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Original Research

Sustainable development index of shale gas exploitation in China, the UK, and the US

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ABSTRACT

While shale gas could complement the world's natural gas supply, its environmental tradeoffs and sustainability potential should be cautiously assessed before using it to satisfy future energy needs. Shale gas development in China is still in its infancy but has been progressing by the Central Government at a fast pace nowadays. Advanced experience from North America would greatly benefit sustainable design and decision-making for energy development in China. However, the lack of consistency concerning internal and external parameters among previous investigations does not allow an integrated impact comparison among shale gas-rich countries. Herein, we applied a meta-analysis to harmonize environmental tradeoff data through a comprehensive literature review. Greenhouse gas emission, water consumption, and energy demand were selected as environmental tradeoff indicators during shale gas production. Data harmonization suggested that environmental tradeoffs ranged from 5.6 to 37.4 g CO_2-eq, 11.0–119.7 mL water, and 0.027–0.127 MJ energy to produce 1 MJ shale gas worldwide. Furthermore, sustainable development indexes (SDIs) for shale gas exploitation in China were analyzed and compared to the United States and the United Kingdom by considering environment, economy, and social demand through an analytic hierarchy process. The United States and China elicit higher SDIs than the United Kingdom, indicating higher feasibility for shale gas exploitation. Although China has relatively low scores in the environmental aspect, large reservoirs and high future market demand make Chinese shale gas favorable in the social demand aspect. Region-specific SDI characteristics identified among representative countries could improve the sustainability potential of regional development and global energy supply.

1. Introduction

Since the transition from fossil fuel to renewable energy is unlikely to be substantially achieved within the short term [1], exploring substitute energy sources (such as natural gas) becomes a promising complement to the world's energy shortage and benefits toward carbon neutrality. Shale gas is an unconventional natural gas. Sustainable exploitation of shale gas has the potential to adequately supply the continuously growing energy demand [2], stabilize the soaring gas prices for global economic security, and promote responsible energy strategy transformation for the next few decades [3]; however, opposition to the development of shale gas has been raised due to complicated environmental and socioeconomic implications [4,5]. Though there are expanding studies relating to the impacts of shale gas development in several areas, including climate change [6], water quality [7], water scarcity [8], ecosystem and human health [9], jobs [10], and energy prices [11], comprehensive impact assessments that leverage environmental and socioeconomic parameters are still lacking. The conditions for developing shale gas vary greatly among regions and nations, such as geological features, technology levels, market demands, and regulation systems, which could influence the sustainable development of shale gas. Thus, recognizing environmental tradeoffs and

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List of abbreviations

AHP	analytic hierarchy process
bcf	billion cubic feet
bcm	billion cubic meter
D/P	domestic natural gas demand versus production
EC	shale gas exploitation cost
ED	energy demand
EUR	estimated ultimate recovery
FPW	flowback and produced water
HF-FPW	hydraulic fracturing flowback and produced water
FT	future trends of natural gas demand
GHG	greenhouse gas
HF	hydraulic fracturing
IP	natural gas imported price
LCA	life cycle assessment
mcf	million cubic feet
SDIs	sustainable development indexes
SP	shale gas production volume
SR	shale gas reservoir
tcf	trillion cubic feet
UK	United Kingdom
US	United States
WC	water consumption

barriers that dictate the sustainability of shale gas exploitation among regions is vital to understanding the rapidly evolving worldwide energy landscape.

Life cycle assessment (LCA) is an environmental tradeoff assessment tool that has been previously used to investigate macroscale environmental impacts of shale gas development during different operational stages, including drilling and hydraulic fracturing (HF) [12,13], transportation [14], and combustion for electricity and vehicles [15]. These studies suggest that the three most concerning life cycle environmental tradeoff categories are greenhouse gas (GHG) emission, water consumption (WC), and energy demand (ED) [16,17]. Laurenzi et al. [18] evaluated GHG emissions in Marcellus shales in the United States (US) and revealed that GHG emissions ranged from 62.8 to 79.1 g CO_2-eq MJ^{-1}, whereas Dale et al. [16] reported GHG emissions of 10.7 CO_2-eq MJ^{-1} in the same location. Large variations were found due to different functional units and system boundaries applied. Comparatively, China's GHG emissions ranged from 18.8 to 39.7 g CO_2-eq MJ^{-1} [19,20]. Large variations noted within and between the two countries were likely due to different geographical characteristics, technologies, assumptions, comparison baselines, and other internal/external factors [21–23]. Despite an internationally recognized standard of practice [24,25], directly pooling LCA results for comparison inhibits fair evaluation and hinders common understandings in environmental tradeoffs of shale gas development.

To minimize this inconsistency, Heath et al. [6] applied a meta-analysis to develop robust life cycle GHG emission comparisons among shale gas and other conventional fuel sources from production to end-use in the US. Their meta-analysis revealed that median estimates of GHG emissions from shale gas-generated electricity are similar to those from conventional natural gas and half the GHG emissions from coal [6]. However, WC and ED were ignored in the study by Heath et al., which hindered more comprehensive environmental tradeoffs analyses. In addition, the previous research was limited to comparing shale resources in the US only. Thus, systematic evaluations considering broader comparisons of other global shale resources are necessary to reveal environmental tradeoffs of shale gas exploitation.

Few studies have considered the integrated implication of environment, economy and social demand perspectives when evaluating the sustainability potential of shale gas exploitation. Grecu et al. [26] assessed the sustainability of shale gas exploitation in Romania through a cost-benefit analysis, yet several important environmental impact parameters (such as GHG emission and ED) were ignored. Thomas et al. [5] deliberated the social benefits and impacts of shale gas and oil extraction in the US and the United Kingdom (UK), but environmental impacts were only confined to the hydraulic fracturing stage. Wang et al. [3,27,28] applied different models to compare the sustainability of the shale gas industry in different regions of China from technical and construction perspectives. The results demonstrated that high environmental impacts and core technical capability were the major obstacles to sustainable development. Taken together, it is imperative to systematically integrate major parameters to reflect the overall sustainability for shale gas development across important shale gas reservoirs.

The present work aims to reveal life cycle environmental tradeoffs and identify major environmental and socioeconomical parameters that dictate the sustainability potential during shale gas exploitation. Data from environment, economy, and social demand aspects were integrated to evaluate the sustainability potential from three shale gas research-intensive countries (the US, the UK, and China). The system boundary of the present study was refined to shale gas exploitation for environmental tradeoff exploration (Fig. 1). GHG emission, WC, and ED data are first summarized through a comprehensive literature survey, and the meta-analysis is applied to holistically compare environmental impacts during

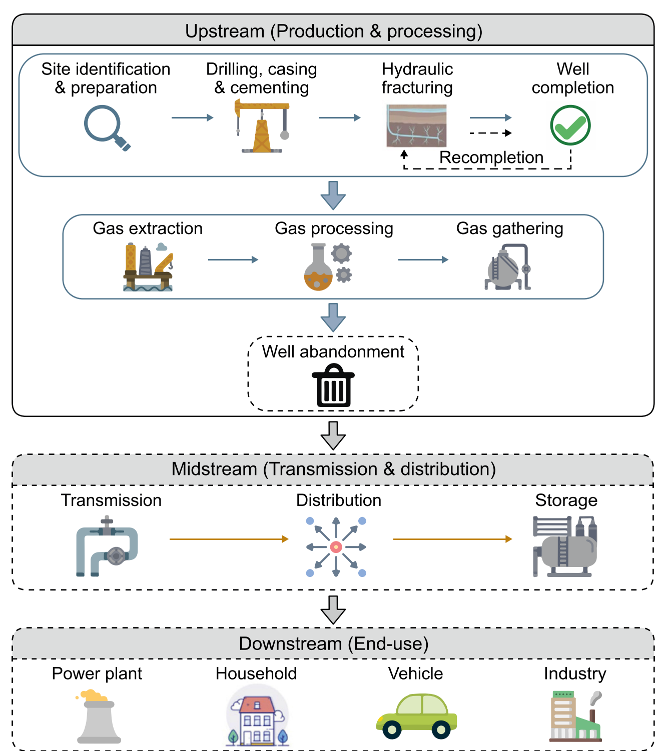

Fig. 1. System overview of shale gas development from cradle to grave. Solid lines indicate stages considered in the present analysis. Black dash arrows in the upstream stage indicate well recompletion.

shale gas exploitation. The harmonized database reduces the variability caused by inconsistent methods and assumptions among studies. Through this process, we can find the central tendency for each environmental impact category. Furthermore, sustainability development indexes (SDI) are generated to examine the feasibility and sustainability potential for shale gas in the US, the UK, and China through the analytic hierarchy process (AHP).

2. Materials and methods

2.1. Literature review

Based on keywords search on the Web of Science ("shale gas" AND "life cycle assessment" OR "shale gas" AND "LCA"), approximately 300 articles were identified by December 1, 2021. After manual selection, life cycle GHG emission, WC, and ED of shale gas development were examined across 50 shale gas cases from 42 articles since 2010. Over half of these studies were based in North America (the US and Canada), followed by China, the UK, Australia, and Spain. Original environmental impact data from the literature are summarized in the Supplemental Information (SI, Table S1).

Our literature review identified that the US, the UK, and China are the primary countries where the life cycle environmental impacts of shale gas exploitation have been evaluated. Seven studies have investigated shale gas life cycle environmental impacts in Europe, and five of these were targeted in the UK. Whitelaw et al. [29] revealed the UK Bowland shale might contain 140 ± 55 trillion cubic feet (tcf) of shale gas, and Monaghan [30] suggested a total of 49.4–134.6 tcf gas in the UK Scotland Midland Valley. Both sites are considered large reservoirs in Europe. The decisions for shale gas exploration in the UK have been debated for years. Although the UK attempted shale gas exploitation within its territories, large-scale extraction has been banned since 2019. European countries, including the UK, have large natural gas demands; however, nearly half of their current natural gas supply relies on imports [31]. Sustainable shale gas exploitation may substantially relieve the energy demand in Europe. The US has the most advanced shale gas exploitation technology and a mature large-scale commercial development market. The US was the first country to start exploiting shale gas and possesses the fourth-largest shale gas reserves in the world. With their well-studied shale gas life cycle impacts, advanced experience from North America would greatly benefit sustainable design and decision-making for energy development in other countries. China contains the current world's largest shale gas reserves. Due to recent incentive policies, shale gas is significant for ensuring China's energy security and long-term stable economic development. Although China has a high potential for shale gas development, large-scale commercial exploitation is still under early-stage investigation, and the sustainability remains largely unknown.

Inconsistent functional units for life cycle impact assessments prohibited a direct comparison among various studies. Among all, 31 studies used energy-based (1 kWh per MWh of electricity generated or 1 MJ per GJ shale gas produced) functional units, and the remaining articles used either mass-based or shale gas well-based functional units. Here, functional units were first normalized to "1 MJ shale gas extracted" to enable cross-comparison among studies. Conversion factors for different functional units are depicted in Table 1.

Table 1
Conversion factors of different functional units to MJ shale gas. EUR: estimated ultimate recovery.

Functional unit	Conversion factor
1 kWh electricity	1 kWh electricity $= \frac{3.6}{\text{Power efficiency}}$ MJ shale gas[a]
1 well shale gas	1 well shale gas = 1 × EUR × Heat value MJ shale gas[b]
1 mcf or m^3 shale gas	1 mcf or m^3 shale gas = 1 × Heat value MJ shale gas[b]

[a] Power efficiency is assumed to be 50% if not provided in the original study.
[b] Heat value is assumed to be 1040 MJ per million cubic feet (mcf) or 36.73 MJ m^{-3} if it is not provided in the original study [32].

2.2. Meta-analysis and data harmonization

Meta-analysis aims to harmonize the life cycle environmental tradeoffs of the currently available studies, holistically compare impacts during shale gas exploitation, and obtain unified environmental parameter ranges to be integrated into AHP for sustainability assessment.

System boundary refinement. Generally, shale gas development can be divided into upstream (production and processing), midstream (transmission and distribution), and downstream (end-use) stages (Fig. 1). The upstream stage includes well site identification, well site preparation, design, drilling, casing, cementing, hydraulic fracturing, well completion, extraction, processing, and well abandonment. Midstream includes shale gas transmission, distribution, and storage. The end-use stage refers to power generation through a power plant and household combustion, automobile fuel, and industrial use.

The major differences in environmental impacts between shale and conventional natural gas generally occur during the exploitation stage due to various technologies applied [33]. In addition, the transmission and use phases of shale gas development could be considerably influenced by the modes and distances of transmission [14,34], as well as the efficiency of the end-use stage [6]. Thus, the system boundary of the current study was refined at the production and processing stage for environmental tradeoff exploration (Fig. 1).

Harmonization steps. Many activities could contribute to environmental impacts. Various studies made different decisions about the inclusion and exclusion of activities within the life cycle of shale gas development. During the production phase, several activities such as well completion, well recompletion, and liquid unloading were highlighted as major contributors to the environmental burden, yet they were often ignored in previous studies [6]. Herein, these activities were included and harmonized to enable consistent comparisons.

The following harmonization steps were performed sequentially. First, impacts of the end-use, transmission, and distribution phases were excluded from the refined system boundaries. Second, impacts associated with shale gas processing were added when they were not previously evaluated. Notably, when shale gas processing impacts were unavailable in certain cases, the country average was used instead. Third, emissions associated with well recompletion were adjusted. A well recompletion was adjusted based on the combined impacts of well completion and hydraulic fracturing and adjusted by the latest USEPA's well recompletion frequency. Since the latest recompletion frequency was downward from 10% to 1% [35,36], environmental impacts from well recompletion were calculated using equation (1),

$$E_{rc} = (E_c + E_{hf}) \times 1\% \times \textit{well life time (year)} \quad (1)$$

where E_{rc}, E_c, and E_{hf} represent environmental impacts of well recompletion, original well completion, and hydraulic fracking, respectively.

Additionally, GHG emission associated with liquid unloading was added. This step was applied to GHG emission only because liquid unloading has been shown as the main methane leakage source during shale gas production [37], but few studies demonstrated this phase would cause great WC and ED during shale gas production. The GHG emission from liquid unloading was adjusted by equation (2),

$$GHG\ emission_{lu} = \frac{7.8}{3.6} \times 51\% \times \frac{2.2}{EUR} \times \frac{well\ life\ time\ (year)}{30} \tag{2}$$

where 7.8 g CO_2-eq kWh^{-1} is the predicted average GHG emission for liquid uploading. When EUR and well lifetime are unavailable, a median value for unconventional gas (2.2 bcf) was used here as the baseline EUR, and 30 years was used as the well lifetime. The number 3.6 is the unit conversation factor from kWh to MJ, and 51% is the powering efficiency suggested in the study by Heath et al. [6].

Detailed harmonized values and harmonization procedures for each shale gas site are summarized in Table S2 and Table S3–S5, respectively.

2.3. Sustainable development analyses

The triple bottom line of sustainability comprises three aspects: environment, economy, and society. We created an SDI to evaluate the sustainability potential of shale gas development in three representative shale gas reservoirs (the US, the UK, and China). Economy and social demand aspects were integrated with harmonized environmental impacts through the AHP. Unlike the environment category, economy and social demand were collected from official resources. These values usually represent the country's average value in a specific year, which does not require further data harmonization. Economic parameters (including natural gas imported price and exploitation cost) from 2014 to 2020 were collected for each country, and domestic natural gas demand/supply ratio, shale gas production volume, shale gas reservoir, and potential growth rate from 2021 to 2025 were considered to project the social demand potential of shale gas in that country. The local hydrological and geological conditions could significantly affect shale gas production and exploitation costs; various production volume and cost data in different shale locations were collected to reflect possible variations. The AHP is a decision-making technique that uses pairwise comparisons based on a numerical scale to structure the decision-making process. As a method originally proposed for multi-objective and multi-criterion conflicting problems [38], AHP has become an effective tool for sustainable assessment in energy systems [39]. Fig. 2 presents the AHP's hierarchical structure considered in the present work. The criteria were chosen and organized in a hierarchy structure descending from an overall goal to the main criteria, followed by sub-criteria levels. The main criteria consist of environment, economy, and social demand aspects. The subsequent level of the hierarchy consists of a series of sub-criteria related to the main criteria. Detailed AHP steps are explained in the SI (Section 1). AHP integrates sorted data to compare the sustainability of shale gas exploitation among different countries.

Despite many advantages of the AHP methodology, AHP partially reflects human thinking and experts' opinion with some degree of uncertainty [40]. Herein, we constructed two scenarios with different emphases to minimize uncertainties associated with criteria weights through the AHP methodology using yaAHP (V12.8.8049). Detailed procedures and values for each discriminant matrix are presented in the SI (Section 1 and Table S9–S18). Consistency checks for both scenarios are presented in Tables S19 and S20. Scenario 1 is an environment-emphasized scenario in which the environment was set with a higher weight compared to economy and social demand (Table S9). Scenario 2 is a balanced scenario, and environment, economy, and social demand were

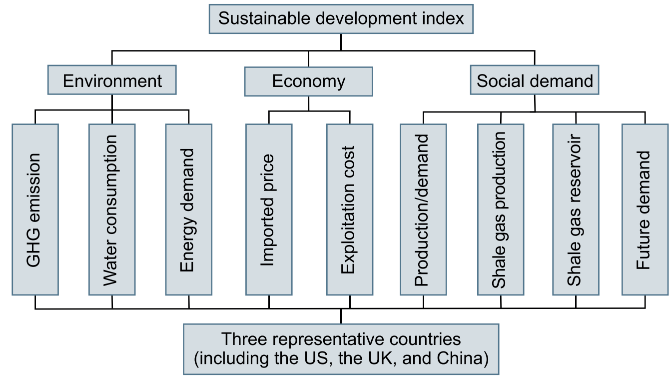

Fig. 2. Analytic hierarchy process structure for shale gas sustainable assessment. The sustainable development potential of shale gas exploitation is assessed by generating a sustainable development index (SDI). The lowest level of the hierarchy is three representative countries, including the US, the UK, and China.

assigned an equal weight (Table S10). Moreover, cumulative SDI variation subjects to the changes in weight score for each main criterion were analyzed.

The SDI was regulated with full marks of 100. Higher SDI indicates more sustainable potential for shale gas exploitation in the study area. The relationship of each SDI with the sub-criterion was calculated using equations (3) and (4). Eventually, each SDI was obtained by varying an individual input parameter while the remaining parameters held constant.

$$\begin{aligned} SDI_{scenario\ 1} = {} & \frac{17.1}{GHG} \times GHG_{best} + \frac{17.1}{WC} \times WC_{best} + \frac{17.1}{ED} \\ & \times ED_{best} + \frac{9.0}{IP} \times IP_{best} + \frac{18.1}{EC} \times EC_{best} + \frac{6.2}{(\frac{D}{P})} \\ & \times (\frac{D}{P})_{best} + \frac{1.9}{SP_{best}} \times SP + \frac{11.4}{SR_{best}} \times SR + \frac{2.0}{FT_{best}} \times FT \end{aligned} \tag{3}$$

$$\begin{aligned} SDI_{scenario\ 2} = {} & \frac{11.1}{GHG} \times GHG_{best} + \frac{11.1}{WC} \times WC_{best} + \frac{11.1}{ED} a \\ & \times ED_{best} + \frac{16.7}{IP} \times IP_{best} + \frac{16.7}{EC} \times EC_{best} + \frac{8.3}{(\frac{D}{P})} \\ & \times (\frac{D}{P})_{best} + \frac{8.3}{SP_{best}} \times SP + \frac{8.3}{SR_{best}} \times SR + \frac{8.3}{FT_{best}} \times FT \end{aligned} \tag{4}$$

Numbers in the two equations represent the rescaled weight factors (by a factor of 100) for sub-criteria based on the AHP under each scenario (Tables S17 and S18). Sub-criterion values are shown in Table S21. The best-case (*best*) represents the lowest values in GHG, WC, ED, natural gas imported price (IP), shale gas exploitation cost (EC), and domestic natural gas demand versus production (D/P), and the highest values in shale gas production volume (SP), shale gas reservoir (SR), and future trend of natural gas demand (FT). Differences in SDIs and main criteria among study regions were compared by one-way ANOVA using SigmaPlot (V14.0; Systat Software Inc., CA, USA).

2.4. Uncertainty and sensitivity

Weight scores for main and sub-criteria are assigned based on a subjective judgment that inevitably introduces uncertainty to the SDI [40]. In addition, slight variations of the weight allocated might have a pronounced influence on the SDI. Here, appropriate probability distribution functions were fitted based on the software selection for each SDI and main criterion, and Anderson-Darling, Kolmogorov-Smirnov, and Chi-squared tests were used for normality testing. Based on the best-fitted probability distribution function (Beta, Weibull, Uniform, Log-normal, and Extreme value distribution), Monte-Carlo simulations were conducted to obtain 95th confidence intervals and other statistical parameters using Oracle Crystal Ball (V11, Decisioning, Denver, CO, US) for 10000 runs. Sensitivity was also assessed as the percentage change of the average value of SDI by increasing 20% the weight of one main criterion while the weights of the other criteria were held constant. The purpose of the sensitivity analysis is to monitor how much influence one criterion has on the overall SDI, and as such, the key factor that influences the shale gas sustainable development can be identified.

3. Results and discussion

3.1. Literature review

GHG emission: Among the 50 investigated shale gas cases, GHG emissions were analyzed in 32 cases. The production stage emits 0.1−44.8 g CO_2-eq per MJ of shale gas, contributing up to 47% of the total GHG emission during the entire life stage (Fig. 3a). GHG emissions during transmission and distribution stages emit 0.5−27.5 g CO_2-eq per MJ of shale gas. Fifteen cases assessed GHG emissions from production to end-use, and results suggest the end-use phase contributed predominantly to the overall GHG emission (11.0−60.1 g CO_2-eq per MJ of shale gas), with more than 51% contribution during the shale gas life cycle.

Water consumption (WC): In the literature, 22 cases evaluated WC during shale gas development (Fig. 3b). WC ranges from 2.6 to 313.1 mL per MJ of shale gas, with 2.6−118.4 mL per MJ of shale gas during shale gas production, and 68.1−263.9 mL water per MJ of shale gas during the end-use phase.

Energy demand (ED): ED in the present study refers to the amount of energy consumed during exploitation to extract each energy unit of shale gas income (MJ cost per MJ of shale gas) [72]. Life cycle ED is an important index for revealing energy payback for project investment. Most current studies focused on ED during the shale gas production phase, ranging from 0.002 to 0.149 MJ per MJ of shale gas (Fig. 3c).

Collectively, environmental tradeoffs for shale gas development vary greatly among different studies. This variability is attributed to various external and internal reasons. Externally, life cycle environmental tradeoffs are substantially affected by the lack of consistent system boundaries. For instance, the end-use phase has been identified as the environmental hotspot during the shale gas life cycle, contributing more than 50% of GHG emissions and 60% of WC throughout the shale gas life cycle (Fig. 3a and b). During the end-use stage, direct release of CO_2 into the atmosphere after shale gas combustion [73], consumption of steams, and cooling water for electricity generation are the major reasons for the high emissions [17,61], but these activities have been only considered in 33% of sorted studies. Furthermore, other activities, including well recompletion and liquid unloading, have also been largely ignored during the exploitation stage.

Environmental tradeoffs of shale gas development could also be strongly affected by several internal factors. Electricity generation efficiency varies between 28% and 58% during the end-use phase [6], which is a confounding factor affecting corresponding environmental impacts [42,74]. For the transmission phase, modes and transportation distances are major confounding factors. For instance, liquefied natural gas chains have been found to generate significantly higher GHG emissions than pipeline chains due to extra liquefication processes for liquefied natural gas [34]. When considering the transmission of shale gas over distance, GHG emission ranges from 0.77 to 1.78 g CO_2-eq GJ^{-1} km^{-1} during pipeline transmission, and long-distance transmission inevitably generates high environmental burdens and operational costs [14].

During shale gas production, estimated ultimate recovery (EUR), drilling and fracturing technologies, and fugitive methane emission exert tremendous environmental tradeoffs. EUR indicates the cumulated shale gas production throughout the life span of a well. First, a higher EUR indicates that more shale gas will be produced with the same amount of energy being put into a well. As the most sensitive parameter to GHG emissions and ED of shale gas wells [18,71,73], EUR is subject to the geology, geomechanics, and petrophysical conditions of the formation, affecting the initial shale gas production, exploitation technology, and the decline of gas production over time [19,75,76]. Previous studies indicated the shale gas EUR ranged from 0.8 to 7.5 billion cubic feet (bcf) in China [19,67], 0.7−6.3 bcf in the US [55,61], and 0.1−44.5 bcf in the UK [33,48]. The low- and high-end ranges of EUR were quite large, especially in the UK, introducing high uncertainty to environmental impact assessment.

Secondly, drilling and fracturing represent the largest share of the total energy consumption and GHG emissions associated with diesel and material usage [23]. Drilling and hydraulic fracking technologies vary dramatically under different geological conditions, resulting in considerable deviations in environmental tradeoffs among various shale gas basins [13]. Hydraulic fracking

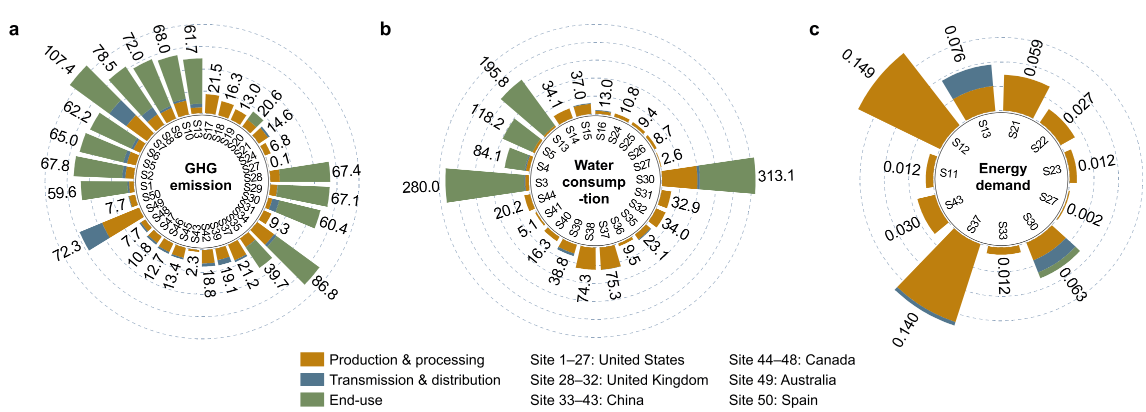

Fig. 3. Environmental tradeoff comparisons among different shale gas development studies based on a systematic literature review. **a**, GHG emission (g CO_2-eq per MJ of shale gas) [15–21,23,33,41–58]; **b**, water consumption (mL per MJ of shale gas) [8,16–18,20,46,47,49,51,52,59–68]; **c**, energy demand (MJ per MJ of shale gas) [16,17,23,45,47,51,69–72]. When a color is not shown in the figure for a site, it suggests the corresponding phase was not considered in the original research.

has been reported to consume more than 80% of water resources during shale gas production [8,18], and many shale gas sites are located in water-scarce areas, potentially exacerbating regional water shortage [77–79]. As flowback and produced water (FPW) contains a variety of inorganic (e.g., salts, heavy metals, radionuclides) and organic (e.g., hydrocarbons, chemicals additives) contaminants [80,81], the treatment of FPW often requires a large quantity of clean water for dilution, exacerbating WC in shale gas exploitation sites [60].

Moreover, fugitive methane from shale gas production sites is a major uncertain source of GHG emissions, ranking as the 10th largest anthropogenic methane emission source in the US [82]. Research suggests that gas production processes involve 3.6–7.9% of methane leakage over the lifetime of a shale gas well [42]. Lifetime GHG emissions from methane leakage range from 0.51 to 4.4 g CO_2-eq MJ^{-1} during the entire shale gas life cycle [42,43,73,83,84]. The average methane emission rate reaches 6 g h^{-1} per well in Canada and the US, depending on plugging status, well type, and region [82]. Most studies have considered the GHG emission by fugitive methane emissions but have omitted it after well abandonment [21,33,49]. Taken together, refining system boundaries and harmonizing unique features of shale gas exploitation sites could potentially decrease uncertainties and enable fair environmental tradeoff comparisons among regions.

3.2. Meta-analysis

Meta-analysis was applied to minimize uncertainties and reveal environmental tradeoffs for shale gas exploitation. Table S6 summarizes harmonized results that were categorized by different regions through meta-analysis. GHG emission resulted in a 70–92% reduction after harmonization (Fig. 4a). Harmonized GHG emissions (CO_2-eq per MJ of shale gas) are 12.4 (5.6–32.5) (median (range)) in the US, 9.2 (6.0–10.8) in the UK, 10.9 (6.7–12.3) in Canada, and 15.8 (7.2–23.5) in China (Table S6). The average GHG emission in China is relatively higher than in other countries.

Harmonized WC is 11.1 (7.5–49.5), 79.9 (40.1–119.7), 20.4, and 22.4 (10.0–83.0) mL per MJ of shale gas in the US, the UK, Canada, and China, respectively (Fig. 4b, Table S6). Meanwhile, harmonized ED range from 0.041 (0.027–0.172) MJ per MJ of shale gas among all studied regions (Fig. 4c). Harmonized ED are 0.040 (0.027–0.172), 0.036, and 0.031–0.139 (0.048) MJ per MJ of shale gas in the US, the UK, and China, respectively (Table S6). All three environmental tradeoffs in China are found to be higher than those in the US during shale gas exploitation. This could be attributed to different geological features of shale gas sites and varying drilling and fracturing technologies applied [23,64].

Higher environmental impacts may occur during shale gas exploitation in China than in the US (Fig. 4). The deeper well depth in China could elevate higher environmental tradeoffs than in the US. Research has found that more than 65% of shale gas resources are buried at depths exceeding 3500 m in China, whereas the shale burial depths in the US are within 1500–3500 m [85,86]. Deeper wells require more diesel for powering drilling and fracturing equipment, oil-based drilling fluids, and more cement and casing utilization for well casing [23], which would increase both GHG emissions and energy required to extract the shale gas.

Drilling technologies could also affect environmental tradeoffs. Most shale gas sites in the US use water-based fluid for well drilling. In China, however, both water and oil-based fluids are used due to the lack of techniques to maintain the stability of the wellbore [19,23]. Oil-based drilling fluid is used after the drill bit enters the desired geological formation, resulting in a large amount of diesel and oil consumption [23]. In addition, since GHG emission and energy usage from upstream material production account for a considerable proportion of the total GHG emission of shale gas development [19], emissions associated with diesel and oil combustion (for powering the drilling rig and fracturing fleet) and raw material inputs could result in higher GHG emissions in China than those in the US.

The amount of fracturing water used for each well in China is generally higher than that in the US. Shi et al. [13] reported that volumes of fracturing fluid per meter were 20.15 m^3 m^{-1} and 23.97 m^3 m^{-1} in Weiyuan and Fuling shale gas basin in China, respectively. Alternatively, less water utilization was found in the US, for example, 14.35 m^3 m^{-1} in Marcellus and 11.2 m^3 m^{-1} in Barnett shale. In addition, almost all shale gas wells in China use slick-water fracturing, while many shale gas wells in the US consume a mixture of energized slick-water and gel slick-water for fracturing, which consumes less water [67,87]. Together, well length and fracturing water recipe are both critical for water consumption in shale gas exploitation.

Previous studies reported that GHG emissions are similar between shale gas and conventional natural gas production [41,57,73,88,89]. However, the average WC for shale gas production (32.7 mL MJ^{-1}) is much higher than the conventional natural gas production (9.3–9.6 mL MJ^{-1}) [61]. Higher WC is primarily driven by hydraulic fracturing fluid used for shale gas production. Dale et al. [16] and Chen et al. [72] claimed that the higher ED for shale gas than conventional natural gas resulted from more resource inputs and auxiliary services desired. Nevertheless, three other studies drew contrary conclusions due to higher EUR in shale formation [23,45,71]. Taken together, environmental tradeoffs for shale gas may be higher than for conventional natural gas during production. However, the potential sustainability of shale gas exploitation should be evaluated systematically by integrating environmental and socioeconomic aspects.

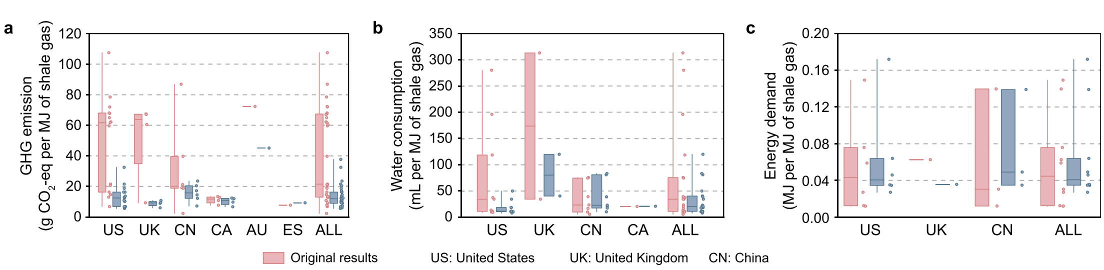

Fig. 4. Environmental tradeoff comparisons between published original and harmonized results for shale gas exploitation among various countries. Original results (pink bars) were only adjusted for units. **a**, GHG emission (g CO_2-eq per MJ of shale gas); **b**, water consumption (mL per MJ of shale gas); **c**, energy demand (MJ per MJ of shale gas). Harmonized results (blue bars) were adjusted using meta-analysis. Scattered dots next to each bar represent corresponding data points before (pink) and after (blue) harmonization.

3.3. Sustainability potential assessments

The AHP was applied to construct sustainability assessments for shale gas production based on environment, economy, and social demand aspects. Fig. 5 shows functional relationships between each sub-criterion and the corresponding SDI to better illustrate possible SDI ranges and how sub-criterion indexes were constructed. With increasing environmental tradeoffs, costs, and demand/supply, the corresponding SDI decreases (Fig. 5a–f). Conversely, SDI increases linearly for three social indicators until reaching a plateau (Fig. 5g–i). The overall SDI for each country consists of the sum of nine sub-criterion indexes.

Environmental tradeoff data were collected from shale gas wells located in different regions within a country, and these data covered most available impact ranges of shale gas extraction in that country with different characteristics among regions. Country-level economic and social demand's indicators were considered because these parameters generally remain similar within a country, especially in China following the central government policies. Together, 680400, 1680, and 370440 data points were integrated to show sustainability potential for the three analyzed countries (Fig. 6). In the environment-emphasized scenario 1, SDI scores for China (48.6 ± 6.3) are significantly higher than the UK (38.0 ± 3.3) but lower than the US (63.5 ± 8.9) (Fig. 6a) (Dunn's test, $p < 0.001$). Environment and economy indexes in China are both significantly lower than those in the US, but the social demand index in China (13.4 ± 0.5) is higher than that in both the US (13.4 ± 0.5) and the UK (3.2 ± 0.1) (Fig. 6b). In scenario 2 (balanced case), although SDIs and main-criteria index values are modified due to the changes in

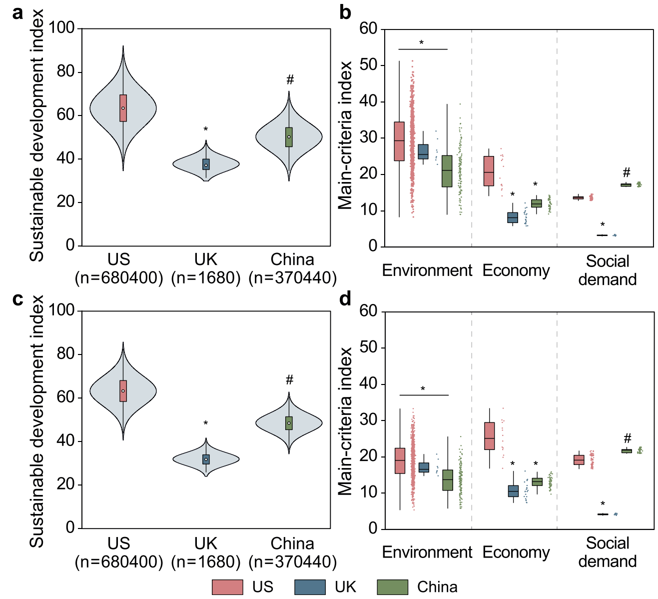

Fig. 6. Comparison of SDI and main-criterion index among the US, the UK, and China (n indicates the sample size generated through AHP): **a**–**b**, scenario 1 (environment-emphasized); **c**–**d**, scenario 2 (balanced case). Error bars represent uncertainties of each index. n represents the sample size of SDI, which is obtained from different results calculated by equations (3) and (4). Scattered dots next to each bar represent corresponding data points calculated by AHP under each main criterion for scenarios 1 (**b**) and 2 (**d**).

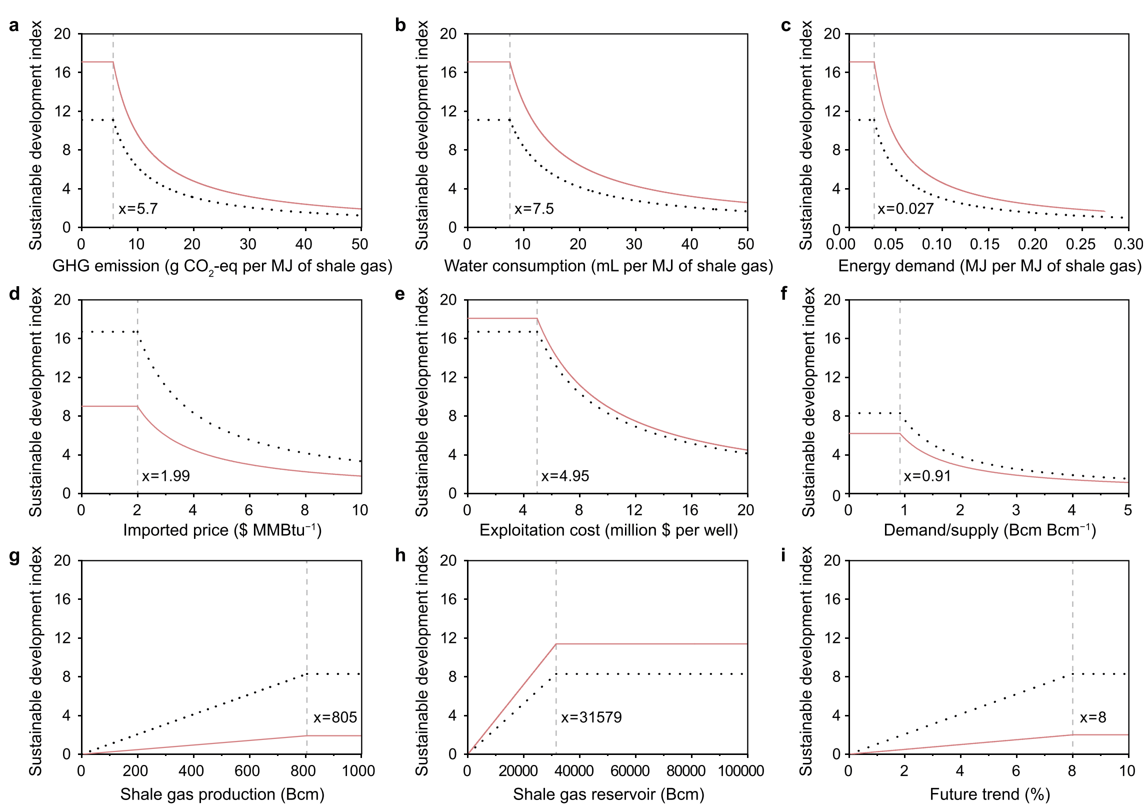

Fig. 5. Functional relationships between each sub-criterion and sustainable development indexes (SDIs) are plotted based on equations (3) and (4). **a**, GHG emission; **b**, water consumption; **c**, energy demand; **d**, imported price; **e**, exploitation cost; **f**, natural gas demand/supply; **g**, shale gas production volume; **h**, shale gas reservoir; **i**, future trend. Vertical dash lines represent the maximum value (x) of each sub-criterion that could potentially achieve based on the current best scenarios (optimized data from all three countries were adopted).

assigned scores, the rank of SDIs for three countries remained consistent.

In the present study, environment, economy, and social demand parameters were quantified from previous research, government reports, and official resources. Previous studies discussed the sustainability of shale gas exploitation considering many qualitative technological and political parameters, such as pipe network monopoly, local employment, regulatory system, local proved reserves, and market risks [27,90]. These parameters are either more focused on local-scale impact rather than national scale or considered subjective qualitative parameters, which are difficult to quantitatively compare among various countries and may increase subjectivity and uncertainty.

Additionally, AHP partially reflects human thinking and experts' opinion with some degrees of uncertainty. In scenario 1, higher weight was subjectively assigned to the environment criterion, whereas equal weights were given to environment, economy, and social demand in scenario 2. Since the SDI score is subject to the weight score of each criterion, to minimize the subjectivity and explore the sustainable development potential of shale gas exploitation under different weighting scenarios, the main-criteria weights varied to analyze all possible scenarios where SDI ranks shift for the three countries (Fig. S1). Green surfaces above the intersection lines (L1, L3, and L5) suggest China could have higher SDIs than the US (pink surfaces) under an extreme condition, where social demand should contribute over 67% of the total weight score. Similarly, green surfaces below the intersection lines (L2, L4, and L6) indicate that China may have lower SDIs than the UK (blue surfaces) under certain conditions. The SDI in the US is always higher than that in the UK since there is no intersection between pink and blue surfaces.

The uncertainty of SDIs and main-criteria indexes are presented in Fig. S2−S25. Uncertainty analyses suggest that the variation of SDIs is dictated by environmental and economic parameters (Table S22−S27). Uncertainty analyses for scenario 1 revealed that the SDI value and 95% confident intervals are 63.3 (48.8−78.0), 37.8 (9.1−48.2), and 50.2 (40.0−61.1) for the US, the UK, and China, respectively (detailed information is shown in the SI, Tables S22−S27). In addition, all three parameters showed relatively similar sensitivity for the SDI in the US. Increasing 20% the weight of one main criterion led to a 3−12% change in the average value of SDIs. Environment and social demand were identified as the most sensitive SDI parameters for the UK and China, respectively (Fig. S26, Table S28).

Based on Tables S29 and S30, each median sub-criterion index was calculated and then integrated into a spider graph to illustrate how individual sub-criteria dictate the overall sustainability potential of shale gas development in three countries (Fig. 7). The sustainable potential for the US (area covered in pink) is higher than that for the other two countries under both scenarios. Higher scores represent more advantages in the corresponding categories for each country. The US performs better than the other countries in WC, IP, EC, D/P, and SP. The UK leads in GHG and ED due to the lowest GHG emission and ED during shale gas exploitation, while the other sub-criteria for this country show the lowest performance. China displays great advantages in the SR and FT, with intermediate levels in most sub-criteria. The high social demand trend is more noticeable in scenario 2 for the balanced scenario.

The US has a mature market and industry for shale gas exploitation. With an average annual growth rate of 12.7% from 2015 to 2020, the shale gas production volume reached 805 bcm in 2020 for the US, much higher than China's 20 bcm [31], which provided the US higher SDI score in the SP category. In addition, owing to their advanced and developed technologies, SDI scores for WC and EC are relatively high in the US. In China, the market demand for natural

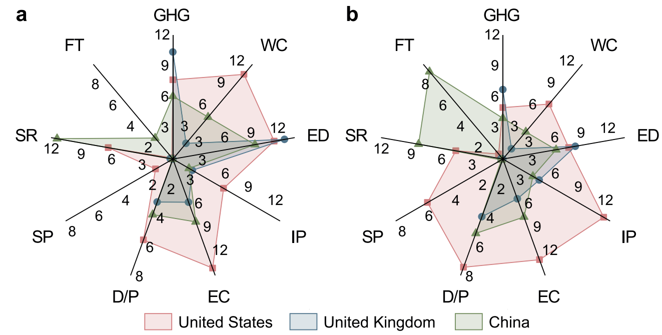

Fig. 7. Sustainable development potential of shale gas exploitation in the US, the UK, and China based on median sub-criterion indexes in analytic hierarchy process: **a**, scenario 1; **b**, scenario 2. GHG: greenhouse gas emission; WC: water consumption; ED: energy demand; IP: natural gas imported price; EC: shale gas exploitation cost; D/P: domestic natural demand versus production; SP: shale gas production volume; SR: shale gas reservoir; FT: future trends of natural gas demand.

gas is rapidly growing at an annual rate of 7−9% by 2025 [91]. However, present natural gas production in China falls far behind market demand. Nowadays, natural gas in China still relies primarily on imports from other countries with relatively high import prices, which leads to low IP values. With a strong driving force of government support, the exploitation of shale gas is expected to decrease China's dependence on natural gas imports.

On the other hand, hydraulic fracturing for shale gas production has encountered opposition due to its potential environmental risks despite the huge economic benefit and employment depressurization. Although China has the largest shale gas reservoir worldwide [92], weak technology, along with complex geological structures, insufficient geological surveys, and water scarcity in China resulted in low production, high exploitation cost, and high environmental pollution in the past few years [90]. This led to higher environmental burdens during shale gas exploitation in China (Fig. 7). To change this situation, China has established an independent horizontal well drilling and completion technology system in recent years to enhance shale gas production yield [93]. The estimated production volume of shale gas has increased by 30% from 2019 to 2020, accounting for 10% of natural gas production in China in 2020 [94]. Comparatively, dry shale gas production in the US attributed to about 79% of total US dry natural gas production in 2020 [95].

Additionally, policy incentives, including financial subsidies, tax breaks, and technical support, are important factors for local and national shale gas producers [96]. Both China and the US have issued tax incentives and subsidies for shale gas explorations. The US issued a $0.014 per m^3 of shale gas tax relief and a subsidy of $22.05 per ton oil equivalent for unconventional gas. Over $45 million per year in shale gas research and development have been invested from 2005 to 2015 [97]. In China, a two-year tax incentive was exempted for Chinese-foreign joint ventures in shale gas projects to promote international technical cooperation since 2011 [98]. The financial subsidies for shale gas exploitation from 2012 to 2020 were approximately $0.03−0.06 per m^3 of shale gas [99]. In addition, the construction of nation-level demonstration zones by breaking down barriers among businesses, advanced technologies, and best practices is an efficient way to accelerate shale gas development in China, and the Chinese shale gas production has increased from 4.6 billion cubic meters (bcm) to 20 bcm from 2015 to 2020 [31,96]. However, on November 2, 2019, the UK Government announced that it would take a presumption against issuing any further hydraulic fracturing consents in England. An annual survey commissioned by the Department for Business, Energy &

Industrial Strategy in 2021 found that only 17% of the UK public supported fracking. This may extremely hinder shale gas development in the UK [100]. Taken together, based on the growing production volume, government promotion, and evolving drilling technologies, there remains a growing opportunity for shale gas production in China.

It is worth mentioning that shale gas production not only consumes a significant amount of water resources but also causes severe water contamination due to the lack of proper management of hydraulic fracturing flowback and produced water (HF-FWP) which returns to the surface after fracturing activity. HF-FPW is a complex, tripartite mixture of injected HF fluid components, deep formation water, and secondary byproducts of downhole reactions with the formation environment [101,102]. Although our work did not consider potential water contamination, due to the limited knowledge of the chemical contents and lacks standardized treatment technologies, this could become an increasingly stringent issue facing shale developers and determining whether shale development would be allowed in many countries.

Shale oil (also known as tight oil) is oil embedded in low-permeable shale, sandstone, and carbonate rock formations. Although shale oil may have great potential to revolutionize the traditional oil industry, the development of shale oil in China is still in its very infant stage and has not been widely exploited yet [103]. Comparatively, the US EIA estimates that in 2021, about 2.64 billion barrels (or about 7.22 million barrels per day) of crude oil will be produced directly from tight oil resources in the US. This was about 65% of total US crude oil production in 2021 [104]. Although shale oil extraction also relies on hydraulic fracturing technologies, this study only considered the sustainability of shale gas production, and all data utilized in the present study focused on shale gas exploitation rather than shale oil.

4. Conclusions and perspectives

Understanding the limitations of current knowledge, recent research regarding life cycle environmental tradeoffs of shale gas has come to different conclusions due to varied system boundaries, geological features, and exploitation technologies. Through meta-analyses, we have developed a consistent and robust foundation regarding three major life cycle environmental tradeoffs from shale gas exploitation in various countries. Furthermore, major environmental and socioeconomic characteristics dictate the sustainability of nationwide assessment of shale gas exploitation, which varies among countries. There are higher environmental tradeoffs in China than in the US during shale gas exploitation. However, the current assessment suggests that a high potential for sustainable shale gas production remains in China under certain conditions.

As the largest shale gas reservoir worldwide, China is motivated to develop shale gas processes due to the urgency in energy strategy transformation and to meet the carbon peak and neutrality pledge. Research predicts that the Chinese government will increase the mixed grid of non-fossil fuels and natural gas from 23% to 45% by 2030. Future technology innovation could increase EUR and decrease the extraction costs, providing robust and substantial long-term sustainable paybacks. The present work defines uncertainties of environmental tradeoffs and demonstrates the sustainability tendency of shale gas development in different countries under multiple levels. Although our large-scale comparisons mainly focus on nation-level sustainability assessment, local governments could also consider the regional specific environmental, economic and social factors to develop locally-based standards towards achieving sustainable energy supply, a global issue with regional solutions.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2022.100202.

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