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Sustainability performance of enhanced weathering across countries: A triple bottom line approach

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ABSTRACT

Enhanced weathering (EW) is a promising negative emission technology involving the application of crushed silicate rocks to croplands for carbon capture. There is limited research about the broad sustainability impacts in rolling out this intervention on a large scale. This research assesses the triple bottom line sustainability of EW in eight top-emitting countries using an extended input-output model. Results indicate that overall sustainability performance of EW is influenced by each country's environmental and social metrics than the economic. Compared to developed countries (UK, France, Germany, USA), emerging economies (Brazil, Russia, India, China) show relatively lower economic sustainability due to high working hours impact but benefit from higher socio-economic contributions. Improving practices, particularly reducing emissions, energy use, labour rights and health and safety risk for silicate rock production, is vital for better sustainability outcomes.

1. Introduction

The current global challenge of climate change can be traced back to a historical trajectory where countries pursuing economic growth through industrial development often overlooked the impact on the environment. Over the years, there is growing consensus for the development and implementation of climate policies and industrial policies to be done in such a way that, there is a synergy between the two; mostly referred to as green industrial policies (Hallegatte et al., 2013; Rodrik, 2014; Nilsson et al., 2021). In other words, implementing industrial policies to stimulate economic growth and address inequalities should not be at the expense or detriment of the environment and vice versa (Belaïd and Zrelli, 2019). To achieve this, both national and international climate change discussions acknowledge the need to adopt a low-carbon pathway to industrial development (Maeno, 2023; Jiang et al., 2024).

Pursuing such a low-carbon strategy on a large scale will mirror the industrial structure within an economy. Implementation of low-carbon pathways strategies will require relying on other sectors within the economy and therefore whatever is happening within a country in terms of the industrial setup would also reflect how sustainable these climate policies will be. Accordingly, to access the sustainability of low carbon strategies, methods and approaches employed should enable economy-wide impacts to be assessed (Jiang et al., 2024). To captures macro-level and industry-wide impacts, our paper employs an input-output (IO) modelling which is considered a useful approach in carrying out such analysis (Lave, 1995; Duarte et al., 2018; Giannakis et al., 2019).

Energy is central to the discussion of climate mitigation policies and industrial policies (Foxon, 2013; Creutzig et al., 2019). Industrial policies targeted at reducing economic inequalities that includes energy efficiency improvements can considerably lower carbon emissions and aid in combating climate change (Belaïd and Massié, 2023). The energy mix within countries can also determine the effectiveness and success of climate policy such as carbon dioxide removal (CDR) technologies (Eufrasio et al., 2022). However, assessing the sustainability of climate solutions based on energy efficiency alone is not enough and narrows the sustainability assessment of low-carbon strategies. The economic, environmental and social impacts of climate solutions must be accessed (Deprez et al., 2024) to facilitate a holistic and evidence base decision making by policy makers. To address this, the first contribution our study makes is to develop an extended input-output model which includes economic, environmental, and social impacts to access sustainability of a climate solution. For the economic impacts, the selected impacts are Gross Domestic Product (GDP), Gross Operating Surplus (GOS), imports, employee compensation and working hours while energy use, Greenhouse Gases (GHG) emissions, material use, acidification potential and eutrophication potential are selected for the

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Nomenclature

CDR	Carbon Dioxide Removal
EC Index	Economic Index
EN Index	Environmental Index
EW	Enhanced Weathering
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GOS	Gross Operating Surplus
IO	Input-Output
LCSA	Lifecycle Sustainability Assessment
LCSD	Lifecycle Sustainability Dashboard
NETs	Negative Emissions Technologies
SHDB	Social Hotspot Database
SR Index	Social Risk Index
TBL	Triple Bottom Line
WIOD	World Input-Output Database

environmental impacts. Social impact categories include Labour Rights and Decent Work, Human Rights, Health and Safety, Community and Socio-economic contribution. Our approach also allows for identification of the critical factors that impacts overall sustainability performance, highlighting those impacts countries should target for improvements.

Countries differ in their economy set up and therefore, the economy-wide impacts of climate change mitigation strategies between different groups of countries will also differ and this must be taken into account when formulating climate and industrial policies. The wide-scale adoption and implementation of the different climate change mitigation strategies will need to be reflective of individual national circumstances to enable effective climate policy formulations and decisions (Ari and Sari, 2017; Fyson et al., 2020). The paper uses integrated indices allowing comparison between eight selected top GHG emitting countries from (Larkin et al., 2018) study; four developing or emerging economies (Brazil, Russia, India, and China) and four developed economies (USA, UK, France, and Germany).

In response to climate change crises, different negative emission technologies (NETs) have emerged as solutions towards achieving low-carbon pathway in industrial development (Haszeldine et al., 2018; Pires, 2019; Fawzy et al., 2020). These may broadly fall under carbon dioxide removal (CDR) technologies and include bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), soil carbon sequestration (SCS), afforestation and reafforestation(AR) (Jeswani et al., 2022). Despite several studies on the technical potential of these NETS as highlighted in review by Fuss et al. (2018), most sustainability assessment of NETS have focus on environmental impacts (Schuiling and Krijgsman, 2006; Li and Wright, 2020; Tan and Aviso, 2021; Wang et al., 2023) with very limited studies conducted on their triple bottom line (TBL) performance for different groups of countries.

One of such emerging NETs is enhanced weathering (EW) which involves the spreading of crushed silicate rocks on croplands to aid in carbon capture (Schuiling and Krijgsman, 2006; Moosdorf et al., 2014; Strefler et al., 2018). There is very limited research about the broader sustainability impacts in rolling out this intervention on a large scale to inform policy. Therefore, the second contribution our study makes is that it extends the discourse on EW as a CDR solution to include the associated industry-wide sustainability impacts. We employ the extended IO model to include the 15 economic, environmental, and social impact assessment. This method is useful as the production of crushed silicates for EW purposes which mostly takes place in the mining and quarrying sector, requires inputs from other sectors within an economy and therefore the IO model captures these knock-on impacts.

The remainder of this article proceeds as follows; Section 2 presents an overview of enhanced weathering and its sustainability. Section 3 explores the relevant academic literature on measurement of TBL impacts. Section 4 describes our data and model specifications. Section 5 presents the results along with index sensitivity analyses and a discussion of countries' critical TBL impacts. Finally, we conclude in Section 6.

2. Enhanced weathering: Overview and sustainability

Enhanced Weathering (EW) is an artificial acceleration of carbon capture from the weathering or chemical breakdown of silicate rocks (Taylor et al., 2016; Beerling et al., 2020). Rock weathering has been a long-established research field in the geological literature (Goldich, 1938) but it is not until recently that it has been explored as a form of climate change mitigation strategy (House et al., 2007). The science of rock weathering is based on carbon dioxide being sequestered from the atmosphere through the dissolution of silicate minerals in rocks. Carbon dioxide in the atmosphere dissolves in rainwater forming carbonic acid, which, once in contact with rocks, slowly dissolves them. The weathered by-products which include carbon is then transported by surface and groundwater runoff into the oceans, which act as sink for the trapped carbon (Taylor et al., 2016).

The 'weathering', or breaking down, of rocks is a hugely important but very slow part of the carbon cycle under atmospheric conditions. As such, to accelerate this process within the context of using EW as a climate change mitigation strategy, the weathering process will need to be artificially enhanced or accelerated. This may involve industrial scale mining, grinding, transporting, and spreading of crushed silicate rocks over land or in the sea banks in order to speed up the carbon sequestration process (Moosdorf et al., 2014). The science behind this has been hailed as credible (Cressey, 2014), with reported annual carbon removal estimates between 4.9 Gt CO_2 to 95 Gt CO_2 (Strefler et al., 2018). There are several studies on the potential of EW as a climate change mitigation strategy. One study in the UK estimates a theoretical carbon dioxide capture potential of 430 billion tonnes from silicate rock resources in the country (Renforth et al., 2011). Taylor et al. (2016) also suggests that idealized scenarios of enhanced weathering on a global scale can potentially result in 30–330 ppm atmospheric CO_2 by 2100.

EW is gaining prominence as a viable negative emission technology as its implementation requires already available structures compared to other technologies such as Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) which involves the setting up of entirely new infrastructure solely for its purpose. In the case of EW, quarry industries and mines are already a huge part of the primary aggregates sector in most countries and therefore the sourcing of silicate rocks will be relatively less challenging. It is reported that in the UK for instance, 47 million tonnes of igneous rock are mined yearly (Renforth et al., 2011) and therefore represents great potential for use in EW.

While the underlying science and co-benefits for the rock weathering process is well understood, there is limited studies, which would provide the needed insight into the effectiveness or feasibility of the EW strategy from a supply chain sustainability point of view. The potential unknown consequences including environmental impacts of the EW supply chain process, social acceptability and cost implications of EW supply chain remains therefore important but rather under researched (Taylor et al., 2016). In particular, for environmental sustainability, it has been reported that lifecycle stages of key processes and inputs can identify the overall environmental impacts and unravel the carbon hot-spots of product supply chains (Acquaye et al., 2011; Barthel et al., 2015). Hangx and Spiers (2009) also asserts that the overall efficiency of CO_2 sequestration due to EW depends on the amount of carbon dioxide produced during key lifecycle stages such as mining, grinding and transportation of the crushed rocks and therefore emphasised that these processes must be considered carefully in order to determine the net environmental benefits of EW.

Further to this, assuming the broader environmental impact is acceptable, questions regarding scalability, scenario modelling, logistics, social acceptability, and ethical dimensions remain unresolve(Cox et al., 2020). Beyond techno-economic feasibility, it's essential to assess the feasibility, effectiveness, and potential side impacts of climate change mitigation solutions Renforth (2012) estimates that an expansion to 125 Mt. per year is necessary to achieve a substantial emission reduction of 50 $MtCO_2$. This expansion entails economic, environmental, and socio-economic costs, but comprehensive impacts on the triple bottom line (economic, environmental, and social) are under-researched.

Carbon removal strategies must consider technical efficiency and social perspectives. Most research focuses on EW's functional efficiency and overlooks societal implications, which are challenging to predict and measure. Addressing these supply chain issues is crucial for making EW a feasible climate change mitigation option. Gaining insights into these factors from an economy-wide perspective will help resolve research gaps and develop new lifecycle thinking for the EW supply chain, achievable through sustainable supply chain management(Jiang et al., 2024).

This paper aims to perform a macro-level analysis, extending the EW discourse to cover economy-wide supply chain impacts. Producing crushed silicates for EW, primarily in the mining sector, involves inputs from various economic sectors. A comprehensive assessment must capture this feedback. While direct inputs like explosives and energy are expected, it's impossible to include and analyze all direct inputs. Moreover, limited information exists on indirect inputs and processes beyond a single quarry firm producing crushed silicate rocks for EW. These occur at different supply chain tiers, making it challenging to estimate upstream impacts.

Sustainability assessments of EW mainly focus on techno-economic costs (Strefler et al., 2018; Tan and Aviso, 2019; Jia et al., 2022; Feng and Hicks, 2023a) (Strefler et al., 2018; Tan and Aviso, 2019; Jia et al., 2022; Feng and Hicks, 2023b) with few on environmental sustainability (Lefebvre et al., 2019; Eufrasio et al., 2022). For instance, Strefler et al. (2018) assess investment and operation costs using economic reports of open-pit mines, while Tan and Aviso (2019) use a linear programming model to optimize EW carbon sequestration capacity. A review shows that assessments are performed at the micro and firm levels, excluding the knock-on impacts of indirect inputs from other sectors due to large-scale silicate production. Although such micro- level evaluations are essential, it is also critical, especially in terms of policy formulation on EW that macro-level assessments are carried out (Oppon et al., 2023). In this study, all three sustainability impacts are accessed, therefore completing the triple bottom line (TBL) and ensuring the broader implications of EW supply chain are well understood.

3. Measuring triple bottom line impacts

The term sustainability in management literature is an abstract terminology used broadly to describe an integration of economic, environmental and social responsibilities of organisations Carter and Rogers (2008). According to Maloni and Brown (2006) the application of sustainability in assessing supply chains was not done until late 1980s. Despite the three-dimension feature of sustainability, a review of the management literature shows that most conceptualization of the term typically take a one dimensional view, usually with focus on environmental sustainability (Vachon and Klassen, 2006; Abbasi and Nilsson, 2012; Bai et al., 2012) with just few studies integrating the socio-economic dimension in the modelling framework (Jennings and Zandbergen, 1995; Starik and Rands, 1995; Wagner, 2015; Wilson, 2015).

One concept that runs through the supply chain sustainability literature is Triple Bottom Line (TBL) approach, which is described by Willard (2012) as providing a new sustainability advantage from a three-dimension view. First coined by Elkington (1998b) the TBL concept is an accounting framework that differs from traditional models by integrating the three sustainability pillars (economic, environment and social). In the past, the bottom line of firms in a strategic management sense was to make financial gains. However, as stakeholder pressure from customers, shareholders and regulators began to rise, firms started broadening their bottom line to go beyond economic gains and include the other equally important core aims namely environmental and social (Govindan et al., 2013).

The basic premise of TBL reporting is to measure sustainability based on what is commonly referred to as the three Ps that is profits, planet and people relating to economic, environmental and social impacts respectively (Slaper and Hall, 2011). Before the introduction of TBL by Elkington (1998a) and the three Ps, measuring how sustainable a firm was remained a challenge as there were no criteria for measuring sustainability. With the introduction of the TBL approach, firms can be evaluated based on their impacts to economy, environment, and society. It is worth noting however that pursuing a TBL approach does not undermine the importance of economic sustainability or bottom line of organisations (Willard, 2012). Advocates of TBL strategy assert that the approach to engage in environmentally and socially responsible behaviours must be seen as complementary to achieving sustainable financial gains in the long term (Willard, 2012; Savitz, 2013). According to Carter and Rogers (2008) adoption of this approach can help organisations achieve competitive advantage over firms that are still stuck with the bottom line of financial profits. Aside the benefit of competitive advantage that a TBL approach offers, in recent times it is becoming increasing important to be responsive to the requirements for sustainability reporting as driven by regulation and legislation (Govindan et al., 2013).

There is no universal standard method for calculating integrated TBL supply chain impacts(Wang and Lin, 2007). Slaper and Hall (2011) submitted that the lack of a standardised method for TBL measurement should be considered as an opportunity for researchers and practitioners to develop frameworks that allows for TBL assessment from different perspectives such as geographic boundaries. In line with this thinking, various authors have attempted to make some valuable methodological contributions in the area of TBL assessment (Finkbeiner et al., 2010; Halog and Manik, 2011; Onat, 2015).

The challenge with an integrated TBL analysis is the common unit problem (Slaper and Hall, 2011). This problem arises because each of the TBL factors have different functional unit of measurement. Slaper and Hall (2011) in their work, reported that there are two ways to deal with the unit problem. The first approach involves monetizing each TBL factor. The challenge however with this approach is that not all the TBL factors especially those relating to environmental and social impacts can be monetized. The second approach they suggest which is more preferred involves calculating the TBL in terms of an index. The use of an index eliminates the unit problem and allows for comparing sustainability performance between entities (Slaper and Hall, 2011).

An example of a study that uses index system for integrated TBL measurement is the lifecycle sustainability dashboard (LCSD) framework first introduced by (Traverso et al., 2012). The LCSD is a straightforward but comprehensive presentation of LCSA results based on graphical representation (a cartogram). The methodological framework of the LCSD is based on an overall sustainability performance index, underpinned by individual index for economic, environmental, and social. The LCSD model uses the Dashboard of Sustainability tool; a software tool developed by Joint Research Centre of Ispra, Italy and assesses overall sustainability performance which they term as policy performance index and individual index for each TBL factor. Dashboard of sustainability tool which is supported by the International Institute of Sustainable Development (IISD) presents results using graphical representation (cartogram) based on chromatic scale and ranking score. Traverso et al. (2012) applied the LCSD on natural hard floor coverings.

Wang and Lin (2007) use a quantitative TBL framework for sustainability analysis at the corporate level. Their TBL framework is based on a sustainability index system. The authors use a 'sustainability optimization' model and acknowledges the fact that sustainability can be conducted from either a macro-level which covers regional or national level or micro-level which covers the corporate level. The methodological approach adopted in this study is the same approach taken in study by Traverso et al. (2012) and Wang and Lin (2007) where an overall sustainability index, is developed underpinned by individual index set is developed for each TBL factor.

The sustainability index model presented in this study is in line with the extension of the input-output framework (Leontief, 1986) and can be referred to as triple bottom line input-output analysis (TBL-IO) model (Foran et al., 2005; Wang and Lin, 2007; Onat et al., 2014b). Extensions of I–O models have been used to quantify environmental burdens (Ferng, 2009; Wiedmann, 2009; Dietzenbacher and Yan, 2024) in what is commonly referred to as the environmentally extended input-output (EEIO). The TBL-IO model used in this study however developed with the capability to quantify not only environmental loads but also social and economic impacts. The first comprehensive TBL-IO model developed by Foran et al. (2005) was used for macro-level industrial assessment of Australia's economy. Their model was called the Balancing Act and was based on economic, environmental, and social metrics for 135 sectors. The TBL-IO model has also been applied to assess sustainability of US final consumption (Kucukvar et al., 2014), food manufacturing sectors (Egilmez et al., 2014) and wind turbines (Noori et al., 2015). The study by (Onat et al., 2014a) also performs an economy-wide and macro-level lifecycle sustainability assessment of US buildings based on the TBL-IO. Their study used 16 macro-level indicators categorised under three economic, environmental, and social impacts. In the current study, 15 macro-level sustainability indicators are selected grouped under the TBL factors: 5 indicators under each TBL factor (Fig. 1).

In terms of TBL measurements for EW, the literature shows no such study. The few recent studies on sustainability assessment of EW have usually focused on one or two dimensions of sustainability (Strefler et al., 2018; Lefebvre et al., 2019; Cox et al., 2020). In measuring the TBL impacts of silicate production for EW, the current study is informed by similar approaches in the studies discussed above. The method and data section which follows next, illustrates in detail the IO framework which forms the basis of the analysis and in addition shows the method that is used in developing individual and integrated TBL sustainability indices.

4. Method and data

4.1. Input-output framework

To capture the complexities of the production and consumption activities of industrial supply chains and related economy-wide impacts (Gallego and Lenzen, 2005; Hayami et al., 2015; Camanzi et al., 2017), the research methodology employed must encapsulate such a framework. Economy-wide impacts associated with large-scale production of silicates for EW extends beyond the firm level (that is a single quarry business) due to the inter-dependencies of the EW supply chain on other supply chains. Collecting site-specific data throughout a complex supply chain would be a time and cost-prohibitive endeavour (Rebitzer and Hunkeler, 2003); hence the adoption of the economy-wide input-output framework (Miller and Blair, 2009). When a bottom-up, firm-level data collection approach is used exclusively, very few supply chain inputs can be captured due to the cut off or boundary problem (Swarr et al., 2011).

A preferred top-down approach which makes it possible to capture impacts from extended supply chains is made possible through the use of the input-output method (Richardson, 1985; Leontief, 1986). This advantage of the input-output method comes at an opportunity cost to the bottom-up approach which offers greater detail impacts at the firm level that may be lost through aggregation of impacts which usually occurs in macro-level analysis (Ibn-Mohammed et al., 2014). However, given the focus of this paper, which aims to provide insight into economy-wide impacts associated with production (mining and crushing) of silicate rocks for EW purpose, the use of bottom-up approach is inappropriate.

The principle of Input-Output (I–O) analysis was developed through the seminal work of the Nobel Prize winner in economics, Leontief

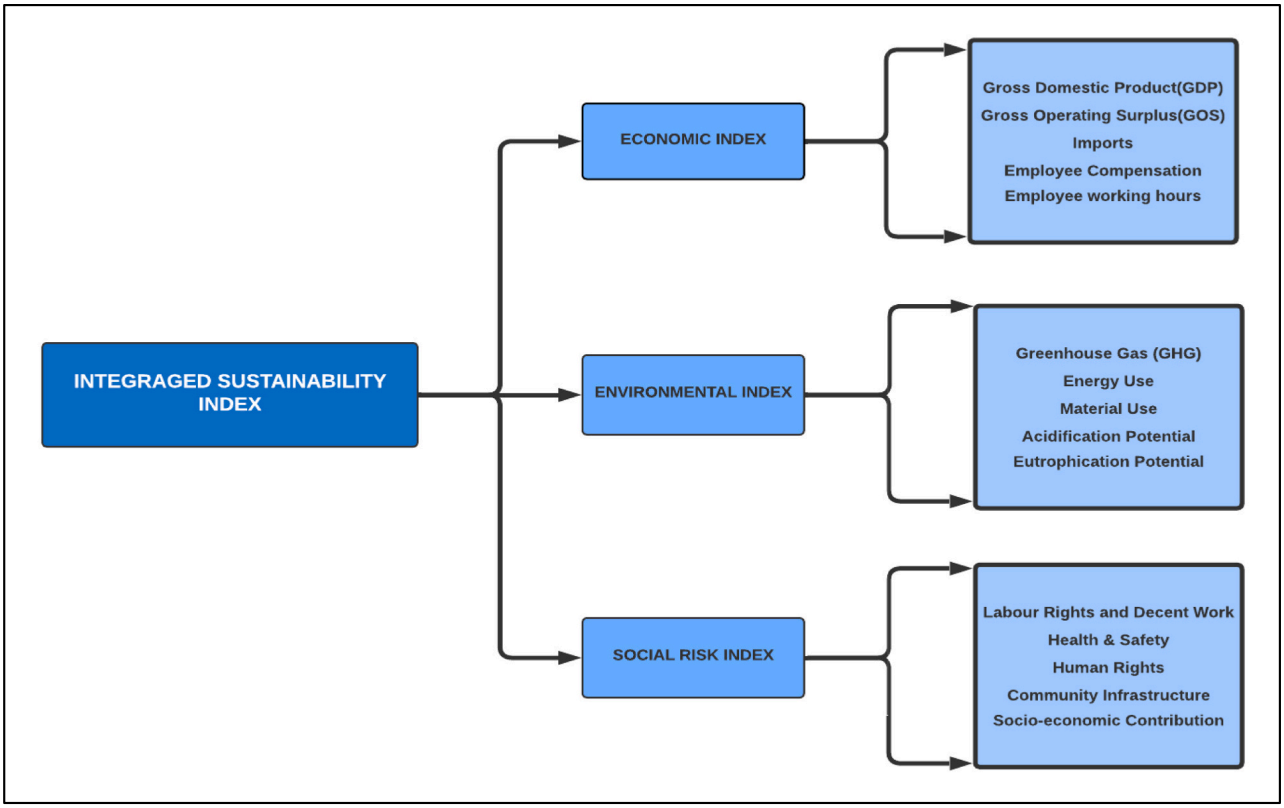

Fig. 1. Overview of macro-level indicators used in constructing sustainability indices.

(1986). The framework is based on the structure of the economy flow of resources (products and services) recorded as monetary transaction usually in US dollars or other national currencies depending on the source of data. The I–O model is centered on the idea of inter-industry transactions. In various studies (Hauknes and Knell, 2009; Guo and Murphy, 2012; Chen et al., 2017), inter-industry transactions are used inter-changeably with inter-sectoral transaction and the same implication is inferred in the current study.

4.1.1. *Description of I–O framework*

The input-output (I–O) framework is a quantitative economic technique that represents the interdependencies between different branches of a national economy. In this study, we utilize this framework to assess the sustainability impacts of enhanced weathering.

Industries use the products of other industries to produce their own products (McNerney et al., 2013). For example, the mining and quarry industry utilises fabricated metal products, machinery and equipment, electricity, and gas etc. to produce primary aggregates including crushed silicate rocks. Outputs from one industry therefore become inputs to another. The implication is that when crushed silicates are produced, the demand for other supply chain inputs such as metal products, electricity and gas, machineries etc. are affected.

These inter-connections are captured in I–O tables which are national accounting data usually compiled by statistical agencies in a country (McNerney et al., 2013). In the I–O table (see Fig. 2) this inter-industry relationship is known as the intermediate consumption (*Z*) and represents the amount of product (*i*) used as an intermediate input in the production Process of industry (*j*). Other parts of the I–O table show the Final demand (*Y*) of commodities by households, governments, investment, or exports and the Total Output (*X*) of a sector.

The relationship between Intermediate consumption (*Z*), Final demand (*Y*) and Total output (*X*) is given by:

$$x_i = x_j = \sum_j z_{ij} + \sum_i y_i \tag{1a}$$

where:

x_i= Total output of industry i,

x_j= Total input of industry j,

z_{ij}= Intermediate consumption between industry i and j,

y_i = Final demand for industry i.

In a generalised form, Eq. 1a can be expressed as:

$$x = Z + y \tag{1b}$$

Which implies total output(X) for a given sector is the sum of the intermediate consumption (Z) and Final demand (Y).

We can now derive Eq. (2) below which depicts the technology matrix (A) derived from intermediate consumption (Z) and total output (X):

Technology Matrix (A), is given by:

$$\mathrm{A} = \frac{\text{Intermediate consumption}}{\text{Total output}} = \frac{\mathrm{Z}}{\mathrm{X}} \tag{2}$$

Technology matrix in Eq. (2) only depicts the direct inputs requited to produce a unit of output in a sector, that is the inputs from tier 1 supply chain level (Wiedmann, 2009; Acquaye and Duffy, 2010). However, to production of these direct inputs also requires other inputs from other sectors that is tier 2, tier 3, etc. Therefore, to capture total requirements needed to produce a unit of output we need to estimate the direct and indirect inputs, and this is depicted in Eq. 3 below:.

$$\mathrm{X} = (\mathrm{I} - \mathrm{A})^{-1}\mathrm{Y} \tag{3}$$

$(I - A)^{-1}$ in Eq. 3 is referred to as the Leontief Inverse Matrix, named after Wassily Leontief and is the matrix of cumulative (direct and indirect) deliveries needed to produce per unit of total output(Miller and Blair, 2009). It is also known as total requirement matrix depicting the direct and indirect input required to produce a unit of output. Emphasis is now being placed not just on what goes on within the firm (direct) but on a life cycle wide assessment that traces impact through the entire production and supply chain (upstream).

The I–O framework can be combined with a TBL extension matrix to generate results, which can be used to account for the impacts of TBL externalities associated with crushed silicate production as a result of the linkages in the economic sectors. To achieve this, we first need to estimate the direct intensity matrix or DiM (Wiedmann, 2009). DiM is

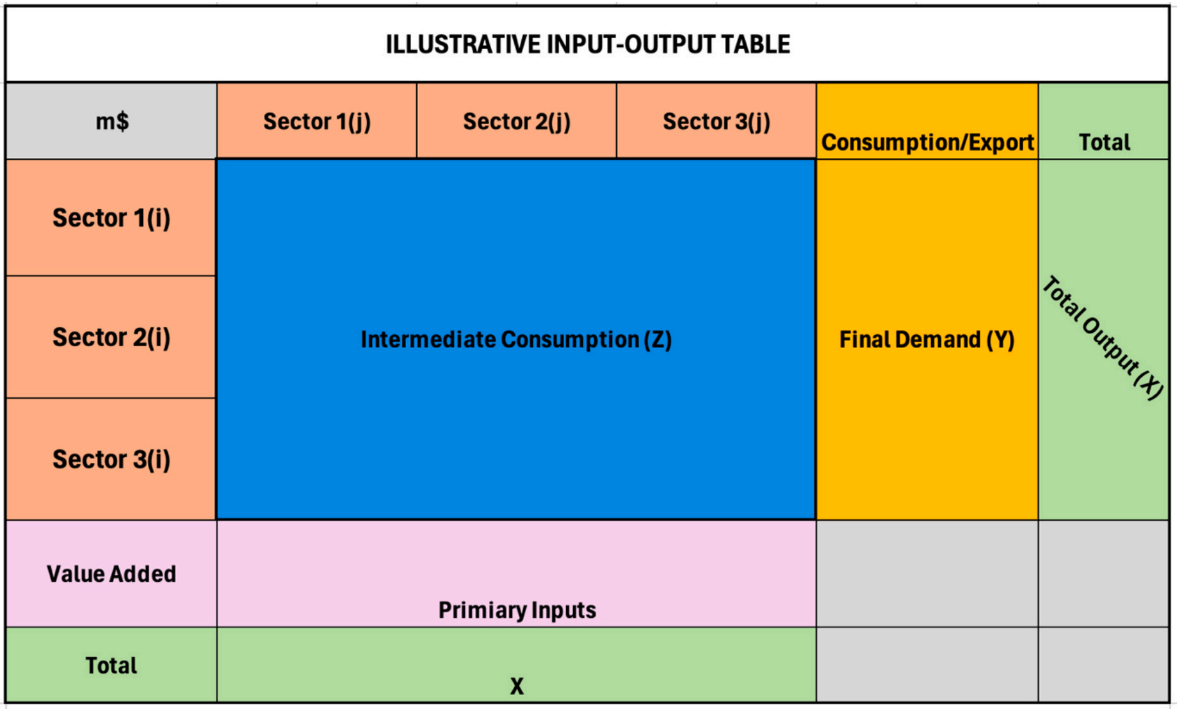

Fig. 2. An illustrative diagram of Input-Output Framework.

the matrix representation of direct environmental, economic, or social intensity matrix of all industries in each country within the TBL-IO framework (Wiedmann, 2009; Kucukvar et al., 2014; Acquaye et al., 2018; Oppon et al., 2023).

Let:

E_{jp} represents the direct TBL (economic, environmental, social) output for any industry j in a particular country p. Given that X_{jp} is the total industry production output expressed in million $, the direct intensity matrix (DiM) of any industry j in a particular country p is given by (Wiedmann, 2009):

$$\mathrm{DiM} = \frac{\text{Direct TBL Output}}{\text{Total Industry Output}} = \frac{\mathrm{E_{jp}}}{\mathrm{X_{jp}}} \tag{4}$$

Eq. (4) represents DiM and quantifies the direct environmental, economic, or social impacts per unit of industry output, thereby providing a comprehensive measure of the immediate sustainability impacts associated with industry activities. For example, the direct GDP, (economic) GHG emissions (environment) and labour rights (social) impacts for a mining sector within a country.

Eq. (5) builds on Eq. (4) by incorporating the Leontief inverse matrix by $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ which accounts for both direct and indirect impacts across the supply chain. This integration ensures that the total TBL impacts reflect the cumulative effects of economic activities, including those propagated through inter-industry transactions. In Eq. (5), the total TBL impact is derived by multiplying the direct intensity matrix (DiM) that is Eq. (4) with the Leontief inverse matrix (by $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ and the final demand vector (Y) that is Eq. (3). This approach integrates the economic, environmental, and social dimensions, thus offering a holistic view of sustainability impacts across the entire supply chain.

Given that Eq. (3) represents the total requirements needed to produce the output X for a given final Y, it implies that if the environmental, economic or social externality per unit industrial output is DiM (Eq. 4) then the total TBL impacts is represented below as Eq. (5) (Miller and Blair, 2009):

$$Total\ TBL\ impact = DiM\ (I-A)^{-1}Y \tag{5}$$

In Eq. (5), the use of the Leontief inverse matrix represented by $(\boldsymbol{I}-\boldsymbol{A})^{-1}$ in the analytical framework ensures complete supply chain visibility of all economic activities as associated impacts within the TBL-IO model and therefore captures both direct (operational) and indirect (supply-chain) components of TBL impacts(Foran et al., 2005; Ferng, 2009; Kitzes, 2013).

4.2. Data source for sustainability impacts

The TBL-IO framework comprises fifteen (15) sustainability impacts with five selected for each TBL factor. For the economic impacts, the selected impacts are Gross Domestic Product (GDP), Gross Operating Surplus (GOS), imports, employee compensation and working hours while energy use, GHG emissions, material use, acidification potential and eutrophication potential are selected for the environmental impacts. For both the economic and environmental impacts, single IO impacts were obtained from the 2011 World Input Output Database (WIOD). Data of social impacts is obtained from the social hotspot database (SHDB) created by New Earth B Enterprise (Benoit-Norris et al., 2012). The SHDB is made up of country and sector-specific indicator tables to help identify hotspots, based on potential social impacts (Norris et al., 2013). From the SHDB, the selected social impact categories include Labour Rights and Decent Work, Human Rights, Health and Safety, Community and Socio-economic contribution. There are several social sub-category indicators under each of the social themes.

National policy decisions on climate change mitigation are largely influenced both directly and indirectly by academic research and therefore the unique national circumstances of countries must also be reflected in such research (Larkin et al., 2018). The implementation of EW will differ from country to country, consequently the current research aims to provides insights into how the different countries are impacted economically. Although countries differ, some similarities allow for classification. For instance, EW in a developed economy such as the United Kingdom (Renforth, 2012) or USA(Kantola et al., 2023) may differ from an emerging economy such as Brazil (Lefebvre et al., 2019) or China (Guo et al., 2023). For this reason, the study focuses the analysis by selecting countries from these two groups of countries; that is developing (referred in the study mostly as emerging economies) and developed economies.

Overall, eight countries are selected; four from emerging economies (Brazil, Russia, India, and China or also referred to as BRIC nations) and four from the developed economies (USA, UK, France, and Germany). The rationale for choosing these countries is based on two main reasons. Firstly, they form part of the top emitters of GHGs globally (Nejat et al., 2015). Secondly, evidence from previous studies suggest that economic growth in these countries have mainly been associated with an increase in global emissions (Fankhauser and Tol, 2005; Tamazian et al., 2009; Pao and Tsai, 2010; Knight and Schor, 2014). It is therefore expected that such countries are most likely to lead the fight against climate change by adopting climate change mitigation strategies which may include enhanced weathering. In addition, wide-scale implementation of EW like other climate change mitigation efforts will have to be reflective of national circumstances (Winkler et al., 2006), therefore selecting countries from both emerging and developed economies allow for effective climate policy formulations and decisions for countries with similar national circumstances.

4.3. Estimating integrated sustainability indices

The use of indices has a number of advantages. Indices are useful tools in benchmarking performance of countries in complex issues (Saltelli, 2007). They are also useful in presenting a summary of issues that are multi-dimensional in nature. By summarizing complex issues into relatable values, indices also enhance easy communication with relevant stakeholders. In addition, when periodically calculated at regular time intervals, they can be used to access country progress in achieving set goal or target. These advantages influenced the decision to use indices in the current study. Despite the pros of using indices, there are some limitations associated with the use of indices that must also be highlighted. For instance, the use of indices presents some challenges such as over-simplification of issues which could lead to misleading policy signals. Also, the results are subject to the selection of the different methods used in calculating the index. For instance, the choice and number of indicators, the normalisation and weighting method can all influence the values obtained. In dealing with these challenges, transparency is key so that more useful and guiding interpretations can be made. The methodological framework and data used prior to the construction of the index must be transparent and issues which has been clearly outlined in order to avoid any misinterpretation of the index (Commission, 2008). In line with this, the IO framework which is the fundamental methodology used in the macro-level TBL analysis of the EW supply chain is illustrated in detail in the method section.

The units for the various impact categories differ among the TBL factors. For effective comparison between say GWP which is measured in $CO_{2\text{-eq},}$ and energy use measured in MJ, the units must be eliminated by normalising the data. In addition, not all impacts have equal weights in how they affect overall sustainability performance and therefore normalising the data and assigning weights to the individual impacts allows for effective comparison based on contribution to overall sustainability performance (Traverso et al., 2012). Based on such an analysis, we can identify and focus on the impacts that are relatively high in a country and justify where operational practices and policies should be targeted. According to the OECD handbook on composite indicators (Commission, 2008), there are different normalisation methods that can be used such as the distance to reference method, max-min method and z-score method (Commission, 2008).

In the current study, the distance to reference (DTR) also known as distance to target method is used. The distance to reference (DTR) method was chosen for normalisation due to its simplicity and effectiveness in comparing different units. This method normalizes values relative to a reference value, usually the maximum value in a given impact category, making it straightforward to identify relative performance across different metrics. Compared to the max-min method and z-score method, the DTR method provides a more intuitive comparison by focusing on the best achievable performance as a benchmark.

In this method, values are normalised in relation to a reference value, usually the maximum (best) value in a given impact category.

Normalised impact category in a country is estimated based on its percentage share of the maximum value in the given impact category shown in equation below.

$$Y^t_{qc} = \frac{x^t_{qc}}{max(x)} \tag{6}$$

where Y^t_{qc} is the normalised value of impact q (example GDP, energy use, health and safety, etc) for country c at time t.

where x^t_{qc} is the raw value of individual impact q for country c at time t.

where $max(x)$ is the maximum value for a given impact category.

Based on the weights estimated in Eq. (6), an index is calculated for each individual TBL factor as a measure of sustainability performance in a country. The economic index score (EC index) is a combined weighted value of all the economic impact categories (GDP, GOS, imports, employee compensation, and working hours) and indicates the overall economic sustainability performance of countries in producing silicates for EW. The environmental index score (EN index) is a combined weighted value of all the environmental impact categories (GWP, energy use, material use, acidification, and eutrophication potential) and indicates the overall environmental sustainability performance of countries in producing silicates for EW. The social index score (SR index) is a combined weighted value of all the social risk impact categories (labour rights, Human health, Human rights, Community infrastructure and socio-economic contribution) and indicates the overall social sustainability performance of countries in producing crushed silicates for EW. The individual sustainability index score is estimated as follows:

$$Individual\ TBL_{index(p)}\Sigma = \frac{Y^t_{qc}}{n} \tag{7}$$

After estimating the individual TBL index, (EC index, EN index and SR index), an overall sustainability index is calculated to estimate the lifecycle sustainability index score. Lifecycle sustainability index score (LCSA index) represents an integrated TBL impact for each country based on combined weight of all the impact categories under each sustainability pillar.

The impact categories that are included in the three TBL factors may be negative or positive and therefore it is important that these are reflected in the overall sustainability index score for a country. The way to view an impact as positive or negative can be rationalised as whether the impact is a benefit or cost to the economy, environment or society, such that positive impacts are considered as a benefit while negative impacts are considered as a cost. In the Economic Index score (EC index), GDP, GOS and employee compensation are positive impacts while imports and working hours are considered as negative. For the environmental Index score (EN index) all the impacts including GWP, energy use, material use, acidification, and eutrophication potential are considered as negative impact. For the Social Index score all impacts including labour rights, health and safety, human rights and community infrastructure are considered negative while socio-economic impact contribution is positive.

The combined sum of the EC index, EN index and SR index makes up the LCSA index score. Which provides an overall sustainability performance measure for a country with regards to production of crushed silicate rocks. The LCSA index is represented as eq. 8 below:

$$LCSA_{index(p)} = EC_{index(p)} + EN_{index(p)} + SR_{index(p)} \tag{8}$$

The LCSA index is an aggregate measure that combines the weighted values of economic, environmental, and social indices. This score provides an overall assessment of a country's sustainability performance concerning the production of crushed silicates.

5. Results and discussion

Analysis and results based on the method described in previous section are presented here. The specific results presented are as follows:

- Sustainability impact: First the normalised weight of each impact that makes up the index are presented. This makes it possible to identify which impact has the highest influence on the sustainability index score for a given country (Brazil, Russia, India, China, USA, UK, France and Germany).
- Integrated sustainability indices: This shows results for integrated individual and overall TBL sustainability impact of crushed silicate production represented by the EC index, EN index, SR index and LCSA index.

5.1. Sustainability impact

5.1.1. Economic sustainability impact

In this section, results on the economic sustainability impact in the production of crushed silicates for EW based on weight is presented. Fig. 2 shows impacts based on a weight scale from 0 to 1. The closer a value is to the outer circumference, the higher the weight, while values closer to the inner circumference indicates a lower weight. Presenting the results in this way helps to easily identify which indicator has the highest contribution to each country's overall economic index score (EC index score). This can also be interpreted as the 'hotspot' in terms of overall economic sustainability impact.

From Fig. 3, it can be observed that most of the economic sustainability impacts are skewed to left of the graph (that is the developed economies) depicting that economic impacts are higher in these countries compared to the emerging economies (located on the left side of the graph). An impact with weights of 1 or closer to 1 have higher contribution to the country's EC index. For Germany, employee compensation is the highest contributing impact and for the UK, the weight of imports is the highest contributor to the country's EC index. For the USA, GOS is the highest contributor to the country's EC index. For France, both GDP and employee compensation have the highest contribution to the country's EC index.

For the emerging economies, highest contributor to country's EC index in Brazil is attributed to weight of import. For Russia, GOS has the highest contributor to the country's EC index score. Working hours in India is the highest contributor to the country's EC index while for China it is GDP.

5.1.2. Environmental sustainability impact

In this section, results on the potential environmental sustainability impact for countries in the production of crushed silicates for EW are presented. Contrary to the economic sustainability impacts where impacts are skewed towards the developed economies (see Fig. 3), in the case of environmental impact based on weight (see Fig. 4), the greater impacts are skewed more towards the emerging economies. For Germany, material use is the highest contributing impact to the country's EN index score. In the case of UK, the weight of eutrophication potential is the highest contributor to their EN index. For the USA, global warming impact is the highest contributor to the country's EN index. For France's

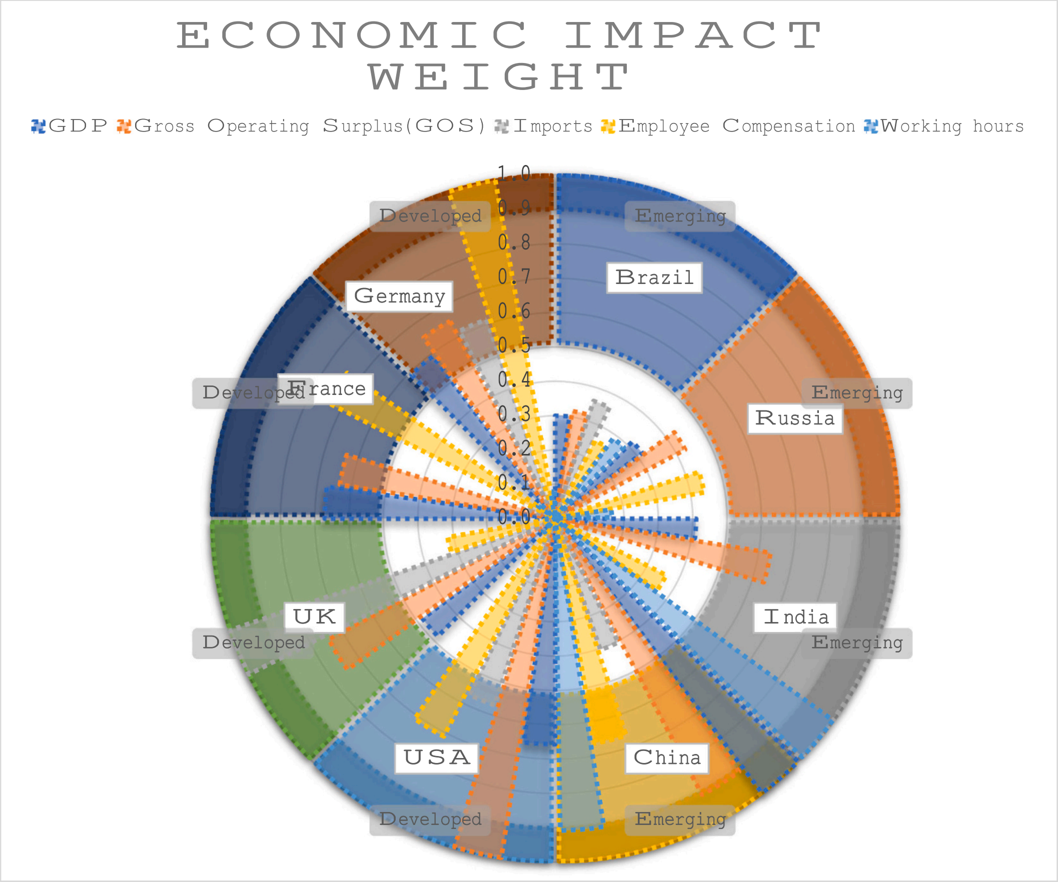

Fig. 3. Economic Impact weight for emerging and developed economies.

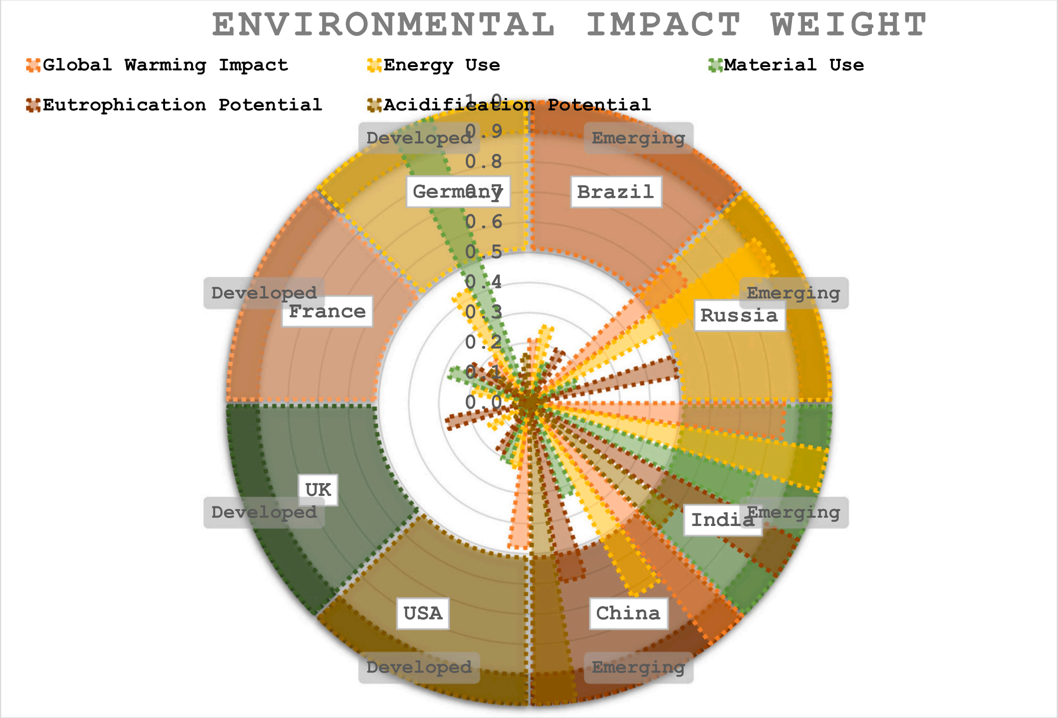

Fig. 4. Environmental impact weight for developed and emerging economies.

EN index score, material use is the highest contributor. For the emerging economies, highest contributor to EN index score for Brazil, Russia and India is attributed to energy use. In the case of China, highest contributors to the country's EN index score are global warming impact and acidification potential.

5.1.3. Social sustainability impact

The results from social sustainability impacts based on weights shown in Fig. 5 are similar to the environmental impacts in that, the greater risk of negative social impacts is also skewed towards emerging economies. This suggests that social impacts from the emerging economies are relatively very high compared to the emerging economies. The only developed country with some noticeable social risk impacts is the USA, where Labour rights and decent work is a dominant social risk impact in the country. In China, human rights and Health & Safety have more weight contributing to the country's SR index compared to other social risk impacts categories. In India, labour rights and community infrastructure are the dominant social risk impact issue with significant contribution to the country's SR index. In Russia, socio-economic contribution and health & safety are the dominant social risk impacts. In the case of Brazil, the dominant social risk impact is from socio-economic contribution.

5.2. Integrated sustainability indices

This section presents results for all sustainability indices (EC index, EN index, SR index and LSCA index) for countries. The relevance of these findings is to highlight how countries perform based on individual sustainability pillars in addition to overall sustainability with regards to crushed silicates production.

5.2.1. Economic index score (EC index)

A relatively high EC index score is interpreted as good economic sustainability performance while relatively low EC index score is considered as poor economic sustainability performance with regards to crushed silicate production (Fig. 6a). Among all selected countries, France has the highest *EC index* score of 1.9 followed by the USA and Germany with *EC index* score of 1.75 and 1.55, respectively which suggest that these countries perform better economically in the production of silicates for EW. The high positive weighted impact of employee compensation in France (0.74), USA (0.71), and Germany (1.00) significantly contributes to the relatively high EC index score these countries (See Fig. 3). The implication is that USA, France, and Germany have better employee compensation in place for workers compared to the other countries.

The UK has the lowest EC index score among the developed economies. In addition, the result indicate that the UK's EC index score is far lower than China and Russia that have EC index core of 1.26 and 0.98, respectively. The reason for the UK's low EC index score is attributed to the relatively high negative weighted impact of imports involved in crushed silicate production in the country. India and Brazil have the lowest EC index score among all the countries that is 0.38 and 0.22, respectively.

Generally, the low EC index score in emerging economies compared to the developed economies can be attributed to the relatively high negative weighted impact of working hours in these countries compared to developed economies. The weighted impact of working hours especially in India and China is very high that is 1.00 and 0.9, respectively compared for instance to developed economies like USA and France which is 0.05 and 0.06 only. Subsequently the results indicate that although India and China specifically have high EC index score among the emerging economies, the excessive working hours in these countries gives them an overall lower EC index compared to the USA and France.

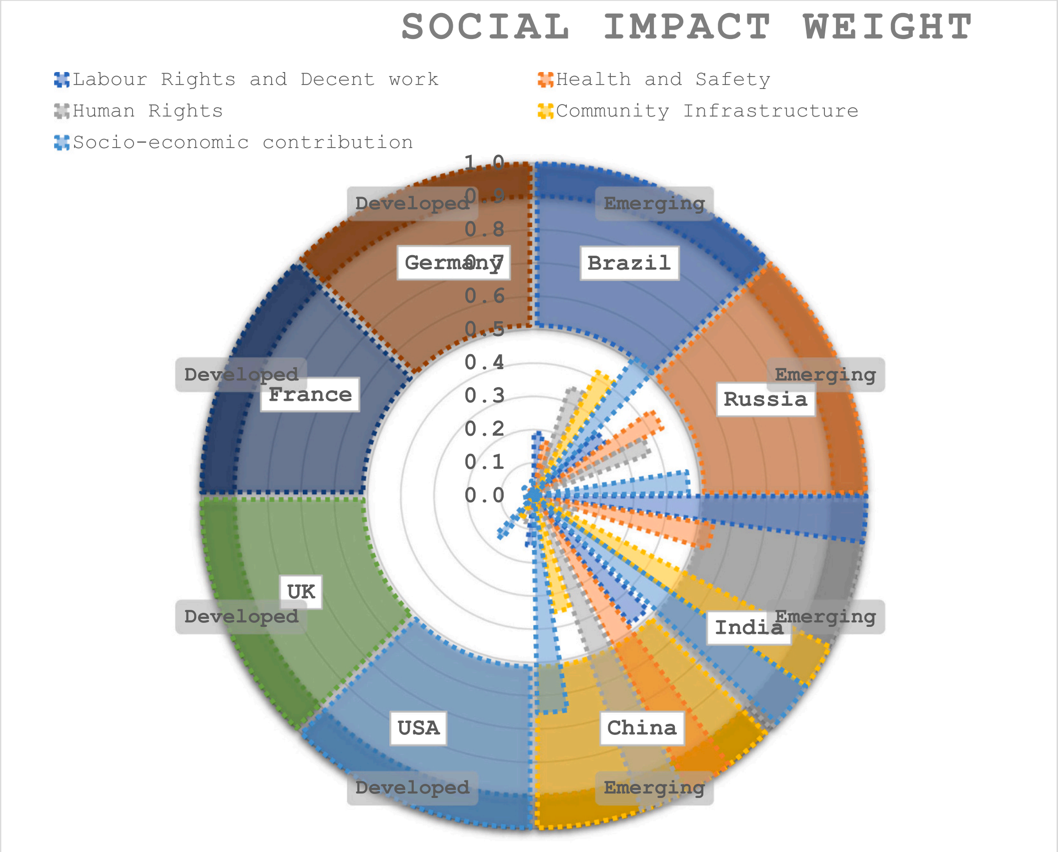

Fig. 5. Social indicator weight for emerging and developed economies.

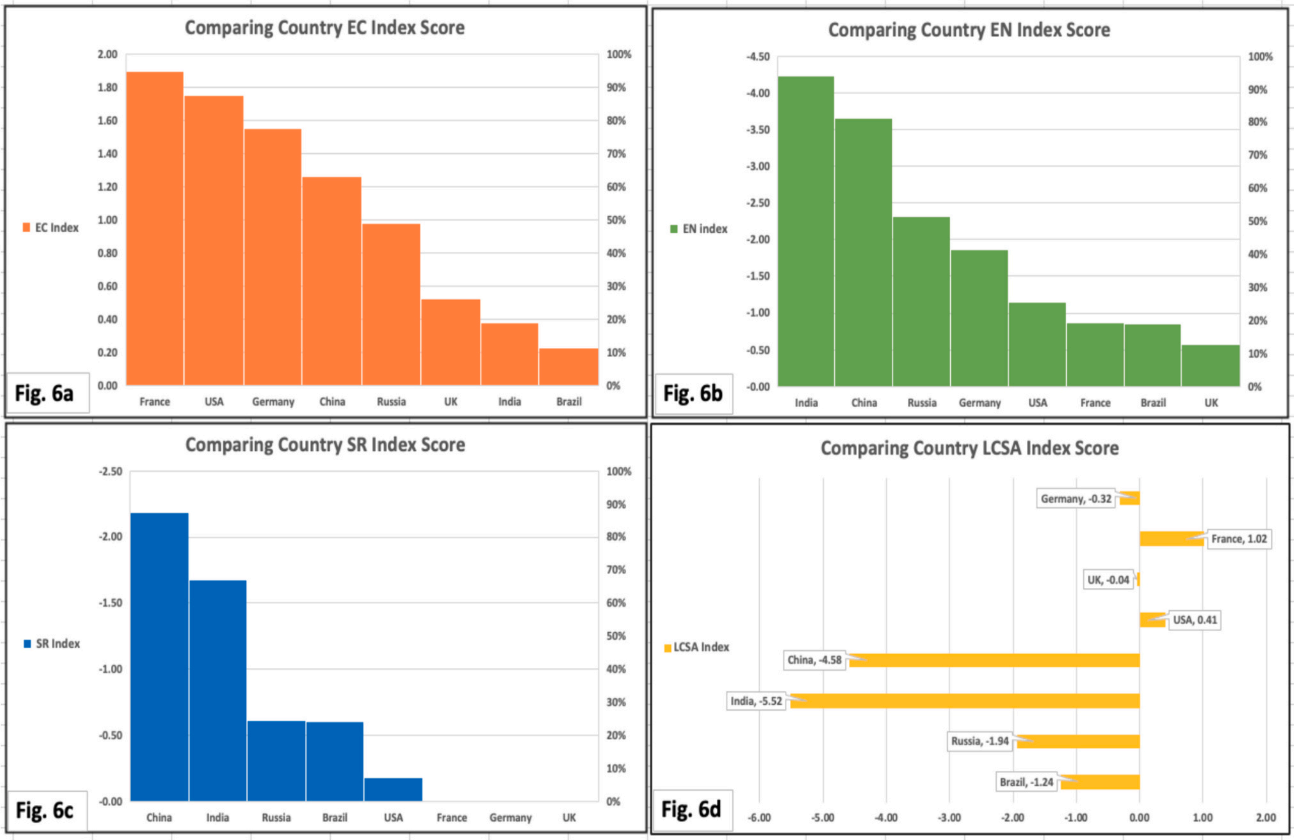

Fig. 6. Results of TBL Sustainability indices.

Another reason why the developed economies potentially perform better economically in crushed silicate production is attributed the high positive weighted GDP impact in these countries compared to the emerging economies except for China. On the average, GDP weighted impact in the developed economies ranges from 0.48 to 0.67 whereas for emerging economies particularly Brazil, Russia and India, average weighted GDP impact ranges from 0.30 to 0.41. China's weighted GDP impact of 1 is the highest among both developed and emerging economies which explains why among the emerging economies they perform better.

5.2.2. Environmental index score (EN index)

A relatively high EN index score is interpreted as good environmental sustainability performance while relatively low EN index score is considered as poor environmental sustainability performance. In Fig. 6b, result shows that the developed economies have high EN index score and therefore generally perform better environmentally than the emerging economies with regards to crushed silicate production. EN index for UK -0.57 and France −0.87 are the highest among the developed economies compared to the low EN index in USA −1.15 and Germany −1.87.

India's EN index score of −4.23 is the lowest among the all the countries (both emerging and developed) indicating relatively very poor environmental sustainability performance in this country associated with the production of silicates. China and Russia with relatively low EN index score of −3.66 and − 2.31, respectively also have poor environmental sustainability performance. Brazil is EN index score (−0.86) indicates a relatively good environmental performance compared to the other emerging economies. In addition, the country's EN index is slightly higher than that of France −0.87.

For the emerging economies, the weighted negative impact of GWP and energy use contributes to the low EN index scores in these countries. Therefore, improvements in EN index score for emerging economies especially must be centred on lowering global warming impact and energy use involved in the production of silicates. The weighted negative impact from acidification and eutrophication potential has less significant contribution to EN index score for most of the countries except Russia where the weighted impact from acidification potential is at the same high level as GWP in the country.

5.2.3. Social risk impact index score (SR index)

The social risk impact index score (SR index) for a country is a combined weighted value of all social risk impact categories (Labour rights, health & safety, Human rights, community infrastructure, and socio-economic contribution) measured and indicates the overall social sustainability performance of countries in producing silicates for EW. A relatively high SR index score is interpreted as good social sustainability performance while relatively low SR index score is considered as poor social sustainability performance in terms of crushed silicate production.

Similar to results in EN index score, the SR index score results (Fig. 6c) show that the developed economies have relatively high SR index score and therefore generally have a good social sustainability performance compared to the emerging economies which have low SR index score suggesting poor sustainability performance. Among the developed economies, SR index score for UK, Germany and France are the highest compared to a relatively lower SR index for USA. The negative weighted impact from Labour rights and decent work is a significant contributor to USA's relatively low SR index compared to the other developed economies. The implication here is that addressing negative labour rights risk in the country can potentially lead to significant improvement in USA's social sustainability performance in crushed silicate production.

China's SR index score of −2.18 is the lowest among the developed economies indicating relatively very poor social sustainability performance in this country with regards to crushed silicate production. India also has a poor social sustainability performance indicated by the country's low SR index score of −1.68. Brazil and Russia's SR index score indicates a relatively better social sustainability performance compared to China and India. Improvements in SR index score for emerging economies especially, must be centred on the social risk impacts that have significant contribution to country's SR index. For Brazil community infrastructure and human rights have significant impact on the low SR index scores in the country. For Russia and China, it is the health and safety and human rights risk impacts that contribute significantly to these country's low SR index score. For India it is the labour rights and decent work and community infrastructure that have the most significant contribution to the country's SR index. Although social sustainability performance in the developed countries is low, the positive weighted impact from socio-economic contribution from crushed silicate production is relatively higher compared to the developed economies.

5.2.4. *Lifecycle sustainability assessment index (LCSA index)*

As stated previously, the lifecycle sustainability index score (LCSA index) for a country is an aggregated value of the individual TBL impact index scores (EC index, EN index and SR index) and indicates the overall sustainability performance of countries in producing crushed silicates for EW. A high LCSA index score is interpreted as relatively good lifecycle sustainability performance while relatively low LCSA index score is considered as relatively poor lifecycle sustainability performance.

Generally, the results (Fig. 6d) suggest that countries in the developed economies group have relatively good lifecycle sustainability performance compared to the emerging economies. This is indicated by the high LCSA index score in developed economies compared to emerging economies. The highest LCSA index is in France 1.02 followed by the USA 0.41. However, LCSA score in the UK −0.04 and Germany −0.32 are the lowest among the developed economies. The lowest LCSA score of −5.52 is recorded in India. Like India, China also has poor lifecycle sustainability performance depicted by the country's low LCSA index score of −4.58. In comparison to the other emerging economies, Russia (−1.94) and Brazil(−1.24) have relatively high LCSA although still significantly lower than the developed economies.

The significant contributor to the LCSA index score of both developed and emerging economies is attributed to the environmental sustainability performance represented by the negative EN index score. The implication here is that improvement in country's lifecycle sustainability performance associated with crushed silicate production must be targeted at addressing environmental impacts. The second significant contributor which lowers a country's LCSA index score is social sustainability performance represented by the SR index. The high LCSA scores in the developed economies is attributed to high economic sustainability performance in these countries represented by the EC index score. However, a close look at the results reveals that the improved LCSA scores for developed economies is attributed to the high imports in these countries compared to the emerging economies. Consequently, the developed economies rely more on imports in producing silicates and therefore there is a high possibility that the negative environmental and social impacts are incurred by the countries they trade with. This assertion is also supported by the low working hours associated with silicate production in these countries.

In Table 1, a summary of country rankings for the various sustainability indices (LCSA, EC, EN and SR index) is shown. France is ranked first among all the countries in terms of LCSA index followed by the USA and UK. Among the four developed economies, Germany is the least ranked. India and China have very low ranking compared to Brazil and China in terms of the overall sustainability performance (that is LCSA index) in crushed silicate production. Similar to the LSCA index, France and USA are ranked first and second respectively in EC index. An interesting result highlighted by the EC index score ranking, is that China and Russia have a relatively high ranking than the UK. The low ranking for UK can be traced to the high imports involved in the production of crushed silicates. On the other hand, the high ranking for China especially can be attributed to the relatively high GDP generated in the country through the production of crushed silicates. India and Brazil have the lowest ranking attributed to negative impact of working hours in the case of India and in the case of Brazil, relatively low GDP. (See Fig. 3).

With regards to EN index, countries performing well depicted by their high ranking is the UK and Brazil which is attributed to low energy and material use in these countries in the production of crushed silicates. Although classified as developed economies, the USA and Germany in particular have relatively low rankings in the EN index, ranked 4th and 5th. The worst performing countries in terms on EN index are China and India depicted by their low rankings. Again, similar to the EN index, the UK is also ranked 1st with regards to the SR index rankings followed by Germany. Among the four developed economies, the USA has the lowest ranking. Russia, India and China are the bottom three countries in terms of SR index.

The summary of country rankings presented in Table 1 also makes it easy to identify the trade-offs between the TBL factors for a given country. For example, in the case of Brazil, it can be observed that although there is a trade-off between economic performance (EC index) ranked low compared to EN and SR index where the country has relatively high rankings. This implies that to increase the LCSA index ranking of Brazil, the country's EC index must be targeted. Another example is China, where it can be seen that although the country has high ranking for EC index, the low EN and SR index ranking leads to an overall low LSCA ranking. For Germany, the trade-off is seen between the country's relatively high EC and SR index on one hand and the relatively low EN index on the other hand leading to relatively low LSCA ranking when compared to the other developed economies.

Table 1
Summary of country rankings for sustainability indices.

Ranking	LSCA Index	EC Index	EN Index	SR Index
1st	France	France	UK	UK
2nd	USA	USA	Brazil	Germany
3rd	UK	Germany	France	France
4th	Germany	China	USA	USA
5th	Brazil	Russia	Germany	Brazil
6th	Russia	UK	Russia	Russia
7th	China	India	China	India
8th	India	Brazil	India	China

5.2.5. *Index sensitivity analysis*

In line with recommendation from the OECD Handbook, an index sensitivity analysis is carried out to the test the robustness of the results. Sensitivity analysis is carried out based on a different linear normalisation method than the distance to reference (DTR) method used in the analysis. Specifically, the Min-Max method also known as vector normalisation is employed to test the robustness of the indices. Normalised values based on the max-min method is calculated using equation below:

$$Y_{qc}^{t} = \frac{x_{qc}^{t} - min(x)}{max(x) - min(x)}$$

where Y_{qc}^{t} is the normalised value of impact q for country c at time t.

where x_{qc}^{t} is the raw value of individual impact q for country c at time t.

where $max(x)$ is the maximum value for a given impact category.

where $min(x)$ is the minimum value for a given impact category.

When LCSA index based on DTR and Min-Max normalisation method are compared (see Table 2), it is observed that the rankings remain the same which signals a robustness of the results. The differences in values does not change the country performance in the overall performance in crushed silicate production. Using the min-max method, the index

Table 2
LCSA index comparison based on different normalisation methods.

Country	DTR[*]	Min-Max	Country Rank
France	1.02	1.77	1st
USA	0.41	1.31	2nd
UK	-0.04	0.53	3rd
Germany	−0.32	0.41	4th
Brazil	−1.24	−0.96	5th
Russia	−1.94	−1.70	6th
China	−4.58	−3.82	7th
India	−5.52	−5.30	8th

[*] Distance to Reference normalisation.

values for emerging economies improves slightly (that is increases) although still negative depicting relatively poor overall sustainability performance in crushed silicate production compared to developed economy. Another slight difference is noticeable in LCSA index for UK, where in min-max method it increases beyond the zero mark and becomes positive.

When LCSA index based on DTR and Min-Max normalisation method are compared, it is observed that the rankings remain the same which signals a robustness of the results. The differences in values does not change the country performance in the overall performance in crushed silicate production. Using the min-max method, the index values for emerging economies improves slightly (that is increases) although still negative depicting relatively poor overall sustainability performance in crushed silicate production compared to developed economy. Another slight difference is noticeable in LCSA index for UK, where in min-max method it increases beyond the zero mark and becomes positive.

5.3. *Critical impacts affecting sustainability index*

There are a number of insightful findings from the study that can serve as evidence for effective national policy planning in developing a more sustainable agenda for EW. At the country-level, the results highlight the specific areas of focus that must be addressed in order to promote sustainable production of crushed silicates for EW. It is assumed that not all impacts within the individual sustainability category carry equal weight (Tyrrell et al., 2013) and therefore these must be captured within the analysis. By providing weights for the impacts, the study highlights both the negative and positive areas that should be mitigated (in the case of negative impacts) and those with opportunities (in the case of positive impacts) with regards to supply chain management of EW. For instance, in the case of developed countries, imports were the main economic impact that lowered countries' EC index while GDP increased their EC index; a similar conclusion in study by Wiedmann and Lenzen (2018). The EC index for emerging economies on the other hand, were mostly affected by the excessive employee working hours.

In terms of environmental performance represented by the EN index, the contributing factors differed from country to country as presented in the analysis and results section. However, impacts relating to energy use, GHG and material use were among some of the impacts with significant contribution lowering countries' EN index. In terms of social impacts, issues relating to labour rights and health and safety were the main impacts with significant contribution to lowering countries SR index especially for the emerging economies.

A network diagram can be used to identify the specific TBL impacts that are critical and must be addressed in order to improve sustainability in crushed silicates. Although a total of 15 TBL impacts were used in the integrated sustainability assessment of crushed silicate production, some impacts were more critical in affecting the sustainability indices for countries. Referring to the network diagram in Fig. 7, we can identify the specific impacts that were critical in lowering countries' score in the three individual TBL index that is EC, EN and SR index. This can be

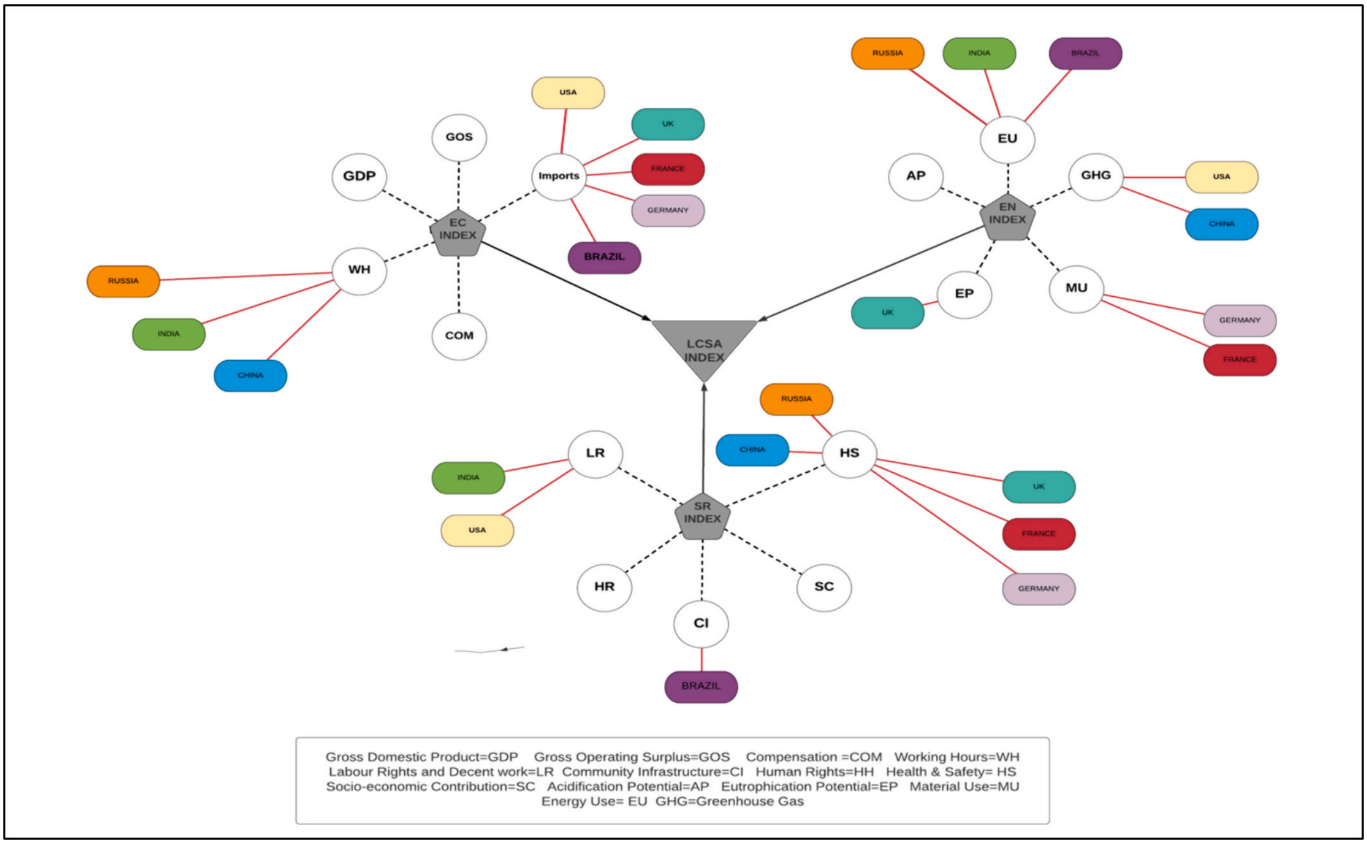

Fig. 7. Network diagram of critical TBL impacts affecting sustainability indices.

observed by counting the number of countries (nodes) extending from an impact. As a guiding rule, an impact is considered critical in an index if it has at least two extending nodes. For the EC index the critical impacts are imports and working hours which has five and three nodes respectively. For the EN index the critical impacts are energy use followed by material use and GHG emissions while for the SR index the critical impacts are health and safety followed by labour rights and decent work.

The integration of TBL factors based on the index method used in the study allows for easy comparison between countries. This is made possible through the formulation of the LCSA index, which takes in to account all individual sustainability assessment indices. Although countries LCSA index may vary depending on the component of the indices used (that is the selected impacts for each TBL factor), its relevance however remains valid and easy to use and interpret. The study also highlights important insights into the possible interactions and trade-off that exist between the TBL factors. One of such trade-offs highlighted in the paper is how developed economies through imports are able to achieve a better environmental sustainability performance in crushed silicate production within national boundaries. If analysis is based on just economic performance without considering the environmental then it could easily be concluded that developed economies perform better in production of crushed silicates. Our findings also align with results in study by (Dietzenbacher and Yan, 2024) that found that Brazil is a pollution haven for the developed economy USA. Their study also showed that Russia's Mining and Quarrying industry which have relatively high CO_2 emission multipliers accounts for 30%–50% of the country's exports. These findings complement the results in our study, which found that global warming impact (GHG emissions) and energy use were the highest factors that lowered the EW environmental sustainability among the emerging countries.

Beyond trade-offs between economic and environmental impacts, it may be difficult to establish such a direct link from the current study between economic and social sustainability impact in making assertions that economic sustainability in the developed country is achieved at the back end of negative social risk impacts in other countries it imports from. However, such an assertion is not far off as study by Wiedmann and Lenzen (2018) confirmed that direct link exists between improved economic sustainability against negative environmental and social impacts via trade.

6. Conclusion and future research

In conclusion, the study provides a comprehensive assessment of the triple bottom line (TBL) sustainability impacts of enhanced weathering (EW) as a negative emission technology (NET). To the best of the authors' knowledge, this is the first study that assesses EW sustainability using these new indices through the TBL approach, which considers and combines economic, environmental, and social impacts to examine lifecycle sustainability. More specifically, input-output model and composite indices methods were integrated to develop four indices (EC, EN, SR, and LSCA), where the final integrated score of LCSA provides a holistic understanding of EW lifecycle sustainability. Using these new indices and methods, we compared eight (8) top emitting countries – USA, UK, France, Germany, China, India, Brazil, and Russia. We found that France ranks first in terms of highest overall EW sustainability performance, whereas India has relatively the least EW sustainability performance.

The findings indicate that environmental and social sustainability metrics significantly influence overall sustainability performance, particularly in emerging economies. Developed countries exhibit higher economic sustainability due to favourable GDP. To improve sustainability outcomes, it is imperative to focus on reducing emissions and energy use associated with silicate rock production, particularly in developing regions. The critical impacts that must be focused on for social sustainability are improvements in labour rights and health and safety. For the economic sustainability index, the critical impacts where improvement efforts should be directed are imports and working hours.

The findings of this study have significant policy implications. Policymakers should focus on improving environmental practices, particularly in emerging economies, by implementing regulations to reduce greenhouse gas emissions and energy use associated with the production of silicate rocks. Developed countries, on the other hand, should leverage their economic and social strengths to support global sustainability initiatives. For instance, the UK and France perform best in environmental and social sustainability metrics, indicating the effectiveness of their existing policies. By adopting best practices from these countries, other nations can enhance their own sustainability outcomes.

Future research should explore the comparative sustainability impacts of various NETs to guide effective climate policy formulations. Solutions to climate change mostly involve using multiple approaches with different NETs. A study that looks at how the different NETs compare with each other in terms of TBL impacts will be essential in providing more evidence-based decisions on climate policies. Based on a similar approach adopted in this study (i.e., integrated TBL assessment), future studies can provide further evidence on sustainability concerns associated with the different NETs to guide policy formulation on climate change mitigation. Given the importance and relevance of imports to the TBL sustainability performance of EW as introduced in this paper, it is recommended that multi-regional input-output (MRIO) analysis be used to analyze sustainability impacts based on the origin-destination of global production of crushed silicates(Zhang et al., 2017; He et al., 2019).

CRediT authorship contribution statement

Eunice Oppon: Writing - reviw & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **S.C. Lenny Koh:** Writing – review & editing, Data curation, Conceptualization. **Rafael Eufrasio:** Writing – review & editing, Visualization, Methodology, Formal analysis.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107722.

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