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Original article

Global assessment of biomass suitability for ironmaking – Opportunities for co-location of sustainable biomass, iron and steel production and supportive policies

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ABSTRACT

Iron and steel production processes are amongst the biggest industrial contributors to the global carbon emissions, and national as well as international obligations are set to drive their significant emission reductions. One of the possible strategies is to partially substitute fossil fuels used during the iron ore reduction process by sustainably-sourced biomass. The extent of the opportunities for such fuel switching, however, varies for each country. Theoretically, biomass into ironmaking should be only supported for countries which present co-location of sustainably domestically sourced biomass in sufficient quantity, a substantial iron and steel industry and supportive national policies.

Using a multi-criteria global suitability assessment approach developed in this research, the status of countries' steel industry, sustainable biomass resources and supportive policies were examined for top 40 steel production countries via the blast furnace ironmaking route. The results highlight those countries with significant potential to use domestically sourced biomass for such application and advance the efficient use of the limited biomass resources from the global perspective. Specifically countries such as Canada, Sweden, China, USA and France were identified as the most suitable, but other countries present opportunities that could be overcome if the corresponding barriers are identified.

Introduction

The iron and steel sector is the largest industrial CO_2 emitter, contributing to nearly 7% of the total global industrial greenhouse gas emissions [1] and requiring on average of 800 kg of coal for every metric ton of crude steel [2]. Due to the importance of steel's numerous applications in economic development and in low carbon technologies, increasing demand for steel products has been forecasted until at least 2050 [3]. Therefore to limit global warming below 2 °C, it is estimated the sector must lower the CO_2 emissions relative to those in 2011 by 13% by 2025 [4]. Application of sustainably sourced biomass has been identified as an effective short term CO_2 mitigation strategy for ironmaking [5]. Materials for iron and steel production, such as iron ore, limestone and metallurgical coal/coke are globally traded, hence so can be biomass for use in ironmaking. However, fuel switching for those geographic locations that have a sufficient amount of nationally produced biomass can additionally:

- reduce emissions by eliminating those occurring from very long distance bulk transport of the fossil fuels – for example, Borjesson and Gustavsson [6] estimated that sourcing biomass regionally could emit over 70% less of CO_2 emissions than importing coal;
- benefit the local economy – looking at Brazil for example, one can see that support for local agriculture can be a very significant political driver for biomass utilization [7];
- provide the steel industry with a better opportunity to control the sustainability of biomass sourcing – keep the regulation of the sustainability of biomass supply and use within the same government.

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The objective of the work is hence to identify which countries have the potential to use domestic biomass resources for emission reduction purposes in their iron and steel industry.

The importance of emission reduction within the iron and steel sector is acknowledged by the industry, but its low profitability [8], the current economic uncertainty, oversupply of steel on the market together with maintaining competitive advantage limit any low carbon technological investments in this sector [9]. As biomass production is different to fossil fuels, biomass could reduce the industry's issues related to the fluctuation of the fossil fuel prices, as well as overcome concerns related to fuel security and diversity - as long as an efficient utilization of the limited biomass resources is reached and biomass is sustainably sourced. Sustainable sourcing in this work is defined as a biomass supply chain that preserves or enhances the role of biomass in the already existing ecosystem. Therefore, to be treated as suitable in the present work, policies incentivizing biomass use for ironmaking applications should not only include the appropriateness of biomass for the given country [10] but also cover strategies for its sustainable sourcing.

Multiple review papers recently published on biomass utilization within iron and steel plants [11–13] indicate a rising interest in such application from both academia and industry. The greatest potential for on-site biomass integration is for the integrated blast furnace-basic oxygen furnace (BF-BOF) route [14], which provides 73% of the world's steel [15]. Here, biomass can partially substitute for fossil fuels at the coke making stage [16], in the sintering process [17] or directly in the blast furnace [18]. The varied characteristics that different biomass types have, as well as the diverse upgrading technologies, provide multiple possibilities, but also complex constraints for its utilization within the ironmaking process [19]. Mathieson et al. [14] estimated that biomass can overall reduce up to 58% of net CO_2 emissions from a common BF-BOF route. Such emission saving, however, can be only achieved when the utilized biomass is satisfying carbon neutrality, and it is required that the governments provide support and control to the private and third sector to achieve biomass adoption [20].

The uncertainty in the whole system viability of biomass use is currently a bigger drawback than the technical limitations of using such fuel in the process [21]. The fuel cost and availability [22,23], and rising concerns about sustainability of biomass supply [24] greatly limit its further deployment. A study by Thrän et al. [25] identified that the biomass potential greatly varies under different scenarios and for different regions. Hence the overall question of where the use of bioenergy in the iron and steel making industry is actually suitable can only be answered meaningfully in context. This is because the size of the steel industry, nature and origin of biomass resources and policies all differ between countries.

Knowledge on the regional fitness of bioenergy for iron and steel industry also benefits both the steel industry and policy formulation, in the latter case aiming at supporting long term sustainability of renewable energy integration [26]. As an illustration of the different outcomes of general, versus country specific studies, a previous general study on the electricity sector identified bioenergy as the least suitable amongst all renewables [27], but a different study stated that bioenergy can play an important role in more site-specific energy projects [26]. Hence bioenergy application is not suitable for every application and across all locations, and should be supported only after its suitability for the specific location and application is assessed. Increasing confidence in such suitability is especially important at present, as currently the integration of renewable fuels into ironmaking is not attractive for investors and requires substantial support and co-operation from policy makers to promote it [28].

Location suitability studies have been done primarily on electricity generation from renewables, such as wind [29,30] and solar [31], which demonstrated the different suitability of renewables for different locations on national as well as international level. However, there is a gap in literature for bioenergy and particularly its application into industries such as iron and steel. Wang et al. [32] and Suopajärvi and Fabritius [33] analyzed the possibility of biomass use for iron making in Sweden and Finland, respectively, but those countries correspond together to less than 1% of the total global crude steel production via BF-BOF [15]. The gap leaves decision makers in steel producing countries across the world with the strategic decision of whether the adoption of bioenergy in the industry is actually a suitable strategy for its decarbonization. The present study was done to bridge the gap and reveal how opportunities or barriers differ between countries and ensure sustainable use of biomass.

The overall aim of this work is to identify and down select countries which are potentially suitable for integrating bioenergy into their iron and steel making processes via the BF-BOF route. Specifically, the study covers bioenergy possibilities within coke oven, sinter plant as well as blast furnace (for top charging as well as pulverized coal injection). The specific objectives are:

- to develop a Global Suitability Index, an assessment framework that uses steel production, bioenergy and policy factors for each country to provide a quantitative measure of suitability for domestically sourced biomass use in blast furnace ironmaking; and
- to provide an informed judgment for which countries domestically sourced bioenergy in blast furnace ironmaking should be further considered.

Defining the suitability of countries convincingly requires in depth analysis, such as detailed techno-economic and life cycle assessment [34], which implies a significant investment of time and effort. The current work is the initial step before such analyses are performed. As such, it avoids expending effort on detailed studies of unsuitable locations, but also allows the policy community to evaluate countries which would not be considered otherwise.

Previously, there have been various efforts to develop indices that identify and/or rank entities by their fitness as a function of purpose or context. Some key examples of these are the:

- Habitat Suitability Index [35], the approach popular for ecosystem assessment studies;
- World Trilemma Index [36] for comparison countries based on their ability to provide sustainable energy policies; and
- Land Suitability Index [37] evaluating the land suitability for the defined use.

Adaption of each of these indices, in isolation, would be able to indicate the fitness of deployment of bioenergy in iron and steelmaking across the world, but only from a single perspective. Instead, to provide a holistic picture, it is necessary to integrate these into a single index that captures the key top level factors as a function of geography. The methodology used in the present paper for achieving this integration is to formulate a new multi-criteria global suitability assessment. The work concentrates exclusively on the BF-BOF route, and there bioenergy opportunities specifically presented by the coke oven, sinter plant and blast furnace, to facilitate comparison of like with like. However, with suitable input data, the presented approach can be adapted to other routes to iron and steel production and a Global Suitability Index methodology could readily be modified to consider the insertion of renewables into other industries. A key focus of the work is to reduce the extent of subjectivity in assessing fitness for purpose, when compared with established methods [38], although this cannot be eliminated entirely.

The next Section "Methodology" describes the Global Suitability Index, the methodology developed for this assessment study, followed by the obtained results. Section "Discussion" compares the outcomes with the current practice and summarizes the model's limitations and future improvements. The final Section presents the conclusions of the study.

Methodology

'Global suitability' is defined here as the disposition of a country for adapting alternative fuels in the studied sector, determined by comparing countries. This section describes the algorithm used to assess global suitability.

Methodology development

In this paper, we have developed a Global Suitability Index which is an integrated approach for assessing fitness, taking into consideration a combination of variables of intended purpose (in the present case insertion of bioenergy into BF ironmaking). Most of the time, the assessment of suitability requires using corresponding standards and/or an expert judgement [38] on setting the threshold for the fitness levels. An innovative methodology has been created in the present work, which does not require such a step, as the thresholds are defined by the data. This reduces the subjectivity aspects in the fitness assessment analysis and makes suitability assessments easier.

The methodology incorporates the relevant features of previous indices. In detail, the hierarchical approach of the Habitat Suitability Index [35], where the variables are grouped into sub-indicators to reflect the suitability of a specie in a given aspect, is followed to combine the sub-indicators into the final index value. The required standardization and transformation of the data were revised from the World Energy Trilemma Index [36]. Categorization of the obtained values and meaning of each level were adapted from the Land Suitability Index [37]. The summary of adapted features from each model is provided in Fig. 1. To facilitate the end use, the proposed methodology for this work was designed to be able to be reproduced without the need for any sophisticated software.

Global Suitability Index

To obtain the suitability value for each country, several of socio-economical, geographical, technical as well as political variables were considered (Table 1). Those variables were grouped into three factors to provide information on steel production status via BF-BOF route, sustainable biomass resources and governmental inclination for the use of alternative fuels for each country. There are numerous variables that could (and ideally should) be included in the Global Suitability Index. However, there were various limitations on the variable selection, including:

- Limitations on the available data in literature – data available for some relevant countries, but not others
- Data reliability – e.g. data that is anecdotal and/or lacking in validation
- Data applicability – data was found only for specific steelworks and not the country's entire iron and steel industry
- Data compatibility – cases where it was not practicable to render data in a consistent form, e.g. the unit of assessment differed between countries.

Table 1 is a list of all variables that the authors contemplated to include in the Global Suitability Index and summarizes the reasoning for their inclusion/exclusion (for further detail, see Appendix A).

The final Global Suitability Index as well as its intermediate factors are on a scale between 0 and 3, which is split into three categories to classify each country's suitability as either low (< 1), moderate (≥ 1 and < 2) or high (≥ 2) in the studied aspect (explained in further detail in results section "Results"). The following subsections provide details on the calculations, supported by graphical representation in Fig. 2. Due to page limits, the sections below present a methodological overview and the full details of mathematical methodology may be found in the supplementary material.

Calculation of the intermediate factors

For the final Global Suitability Index, in total 15 variables (plus 1 sustainable forest policy variable) were evaluated and split into three factors: steel production (SF), bioenergy (BF) and policy (PF). In detail, the steel production factor synthesizes variables to assess country's potential for the alloy's long term production via the BF-BOF route. The bioenergy factor, on the other hand, estimates the size of the bioenergy resources relative to the size of the steel production via the BF-BOF route. The policy factor then reflects the country's governmental incentive, motivation and support for the use of alternative fuels, important aspect for successful fuel switching. Information how variables

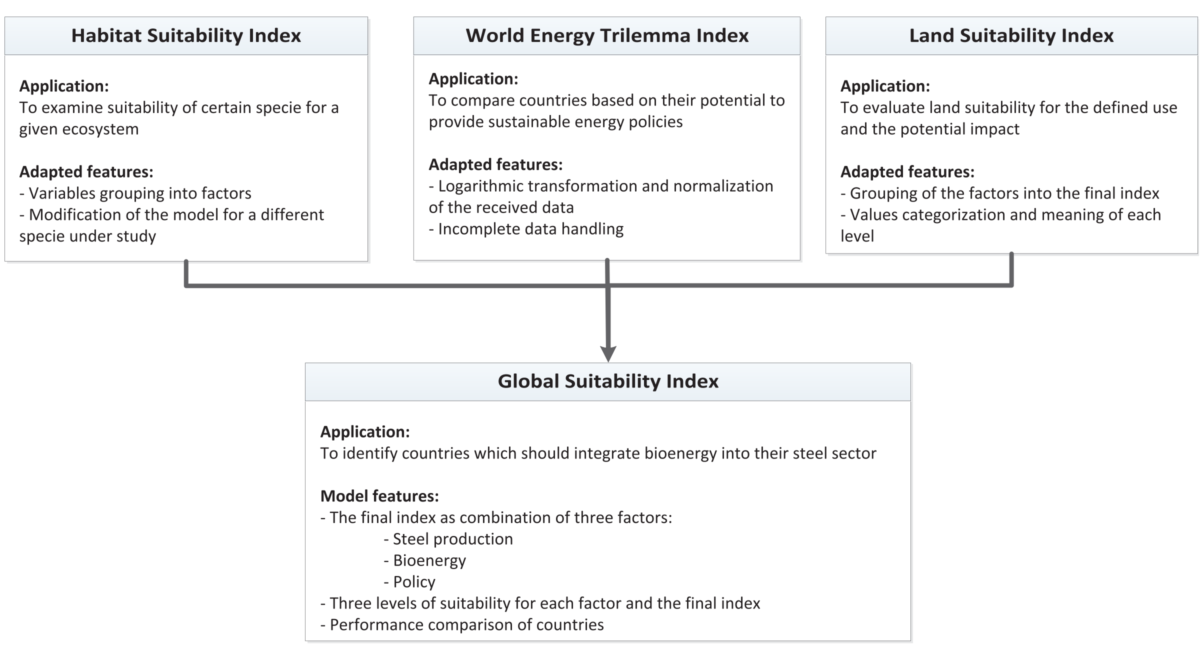


Fig. 1. Summary of features adapted by the Global Suitability Index from the three previous models. The main concept was adapted from the Habitat Suitability Index [35]. The data transformation and handling performed in this study was customized from World Energy Trilemma Index [36] and Land Suitability Index [37].

Table 1
List of all considered variables. The list includes explanation of why the present authors considered them necessary to include, or not and the sources from where the data were collected. Search structure is provided for cases where specific data have to be selected in the provided source.

Considered Variable	Reasoning for inclusion	Included in analysis and further explanation	Source (Search structure)
Agricultural area	To represent the amount of arable land.	Yes	[39] (Indicator: Agricultural land; Units: sq.km; Year: 2013)
Agricultural residue	To represent the size of agricultural residues. *Sum of residues from barley, coconuts, groundnuts, oats, rapeseed, rice, rye, sugarcane, sunflower seed and wheat was performed. The biomass selection was done based on study by Zandi et al.* [40]*. The residue amounts were estimated using the harvest index.*	Yes	[41] (Elements: Production quantity, Items: barley, coconuts, groundnuts with shells, oats, rapeseed, rice paddy, rye, sugar cane, sunflower seed, wheat; Year: 2014)
Apparent steel use	To indicate the demand for steel in the country – *represented as the total amount of crude steel utilized for further manufacturing.*	Yes	[15]
Available biomass resources	To quantify the amount of unused and available biomass resources which are also suitable for iron and steel making.	No Limitation in the data availability and their reliability.	
Circular economy motivation	To indicate the country's attitude for keeping resources in the economy – *represented as landfill rate per capita.*	Yes	[42–44]
Coastline	To indicate the access to sea and possibilities for importing resources.	Omitted Indicated as insignificant by PCA, see Appendix A	[45]
Coking coal consumption	To reflect the amount of coking coal consumed.	Yes	[46]
Coking coal production	To reflect the amount of coking coal produced.	Omitted Indicated as insignificant by PCA, see Appendix A	[46]
Contribution to total greenhouse gas emissions	To express the national motivation to decarbonize their BF-BOF steel production route – *represented as percentage of the total greenhouse gas emitted.*	Yes	See Appendix B for further details
Cost of coking coal	To indicate the average price of coking coal in the country.	No Limitation of the available data and their reliability.	
Cost of biomass	To indicate the average price of the alternative fuel.	No Limitation in the data availability and compatibility.	
Development level	To indicate the development status of the country – *represented using Human Development Index.*	Omitted Indicated as insignificant by PCA, see Appendix A	[47]
Economic growth	To represent economic growth of the country – *represented as average GDP growth over 5 years.*	Yes	[39] (Indicator: GDP growth; Units: annual %; Years: 2010 to 2014)
Economic performance	To represent economic performance of the country – *represented by two variables: GDP as well as GDP per capita.*	Omitted Indicated as insignificant by PCA, see Appendix A	[39] (Indicator: GDP, PPP; Units: current international $; Years: 2014 or value from past 5 years Indicator: GDP per capita, PPP; Units: current international $; Year: 2014 or value from past 5 years)
Energy cost	To account the difference in the energy costs – *represented by GDP per unit of energy use.*	Omitted Indicated as insignificant by PCA, see Appendix A	[39] (Indicator: GDP per unit of energy use; Units: constant 2011 PPP $ per kg of oil equivalent; Years: 2013)
Forest area	To represent the available forest area, excluding protected area.	Yes	[48] (Variable: Forest – Protected Area; Units: 1 000 ha; Year: 2015)
Governmental support for development	To indicate the ability of the government to promote private sector development – *Represented by index measuring regulatory quality.*	Yes	[49] (Indicator: Regulatory Quality; Year: 2014)
Industrialization rate	To represent the economic importance of the industrial sector – *represented by the percentage of GDP coming from the industrial sector.*	Omitted Indicated as insignificant by PCA, see Appendix A	[36] (Key metrics: Industrial sector; Units: % of GDP; Year: 2015)
Iron ore production	To account for the amount of iron ore produced.	Omitted Indicated as insignificant by PCA, see Appendix A	[15,50]
Labor cost	To evaluate the difference in the cost of labor – *represented by average wage in manufacturing sector.*	Omitted Indicated as insignificant by PCA, see Appendix A	[51]
Land area	To represent the total land area of the country.	Omitted Indicated as insignificant by PCA, see Appendix A	[39] (Indicator: Land area; Units: sq.km; Year: 2015)
Limestone production	To account for the amount of limestone produced.	Omitted Indicated as insignificant by PCA, see Appendix A	[52]
Population size	To express the population size of the country.	Omitted Indicated as insignificant by PCA, see Appendix A	[39] (Indicator: Population, total; Units: thousand; Year: 2014)

(*continued on next page*)

Table 1 (*continued*)

Considered Variable	Reasoning for inclusion	Included in analysis and further explanation	Source (Search structure)
Process units within BF-BOF route	To define which process units are presented at each country (e.g. coke ovens or blast furnaces using pulverized coal) and identify the bioenergy opportunities for them accordingly.	No Limitation in availability of public data of this kind.	
Proportion via BF-BOF	To express the significance of BF-BOF route for the steel production in the country – *represented as the percentage of total steel produced.*	Yes	[15]
Reliance on imported coking coal	To express the motivation for decreasing country's reliance on imported fuels – *represented as ratio of the amount of coking coal imported over the amount of coking coal consumed.*	Yes	[46]
Steel production via BF-BOF	To indicate the amount of steel produced via BF-BOF route.	Yes	[15]
Strength in policy proposals	To indicate the quality of policy formulation and implementation – *represented by index measuring governmental effectiveness.*	Yes	[49] (Indicator: Government Effectiveness; Year: 2014)
Substitution rate possibility	To evaluate the substitution rate for biomass possible with the existing technologies in each specific country.	No Limitation in data consistency and availability as no data like this exist.	
Sustainable forest policy	To ensure the country has legislation and regulations supporting sustainable forest management at national and regional level – *represented as yes or no based on their forest protection legislation.*	Yes	[48]
Total steel production	To express the total amount of steel produced.	Yes	[15]
Wood residue	To account the amount of forest residue – *represented by the amount of wood processing co-products including wood waste and scrap not useable as timber, but excluding bark.*	Yes	[53] (Elements: Production quantity; Items: Wood residues; Year: 2014)

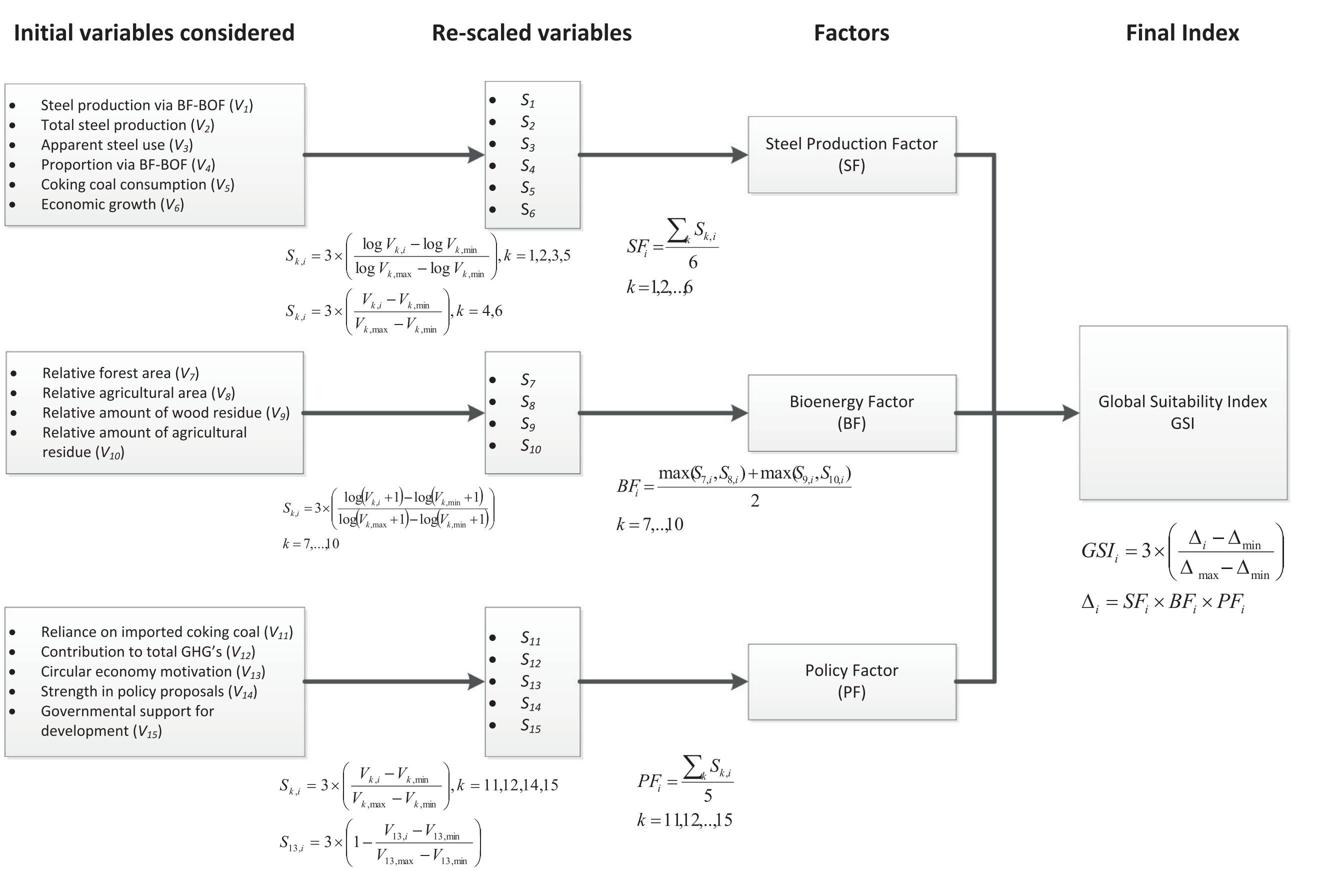


Fig. 2. Schematic representation of the methodology for obtaining the Global Suitability Index. The initial variables were re-sized to a scale between 0 and 3 and then combined into the corresponding factors. The final global suitability values were obtained from the multiplication of all factors and their further re-sizing.

Table 2
List of variables considered for the global suitability analysis and their grouping into the relevant factors. The table presents variable names, their corresponding symbols and information on any data modification performed to the original data collected.

Variable considered	Symbol	Calculations	Units	Year
Steel Production Factor				
Steel production via BF-BOF	V_1	None	kt	2014
Total steel production	V_2	None	kt	2014
Apparent steel use	V_3	None	kt	2014
Proportion via BF-BOF	V_4	None	%	2014
Coking coal consumption	V_5	None	kt	2015
Economic growth	V_6	Average across 5 years	%	Between 2010 and 2014

Variable considered	Symbol	Calculations	Units	Year
Bioenergy Factor				
Sustainable forest policy			Binary variable yes/no	2014
Relative forest area	V_7	Sustainable forest policy$*\frac{\text{Forest area}}{\text{Steel production via BF-BOF}}$	ha/t	$\frac{2015}{2014}$
Relative agricultural area	V_8	$\frac{\text{Agricultural area}}{\text{Steel production via BF-BOF}}$	ha/t	$\frac{2013}{2014}$
Relative amount of wood residue	V_9	$\frac{\text{Wood residue}}{\text{Steel production via BF-BOF}}$	m^3/t	$\frac{2014}{2014}$
Relative amount of agricultural residue	V_{10}	$\frac{\text{Agricultural residue}}{\text{Steel production via BF-BOF}}$	t/kt	$\frac{2014}{2014}$

Variable considered	Symbol	Calculations	Units	Year
Policy Factor				
Reliance on imported coking coal	V_{11}	$\frac{\text{Coking coal consumption} - \text{Coking coal production}}{\text{Coking coal consumption}}$		$\frac{2015}{2015}$
Contribution to total GHG's	V_{12}	See Appendix B for further details	%	2014
Circular economy motivation (see Table 1)	V_{13}	None	kg per capita	2014
Strength in policy proposals	V_{14}	None		2014
Governmental support for development	V_{15}	None		2014

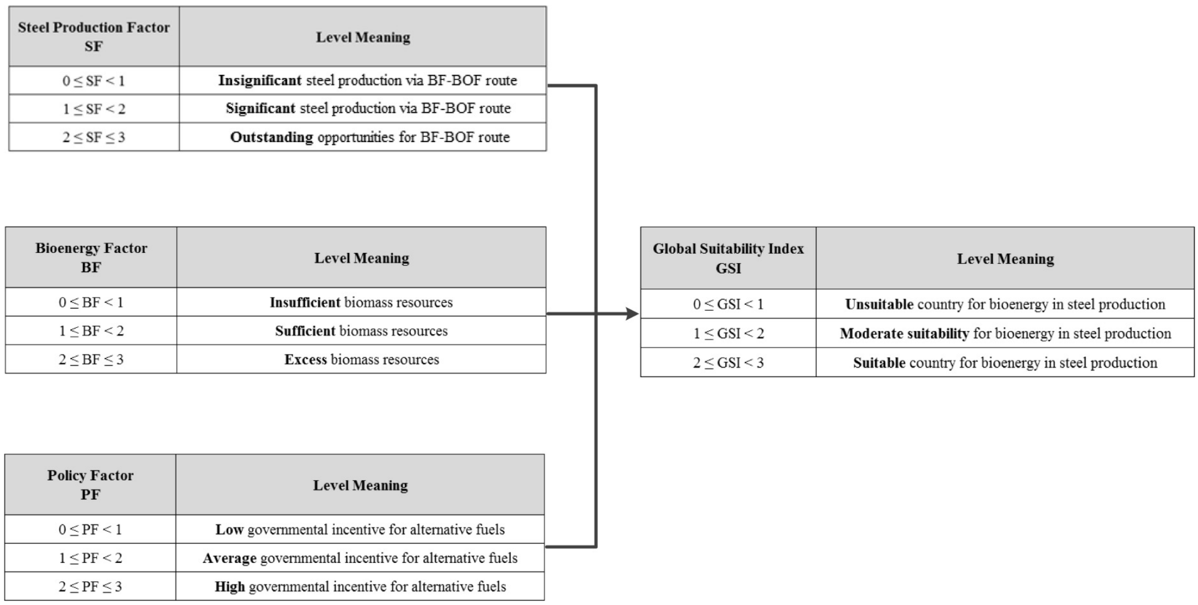


Fig. 3. Meaning of values for each factor and the final Global Suitability Index. The scale ranges between 0 and 3, where values up to 1 indicate low performance, between 1 and 2 moderate performance, and above 2 outstanding performance of a country in the studied aspect.

listed in Table 1 were transformed and grouped into the factors described above is provided in Table 2.

The associated variables for steel production factor were selected using a multivariate statistical tool, principal component analysis (PCA), which identified correlated variables to blast furnace route ironmaking and subsequent steel production. The issue of incomplete data was overcome by using nonlinear iterative partial least squares (NIPALS) algorithm. The details on the mathematics are provided in Appendix A. The choice of variables for bioenergy factor was to ensure sustainable sourcing of woody biomass. Therefore the forest area variable V_7 is omitted from analysis for those countries which do not hold forest protection legislation and sustainable forest policy.

The methodology puts each variable on a common scale by value comparison, to provide end users with robust and flexible evaluation without requiring them to have expert knowledge in any of the individual variables. In further detail, the values for each variable are rescaled to values between 0 and 3, where 0 is given to the smallest value in the dataset and 3 to the largest. Intermediate values $S_{k,i}$ for each variable k are hence obtained using the following equation

$$S_{k,i} = 3 \times \left(\frac{V_{k,i} - V_{k,\min}}{V_{k,\max} - V_{k,\min}} \right) \quad (1)$$

Where $V_{k,i}$ is the recorded value for variable k for country i, and $V_{k,\max}$ and $V_{k,\min}$ are the corresponding maximum and minimum values respectively.

The varying nature of the collected data requires modification of Eq. (1) for certain variables to retain their meaning, whilst still keeping them on the same scale. For variables V_k with a high magnitude outlier (mainly for the steel production factor, due to China or India's values), variables V_k were logarithmically transformed before the data re-scaling to decrease the impact of the outliers.

Variables V_k in bioenergy factor contained both high magnitude outliers as well as values smaller than one. To those, 1 has been added to the observed values before the logarithmic transformation took place to prevent taking logarithms of values smaller than 1. Variable V_{13}, occurring in the policy factor, required to be reversed as its increasing values actually indicated lower fit. This was done by subtracting the values from 1.

The sub-indicators S_k for each factor were combined by addition and averaged. The equal importance of each variable is assumed because the information found in the literature was not sufficient to make a non-arbitrary consistent unequal weighting (although it would be easy for researchers using this methodology in future to assign non-equal weightings if they wish). For the bioenergy factor, the supply of woody biomass and agricultural residues was given equal weighting, to avoid discriminating between sources. Given that there is competition for biomass resources in most countries, whichever of these two was the larger supply was considered, rather than the sum of these or treating these individually. In view of the sustainability implications of the use of woody biomass, a country was only considered to have a supply of this, if either there is legislation on the sustainable use of forest products or the supply concerned consists only of residue from other applications of wood.

The authors are aware of the subjectivity implicit in any ranking system that uses weightings (equal or otherwise), but see this as unavoidable in an initial down selection. Further details on the methodology are represented in Fig. 2 and can be found in the supplementary material that accompanies this paper.

Calculation of the Global Suitability Index

The Global Suitability Index assesses the suitability of introducing bioenergy into a country's steel sector by simultaneously assessing the potential for steel production via BF-BOF route, relative bioenergy resources and governmental support. The three factors are combined via multiplication $\Delta_i = SF_i \times BF_i \times PF_i$, using the approach adopted in the Land Suitability Index, to score higher countries consistent across all three factors above countries which are strong in one and weak in the other. Achieving the Global Suitability Index (GSI_i) values split across the levels from 0 (low) to 3 (high) was performed using Eq. (2):

$$GSI_i = 3 \times \left(\frac{\Delta_i - \Delta_{\min}}{\Delta_{\max} - \Delta_{\min}} \right) \quad (2)$$

where $\Delta_{\min}$ and $\Delta_{\max}$ are the minimum and maximum values achieved from multiplying together all factors.

Results

The final suitability value for using sustainably sourced bioenergy for the iron and steel production via BF-BOF is a reflection of countries' relative performance across the three studied factors: steel production,

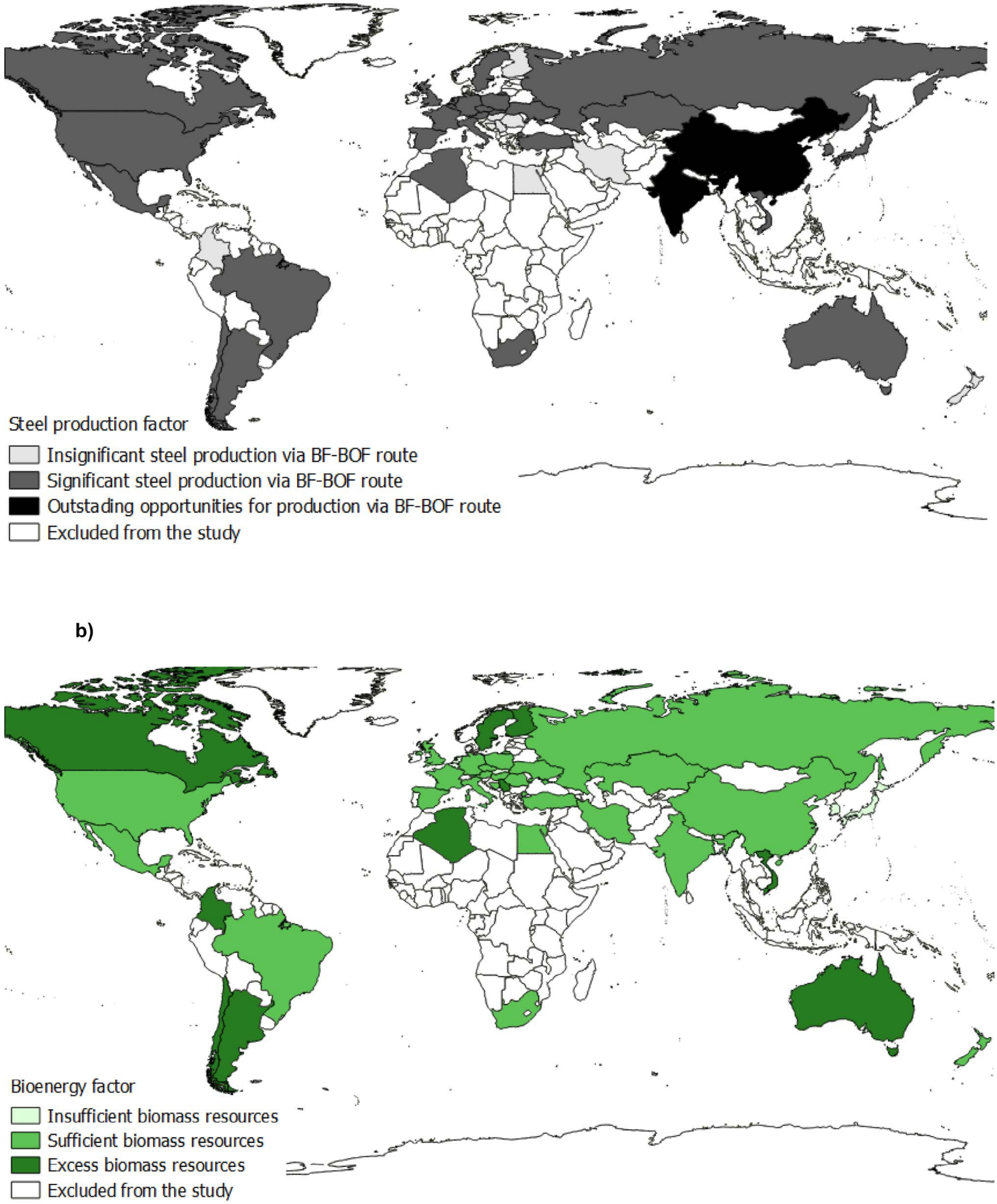
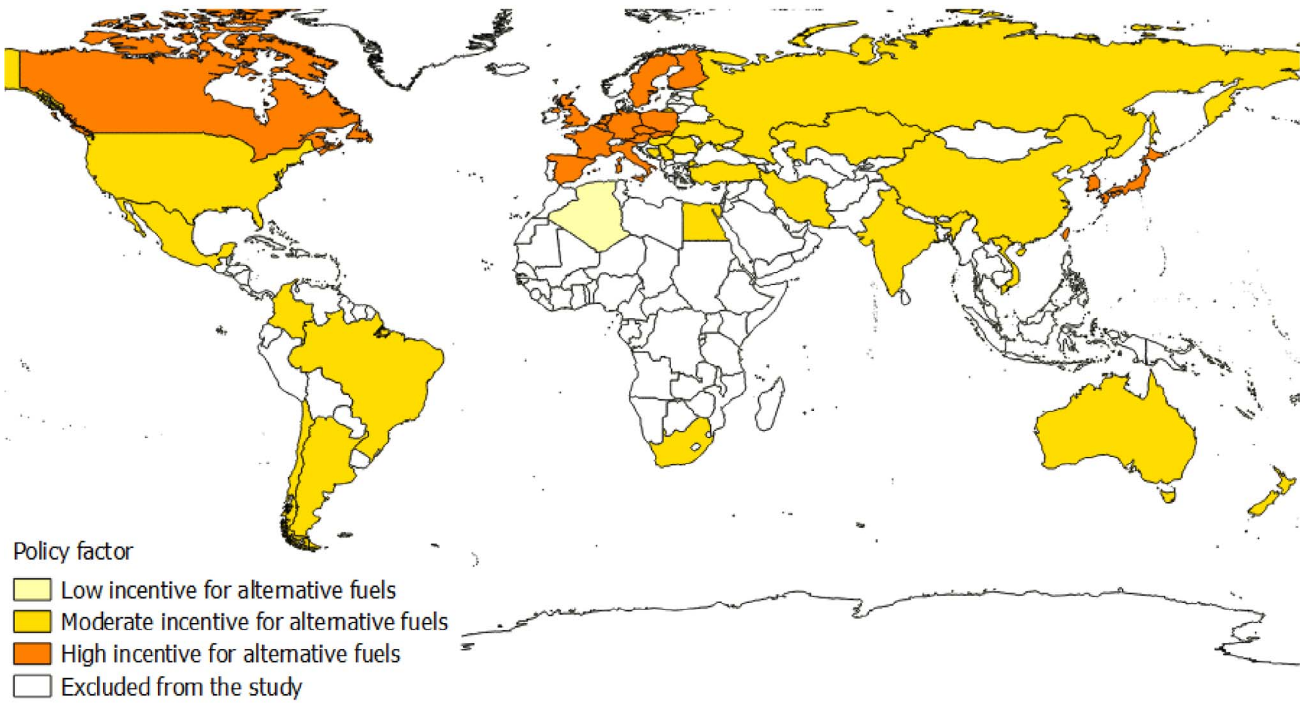


Fig. 4. Graphical representation of the results for the steel production factor in a), bioenergy factor in b), policy factor in c) and for the final Global Suitability Index in d).

bioenergy and policy. For each indicator, every country obtained a score on continuous scale between 0 and 3. This scale was split into three categories, to classify each country either as insignificant, average or dominant first with respect to each factor and then with respect to the global suitability. Detailed meaning of each category in relation to the studied indicator is presented in Fig. 3. The classified results are presented graphically via four global maps in Fig. 4 (see Table C in Appendix C for the exact values). The following sections will summarize the results obtained for individual factor and the final index.

c)



d)

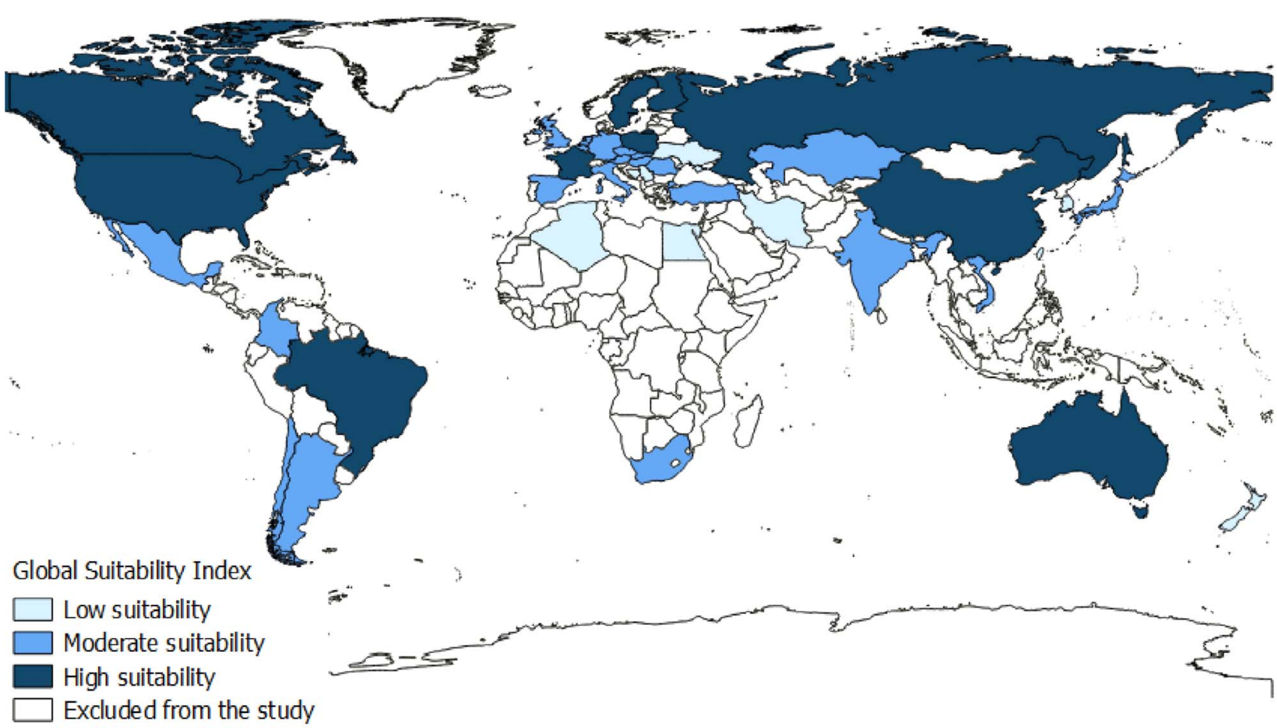


Fig. 4. (*continued*)

Steel production factor

The classification of the countries based on their significance in terms of long term iron and steel production via BF-BOF route is presented in Fig. 4a. Countries shaded black present outstanding opportunities for iron and steel production by this route. Darker grey are countries which steel production via BF-BOF route is still significant for the global steel market and light grey are countries classified as insignificant, all done by relatively comparing countries under study.

Out of the total 40 countries studied, the steel production factor classified 2 countries as world leading and 9 with steel production as insignificant. China scored the highest in the factor, with a high lead before India, all classified as world leading and listed based on the given scores. Japan, Russia and South Korea, world second, third and fourth biggest producers of steel via BF-BOF route respectively [15], are classified just below the class split and are shown as significant. Countries classified as insignificant for the world steel production market are Hungary, Finland, Iran, Bosnia and Herzegovina, Colombia, Romania, Egypt, Serbia and New Zealand, listed in descending order.

Bioenergy factor

The amount of technically suitable and sustainably sourced biomass resources relative to the country's amount of the steel production via BF-BOF route is graphically represented in Fig. 4b. Comparable countries with a relative excess amount of suitable biomass resources ($\geqslant 2$) are colored dark green. Mint green are countries with a sufficient amount of suitable biomass for partial fossil fuel substitution ($\geqslant 1$ and < 2), and countries with insufficient biomass resources are highlighted light green.

The bioenergy factor selected 10 countries with surplus sustainable biomass resources and identified 6 with insufficient biomass resources. Countries with score higher than or equal to 2 are Colombia, Australia, Chile, Canada, Argentina, Algeria, Serbia, Sweden, Vietnam and Finland, listed in descending order. There are in total twenty-four countries with potentially sufficient suitable and sustainable biomass resources (having values < 2 and $\geqslant 1$), where Kazakhstan, Romania and Brazil obtained scores just below the threshold for being classified in the higher category and United Kingdom, Czech Republic, Bosnia and Herzegovina, China, Ukraine and Germany were touching the threshold for lower category (see Table C in the appendix). Countries with scores below 1 are Slovakia, Netherlands, Belgium, Japan, South Korea and Taiwan, also listed in descending order.

Policy factor

The governmental motivation for using the alternative fuels in iron and steel making via BF-BOF route is represented using the policy factor, and the results are shown in Fig. 4c. Orange color represents countries for which it is expected that the government would and is able to successfully support the use of alternative fuels. Governments for countries colored yellow are expected to give moderate support and incentive. Lastly, light yellow shades indicate countries with expected limited support for the fuel switching.

In the policy factor, 17 countries were classified with highly supportive governments for the alternative fuels. In the top category, i.e., with values above and including 2, were mainly European countries such as Sweden, Austria, Finland, Germany, Belgium, Netherlands, Slovakia, UK, France, Czech Republic, Spain, Italy and Poland. Japan, Taiwan, South Korea as well as Canada were also categorized with high governmental support. Algeria, on the other hand, was the only country with score on the other side of the scale with value less than 1, where a low or non-existing interest from government for the use of alternative fuels in the steel sector can be expected.

Dominant countries overall

The combined performance across all factors, expressed by the Global Suitability Index, is shown in the world map in Fig. 4d. Countries colored dark blue are identified as countries with high suitability for integrating bioenergy into their steel production via the BF-BOF route. Turquois colored countries are countries with moderate suitability and light blue countries with low suitability for the use of the alternative fuels in the steel sector. The final global suitability values are also presented in Fig. 5, where countries are ordered in their ascending values. Comparison of countries' performances across all three factors reveals the factors in which each specific country underperforms or over-performs, and enhances understanding about the potential barriers for deployment of sustainable bioenergy in the studied sector.

The Global Suitability Index identified 10 countries as highly suitable for the bioenergy integration into iron and steel making. Top five are Canada, Sweden, China, the United States, France, listed in the descending order. China scored the highest in the steel production factor, whereas Canada and the United States scored the highest in the bioenergy factor. For France and Sweden, on the other hand, the policy factor was the most dominant. Other highly suitable countries are Finland, Australia, Poland, Brazil and Russia. However, a gap of 0.2 can be observed between the last country in the top 5 (France) and the next country (Finland).

Out of the 40 studied countries in total, 9 of them were identified as unsuitable. Those were Ukraine, Iran, Serbia, Egypt, New Zealand, Algeria, Bosnia and Herzegovina, South Korea and Taiwan. Even though some of them scored in the highest category in one of the examined factors, e.g., Serbia (Bioenergy factor of 2.1), Algeria (Bioenergy factor of 2.2), South Korea (Policy factor of 2.57) or Taiwan (Policy factor of 2.5), their underperformance in other factors gave them an overall Global Suitability Index value below 1.

Multiple countries presented a strong performance across a combination of two factors, but greatly lacking the third factor. The Venn diagram in Fig. 6 demonstrates the opportunities as well barriers that each country would be facing, based on which set they are included in or excluded from, respectively. Certain countries are also listed on the borders of a particular set (such as Brazil, Russia, China, etc.), which demonstrates they satisfy the studied factor with limitations. Bosnia-Herzegovina, New Zealand and Iran are placed outside the Venn diagram as their results demonstrated low significance (i.e., values below median value) across all studied sets.

Discussion

Current bioenergy use in the steel sector and model credibility

Comparing the global suitability indices with national shares of world production of iron and steel using the BF-BOF route (Fig. 7), it can be seen that several of major players in iron and steelmaking, i.e. China, Russia, USA and Brazil have high suitability for sustainable bioenergy use in BF-BOF. Combining their high suitability index, with their major role in world steel production, suggests that widespread deployment of bioenergy in these few countries would be a significant step towards transitioning the global iron and steel industry to the use of renewables. On the other hand, the moderate suitability of Japan, India and Germany, and low suitability of South Korea, Ukraine and Taiwan indicate that major steelmaking countries can contain barriers which limit the deployment of bioenergy in the sector. Therefore choosing where to introduce alternative fuels based purely on the size of the steel industry would be a deficient approach.

The authors attempted to compare the outcomes of the Global Suitability Index with:

- studies of the future potential of bioenergy in individual countries, as found in the literature;

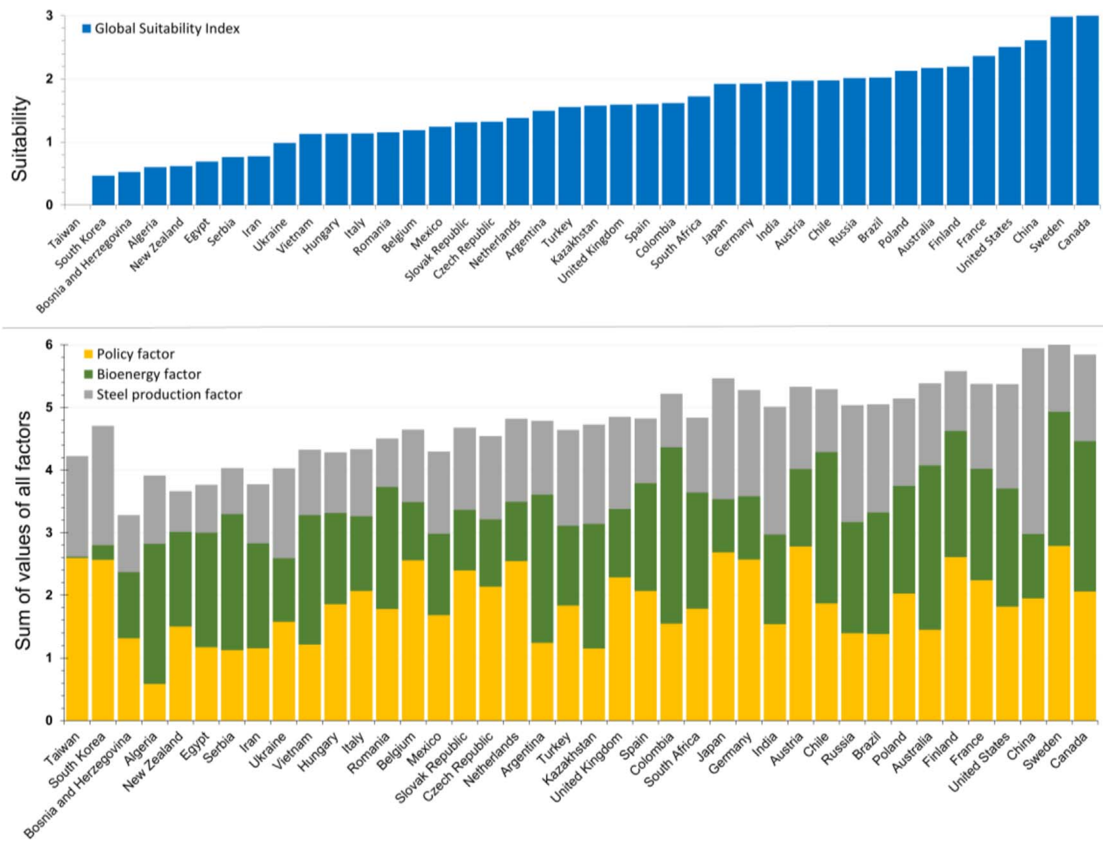


Fig. 5. Comparison of the final Global Suitability Index values (top) and the sum of all three factors considered (bottom). Size of the individual bar represents the country's opportunity or barrier in the studied factor when compared with other countries.

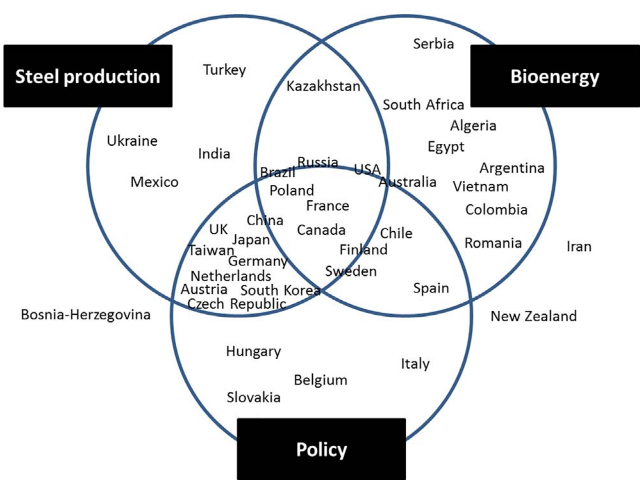


Fig. 6. Venn diagram comparing opportunities and barriers that each studied country is facing for blast furnace ironmaking. Countries within steel production set have iron and steel industry that has been identified as significant on the global market, those within bioenergy set as containing sufficiently large sustainably sourced biomass resources for iron making application, and countries with supporting national policies for adaptation of alternative fuel uses have been enclosed in the policy set.

- evidence of actual deployment of bioenergy in iron and steelmaking.

The availability of data for such validation were not sufficient to deliver a full validation of the Global Suitability Index approach but arguably, the lack of such data is the reason why a Global Suitability Index is needed, as an initial ranking tool. Nonetheless, a number of interesting observations were made:

- Sweden, Finland, Australia and Brazil with a high Global Suitability Index are either already using bioenergy in iron and steelmaking or have done extensive research in the field.

Out of the listed countries, only Brazil has full scale industrial practice of bioenergy in steelmaking, with a number of fully operational charcoal blast furnaces [54]. Brazil is the world's largest wood-based charcoal producer, where most of it is used by the iron and steel sector [55]. Even with this successful practice, Brazil achieved a Global Suitability Index of just 2.0 putting it in the lower half of the high suitability category. This is due to a below average score in the policy factor, indicating potential barriers from the governmental side and a need for increased attention to be paid to the sustainability of biomass usage, e.g. through managed forests.

The situation in Sweden, by contrast, is different. The very high policy factor and high bioenergy factor classify Sweden as one of the most suitable countries, even though biomass has not been commercially applied into iron and steelmaking yet. Multiple studies have focused on this topic [56,57] and with the Fossil Free Sweden initiative to become first fossil-free wealthy nation [58], the very high global suitability value of 2.9 indicates high suitability and an excellent opportunity.

Extensive research on bioenergy in iron and steel production has been done also in Australia [59]. Australia's high suitability value is mainly due to high bioenergy factor, corresponding to the potential of unused wood residues [60]. However, in view of Australian's extensive coking coal resources [61] and costs of charcoal of US$386 per metric ton, in comparison to coal of around US$90 per metric ton [62], biomass is not currently competitive with coal in BF-BOF applications. As a result, companies considering biomass, such as Arrium, have put any further research and development in this area on hold. Hence the suitability value of 2.1 reflects the country's major potential, but

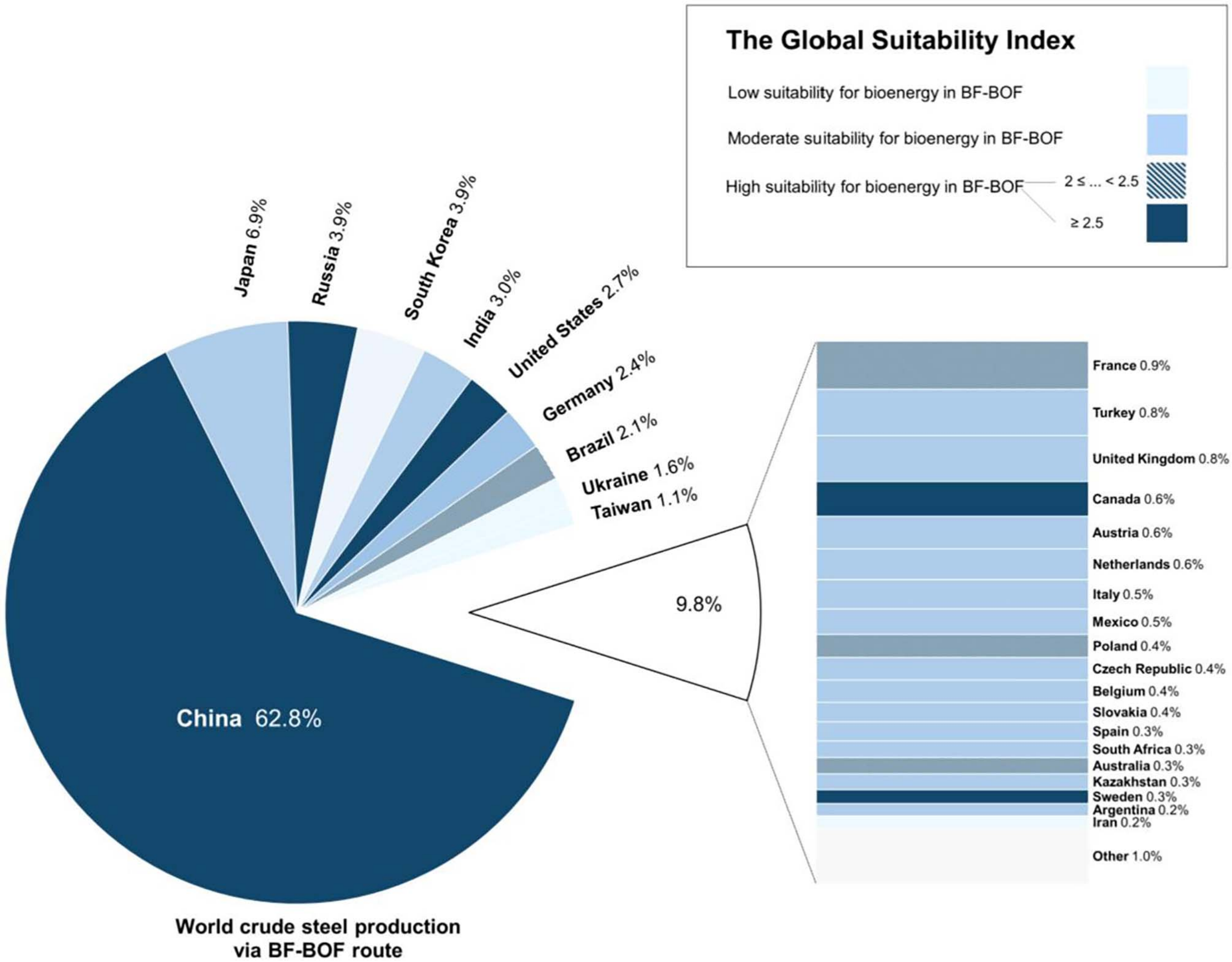


Fig. 7. The suitability values for biomass integration into iron and steel making based on the country's share in the global crude steel production via BF-BOF route in 2014. Based on data from World Steel Association [15].

exploitation of this would require a desire to move away from coal.

Finland's suitability value of 2.1 indicates the potential, as discussed in work by Suopajärvi [33,63]; however, its low significance on the steel market (steel production factor of 0.9) makes it sit on the threshold.

- In common with Sweden, the countries Canada, China, the USA and France also have very high Global Suitability Index, but unlike Sweden, these countries do not yet appear to be actively considering the opportunity.

The highest suitability index was that of Canada, which same as France scored above median value across all contributory factors. Canadian program run by the Canadian Steel Producers Association showed strong interest on the use of biomass in iron and steel making as a substitute for fossil fuels [28]. The contribution of only 0.6% to the global steel produced via BF-BOF route [15], however, might not have a sufficient impact on the global bioenergy integration into this sector.

The opposite in terms of the global steel production is true for China, which steel production factor of 3 significantly impacted its final index value. The low value of China's bioenergy factor is due to its high steel production and indicates the size of the resource in relative terms. In absolute terms China is a large producer of biomass and is already supplying a large amount of charcoal to Japan and South Korea producing 10% of the global fuel wood in 2010 [64]. As China is targeting to have a 15 and 20% non-fossil fuel share of its total energy supply by 2020 and 2030 respectively [65], the Global Suitability Index indicated a potential opportunity for the use of bioenergy in iron and steel sector in this country, with the important caveat that the biomass needs to be sourced sustainably.

Large existing biomass resources are also in the USA. The USA has the potential to supply 15–20% of the total global biomass [66], and is expected to see the largest annual growth in bioenergy use in industry between 2010 and 2030 [67]. However, charcoal prices would have to be the lowest in the world so that it is competitive with coal [62]. On the other hand, a study specific for a plant in the North East of France showed that the injection of charcoal fines at tuyeres can be profitable for this plant [34], and the observed high Global Suitability Index value in this study encourages to perform further research into bioenergy integration within iron and steel industry for this region.

- Argentina have chosen to deploy bioenergy in iron and steelmaking, although its Global Suitability Index is moderate.

Argentina has two charcoal fired blast furnaces in the northwest of the country, where plantations of eucalyptuses are specially grown mainly for this purpose [68]. The medium performance in the final suitability index is mostly due to the steel production and policy factors. The high bioenergy factor highlight the bioenergy potential, however the other factors show the low significance of Argentina's steel production and potential issues with low governmental support and concerns about sustainable biomass sourcing. We stress that this refers only to BF-BOF and differs from the stance that Argentina is demonstrating, for electricity production, through their Renewables program, where they want to reach 20% of their electricity production from renewables by 2025 [69].

- Belgium and Netherlands have successfully deployed bioenergy on a significant scale in cement industry, another carbon intensive industry, however their suitability index for bioenergy in the steel industry is close to 1.0 (i.e., sitting at the limited suitability threshold).

The successful deployment of bioenergy in other industries suggests that it should be relatively easy for them to expand their current efforts into iron and steelmaking [70]. However, the Global Suitability Index is pointing out the limitation in biomass availability for the two countries by scoring 0.9 in the bioenergy factor. Indeed, biomass is imported and biomass availability is already considered as a barrier for it further implementation [71]. Hence the identified low suitability of bioenergy for iron and steel sector for this country is rational when aiming at promoting the use of local resources.

- Several countries scored particularly high in bioenergy and policy factors, however, their Global Suitability Index value was then greatly reduced due to their low steel production factor. This reveals biomass opportunities for different sectors within the country or for biomass trade deals between countries.

If only policy and bioenergy factors were considered, Colombia, Chile, Canada, Finland and Sweden would be amongst the top 5 most suitable countries, (Fig. 5). This indicates these countries have untapped sustainable biomass resource potential and that further focus on effectively utilizing it might be worthwhile – not only for the iron and steel industry.

Limitations and potential for further improvements

The bioenergy factor used in this paper accounts only for the total amount of biomass resources that are potentially suitable for use in ironmaking and can be sustainably sourced. Thus the Global Suitability Index does not consider competition for the resources from other sectors. This limitation of the work should be recognized when a selected country is chosen for possible bioenergy deployment. Further analysis of total available biomass resources – specifically identifying their type as well as upgrading possibilities – and projected demand from other industries should be performed to accurately identify their true extent. Additionally, life cycle assessment studies should be performed to achieve the greatest environmental benefit. This was out of the scope of this work as its purpose is developing a tool for initial screening of suitable country based on potential, when compared with other countries.

The lack of publicly available data on the ironmaking process units in each country limited more accurate definition of possibilities for bioenergy integration into this industry. Different biomass types and later their upgrading process allow fossil fuel substitution at different amounts at each unit. The choice of the biomass type, upgrading process and the unit in which the bio-based product will be utilized then impacts feasibility of the solution. As each country is specific in producing different types of bio-based fuels and in characteristics of its ironmaking process units, the combination of these two factors influences greatly the overall suitability of each country. This work treated this simplification as inevitable, however, scope for improvement is present.

The proposed methodology also treated each of the factors: steel production, bioenergy and policy, with the same importance, and results might differ where the weightings are otherwise. Therefore a sensitivity analysis should be performed to see the impact of each factor. This is considered as future work together with scenario modelling. Such work will further reveal which factor is crucial for integrating bioenergy into steel production sector.

Lastly, this methodology has not considered the economical aspects. The financial struggles of the iron and steel plants, recent decrease in production and shut downs of major players make the use of biomass unappealing if it is not profitable. Work done by Feliciano-Bruzual [62] identified the price required for charcoal to be competitive with coal, however only for nine countries. The authors are aware of the high importance of the fuel price on the suitability aspect, which is not only affected by the biomass type but also varies over the year based on its availability. The limited data in the literature made it difficult to obtain consistent information on the specific biomass prices for all the countries under study (where the prices also vary based on the location of the specific plant considered for the biomass utilization), therefore the cost variable was omitted from the present analysis. However, a more detailed economic analysis is planned, wherein a suitable country or countries will be selected based on the current work.

Conclusion

The paper presented a methodology, the Global Suitability Index, for selection of countries which are offering the greatest potential for adoption of domestically and sustainably sourced biomass in their national primary blast furnace ironmaking. Apart from the reduction of process emissions, using nationally sourced biomass would also eliminate emissions from bulk transport of the substituted fossil fuels, ensure sustainable biomass sourcing and benefit local economy. Hence even though biomass can be globally traded, the same as other raw materials required for the iron making process, identifying the co-location of iron and steel production, sustainable biomass resources and supportive policies for using alternative fuels has been considered in this study as the most effective way for adaptation of the alternative fuel. The Global Suitability Index developed thus consists of three factors, labelled as steel production, bioenergy and policy respectively. The study particularly focused on the top 40 countries by volume for blast furnace ironmaking and their suitability level was defined by their comparison.

Countries with the greatest opportunities to utilize biomass in this way were Canada, Sweden, China, USA and France. For all these countries, significant steel production via BF-BOF route and sustainable biomass resources were present, and they also scored high in the policy factor. It can be conclude that their current policy frameworks have at least the potential to promote alternative fuels in the sector and that it might be worthwhile for policy makers in these countries to consider the opportunity in more depth. At the same time, from the energy management point of view, the utilization of biomass resources for such application in those countries would be a strategic step for the decarbonization of their steel industry. Highly suitable were also Finland, Australia, Poland, Brazil and Russia, however potential barriers have been identified. In detail, Finland and Australia underperformed in the steel production factor, indicating low importance of their BF-BOF routes on the global market, which makes it less attractive from the global emission reduction point of view. Brazil and Russia underperformed in the policy factor, but are strong in the other two factors. This suggests that one of key barriers for success in these countries is a lack of sufficient governmental policy support, which could be addressable.

Overall, whilst we have only developed a methodology for an initial down selection, the results indicate where bioenergy in iron and steel making has a promising prospect, and further evaluation should be considered. This would include evaluation of available resources, cost-analysis and techno-economics which would further examine the potential for such application, and shape policies supporting its implementation.

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Appendix A. Data analysis for the steel production factor

PCA and NIPALS methodology

Principal component analysis (PCA) is a multivariate data analysis tool commonly used for example in the field of chemometrics, study of chemical data [72]. The method examines patterns between the studied data by their transformation into a new set of orthogonal axes, called principal components (PCs). This is done using eigenvectors of the covariance matrix of the data sample [73]. The values of those eigenvectors are further referred to as *loadings* and the newly projected data on the PCs as *scores* [74]. The selected number of PCs is less than or equal to the number of original variables for the data reduction. The relationships between the variables is then studied based on their loadings value for each PC [72,75].

As the used dataset contains missing values, a non-linear iterative partial least squares (NIPALS) algorithm (see for example pages 72 to 74 in [75]) was used to obtain the loadings and scores for each PCs. In detail, the missing values limit the practice of general PCA, which uses the singular value decomposition to obtain the corresponding eigenvalues and eigenvectors [72,75]. NIPALS can numerically calculate the PCs without the need of the covariance matrix by using so-called 'peeling' procedure, where eigenvectors are iteratively calculated and then peeled off from the dataset [76]. In other words, instead of finding all PCs using linear transformation, NIPALS algorithm finds each individual PC using iteration. The required accuracy is achieved by a pre-defined threshold, which checks the convergence of the process.

The detailed mathematics behind PCA and NIPALS is widely discussed in literature [72,75] and current commonly used data analysis software, such as R or Matlab, have these functions pre-defined.

Results obtained for steel production factor

All the data analysis was performed using mathematical software R, 64-bit version, using function **nipals** under **plsdepot** library. First, the choice of the number of PCs to analyze was performed. Generally, the number of PCs is chosen based on one of the three methods, such that:

1) Their cumulative percentage of data variation represents over 80% of the total variance of the data;
2) Only PCs with eigenvalue $\geqslant 1$ are considered;
3) The number of PCs is defined by a change in slope in the scree plot of variation percentage of each PC [72,75,77].

The first approach suggests 6 PCs (giving cumulative percentage of 83%), second 4 PCs (cumulative percentage of 73.7%) and third 3 PCs (66.1%). As the fourth and fifth PC represents only 7.6% and 5.3% variation of the data respectively, no significant relationships between variables would be observed and only first three PCs were considered for further analysis.

The relationship between the variables is observed from loadings values of each PC plot against each other. The variable's distance from the origin and the angle it forms with other variables reveals its link to other variables. In detail, the further the variable is from the origin, the more it influences the particular PC. The sharper angle the two variables between each other, in relation to the origin, the more correlated they are.

As the interest is on variables related to steel production via BF-BOF route, the PCA identifies variables for the steel production factor which are closely placed next to BF-BOF production in Fig. A. The 3-D plot projects all studied variables across all studied PCs and suggests that other than BF-BOF production variable, the steel production factor should also consider variables such as:

- Total steel

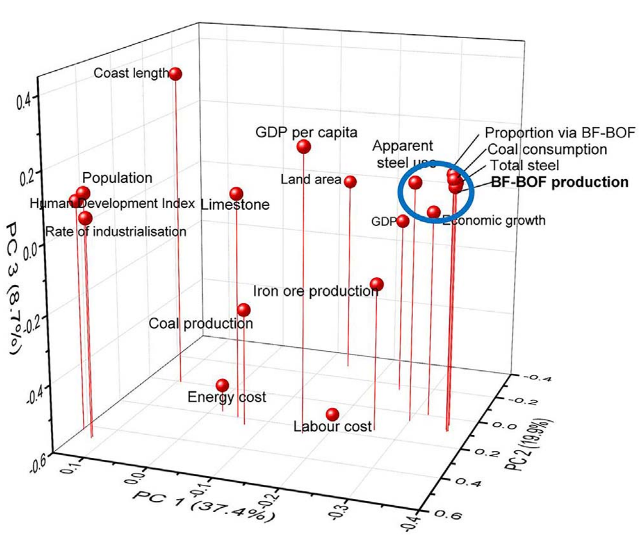

Fig. A. 3D plot of the scores for the first three principal components, representing in total 66.1% of total variation in the data. Strongly correlated variables are grouped closely together. This indicates economic growth, apparent steel use, coking coal consumption, proportion of steel produced via BF-BOF route and total steel production are all variables important for steel production via BF-BOF route.

- Coal consumption
- Apparent steel use
- Proportion of steel produced via BF-BOF route
- Economic growth

The results also revealed interesting information about low impact of population size and rate of industrialization on the steel production, as those variables were on the other side of the graph. Further analysis and discussion on which factors make countries successful candidates for steel production is not within the scope of this paper, because of the focus on initial down-selection.

Appendix B. Further calculation details

Due to the limitation in the available data, the following assumptions and corresponding calculations were performed to obtain the contribution of BF-BOF steelmaking route to country's total greenhouse gas emission (GHG's):

- The crude steel production data via BF-BOF route was obtained from World Steel Association [15] (obtained directly or converted to metric ton).
- Secondary data for the GHG's occurring during the iron and steel production was obtained from Gabi Database [78], focusing on Life Cycle Inventories. From here, the emission intensity of German based BF-BOF route of 1.94 tCO_2eq per metric ton of crude steel was obtained. Assumption was made to use this emission intensity value to calculate the emission intensity of the iron and steel production in other countries. This is likely to underestimate GHG's production for those countries whose iron and steel production processes are less modern than Germany's, but this was unavoidable as iron and steelmaking GHG's data was not available for many of the countries studied.
- The estimated GHG's amount was then a product of the amount of steel produced via the BF-BOF route within each country and the specified emission intensity.
- Total GHG's produced by each country was obtained from World Resources Institute [79] (in $MtCO_2eq$).
- The percentage contribution of the BF-BOF steel production to the country's total GHG's was then the quotient of country's emissions from the BF-BOF steel production and total GHG's.

Appendix C. Detailed results

Table C presents results obtained for each factor and the final GSI values. The results are rounded to 1 decimal place and the scores categorized in

Table C
Obtained results for each factor and the final Global Suitability Index. Highlighted results present values scoring in the highest level in each factor and in the final index.

	Steel production factor	Bioenergy factor	Policy factor	GSI
Algeria	1.0	2.2	0.5	0.5
Argentina	1.1	2.3	1.2	1.4
Australia	1.3	2.6	1.4	2.1
Austria	1.3	1.2	2.7	1.9
Belgium	1.1	0.9	2.5	1.1
Bosnia-Herzegovina	0.9	1.0	1.3	0.5
Brazil	1.7	1.9	1.3	2.0
Canada	1.3	2.4	2.0	3.0
Chile	1.0	2.4	1.8	1.9
China	2.9	1.0	1.9	2.6
Colombia	0.8	2.8	1.5	1.6
Czech Republic	1.3	1.0	2.1	1.3
Egypt	0.7	1.8	1.1	0.6
Finland	0.9	2.0	2.6	2.1
France	1.3	1.7	2.2	2.3
Germany	1.6	1.0	2.5	1.9
Hungary	0.9	1.4	1.8	1.1
India	2.0	1.4	1.5	1.9
Iran	0.9	1.6	1.1	0.7
Italy	1.0	1.1	2.0	1.1
Japan	1.9	0.8	2.6	1.9
Kazakhstan	1.5	1.9	1.1	1.5
Mexico	1.3	1.3	1.6	1.2
Netherlands	1.3	0.9	2.5	1.3
New Zealand	0.6	1.5	1.5	0.6
Poland	1.3	1.7	2.0	2.1
Romania	0.7	1.9	1.7	1.1
Russia	1.8	1.7	1.3	2.0
Serbia	0.7	2.1	1.1	0.7
Slovak Republic	1.3	0.9	2.3	1.3
South Africa	1.1	1.8	1.7	1.7
South Korea	1.9	0.2	2.5	0.4
Spain	1.0	1.7	2.0	1.6
Sweden	1.1	2.1	2.7	2.9
Taiwan	1.6	0.0	2.5	0.0
Turkey	1.5	1.2	1.8	1.5
Ukraine	1.4	1.0	1.5	0.9
United Kingdom	1.4	1.0	2.2	1.5
United States	1.6	1.8	1.8	2.5
Vietnam	1.0	2.0	1.2	1.1

the highest level of each factor.

Appendix D. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.seta.2018.03.001.

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