unless CO_2 costs are applied. The strong carbon lock-in typically visible in energy-intensive industries makes a transition more difficult and requires a comprehensive response from both policy and business [4].

Carbon capture is an option to mitigate CO_2 emissions without breaking up the carbon lock-in. This is probably why it has been extensively explored in various initiates at the early 2000s [14–17]. It is still a major mitigation option in scenarios for deep decarbonisation of steel production as presented in integrated assessment models and bottom-up models [18–20]. However, there are several drawbacks of this technology. Reaching zero emissions with carbon capture requires the injection of biomass, which is only limited available especially when sustainability issues have to be considered [21]. In addition, blast furnaces are only one source of CO_2 emissions in primary steel production. Thus carbon capture would have to be applied at several facilities, e.g. coke ovens and sinter plants thus making this option more complex, more energy intensive and more costly. The transport of the sequestrated CO_2 also adds to complexity and costs. If the CO_2 is stored underground, then the public needs to agree on this, which had not been the case for instance in Germany [22]. When the CO_2 shall be used as input to the chemical industry, then there is a need to assure that it is not released to the atmosphere shorty after as it may be burnt as a fuel or as another product. In addition, the chemical industry has alternatives to using CO_2 from the steel industry, and may not be willing to commit to use fossil CO_2 as feedstock when the goal is carbon neutrality by 2050.

Carbon capture and storage in the steel industry has clearly fallen short of earlier expectations. The slow progress on carbon capture and storage, combined with the falling cost of renewable electricity [3] and the goal of achieving carbon neutrality, which all steel-producing countries committed to in the 2015 Paris Agreement, puts electricity-based steel production at the centre of new developments [19,23,24]. These options aim at shifting production routes away from the use of coal in blast furnaces towards using electricity, as in hydrogen direct reduction or electrowinning processes. A steel transition based on electricity would require that primary steel production abandons and phases out the blast furnace as the core of the production process. The required amounts of renewable electricity will have major impacts on the energy system [25] and thus require the co-evolvement of the energy system and an electrified steel industry. The recent IEA Iron and Steel Roadmap [20] suggests that a long-term renewable transition for primary steel production based on hydrogen or direct electricity is on its way, but sees its upscaling mostly after 2050.

Given the recent and rapidly growing interest from steel producers and government into electrification as a response to the climate change targets set out in the Paris Agreement, there is a lack of analysis and understanding of the national and international preconditions outside the steel industry that would enable such a transition. This paper aims to fill that gap and by assessing the readiness to an electricity-based transition for the steel sector by 2050. In order to assess and map the readiness of the global steel sector, we first identify those countries that are likely to be major producers of coal-based steel and thus major emitters of carbon dioxide. Then we analyse climate and energy policy and the current implementation of low-CO_2 electricity. Finally, we develop indicators to compare the countries according to their readiness for a low-carbon transition of their coal-based steel industry.

The paper is outlined as follows. Section 2 provides a background on low-CO_2 steelmaking technologies. In section 3 we present the approach and the data used and in section 4, the results are presented. We map the countries' readiness for a transition of the steel industry based on a selection of indicators in section 5. Section 6 concludes.

2. Technology options for low-carbon steelmaking

The blast furnace is the main source of CO_2 emissions in primary steelmaking and further efficiency potentials are limited [26,27]. So far, deep decarbonisation for primary steel production can be achieved either by switching to power options such as hydrogen direct reduction, hydrogen plasma smelting and electrolysis of iron ore, or by keeping the blast furnace using CCS in combination with biomass.

In addition to the production of steel from coal or scrap, steel production with natural gas in direct reduction processes is a common technology, but its global share is rather small at less than 5% [28]. Iran has the largest gas-based steel production (19 Mt, 2017), followed by the Russian Federation (7 Mt), Mexico (6 Mt) and the USA (2 Mt) [28]. Direct reduction furnaces are commercially available up to 2.5 million tons per year using natural gas [28]. With regard to an energy transition based on hydrogen, these countries have the advantage that they already have expertise in gas-based steel production and existing direct reduction shaft furnaces. A conversion of direct reduction shaft furnaces from natural gas to hydrogen requires only minor adjustments and investments.

Direct reduction of iron ore with hydrogen is a renewable technology option if the hydrogen is produced from renewable sources such as water electrolysis with renewable electricity. This technology option is currently being tested in the Swedish HYBRIT project and the aim is to demonstrate this technology in a fully renewable system by the mid-2020s [24,29]. Other low-CO_2 alternatives include methane pyrolysis, methane steam reforming with CCS or the electrolysis of water using nuclear electricity.

Hydrogen plasma smelting is a long-term promising technology, which would produce steel from iron ore in a single step in contrast to two or more in other processes. The concept is rather old and research activities have been increased recently, e.g. in Europe and India, but plasma smelting has not yet reached pilot scale. So far, results have been presented for a 100-g batch process, and upscaling is announced for a 50 kg batch process [30].

Electricity can also be used directly in the electrolytic reduction of iron ore, thus avoiding the energy consumption for hydrogen production. Compared to hydrogen direct reduction, this process should be more energy efficient once it available on large scale [31]. Two main configurations are being developed in the steel industry today. First, the low-temperature electrolysis of iron ore in alkaline solution at 110 °C, known as electrowinning, [32]. Second, the high-temperature reduction of iron ore in a molten oxide environment at 1600 °C [25].

Biomass can partially replace coal use in blast furnaces and thus reduce fossil CO_2 emissions. However, it cannot completely replace coke consumption, as coke has special mechanical properties that ensure the necessary gas exchange [33]. However, this option depends on the availability of large quantities of sustainable biomass. Sustainably harvested biomass is a more limited resource compared to solar and wind energy and will be an increasingly attractive decarbonisation option for certain sectors such as chemicals, aviation and for achieving negative emissions. So even if sustainable biomass is available in the future, the price is likely to rise due to competition, while renewable electricity prices are expected to continue to fall.

The alternative to replacing coal with low-carbon energy is to capture CO_2 emissions. These can be used as feedstock in the chemical industry, reducing the need for fossil carbon there (CCU). The captured CO_2 can also be stored underground (CCS). Capturing the CO_2 from the process gas requires that the CO_2 be captured, cleaned, compressed and transported, which increases the overall energy consumption of steelmaking. Applying CCS to primary steelmaking alone is unlikely to reduce emissions to zero, as there are other sources of CO_2, such as sinter plants. However, net-zero emissions can be achieved by combining CCS with biomass [21].

Recently, several European steelmakers have announced demonstration projects aiming at capturing and utilising fossil carbon for the production of chemicals [34–36]. However, CCU is unlikely to become a long-term mitigation solution in line with the Paris Agreement [37]. As long as fossil carbon is used for the production of chemicals from steel off-gases, there is a risk of just displacing the emission source from the steel mill to the end-of-life of the produced chemicals or fuels. To truly decarbonise emerging cross-industrial linkages, the fossil carbon contained in chemicals from steel off-gases must be captured and stored permanently at the end-of-life. Even if the fossil carbon serves to cover an increasing demand for chemicals, eventually it must be prevented from entering the atmosphere. CCU for decarbonising the steel industry depends on a fully cyclic carbon economy and additional capture of carbon outside of the gates of steel plants.

3. Method and data

This study analyses all countries that produce coal-based steel, with the exception of Colombia and Paraguay, whose production levels are marginal at 0.2 Mt and 0.02 Mt respectively in 2017 [6]. The European Union (EU) is treated as a single country, as important climate legislation such as the European Emissions Trading Scheme and other steel-related directives are agreed at this level. Furthermore, this study considers the United Kingdom as part of the European Union despite the recent Brexit.

The central plant for producing steel from coal is the blast furnace. Steel can also be made with coal in rotary furnaces, which is mainly done in India but accounts for only a small share of global production. Global steel production via blast furnaces is currently about 1200 million tonnes, while coal-based direct reduction accounts for about 20 million tonnes [6,28]. This study does not consider the coal consumption in electric arc furnaces that melt scrap or direct reduced iron produced from natural gas.

The approach of this paper follows four steps.

First, countries are mapped by their steel production volumes and by their recent steel production trends to identify which countries may be large CO_2 emitters in the future. Section 4.1 ranks countries by their contribution to global CO_2 emissions from coal-based steel production and by their production trends from 2018 to 2007, providing a rough estimate of the contribution of coal-based steel production to national CO_2 emissions. This is an indication of the economic and climate policy importance of this sector in each country. If the steel industry is a large national CO_2 emitter, then it is more likely that the government will develop effective plans to support its decarbonisation. The ability of a steel sector to change production processes is seen as stronger when production increases. Shrinking industries are thought to have greater difficulty changing their production processes due to a lack of capital. Data are from Worldsteel and the World Bank [6,38]. We do not consider country-specific CO_2 intensities for steel production processes. CO_2 emission intensities are assumed to be 2 t CO_2 per tonne of steel produced via blast furnaces and oxygen blowing furnaces, and 3 t CO_2 per tonne of steel produced via coal-based direct reduction of iron ore and further smelting in electric arc furnaces.

Second, section 4.2 presents the current implementation of low-carbon electricity in the countries studied. We present the electricity generation mixes of the individual countries for 2018, distinguishing between electricity from coal, oil & waste, from natural gas, and from renewable and nuclear sources. Countries or regions that have already started to decarbonise their electricity generation are better able to meet additional electricity demand from low-carbon sources than countries where electricity supply is still largely dependent on fossil fuels. The data comes from the International Energy Agency [1].

Thirdly, as the current coal lock-in of the steel industry needs to be broken up by governments, in section 4.3 we review country-specific climate and energy policies for both the medium and long term. We present CO_2 reduction and renewable energy targets for 2020–2035 and for 2040–2050. Ambitious targets for greenhouse gas emission reductions or for the expansion of renewable electricity set a clear framework and can thus reduce uncertainty for steel producers when deciding on major investments. Data is based on Intended Nationally Determined Contributions (INDCs) submitted to the United Nations Framework Convention on Climate Change and other recent announcements and literature [3,39].

In a fourth step, we develop a set of indicators based on the collected data to map countries according to their readiness for a low-carbon transition (section 5). Climate policy is represented by 'CT', which indicates whether a country is committed to a long-term CO_2 reduction of 80% or more by 2050. Medium-term renewable energy targets represent current energy policy. Therefore, 'RT' indicates whether a country has set a target to have a share of renewable energy of 30% or more in 2030. Finally, three other indicators provide information on the implementation of low-carbon and renewable electricity in 2018: 'R1' is indicated if the share of renewable and nuclear electricity is greater than 50%; 'R2' indicates if the share of renewable electricity generation is greater than 30%; and 'R3' is assigned if the share of renewable electricity excluding hydropower and biofuels (NHB-RES) is greater than 10%.

4. Coal-based steel production, low-CO_2 electricity generation and climate & energy policy

4.1. Coal-based steel production by country

Ranking the countries according to their contribution to the global CO_2 emission from coal-based steelmaking, it turns out that only six countries are responsible for 90% of the emissions (Fig. 1). China is responsible for more than half of the global coal-based CO_2 emissions from steelmaking, with the EU-28, India, Japan, South Korea and the Russian Federation being the other five.

Six further countries contribute to the global CO_2 emissions with 1–2% each. These are the US, Brazil, Ukraine, Taiwan (China), Turkey and Canada. Thus, together with the above mentioned six countries, twelve countries are responsible for 97% of the global emissions from coal-based steelmaking. All remaining countries account each for less than 1% of the global CO_2 emissions from coal-based steelmaking.

As steel assets have long lifetimes, countries that are increasing their production are likely to have high CO_2 emissions from steelmaking in the future. Thus to these countries should be paid more attention concerning CO_2 mitigation than countries whose steel production is likely to decrease. It is noteworthy that countries can increase their total steel production with the recycling of steel, while not further increasing their CO_2 emissions.

Steel industries that contribute with a significant amount to the national CO_2 emissions in countries with ambitious climate targets, seem to have better access to governmental support for decarbonising their processes (e.g. Sweden, Germany). Hence, Fig. 2 maps the production increase (or decrease) of coal-based steel by country from 2007 to 2018 (x-axis) against the share of this industry to the national CO_2 emissions (y-axis). The size of the bubbles reflect the total amount of CO_2

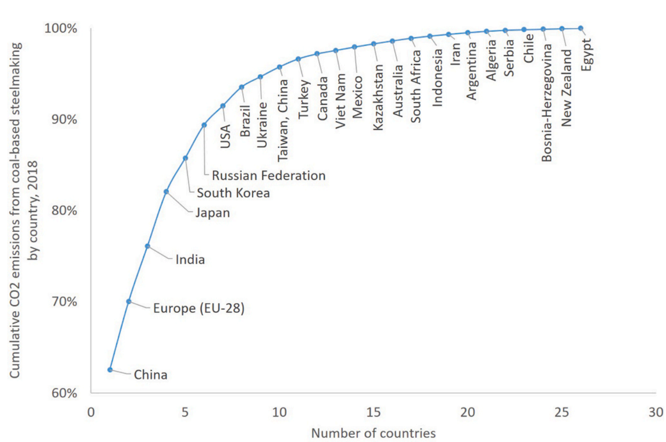

Fig. 1. Cumulative CO_2 emissions from coal-based steelmaking by country, 2018. Sources: [6,28]. Assumptions: blast furnace steelmaking 2 t CO_2/t steel; coal-based direct reduction 3 t CO_2/t steel (mainly in India); CO_2 emissions from electricity generation and coal consumption in scrap-based steelmaking are not considered.

emissions originating from coal-based steel production by country.

The studied national steel industries differ strongly concerning recent trends in coal-based steel production volumes and the contribution of coal-based steelmaking to the national CO_2 emissions.

For the countries with a high share of emissions originating from the steel sector, China and South Korea stand out as their coal-based steel production makes up 15.9% and 16.4%, of the national CO_2 emissions. Ukraine's and Japan's shares are 13% and 12.9% and Brazil's and Taiwan (China) contribution is estimated with 10.6% and 10.2%, respectively. All other coal-based steel industries contribute with less than 10% to their national CO_2 emissions. The national CO_2 emissions in Ukraine, Taiwan (China) and Brazil are strongly affected by coal-based steelmaking, even though they do not belong to the six coal-based steelmaking countries that make up 90% of the global production.

The recent development in steel production reveals that Viet Nam and Indonesia has seen the largest increase but they start from a low point as they only recently took up coal-based steel production. India and China range number three and four in steel production growth and have doubled their production between 2007 and 2018, even though China's steel production seems to have reached its peak by 2014. This reflects the tremendous expansion of its production in the past two decades. India more than doubled its steel production using blast furnaces (21.8 Mt in 2007, 49.7 in 2018), and almost doubled production from coal-based direct reduction direction (from 12 Mt to 20 Mt). Turkey, South Korea and Algeria have also increased their coal-based steel production by a factor of 1.5 and 1.8 comparing 2018 with 2007 production levels. Taiwan (China) and Iran's values are about 1.3 and can thus be considered as countries that have increased their steel production significantly. At the other end are those countries that have faced the largest decreases in coal-based steel production. Chile, Egypt, Australia, Ukraine, and the USA roughly produce two thirds of their 2007 production levels. Except for Ukraine, the coal-based steel production of these countries only marginally contributes to the national CO_2-emissions, i.e. well below 3%.

4.2. Current implementation of low-CO_2 electricity generation

In Fig. 3, the current generation mix is given for the 26 studied countries, divided into low-emitting power (nuclear and renewables), high-emitting electricity (coal, oil and waste[1]), and medium-emitting (natural gas). The likelihood of countries attempting to decarbonise industry through low-carbon electricity depends on their current electricity mix. Countries that already have low-carbon electricity available on a large scale are more likely to electrify their industries than countries whose power generation relies on coal. The reason for this is not only the comparatively lower emission reductions in coal-dependent countries, but also the long investment inertia in the power sector for a transition linked to a higher degree of institutional and behavioural coal lock-in Ref. [10]. Converting their steel industry to low-carbon production would require a simultaneous transformation of the electricity and industrial sectors.

The electricity mix of the countries that produce steel using coal is very diverse. Four groups can be identified. First, there are eight countries that have an electricity generation that is more than half relying on coal (Fig. 3, bottom left). Taiwan (China) electricity share from coal is, however, only 47% but oil adds another 5%. Indonesia has a share of 8% of oil on its electricity generation. For all other countries of this group, electricity generation from oil is marginal. The rest of the electricity is either provided by natural gas (Kazakhstan, Australia, Indonesia and

[1] In most cases, oil contributes only marginally to the national electricity generation (Egypt 13%, Mexico 11%. Argentina 9%, Indonesia and Japan both 8%). Only Japan, the EU-28 and Taiwan (China) have a contribution of waste to the electricity from waste between 1 and 2%, for all other countries it is less than that.

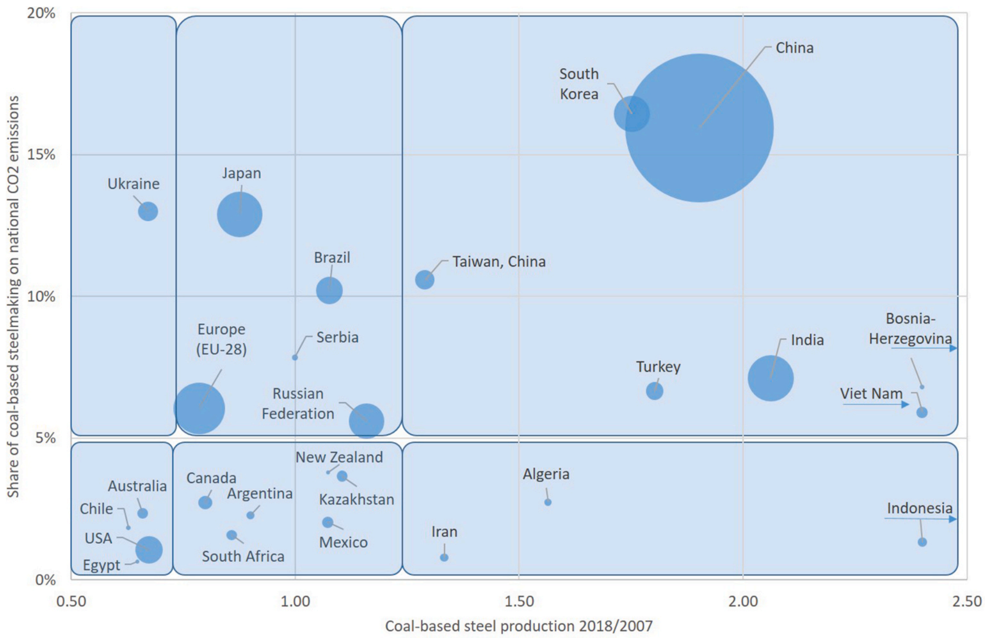

Fig. 2. Y-axis: Share of CO_2 emissions from coal-based steelmaking on the national CO_2 emissions (referring to national CO_2 emissions from 2014 due to data availability). X-axis: Increase (>1) or decrease (<1) in coal-based steel production from 2007 to 2018. The size of the bubbles represents the amount of CO_2 emissions from coal-based steelmaking in 2018. Values for Viet Nam and Indonesia are indicated at a value of 2.5 even though they have been building up blast furnace capacity only recently (in 2007, their production was zero). Production of Bosnia & Herzegovina is cyclic. Sources: [6,28,38]. Assumptions: Blast furnace steelmaking CO_2 intensity: 2 t CO_2/t steel; for coal-based direct reduction CO_2 intensity (India): 3 t CO_2/t steel.

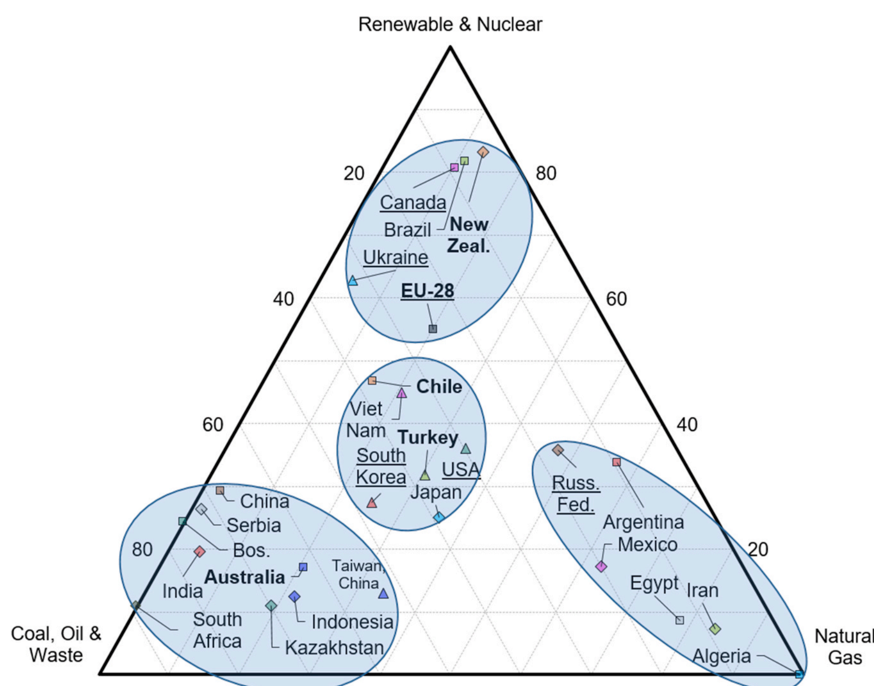

Fig. 3. Electricity production from coal & oil & waste, from natural gas and from renewables & nuclear by 2018. Countries given in **bold** letters have an electricity production from non-hydro, non-biofuels renewable (NHB-RES) sources (mainly wind and solar PV) that contribute more than 10% to the total electricity production; countries underlined have an electricity production from nuclear of more than 15% (data from Ref. [40], Table 2).

Taiwan (China); 19–35%) or by renewables and nuclear (India and China, 20% and 29% respectively). South Africa has the highest contribution of coal to its electricity generation, i.e. 89%. Countries with a high coal share are less likely to electrify their industries in the short term as emissions would not decrease much or not at all. Coal lock-in poses a barrier to those countries. China and India, as those countries with a high steel production today and a predicted high production in the future, are both in this group.

Second, there are countries whose electricity generation strongly depends on natural gas (Fig. 3, bottom right). These are countries with a minor production of coal-based steel. All countries of this group have natural gas-based steel production, apart from Algeria. Iran is the largest global natural gas-based steel producer and Mexico is number three [28]. For Iran and Egypt natural gas-based steelmaking is the dominant steel production route. These five countries contribute with 39 Mt to the global production of gas-based direct reduced iron and thus cover half of it [28]. Those countries whose electricity generation is dominated by natural gas are in a good position for a low-carbon transitions as they already use gas-based direct reduction facilities to produce steel which can also be run with hydrogen. Hence, they already possess - to some extent at least - the capital-intensive plants to produce steel based on hydrogen and are also already familiar with gas-based steelmaking. However, to produce steel from low-carbon hydrogen, they would need to extend electricity production from renewable sources or use "blue" hydrogen derived from natural gas with CCS.

Countries of the third group have an electricity production that is dominated by renewable and nuclear power (Fig. 3, top). New Zealand's, Canada's and Brazil's share of low-carbon electricity ranges between 81 and 83%. These are also the countries that have the highest shares of renewable electricity (i.e. 83%, 65% and 79%, respectively). It is worth mentioning, that also Chile and Viet Nam have a high contribution from renewables to their electricity mix (i.e. 47% and 45%). The EU-28 produces 30% of its electricity from renewables and 25% from nuclear power. Ukraine and the EU-28 have the highest contribution of nuclear power (55% and 25%, respectively). Other countries with high shares of nuclear power are South Korea (23%), USA and Russian Federation (both 19%) as well as Canada (15%). Countries with a high contribution of low-carbon electricity are in a better position to electrify their industries. The EU-28 is among this group, but other large steel production countries such as China, India, Japan, South Korea, and the Russian Federation are not. However, if steel production capacity is globally relocated, countries with high share of renewables may be candidates.

The last group consists of those countries whose electricity generation is mixed. Except for South Korea, all these countries have rather high shares of renewables (i.e. 17–47%). South Korea, the USA and the Russian Federation have high shares of nuclear power (19–23%). All these countries have also rather high shares of coal (16–45%) as well as of natural gas (16–47%). Those countries with a mixed electricity generation are differently suited for low-carbon steel production. Chile, Viet Nam and to some extent also the USA are countries with comparably high contributions from renewable electricity. The Russian Federation, South Korea and Japan that are all big steel producers show little shares of renewable electricity, especially from non-hydro, non-biofuel sources.

The EU-28, China and the USA are the three countries with the highest production of non-hydro, non-bio renewables (NHB-RES) in absolute terms. Together they produced 78% of the NHB-RES of the total countries studied. Only five countries have an NHB-RES share above 10%, i.e. New Zealand (22%), the EU-28 (15%), Turkey and Chile (each 11%), as well as Australia (10%). The USA (9%) and Japan (8%) could join this group in the next few years.

There are also countries with only small contributions from the renewable energy sector, namely South Korea (2%), South Africa (2%), Ukraine (4%) and Iran (5%). Of all major steel producing countries South Korea stands out with the lowest contribution of renewable energies. Its electricity generation from renewables in absolute terms ranges number 17 out of the 26 studied countries.

4.3. National climate and energy policy

This section maps climate and energy policy for the studied countries. It collects CO_2 reduction and renewable power targets both for the medium-term (2025–2035) and for the long-term (2040–2060) (Table 1). Long-term policies are of special importance for the steel industry as investments in these capital intensive production facilities require stable regulatory frameworks [41]. However, medium-term targets are another important pillar of climate and energy policy, as they are crucial for immediate climate mitigation.

Nearly all our selected countries have announced CO_2 reduction targets for 2030 (Table 1). However, only fewer than half of them have published renewable targets for that year. When it comes to long-term commitments, it turns out that even fewer countries have agreed on CO_2 reduction and renewable targets. However, in 2020 the number of steel production countries that committed to carbon neutrality by 2050/2060 doubled from 3 to 6, and these were even major steel producing countries (i.e. China, Japan and South Korea).

Table 1
CO_2 reduction and renewable targets and goals up to 2050.

		CO_2 Reduction Target 2030	Renewable Power Target 2030	CO_2 Reduction Goals 2050	Renewable Power Target 2050
1	China	Peak/-60%…-65% (GDP, 2005)	35%	carbon neutrality 2060	
2	European Union	-40% (1990)	32%	climate neutrality	at the country level
3	India	-33…-35% GDP (2005)	40% (excl. hydro >25 MW)		
4	Japan	-25,4% (2005, incl. LULUCF)	22 … 24%	carbon neutrality	
5	Korea, Rep. of	-37% (BAU)	20%	carbon neutrality	
6	Russian Fed.	-25…30% (1990)	4.5% (2020; non-hydro)		
7	United States	(-26…-28% (2005) by 2025)	at state level	(-80% (2005))	at the state level
8	Brazil	-43% (2005, incl. LULUCF)	23% (non-hydro)		
9	Ukraine	-40% (1990)	20%	-50% (1990)	
10	Taiwan, China	-50% (BAU)	20% (2025)		
11	Turkey	-21% (BAU)	30% (2023)		
12	Canada	-30% (2005)	at state level	-80% (2005)	
13	Viet Nam	-8% (BAU)	10%		100%
14	Mexico	-25% (BAU)	35% (2024)	-50% (2000)	50%
15	Kazakhstan	-15% (1990, incl. LULUCF)	30% (incl. nuclear)	-25% (1992)	50% (incl. nuc.)
16	Australia	-26…-28% (2005, incl. LULUCF)	23% (2020)	at the state level	
17	South Africa	614 Mt CO2,eq; (no reducion)	9%	Peak by 2035	
18	Indonesia	-29% (BAU)	26% (2025)		
19	Iran	-4% (BAU)	[5 GW (2020)]		
20	Argentina	-15% (BAU)	20% (2025)		
21	Algeria	-7% (BAU)	27%		
22	Serbia	-10% (1990)	37% (2020)		
23	Chile	-30% GDP (2007)	20% (2025)	carbon neutrality	
24	Bos. & Herzeg.	-2% (1990)	[40% (2025), final energy]		
25	New Zealand	-30% (2005)	90% (2025)	carbon neutrality	
26	Egypt	no target	42% (2035)		
		Source: [39,43]	Source: [3]	Sources: [39,44,45]	Source: [3]

All 26 studied countries have ratified the Paris Agreement and have submitted Intended Nationally Determined Contributions (INDCs). However, not all of them have committed to binding and absolute CO_2 reduction targets by 2030. The United States, for instance, has withdrawn from the Paris Agreement under the Trump administration but is about to re-join under the Biden Administration. There are indications that on the US state level ambitious climate and renewable targets were pursued even during the Trump Administration [42], however, the renewable targets in those US states that are home to coal-based steelmaking are typically weak (i.e. Ohio, Indiana, Michigan, and Pennsylvania; [3]). China committed to peak its CO_2 emissions before 2030. India and Chile announced intensity-based CO_2 reductions targets referring to gross-domestic product, GDP. Nine countries committed to intensity-based CO_2 reduction targets referring to business-as-usual, BAU, scenarios. Intensity-based targets allow for an increase in future CO_2 emissions. Egypt has not announced any CO_2 reduction target and South Africa targets to have peaked its CO_2 emissions before 2030.

Out of the 26 countries, only 11 have announced CO_2 reduction targets for 2030 that refer to emission levels in the past and thus require to cut current emission levels (Table 1). These are industrialized countries whose CO_2 emissions have already peaked or countries that have faced a sharp economic downturn during the 1990s due to the break-up of the Soviet Union (i.e. Russian Federation, Ukraine) or of Yugoslavia (Serbia, Bosnia & Herzegovina). These countries that had severe economic downturns by 1990, except Kazakhstan, have not yet surpassed their CO_2 emission levels from that time. As a consequence, by 2017/2018 they had achieved their 2030 CO_2 reduction target. Only Brazil has a steady upward trend in CO_2 emissions but has committed to an absolute CO_2 reduction target that refers to the year 2005. Thus, only seven out of the 26 steelmaking countries have committed to climate targets by 2030 that require a reduction of current national CO_2 emissions which could imply a pressure on steelmaking companies as well. However, these countries only account for 17% of current coal-based CO_2 emissions. In other words, 83% of today's coal-based steelmaking CO_2 emissions are not affected by national climate targets. In addition, the Climate Action Tracker (2020) finds that the nationally adopted targets for these countries that refer to emission levels in the past, can be achieved without contributions from their industry sector [39].

While in 2019 only 8 of the 26 countries surveyed envisaged climate targets that extended to 2050, in 2020 three major steel-producing countries followed suit: China, Japan and South Korea. While this can be seen as great progress towards achieving the Paris Agreement, it does not immediately increase the pressure on today's action. It thus remains to be seen which climate measures will actually be implemented in the coming years. The European Union, Chile and New Zealand aim for climate neutrality by 2050 though only New Zealand, whose coal-based steel production is nearly negligible on a global scale, has put it into law so far [46]. Canada set up long-term strategies to reduce CO_2 emissions by 80% from 2010 to 2005 levels, respectively, and so have Mexico, Ukraine and Kazakhstan though with lower CO_2 reduction values [47,48].

Targets for renewable electricity are also an indicator for a long-term steel transition. Only half of the selected countries have set targets for 2030 while the others have only set targets for 2020 to 2025 yet. On the other hand, at least some of those targets are noteworthy. First, India aims for 40% of renewable electricity excluding large-scale hydro-power (>20 MW; [3]). Second, Egypt aims for 42% of renewables by 2035. Third, China recently announced a 35% renewable target by 2030. And finally, there is Europe's 32% target by 2030. In contrast to the 2030 CO_2 reduction targets, the majority of the most ambitious renewables targets for 2030 are proposed by large steel producing countries (China, India, and EU-28).

Long-term renewable targets have been set by Viet Nam (established by the Climate Vulnerable Forum) [3] and Mexico. Some European countries have ambitious renewables targets like Sweden (100% by 2040) or Germany (80% by 2050, though referring to final energy). So have some states of Canada, Australia and the United States, but typically not states that are home to coal-based steelmaking facilities [3,49]. While steelmaking countries seem to be more eager on the deployment of renewable energies rather than on cutting CO_2 emissions (with Japan being an exception), strongly decreasing prices for renewable electricity could explain this trend [50]. Some countries even reach their renewable targets in advance (e.g. Turkey) [3].

5. Mapping coal-based steelmaking countries towards greening their steel production with electricity

This study aims to identify which countries are more ready or ambitious to set their steel industry on a low-carbon transition based on renewables and which are less prepared to do so. For doing that, we collected data climate and energy policy as well as on the current implementation of low-CO_2 electricity generation. Based on the collected data, we define the following indicators for enabling a mapping of the selected countries (Fig. 4):

- Climate policy - long-term CO_2 reduction target ('**CT**'): CO_2 reduction target 2050 greater than 80% or carbon neutrality discussed by governments or already implemented.
- Energy policy - medium-term renewable electricity target ('**RT**'): renewable power target 2030 greater than 30%;
- Implementation of low-CO_2 and renewable electricity by 2018:
  - o **R1**: share of renewables and nuclear power greater than 50%;
  - o **R2**: share of renewables greater than 30%;
  - o **R3**: share of non-hydro, non-biofuels renewables (NHB-RES) greater than 10%;

The allocation of the indicators to the countries shows that the number of fulfilled indicators are evenly represented, i.e. from zero to five indicators (Fig. 4). This suggests that the indicators were reasonably chosen.

Only six countries contribute 90% of global CO_2 emissions from coal-based steel production (top-6 countries). According to this study, only one of these countries has committed to ambitious long-term CO_2 reduction and medium-term renewable energy targets, and also already has NHB-RES production of more than 10%. This is the EU-28 (Fig. 4). All other five countries perform worse in this respect. This suggests that the global steel industry is not well prepared to achieve net zero emissions as required by the Paris Agreement.

The Russian Federation has not committed to a long-term CO_2 reduction target or a medium-term renewable energy target, and its electricity generation is almost free of NHB-RES. South Korea and Japan have recently announced carbon neutrality for 2050, but lag behind in implementing and promoting renewable electricity. India, while not committing to long-term carbon reduction targets, has set an ambitious medium-term renewable energy target. The largest steel-producing country, China, has both a medium-term renewable energy target and a long-term CO_2 reduction target, but its electricity generation - like India's - is still heavily dependent on coal. The EU28, however, appears to be the group of countries most advanced in both climate and energy policies. Among the group of top 6 countries and all countries studied, the EU28 additionally stands out for its electricity generation mix, which has comparatively high shares of low-carbon electricity as well as NHB-RES.

Four of the top 6 countries have committed to carbon neutrality by 2050 or 2060, as in the case of China. This is remarkable in that only Canada, Chile and New Zealand have also done so, the latter two being among the smallest steel-producing countries with almost negligible production volumes on a global scale.

Besides India, China and South Korea, four other countries are massively expanding their coal-based steel production. These are Indonesia, Vietnam, Turkey and Taiwan. None of these countries has yet committed to a medium-term renewable electricity target or a long-term CO_2 reduction target. When it comes to renewable electricity production, Turkey and Vietnam perform better than the other fast-growing and top 6 countries, with the exception of the EU-28. Indonesia and Taiwan not only lack ambitious climate and energy targets, they also lag behind when it comes to renewable electricity production.

Chile and New Zealand stand out in the sense that these smallest of the steel producing countries seem quite well prepared for a low-carbon future. Both have announced carbon neutrality targets by 2050 and both already produce more than 10% of their electricity from NHB-RES. Under such favourable conditions, these countries could represent a kind of nucleus for a low-carbon industry.

If Africa is to increase steel production in the future, South Africa

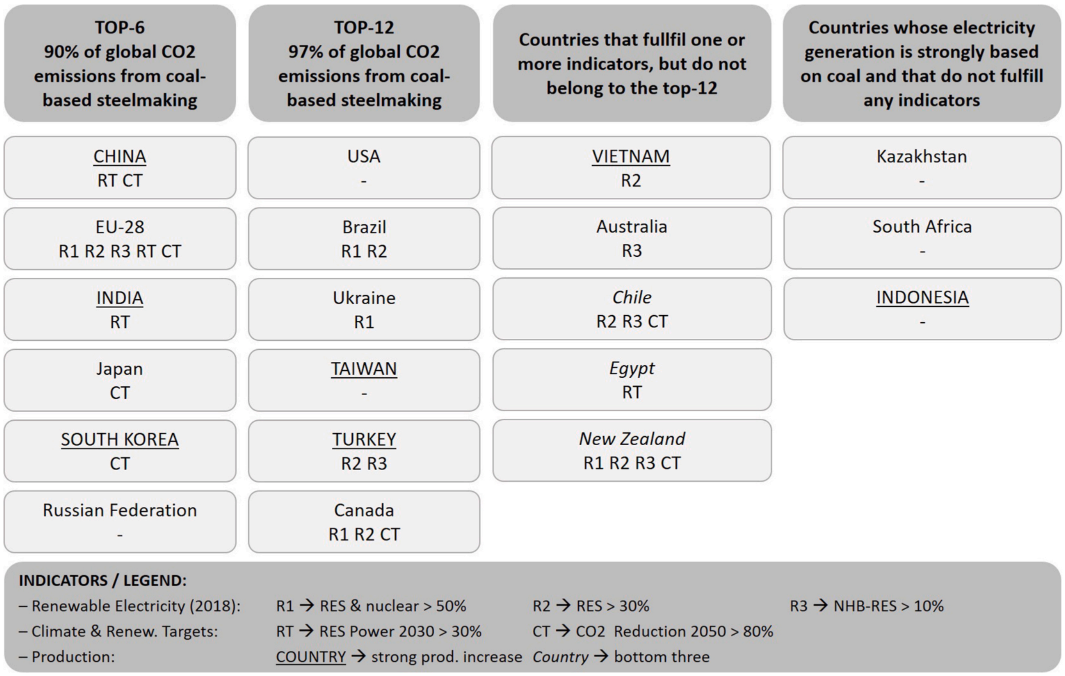

Fig. 4. Mapping of steelmaking countries according to the developed indicators. Each column lists the countries according to their production by 2018, larger ones first.

could play an important role. However, the country seems to be lagging behind in the energy transition as it does not commit to ambitious energy and climate targets and its electricity generation still has one of the highest shares of coal.

The developed indicators ‘R2’ and ‘RT’ (Fig. 4) have an overlap. While ‘R2’ indicates that a country already has a contribution of more than 30% from renewables to its power generation by 2018, ‘RT’ indicates that a country aims for 30% or more contribution from renewables by 2030. However, countries could aim for increasing their current share of renewables by setting a more demanding target, as has done the EU. Countries with already a high share of renewables like New Zealand and Brazil touch somehow the ceiling.

This study positions coal-based steelmaking countries next to each other according to the collected data in order to draw insights on the low-carbon transition of the steel industries in these countries. However, for some dimensions of a system’s transformation that are seen as crucial such as access to early niche markets [41,51], no data was available that covered all selected countries. Also, as interest in deep decarbonisation of industry is relatively new, some activities might undergo which are not covered by the developed indicators or that have been initiated only very recently (e.g. the Swedish-Indian Leadership Group on Industrial Transition launched in September 2019 at the UN Climate Action Summit in New York, USA) or projects and initiatives on the national level, such as HYBRIT in Sweden or SALCOS in Germany [29,52].

6. Conclusions

This paper examined the climate and energy policies and current implementation of low-carbon electricity generation in countries that produce steel from coal. The aim was to map countries according to their capacity to convert their steel industry from coal to low-carbon electricity.

First and foremost, the global coal-based steel industry as a whole does not appear to be in a good position to achieve net zero emissions by 2050. Based on the data analysed in this study, it seems crucial that countries agree on ambitious long-term CO_2 reduction targets and ambitious medium-term renewable energy targets, and that they have also already started to implement non-hydro, non-biofuel renewable electricity generation (NHB-RES). However, only the EU-28 meets these indicators, while all other countries either do not show a strong commitment to the energy transition in the form of climate and energy targets or are lagging behind in implementing low-carbon electricity. Thus, three targets could be a starting point for decarbonisation not only of the steel industry, if they have not already been implemented or achieved: (1) carbon neutrality target by 2050, (2) share of NHB-RES in total electricity generation greater than 30% by 2030, (3) increase NHB-RES share to 10% or more as soon as possible.

In addition to committing to ambitious climate and energy policy targets and expanding electricity generation from NHB-RES, three other steps could contribute to achieving a carbon-neutral steel industry by 2050. First, with only six countries responsible for 90% of global steel-related CO_2 emissions and another four countries currently expanding production, coordinated decarbonisation of these ten steel industries could make a significant contribution. Coordination could be undertaken by international bodies or international initiatives. This would also ensure that the countries that are rapidly expanding their steel production have access to the necessary support, such as R&D funds, information or other financial assistance.

Secondly, roadmaps should be developed by the main steel producing countries as a tool to review and steer the energy transition in the industry. These could also be promoted and supported by international bodies or international initiatives.

Thirdly, there still seems to be a long way to go before global steel production can be decarbonised. Therefore, measures that reduce current CO_2 emissions or that reduce demand for coal-based steel should continue to receive strong attention. These include energy and material efficiency as well as the circular economy.

The steel industry could decarbonise its processes with electricity from nuclear power and/or from renewables. While nuclear power may play a role in a global decarbonised future, the picture remains vague from the perspective of the coal-based steel industry. On the one hand, the share of NHB-RES is above 10% in six countries and the share of nuclear energy is above 15% in another six countries (Table 2). However, looking at the top six producing countries and the fast-growing countries, nuclear energy contributes significantly to electricity generation in only three of them. Moreover, in China and India, which are likely to dominate future steel production, nuclear energy currently has a share of only 3–4%.

This study finds that 2030 climate targets do not put any pressure on current steel production. Even though each studied country has committed to a 2030 target under the Paris Agreement, these targets may for instance still allow future increases in emissions when the targets refer to assumed future scenarios or to economic indicators like GDP. They also might not be demanding for the steel industry, when countries are already on track to reach their set targets, for instance through the transition of the energy sector or through economic developments. Finally, some countries are not on track to reach their set targets, but governments do not seem to take much action on that.

Moving coal-based steelmaking onto a low-carbon transition based on renewables requires the expansion of renewable electricity from non-hydro, non-biofuel sources (NHB-RES). As this contribution points out, the current share of NHB-RES electricity is insufficient in nearly all countries that produce steel from coal today. Only the EU-28, Turkey, Australia, Chile and New Zealand have contributions from NHB-RES electricity that range between 10% and 22% from the national electricity generation. Three countries account with roughly the same share for about 80% of the NHB-RES electricity generation from the studied countries, i.e. the EU-28, China and the US.

Some countries are at the very beginning of adopting climate targets that affect their steel industry. South Korea is strongly increasing its steel production and is among the top-6 producing countries, but its electricity generation from renewables ranks very low and climate targets seem to be weak as well. Taiwan (China) and Indonesia are the other two countries whose steel production is strongly increasing but climate ambitions seem to be low. The Russian Federation is also among the top-6 producers, and there are little indications that its steel industry is prepared for a low-carbon transition.

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.

Acknowledgements

This work has been conducted as part of the HYBRIT research project RP1. We gratefully acknowledge financial support from the Swedish Energy Agency. HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a joint initiative of the three companies SSAB, LKAB and Vattenfall with the aim of developing the world's first fossil-free ore-based steelmaking route. We are grateful for the provision of steel production projections by Worldsteel [7].

Appendix

Table 2
Share on national electricity generation and total NHB-RES generation, 2017/2018 (source: IEA, 2020b).

IEA, 2017/2018	Coal & Oil & Waste & Other	Natural gas	Renewable and Nuclear	Nuclear	NHBRES	NHBRES
	[–]	[–]	[–]	[–]	[–]	[GWh]
Algeria	0%	100%	0%	0%	0%	0
Argentina	10%	57%	34%	4%	0%	632
Australia	62%	21%	17%	0%	10%	25104
Bosnia and Herzegovina	76%	0%	24%	0%	0%	0
Brazil	7%	11%	82%	3%	7%	43205
Canada	9%	10%	81%	15%	5%	33520
Chile	38%	16%	47%	0%	11%	8707
China	68%	3%	29%	4%	6%	425752
Egypt	13%	78%	9%	0%	1%	2780
Europe (EU-28)	25%	20%	55%	25%	15%	489045
India	76%	5%	20%	3%	5%	77096
Indonesia	66%	22%	12%	0%	5%	12770
Iran	9%	84%	7%	2%	0%	0
Japan	39%	36%	25%	6%	8%	77681
Kazakhstan	70%	19%	11%	0%	0%	94
Mexico	20%	63%	17%	4%	3%	8565
New Zealand	4%	13%	83%	0%	22%	9957
Russian Federation	17%	47%	36%	19%	0%	558
Serbia	72%	1%	26%	0%	0%	0
South Africa	89%	0%	11%	6%	3%	8400
South Korea	47%	25%	27%	23%	2%	11746
Taiwan, China	53%	34%	13%	8%	1%	3423
Turkey	38%	30%	32%	0%	11%	34265
Ukraine	32%	5%	63%	55%	1%	1722
USA	30%	34%	36%	19%	9%	384063
Viet Nam	34%	21%	45%	0%	0%	323

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