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Assessing renewable energy efficiency and policies: A combined analysis of LMDI, super-SBM, and fieldwork in Qinghai, China

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ABSTRACT

The significance of renewable energy as a pivotal green industry in decarbonizing the global economy and addressing the climate change is profound. The rise of China's regional renewable energy serves as a testament to its transition from an industrial powerhouse to a leader of sustainable growth, offering valuable insights for a sustainable future worldwide. This study analyzes renewable energy efficiency, alongside the factors that influence it, in Qinghai Province over 2000–2021. It uses a combination of the Logarithmic Mean Divisia Index factor decomposition, Data Envelopment Analysis of Super-SBM models, and field research with a rounded approach. The study finds a robust increase in renewable energy capacity, particularly after 2016. Efficiency in renewable energy generally has risen, although periods of inefficiency were noted from 2014 to 2019. Despite fluctuations, the overall impact of factors such as renewable energy structure, electricity intensity, energy security, energy intensity, carbon productivity, and carbon emissions, all contribute positively to the development of renewable energy, notably in recent years. The paper concludes with a discussion of green industrial policies with wider implications for the renewable energy sector.

Introduction

While fossil fuels continue to contribute significantly to global electricity generation (Qazi et al., 2019), renewable energy is a critical green industry sector for decarbonizing the economy and addressing climate change. The International Energy Agency forecasts a surge in the manufacturing capacity of solar photovoltaics (PV), reaching approximately 1000 GW by 2024, with a dramatic increase in the demand for solar PV and wind turbines, aiming to fulfill net-zero emission targets by 2050 (IEA, 2023a). Notably, China has achieved significant progress in green industrial sectors such as renewable energy and smart transportation technologies since the turn of the century. The country set ambitious goals to peak carbon emissions before 2030 and achieve carbon neutrality by 2060.

China's progress in renewable energy epitomizes its shift from industrial might to sustainable development leadership, offering lessons and hope for a greener future. With its previous heavy reliance on coal and consequent high carbon emissions (Wang & Yan, 2022), China has pivoted towards diversifying its green industry sectors, marked by substantial investments in renewable energy since 2013, outpacing European nations like Germany and France (Holzmann & Grünberg, 2021). China's leadership in solar panel production has reduced global costs, enhancing the accessibility of solar power. Its innovation in solar PV and wind technologies has been bolstered by global collaboration, driven by the expertise fostered through institutional support and domestic policy (Nahm, 2021).

While traditional and energy-intensive sectors still face pressing pollution issues, China's green industries have seen consistent growth (Zhu et al., 2021). With the industrial sector consuming almost 70 % of total energy over the last thirty years, the government has enacted policies favoring green industrial growth (Zeng et al., 2020). The evidence suggests renewable energy and conservation policies are more impactful on green industrial growth than efforts to upgrading fossil fuel industries, with the former showing quicker effectiveness (Zeng et al., 2020). The electric vehicle industry in China exemplifies this rapid advancement and holds the potential to compete globally (Liu et al., 2020).

To meet its carbon neutrality objectives, China must continue to significantly boost its renewable energy capacity. Studies project China's potential to reach 26 % renewable energy by 2030, 60 % by 2050, and 86 % by 2050 (Yang et al., 2016). The estimated cost for the decarbonization of the power system is about 67.6 trillion yuan,

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encompassing wind and solar capacity, storage facilities, and transmission infrastructure (Song & Sun, 2023). However, the inherent intermittency of wind and solar power introduces considerable uncertainty in operation and modeling (Wang et al., 2023). Institutional adaptations are necessary to manage challenges associated with renewable energy integration, focusing on flexibility, reliability, and affordability (Song & Sun, 2023).

China's vast geographical diversity results in regional disparities in green industry development, necessitating a spatiotemporal analysis of these sectors and the factors influencing them throughout the policy development process (Lin & Zhou, 2021). Energy efficiency in green sectors significantly varies across China's main regions (Meng & Qu, 2022). There is a pronounced spatial disparity in renewable energy innovation across provinces, with higher levels in the eastern and southern regions and lower levels in the western and northern regions, indicating spatial entrenchment and path dependency (Ma et al., 2023). The adoption of more market-oriented policies and the establishment of regional coordination mechanisms are recommended to enhance renewable energy adoption (Ma et al., 2023).

In the last decade alone, China has installed about 17 % of the world's photovoltaic capacity and the bulk of it took place in its northwestern desert regions and the Qinghai-Tibet Plateau (QTP) (Luo et al., 2023). The QTP, overlapping with the northwest, plays a pivotal role in renewable energy development, especially from its central and southern regions with further power grid infrastructure (Qiu et al., 2022a). It has a vast carbon sequestration capacity for regional carbon dioxide mitigation (Wo et al., 2023). Importantly, the plateau plays a key role in the thermal dynamics and circulation of the climate system, influencing energy and hydrological cycles (Yu, Du, et al., 2022; Yu, Zhang, et al., 2022). However, the plateau's delicate ecological balance is under threat from global warming, driven by high carbon emissions, particularly from energy production and supply industries (Wo et al., 2023; Yan et al., 2023). While hydropower has the most significant response to ecological conservation measures among the QTP renewable resources, its wind power is most affected by construction challenges and return on investment (Qiu et al., 2022b). Further, provinces in this region face persistent issues with wind and solar energy curtailment, highlighting the need for integrated energy storage solutions (Li et al., 2023).

Characterized by its thin air and harsh winters, energy poverty remains widespread in rural areas of the QTP, with residents relying on biomass and inexpensive coal for heating and cooking as a cost-saving strategy (Jiang et al., 2020; Liu et al., 2018). The prevalent use of organic materials for heating and cooking leads to indoor air pollution and public health concerns (Gyatso et al., 2023; Ping et al., 2012; Zhuang et al., 2021). Even with nearly complete electrification in regions like Qinghai, 80 % of rural energy comes from biomass (Liao et al., 2021), indicating a need to diversify and modernize the energy mix to enhance rural well-being. While wind and solar energy have been proposed as alternative energy solutions, traditional practices, economic considerations, and policy barriers have slowed the energy transition in households (Zhuang et al., 2021). In 2014, China initiated a nationwide campaign to install solar PV systems in rural areas, targeting aid for over two million households (Liao et al., 2021). However, poverty alleviation and energy transition efforts have faced challenges due to a lack of alignment with local needs and effective community engagement (Liao et al., 2021). Although passive solar heating, solar air heating, and solar-powered ultra-low energy houses present promises to reduce emissions and improve efficiency, a multifaceted approach considering technical, economic, social, and policy factors is needed to address energy poverty (Liu et al., 2019; Liu, Zhao, Chen, et al., 2022; Liu, Zhao, Zhang, & Zhou, 2022; Qiang et al., 2023; Zhao et al., 2017). For the sustainable development of solar energy initiatives, it is imperative to conduct comprehensive research to address socio-economic challenges, the lack of electricity in higher altitudes, and preserve the natural environmental capacity and ecosystems (Gyatso et al., 2023; Meng et al., 2021).

Located at the juncture of Northwest China and the QTP, Qinghai serves as a pivotal center for renewable energy due to its rich solar and wind energy resources and extensive water reserves. Since the early 2000s, Qinghai has been a forerunner in off-grid solar initiatives for rural electrification and has propagated solar cookers to mitigate indoor air pollution from biomass combustion (Liao et al., 2021). In recent years, the focus has transitioned to constructing utility-scale, grid-connected PV systems (Liao et al., 2021). Currently, over 87 % of the province's energy infrastructure is considered new (Tian et al., 2023). In consecutive years, Qinghai has successfully operated solely on renewable energy for extended periods, leading to the reduction of coal-fired power stations (Xinhua, 2019). By 2020, renewables were responsible for producing 89 % of the province's total electricity output (Xinhua, 2021). Importantly, the rise of renewable energy-based "green power" has a remarkable effect in reducing Qinghai's carbon emissions (Shi et al., 2023). The province has one of the lowest carbon emissions levels in China, contributing just 0.5 % to the national total (Tian et al., 2023). While the distribution of carbon emissions is imbalanced at prefectural-level cities and industries (Shi et al., 2023), projections indicate that carbon emissions in Qinghai will follow a rise and then decline pattern from 2020 to 2060 (Tian et al., 2023).

Local authorities are cultivating green industries such as renewable energy, positioning the region as an emerging hub for green industry. Qinghai's 14th Five-Year Plan (FYP) outlines a goal to double its clean energy capacity by 2025, with a foundation based on manufacturing solar PV and wind turbine equipment, and developing geothermal, hydropower, ultra-high voltage transmission, energy storage, lithium battery production, and a comprehensive new energy vehicle industry. The province aspires to sustain 100 % clean energy consumption, backed by advancements in science and technology, and the deployment of smart grid infrastructure (Li et al., 2020). Notably, the Qinghai established China's inaugural ultra-high voltage line dedicated exclusively to transmitting 100 % renewable energy (Yu, Du, et al., 2022). With its significant energy sector reforms and abundant resources, Qinghai presents a unique case for evaluating strategies aiming for carbon neutrality.

Previous studies pointed out various limitations and policy considerations within Qinghai's energy sector, including challenges in development, ecological impacts of wind energy, and the need for diverse energy storage and management solutions to address renewable energy intermittency (Fang et al., 2022; Li et al., 2023; Xu et al., 2022; Yu, Du, et al., 2022; Zhang et al., 2022; Zheng & Wong, 2024). Yet, the efficiency of renewable energy and its operational dynamics in emerging green industries require more in-depth analysis at regional and provincial levels. Evaluating renewable energy efficiency is vital for addressing global energy demand and climate change (Liu et al., 2023). This study investigates renewable energy efficiency and its influencing mechanisms in Qinghai using a Logarithmic Mean Divisia Index (LMDI) factor decomposition and Data Envelopment Analysis (DEA) of Super SBM models. Comprehensive field research provides a nuanced perspective. The study also outlines green industrial policy implications that could help not only Qinghai but also other regions and developing countries striving for efficient renewable energy development.

This study makes three key contributions. First, it sheds light on Qinghai's emergence as a hub for renewable energy amidst regional development disparities. Despite this prominence, the trajectory of this development remains largely unexplored within the context of both the province itself and the broader region. The paper undertakes an assessment of renewable energy efficiency and its determinants, with a particular focus on Qinghai. This provincial perspective holds relevance not only for the Qinghai-Tibet Plateau but also for other regions facing similar challenges. Second, the study employs a comprehensive approach, utilizing combined models incorporating multifaceted variables alongside field studies. This method enables a nuanced understanding of the complexities surrounding renewable energy development in the region. Third, with a regional focus, the paper offers invaluable insights into green industrial policy implications. These findings hold significance for stakeholders at regional, national, and international levels who are invested in promoting sustainable energy practices and enhancing energy efficiency. Key recommendations include advocating for stable policy environments, diversifying the energy mix, bolstering grid infrastructure, and fostering sustainable economic growth through the promotion of clean energy initiatives.

Methods

The Super-SBM model has gained wide recognition for its robustness in assessing energy efficiency (Meng & Qu, 2022; Yang et al., 2022; Zhang, Qu, & Zhan, 2023; Zhang, Wang, et al., 2023). Additionally, the Logarithmic Mean Divisia Index (LMDI) decomposition model with the extended Kaya identity has been employed in previous studies to assess the influencing factors of carbon emissions and renewable energy efficiency (Andrei et al., 2022; Fan et al., 2020; Wang et al., 2018; Wang et al., 2022).

For a thorough assessment of renewable energy efficiency, this research integrates the DEA model of super-efficiency SBM, with the LMDI decomposition model in consistent with previous studies. This is complemented by field research in Qinghai. The authors visited solar, wind, and hydropower facilities in the Haixi Mongol and Tibetan Autonomous Prefecture, Hainan Tibetan Autonomous Prefecture, and Huangnan Tibetan Autonomous Prefecture, as delineated in Fig. 1. The former two prefectures are at the forefront of renewable energy adoption in Qinghai, serving as exemplars in the sector.

Data

In this study's super-efficiency SBM model, the inputs include fixed asset investment, labor, and energy, while the outputs are Gross Domestic Product (GDP) and the generation of renewable energy, with carbon dioxide emissions as undesirable outputs. Furthermore, the research utilizes data from 2000 to 2021 on renewable energy generation, electricity generation, energy production, energy consumption, GDP, and total carbon emissions within the Logarithmic Mean Divisia Index (LMDI) model framework, details of which are provided in Table 1.

Table 1
Data and description.

Data	Description
1. Renewable Energy Generation	Total renewable energy (solar, wind, hydro, thermal) generation in terawatt hour.
2. Electricity Generation	Total electricity generation in terawatt hour
3. Carbon emissions	Carbon emissions measured in million metric tons using mass balances based on IPCC guidelines (Shan et al., 2020). For the year 2021, where data gaps existed, imputation was performed using a linear regression model, maintaining continuity in the dataset.
4. Primary Energy Production	Total energy production was converted into a unit of 10,000 tons of standard coal equivalent.
5. Energy consumption	Total energy consumption was converted into a unit of 10,000 tons of standard coal equivalent.
6. GDP	Gross domestic product is at constant 2000 prices using GDP deflator.
7. Labor	Labor figures in 10,000-person units.
8. Capital	The calculation of capital was based on the price deflator index of investment data, employing methodologies outlined in the works of Zhang et al. (2004), Xu et al. (2007), and Shan (2008). The perpetual inventory method was utilized, incorporating a depreciation rate of 10.96 % as per Zong and Liu (2014), with the baseline year set in 2000. In instances where the fixed asset investment price index was unavailable (notably in the 2021–2022 period), the Consumer Price Index served as an alternative metric.

All data over 2000–2021 were from the China Statistical Yearbook, Qinghai Statistical Yearbook, China Energy Statistical Yearbook, Historical Data of China's GDP Accounting 1952–2002, China Fixed Asset Investment Statistical Yearbook 2004–2017, and CEADs.

Efficiency model

In the evaluation of renewable energy efficiency, this research employs a non-radial and non-oriented DEA model, the SBM, as formulated by Tone (2001). This model has been enhanced to incorporate super-efficiency and the treatment of undesirable outputs, as detailed in subsequent studies by Tone (2002, 2003). Within this model, considering n decision-making units (DMUs) characterized by input vectors $X = \left(x_{ij}\right) \in R^{m \times n}$, desired output vectors $Y = \left(y_{kj}\right) \in R^{s_1 \times n}$, and undesired output vectors $Z = \left(z_{lj}\right) \in R^{s_2 \times n}$, let $X > 0, Y > 0, Z > 0$, the production possibility set is delineated as: $P = \{(x,y)|x \ge X\bigwedge, y \le Y\bigwedge, z \ge Z\bigwedge,$

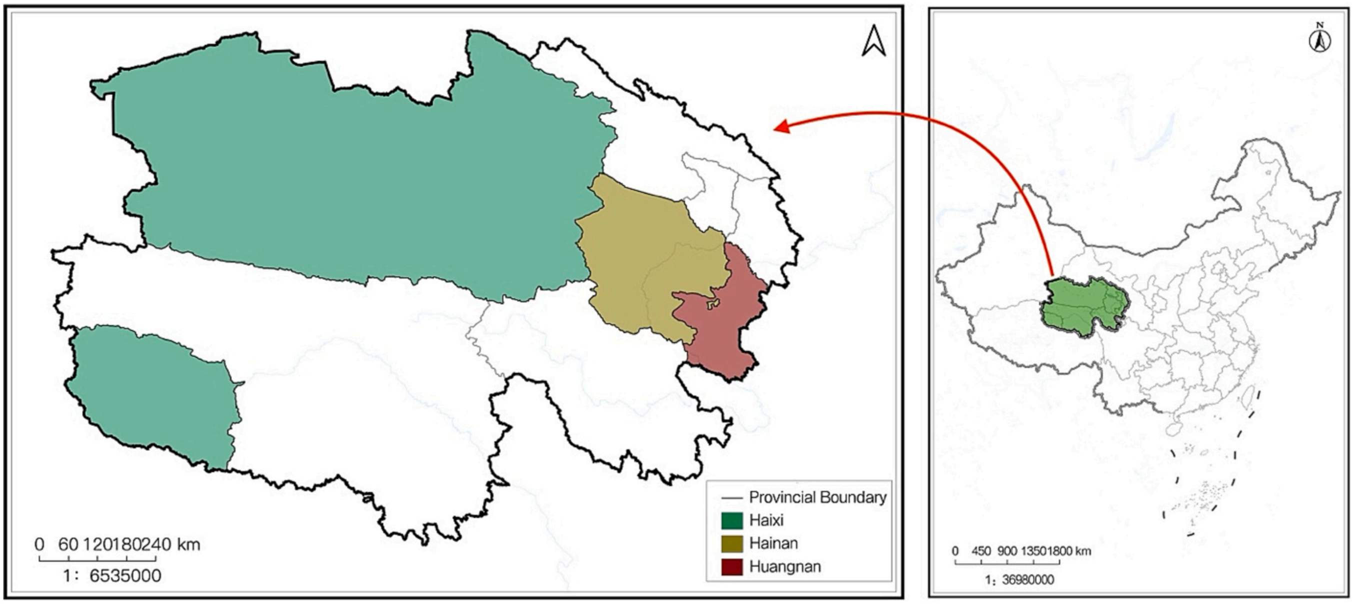

Fig. 1. Map of study area.

$\bigwedge \geq 0\}$, where $\wedge = [\lambda_1, \lambda_2, \ldots, \lambda_n] \in R^n$ signifies the vector of weight coefficient. The set P is thus defined by conditions ensuring that actual inputs at least meet frontier inputs, actual desirable outputs do not exceed frontier outputs, and actual undesirable outputs are not less than frontier outputs. In this formulation, each DMU is depicted by its input (X), desirable output (Y), and undesirable output (Z), with input excesses represented by $s^x \in R^m$, undesirable output excesses by $s^z \in R^{s2}$, and shortfalls in desirable outputs by $s^y \in R^{s1}$ (Tone, 2003).

Since Tone (2003) did not provide a formula for the SBM model encompassing undesirable outputs, this study adopts the formula introduced by Cheng (2014) to ascertain the efficiency of DMUs (x_0,y_0, z_0). The super SBM model, which integrates the undesirable outputs, is subsequently formulated as:

$$\rho = min\frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{w_i^x s_i^x}{x_{i0}}}{1-\frac{1}{s_1+s_2}\left(\sum_{k=1}^{s_1}\frac{w_k^y s_k^y}{y_{k0}}+\sum_{l=1}^{s_2}\frac{w_l^z s_l^z}{z_{i0}}\right)}$$

$$s.t. x_{i0} \geq \sum_{j=1,\neq 0}^{n} \lambda_j x_j - s_i^x, \forall i;$$

$$y_{k0} \leq \sum_{j=1,\neq 0}^{n} \lambda_j y_j + s_k^y, \forall k;$$

$$z_{l0} \geq \sum_{j=1,\neq 0}^{n} \lambda_j z_j - s_l^z, \forall l;$$

$$0 < 1 - \frac{1}{s_1+s_2}\left(\sum_{k=1}^{s_1}\frac{w_k^y s_k^y}{y_{k0}} + \sum_{l=1}^{s_2}\frac{w_l^z s_l^z}{z_{l0}}\right);$$

$$s_i^x \geq 0, s_k^y \geq 0, s_l^z \geq 0, \lambda_j \geq 0, \forall i, j, k, l;$$

therein, ρ denotes the efficiency score assigned to a DMU. The parameters m, s_1 and s_2 represent the count of variables pertaining to the inputs, desired outputs, and undesired outputs respectively. A DMU is deemed efficient, indicated by $\rho = 1$, in the absence of input excesses ($s^x = 0$), desired output shortages ($s^y = 0$), or undesired output excesses ($s^z = 0$). Conversely, a DMU with $\rho < 1$ is considered inefficient, signifying potential areas for enhancement. The model computes efficiency scores with $\rho \geq 1$, assuming equal weighting across variables as reflected by $w_i^x = 1, w_k^y = 1, w_l^z = 1$.

The super-efficiency SBM model, unlike models based on radial and directional DEA approaches, does not restrict its evaluation to the condition where $j \neq 0$ as per Tone (2002). It extends beyond identifying efficient DMUs to ascribing a super-efficiency score of 1 to inefficient ones. The findings for the super-efficiency SBM model in this study are derived from a combined analysis of data from both super-efficiency and non-super-efficiency models. Super-efficiency calculations were employed for the efficient DMUs, while the non-super-efficiency model was applied to the inefficient ones. The slack variables and the coefficients of Lambda were determined using the calculations from the non-super-efficiency model.

Decomposition model

The LMDI has gained prominence as a superior model for the decomposition analysis of factors affecting energy-related carbon emissions (Ang, 2015). The LMDI model is distinguished by its capacity for complete decomposition without residual errors, with consistency in additive and multiplicative decomposition forms. Moreover, its ability to accommodate zero values within the dataset enhances its analytical precision (Ang et al., 1998; Wang & Wang, 2020).

In line with the previous studies on the LMDI method (Ang, 2004, 2005, 2015; Ang et al., 1998), this research applies the Kaya identity (Kaya, 1990) in conjunction with the LMDI approach (Ang, 2015) to further analyze the factors influencing renewable energy efficiency. This process involves decomposing the influencing factors into renewable energy structure, electricity intensity, energy security, energy intensity, carbon productivity, and carbon emissions. By leveraging the Kaya identity, the factors contributing to carbon emissions are systematically quantified as follows:

$$RE = \left(\frac{RE_t}{EG_t}\right) \times \left(\frac{EG_t}{EP_t}\right) \times \left(\frac{EP_t}{EC_t}\right) \times \left(\frac{EC_t}{GD_t}\right) \times \left(\frac{GD_t}{C_t}\right) \times C_t$$
$$= \sum r \times e \times s \times y \times p \times c$$

therein, RE_t denotes renewable energy generation in year t. EG_t denotes total electricity generation in year t. EP_t denotes total energy production in year t. EC_t denotes total energy consumption in year t. GD_t denotes GDP in year t. C_t denotes total carbon emissions in year t. The r, e, s, y, p, and c simplifies variables of renewable energy structure, electricity intensity, energy security, energy intensity, carbon productivity, and carbon emissions, respectively. Using the additive LMDI decomposition model, the change in renewable energy from the base year (0) to the target year (t) is obtained as:

$$\Delta RE = RE_t - RE_0 = \Delta R_r + \Delta R_e + \Delta R_s + \Delta R_y + \Delta R_p + \Delta R_c$$

therein, ΔRE represents the change in the total growth of renewable energy. $\Delta R_r + \Delta R_e + \Delta R_s + \Delta R_y + \Delta R_p + \Delta R_c$ signify the effects of renewable energy structure, electricity intensity, energy security, energy intensity, carbon productivity, and carbon emissions, respectively. The LMDI decomposition factors are expressed as:

$$\Delta R_r = \sum \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)} \times ln\left(\frac{\mathrm{r}_t}{r_0}\right)$$

$$\Delta C_e = \sum \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)} \times ln\left(\frac{e_t}{e_0}\right)$$

$$\Delta C_s = \sum \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)} \times ln\left(\frac{s_t}{s_0}\right)$$

$$\Delta C_y = \sum \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)} \times ln\left(\frac{y_t}{y_0}\right)$$

$$\Delta C_p = \sum \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)} \times ln\left(\frac{p_t}{p_0}\right)$$

$$\Delta C_c = \sum \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)} \times ln\left(\frac{c_t}{c_0}\right)$$

$$= \frac{(RE_t - RE_0)}{(lnRE_t - lnRE_0)}\left(ln\left(\frac{\mathrm{r}_t}{r_0}\right) + ln\left(\frac{e_t}{e_0}\right) + ln\left(\frac{s_t}{s_0}\right) + ln\left(\frac{y_t}{y_0}\right) + ln\left(\frac{p_t}{p_0}\right) + ln\left(\frac{c_t}{c_0}\right)\right)$$

Qualitative approach

Complementing the quantitative analysis, this study incorporates field research through open-ended interviews to attain an in-depth perspective on the development of renewable energy in Qinghai. A bespoke suite of interview questions, curated for distinct renewable energy entities, is provided in Appendix A.1. The participants were consisted of government officials, experts, and firms engaged in the renewable energy sector. These interviews, constituting strategic samples rather than probability samples, underpin the theoretical generalizations aimed at capturing the extensive context of the subject, a methodology elaborated by Grønmo (2019).

Strategic samples are selected via a deliberate and methodical examination of units that hold significant theoretical and analytical value. This approach, unlike probability sampling, may lack precision due to its nature of planning. The interviews conducted in this research were facilitated through self-selection and snowball sampling techniques. The self-selection method enables voluntary participant involvement, providing the researcher limited influence over participant demographics and no insight into the profiles of non-participants (Grønmo, 2019). Conversely, the snowball sampling method commences with initial interviewees recommending subsequent participants, and this referral process continues iteratively until a satisfactory sample size is achieved (Grønmo, 2019). Importantly, these methods focus on gathering information on specific actions, viewpoints, or events from participants. The determination of the sample size in strategic sampling is based on informed assessments rather than statistical generalizations, which predetermine sample size prior to data collection. Consequently, strategic samples are often smaller in scale compared to probability samples.

The insights derived from qualitative approaches have been synthesized with quantitative findings throughout this paper, thus enhancing the analytical depth of the study. Despite the predominance of quantitative data presentation, the qualitative data remains integral, albeit less prominently showcased. The outcomes of fieldwork substantiate the overarching observations drawn from statistical analyses, notably contributing to policy recommendations, and offering a nuanced understanding of the study area's context. This fieldwork has been carried out as an integral component of both this paper and a broader ongoing research initiative. Subsequent analyses of additional qualitative data derived from the fieldwork will be expounded upon in a forthcoming paper related to the present study.

Results and discussion

Efficiency and influencing factors of renewable energy

Measuring installed capacity of renewable energy is a crucial step for assessing progress towards sustainability goals and informing policy decisions. It provides a quantitative measure of a region's ability to generate renewable energy. However, installed capacity alone doesn't fully reflect efficiency. Efficiency relates more to how effectively energy is harnessed and utilized from renewable sources, encompassing factors like technological advancements, grid integration, and energy storage solutions. While high installed capacity indicates potential, optimizing efficiency ensures maximum utilization and effectiveness of renewable energy systems, ultimately contributing to decarbonization efforts and clean energy transition.

In Qinghai, as indicated in Fig. 2, after an initial decline from 2000 to 2003, installed renewable energy capacity in Qinghai experienced modest fluctuations but an overall upward trajectory, increasing from 111.30 terawatts in 2004 to 738 terawatts in 2021, with a notable surge post-2016. This rise of renewable energy has largely driven the reduction of carbon emissions in Qinghai over the years. The renewable energy-driven effect accounts for 54 % of Qinghai's total emission reduction (Shi et al., 2023). These trends highlight the significant growth of renewable energy capacity in Qinghai over the past two decades, signaling a shift towards sustainable energy sources. This trajectory is particularly noteworthy given the global imperative to reduce carbon emissions and combat climate change. Moreover, the quantification of the contribution of renewable energy to emission reduction (54 %) provides concrete evidence of its positive environmental impact, reinforcing the importance of continued investment and policy support for renewable energy initiatives.

Measuring renewable energy efficiency is integral to achieving carbon neutrality. Currently, there is a notable global emphasis among policymakers on energy efficiency, acknowledging its significant role in bolstering energy security, affordability, and expediting the transition to clean energy (IEA, 2023b). Enhanced levels of energy efficiency will be imperative to achieve a peak in fossil fuel demand within this decade, as indicated by the International Energy Agency (IEA, 2023b). Maximization of efficiency can accelerate the transition towards a sustainable energy future and ultimately achieve carbon neutrality goals.

Over a period of 22 years in Qinghai, as illustrated by Fig. 3, renewable energy efficiency exceeded a value of 1 for 14 years, denoting efficiency. A notable period of inefficiency was observed in 2004, 2009, and from 2014 to 2019. The lowest efficiency recorded was 0.7384 in 2016, coinciding with the year Qinghai peaked carbon emissions. However, improvement was evident from 2017 onwards, reaching efficient stage in 2020 and 2021. These trends show renewable energy efficiency over a significant period. The implications lie in assessing the effectiveness of renewable energy initiatives and their impact on reducing carbon emissions. Highlighting periods of inefficiency helps pinpoint areas for improvement and investment, while noting improvements underscores progress and potential strategies for sustainability. The correlation with carbon emissions reduction in 2016 emphasizes the importance of renewable energy in decarbonizing the economy and power sector.

To further decompose the driving forces behind the efficiency trends observed above, Fig. 4 illustrates several underlying factors that contribute to influencing efficiency. Fig. 4 shows that the total effects (TE) of factor contributions over the study period reveals 10 years of positive impact against 11 years of negative impact on renewable energy development. The peak positive influence was in 2018 with a value of 194, marking a significant advancement, whereas years like 2016 and 2021 experienced setbacks with values of −49 and − 16.34, respectively.

The effect of renewable energy structure (RES) saw fluctuations, with the most significant positive impact occurring in 2018, signaling an enhanced share of renewables at 73.62. The effect of electricity intensity (ETI) also displayed fluctuations; positive figures for 2014 and 2015 underscored improvements in electricity generation efficiency. Yet, a predominant presence of negative values over 10 out of 11 years

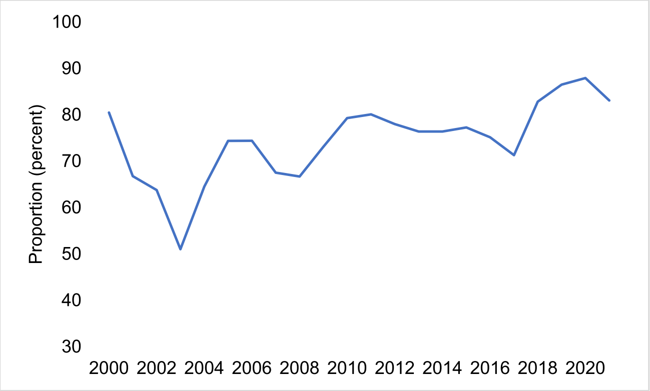

Fig. 2. Proportion of renewable energy to total installed power generation capacity.

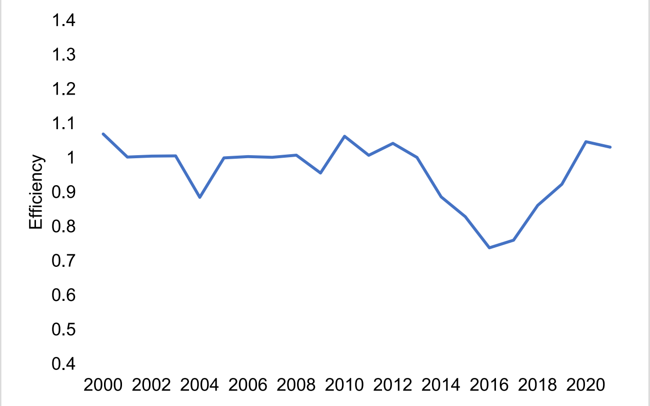

Fig. 3. Renewable energy efficiency over 2000–2021.

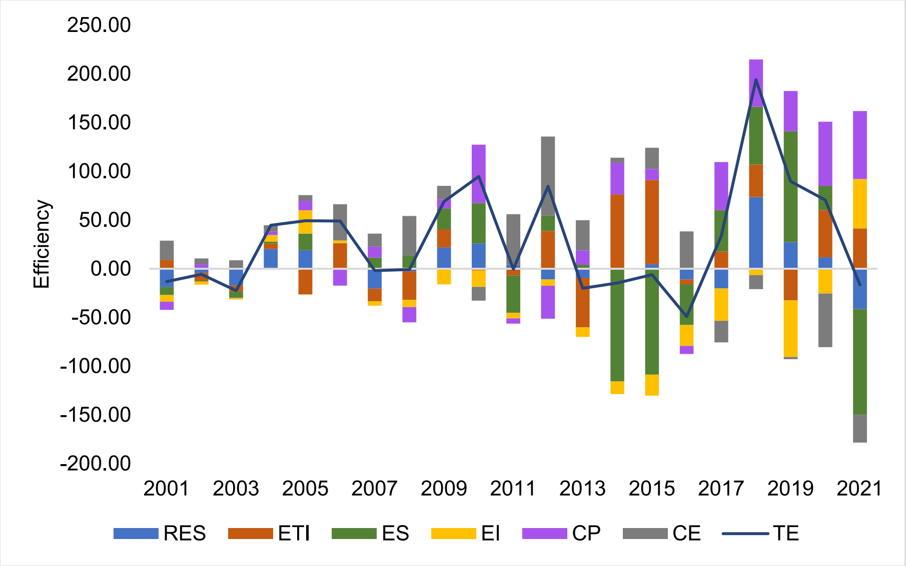

Fig. 4. Annual factor contribution to renewable energy.

suggests areas for development. The contribution of energy security (ES) to renewable energy highlights the province's energy self-sufficiency. The positive figures in 2018 and 2019 indicate an energy production surplus, bolstering energy security and renewable initiatives. Contrastingly, significant negative values for years like 2014 and 2021 reflect the adverse impacts on renewable energy progression.

The effect of energy intensity (EI) on renewable energy presented 17 years of negative effect, pointing to a decrease in energy intensity aligned with economic expansion. However, a notable positive shift occurred in 2021, with an increase in energy intensity marked at 50.64. The trend in carbon productivity (CP) has been predominantly positive, illustrating an economy's growing efficiency with declining carbon emissions. Regarding the effect of carbon emissions (CE) on renewable energy, positive values imply higher emissions, while negative values indicate reductions. Following Qinghai's peak emissions in 2016, the subsequent negative growth in emissions has positively influenced renewable energy development.

Overall, the factors analyzed through the LMDI method are crucial for understanding renewable energy efficiency. These decomposition factors provide a comprehensive framework for assessing and enhancing renewable energy efficiency, crucial for sustainability. The analysis of these factors for Qinghai displays a positive direction in the shift towards renewable energy, despite fluctuations. It highlights the necessity for stable green industrial policies and initiatives to enhance renewable energy adoption. Despite the challenging trends in energy intensity and carbon emissions, there has been a consistent decrease in these factors, suggesting a gradual transition towards more sustainable energy use.

To provide a more comprehensive contextual framework for elucidating the analysis and policy implications pertaining to the attainment of renewable energy efficiency, the following assessment encompasses energy production and consumption, energy portfolio, and significant industrial output. The inclusion of these variables and analyses affords substantive background insights into the efficiency under discussion, as well as its pertinent influencing factors. These analyses also enable policymakers, researchers, and industry leaders to make informed decisions about investment, infrastructure development, and policy implementation to maximize the effectiveness and adoption of renewable energy technologies, ultimately leading to a more sustainable and resilient energy future.

Energy production and consumption

In Qinghai, there is a correlation between energy production and consumption with economic trends. The energy demand typically escalates with rapid industrialization and economic growth. Fig. 5 indicates that there has been an overall increase in primary energy production from 937.90 in 2000 to 4505.16 in 2021. This growth can be segmented into four stages: initial fluctuations from 2000 to 2002, followed by a significant rise from 2003 to 2010 in line with economic and industrial growth. Between 2011 and 2016, production experienced variations potentially due to economic shifts or energy policy reforms. Post-2016, production stabilized, which could point to economic steadiness or transitions in energy sourcing. In addition, the reduction in production after 2014 suggests a pivot away from certain energy types towards renewable sources and policy shifts.

The steady growth of energy consumption from 2000 to 2011 mirrors the rising energy demand from economic progress. The period from 2011 to 2016 saw oscillations likely due to economic or energy efficiency changes. From 2016 onwards, the consumption pattern indicates continuous economic advancement or heightened sectorial energy requirements. In 9 out of 22 years, consumption outpaced production, highlighting a critical energy supply-demand discrepancy and underscoring the need for energy source diversification and domestic production enhancement.

Energy portfolio

Fig. 6 presents that Qinghai's energy profile is led by electricity, coal, natural gas, and oil use. Electricity's share has been substantial yet stable, ranging from 31.5 % to 47.77 %, underscoring its sector-wide importance and the imperative for investment in sustainable electricity generation sources. This steadiness is attributed to a balanced energy mix, with renewables playing a growing role in electricity supply. Coal usage has seen a notable decline from 2000 to 2021, driven by environmental concerns, a shift towards greener energy sources, and heightened climate change awareness. Natural gas has seen a rise, marking its growing importance as a cleaner energy alternative, though a decline in 2021 suggests a potential pivot to even cleaner energy sources or supply constraints. Oil consumption showed an initial decline, followed by fluctuations, maintaining a steady but slightly reduced demand in recent years. This trend reflects the continued necessity in transport and industry and the impact of energy conservation

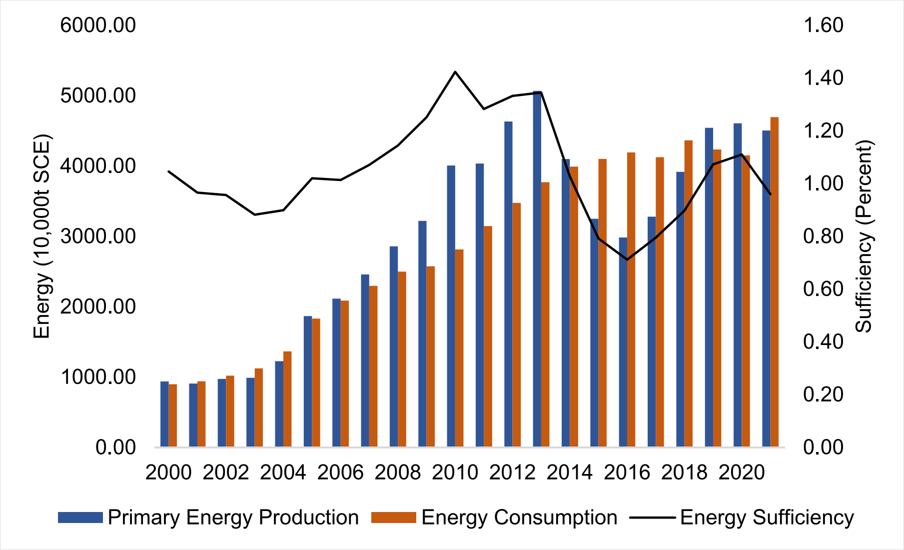

Fig. 5. Energy production, consumption, and sufficiency over 2000–2021.

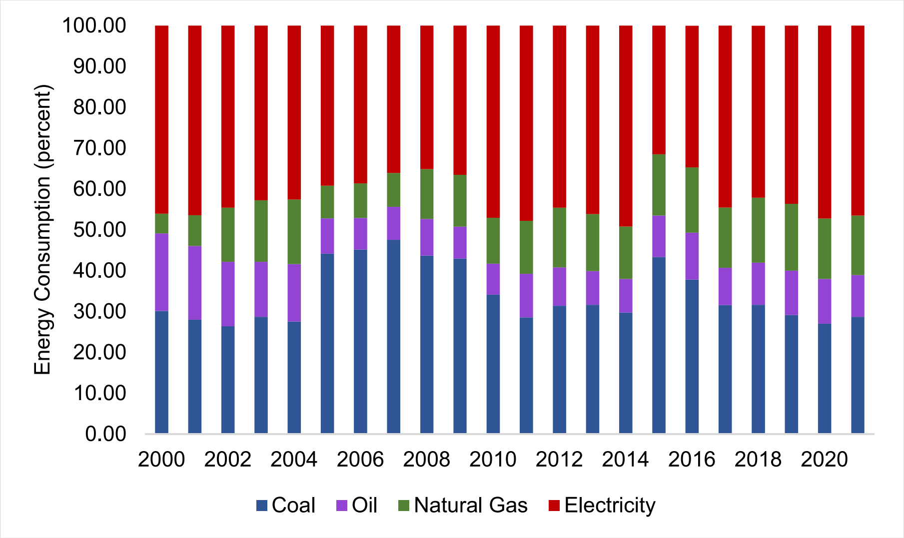

Fig. 6. Energy consumption by sources.

measures and alternative fuels.

Post-2014, the relative stability in all sources of energy consumption may indicate a period where green industrial policy has matured, with a slower shift in consumption behavior due to a more diverse energy mix, including solar, wind, and hydropower contributions. Despite the reduction in coal usage, the sustained consumption of oil, natural gas, and electricity highlights the ongoing imperative to transition towards renewable energy. Sustainable practices demand further fossil fuel reduction and vigilant monitoring of natural gas trends to avoid substituting one environmental issue (carbon emissions) with another (methane emissions).

Fig. 7 demonstrate a sustained increase in total electricity generation, with renewable electricity generation surpassing fossil fuels over the years. This trend reflects Qinghai's active advancement in renewable energy production, bolstered by green industrial policy incentives. Electricity generation is primarily from hydropower, thermal, wind, and solar power. Hydropower has maintained a consistent lead, indicating a well-established and dependable infrastructure. Thermal power exhibits variability, potentially due to fluctuating annual demand or constraints in renewable availability. Notably, since 2014, wind and solar have experienced significant expansion, a testament to the shift towards cleaner energy technologies and successful policy support, spurred by environmental considerations and strategic efforts to decrease reliance on fossil fuels.

The diverse contributions from these sources underscore the complexities inherent in grid management and the provision of stable energy. Qinghai has made rapid investments in renewable energy in recent years, predominantly through solar and wind power. However, there is a notable gap in investment towards complementary power storage facilities (World Energy, 2024). This issue has resulted in imbalanced energy distribution due to the intermittent nature of renewable energy supply and has posed challenges in integrating renewable energy into the already oversupplied grid (World Energy, 2024). These pressing issues are not exclusive to Qinghai but are reflective of the broader region's challenges in renewable energy development (Li et al., 2023). Increased investment in renewable technologies, coupled with advancements in grid storage and transmission capabilities, is likely to enhance the reliability and sustainability of the region's electricity network.

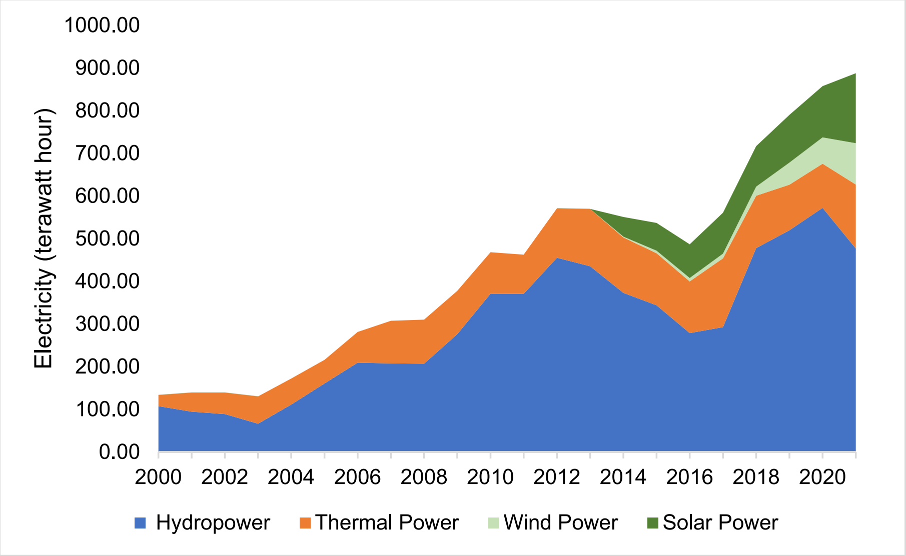

Fig. 7. Electricity generation by sources.

Major industrial output

Qinghai has a diversified industrial landscape, with varying trends in the production of coal, crude oil, steel, aluminum, salt, fertilizers, and cement, as shown in Fig. 8. Coal production, while initially increasing, begins a decline post-2013 owing to ecological concerns and the transition to cleaner energy, with a slight resurgence during the Covid-19 pandemic. Crude oil production has been fairly constant, reflecting steady demand and ongoing investment in the sector. The trends in coal and oil production mirror global shifts towards greener energy sources, propelled by environmental policy and renewable energy advocacy.

Conclusions and policy implications

This research assessed the efficiency of renewable energy and the factors that influence it in Qinghai, employing a LMDI factor decomposition and DEA of Super SBM models. In-depth field studies provided a comprehensive understanding of the context. The findings indicate a significant growth in Qinghai's renewable energy capacity during 2000–2021, with a notable increase observed after 2016. Efficiency in renewable energy generally exhibited an upward trend with periods of inefficiency recorded from 2014 to 2019. Despite fluctuations, the contributory factors of renewable energy structure, electricity intensity, energy security, energy intensity, carbon productivity, and carbon emissions have uniformly fostered the development of renewable energy, particularly in the latter years of the study. The variability of these factors underscores the imperative for consistent green industrial policy measures and strategic initiatives to promote the uptake of renewable energy.

The energy landscape in Qinghai is primarily composed of electricity, coal, natural gas, and oil. The proportion of electricity has been significant and stable, fluctuating between 31.5 % and 47.77 % of the energy mix. Predominantly sourced from hydropower and increasingly from wind and solar energy, the electricity sector signals a transition to a more sustainable and diversified energy portfolio. Concurrently, a decline in coal consumption alongside a steady use of oil and natural gas

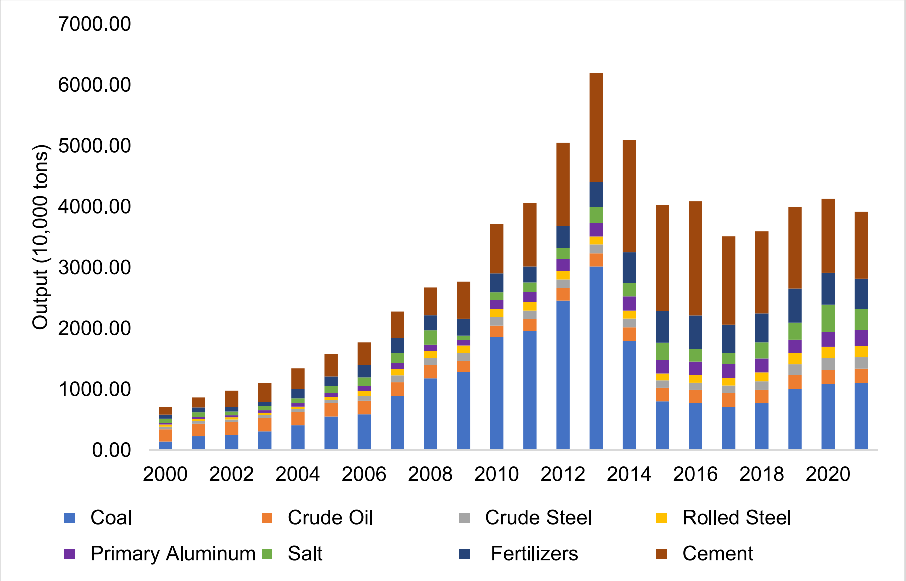

Fig. 8. Output of major industrial products over 2000–2021.

has been observed. The general stability across all energy sources since 2014 suggests a gradual shift in consumption patterns, attributable to an expanding array of energy options, including solar, wind, and geothermal energy.

The findings of this study have broader implications for green industrial policies in improving renewable energy efficiency and achieving carbon neutrality, offering actionable insights at regional, national, and international levels:

1. Enhance Incentive Structures for Efficiency Improvements: Given the fluctuations in renewable energy efficiency, particularly the efficiency dip in 2016, policies should aim to strengthen incentives for consistent efficiency in renewable energy technology. This could include tax credits, rebates for energy-efficient technology, and grants for research and development that targets efficiency improvements. Policy stability can encourage long-term investments, leading to continuous growth in renewable energy production and subsequent reductions in carbon emissions.

2. Sustain and Expand Supportive Policy Frameworks: The analysis reflects that supportive and stable policies are integral to the consistent rise in renewable energy observed since 2016. Policies should therefore continue to favor the development and expansion of renewables through subsidies, feed-in tariffs, and regulatory support that simplifies the deployment of renewable technologies. Additionally, policies that encourage private investment in renewable energy can enhance economic stability and foster further growth in the sector.

3. Diversify Energy Mix and Strengthen Grid Infrastructure: With the significant role of hydropower and the growth of wind and solar power, there is a need for policies that encourage further diversification of the energy mix and storage to compensate for intermittency. This diversification should be coupled with investments in grid infrastructure to manage variability and ensure stability, reliability, and security of the energy supply.

4. Focus on Sustainable Economic Growth Linked to Clean Energy: There is a positive correlation between GDP growth and renewable energy production. Policies should aim for absolute decoupling of economic growth from carbon emissions, as seen in certain years, by promoting clean energy sources and energy efficiency. This can involve further increasing the share of renewables in the overall energy mix, enhancing energy efficiency measures in industries, and adopting cleaner production processes.

There are two primary limitations inherent in this study. First, although fieldwork was conducted within the study area, the qualitative outcomes of this fieldwork have not been thoroughly integrated into the study. Instead, the study predominantly relies on quantitative data and analysis. Second, the study's scope is confined to Qinghai province in China. However, the findings of this research hold potential applicability to other provinces on the Qinghai-Tibetan Plateau and similar contexts.

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.

Appendix A

A.1. Open-ended interview questions

a) To government officials and experts:

1 Could you explain the motivations behind Qinghai's proactive approach to developing renewable energy?
2 Can you detail the allocation and execution processes for renewable energy industrial parks?
3 What benefits do you anticipate renewable energy will bring to Qinghai and beyond?
4 Who fund renewable energy projects?
5 What incentives have been provided to foster business engagement and investment in this sector?
6 Could you describe the supply chain for materials used in solar, wind, and battery technologies, including their procurement, processing, production, and application?
7 In what ways might Qinghai stand to gain from the exportation of renewable energy to other provinces?
8 Have there been any notable successes or failures among the policies enacted? What factors contributed to these outcomes?
9 What are the pivotal elements that underpin the rise of the green industry in general?
10 Could you identify the primary challenges and opportunities present in this field?

b) To firms engaged in the renewable energy sector:

1 Would you be able to recount the rationale that led to your involvement in the renewable energy sector?
2 In what manner do you participate in the policy-making processes relevant to the green industry?
3 What renewable energy projects are you currently undertaking?
4 How do you navigate compliance with environmental regulations?
5 What are the financing mechanisms for your projects?
6 Could you provide an overview of your revenue streams?
7 How do you balance collaboration and competition within the renewable energy industry?
8 What are the critical factors that contribute to the success of the green industry in general?
9 What, in your opinion, are the advantages of expanding the renewable energy sector?
10 Have any of your ventures been particularly successful or unsuccessful? Why?
11 How do you perceive the potential opportunities and risks in the renewable energy sector?

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