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Winners and losers of energy sustainability—Global assessment of the Sustainable Development Goals

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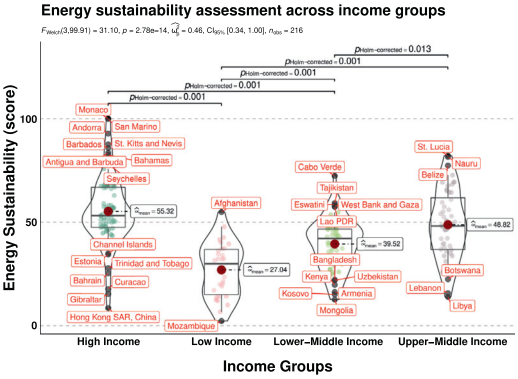
HIGHLIGHTS

- Energy investment participation by the private sector is more visible in low- & middle-income countries.
- High income countries with reduced inequality have high readiness in fulfilling the SDG targets.
- Access to clean fuels and technologies for cooking is still limited in developing countries.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy sustainability plays a crucial role in achieving environmental sustainability, hence, underpins climate change mitigation. Yet, studies assessing the overarching effect of existing sustainability frameworks on energy production and consumption are limited. Here, we provide comprehensive assessment of energy sustainability across 217 countries and territories spanning 1960–2019. Using 11 targets and 15 indicators of the Sustainable Development Goals (SDGs), we present winners and losers of energy sustainability by accounting for pre-millennium development goals (MDGs), MDGs, and SDGs across income groups. While the inception of the 2030 agenda has improved energy and environmental performance across economies, low-income countries are still struggling to meet several of the SDGs. We find that sustained economic growth with reduced income inequality improves energy sustainability in developing economies. However, sustainable climate policies that reduce trade-offs between energy resources and environmental threats are highly recommended in climate-prone regions that depend heavily on water resources to boost power generation capacity.

1. Introduction

The concept of sustainability has enhanced global efforts towards mitigating climate change and its impacts (Blanco et al., 2014). The Brundtland report titled, "our common future" highlights the significance of developmental options that meet present demands without compromising the environment for the sake of future generations (Brundtland, 1987). In this regard, several global goals have been formulated to address and guide present demands while attaining environmental sustainability. However, such ideal developmental pathway appears problematic, owing to the trade-off between energy sustainability and sustained economic development. Energy production and consumption are critical for economic development, hence, remain the major driver of anthropogenic GHG emissions that underpin climate change (Edenhofer et al., 2011). This implies the

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extraction, composition, and adoption of energy resources to meet "*present demand*" and "*future supply*" is crucial to achieving sustainable development. In contrast, economic development (i.e., income level and income inequality) is reported to affect a country's energy production and consumption patterns (Fouquet, 2016). Despite the significant policy implications, existing literature merely examines the drivers of energy consumption, emissions, and economic development—ignoring the progress towards attaining energy sustainability targets. The only existing literature examines the trade-offs between Sustainable Development Goals (SDGs) and energy services, however, calls for extensive energy research that links targets and goals to country-specific and global energy-related issues (Nerini et al., 2018). To date, no existing literature examines the progress of energy sustainability from pre-millennium development goals (MDGs), MDGs, and SDGs. This information is useful to assess the historical development of energy sustainability across countries, territories, and income groups, given the numerous ambitious global goals to promote sustainable development.

Here, we develop and compare energy sustainability indicators using 11 targets and 15 indicators of the SDGs across 217 countries and territories (Supplementary Table 1) from 1960 to 2019. Besides, we account for the coupling effect of several dimensions of sustainable development covering energy production and consumption, economic policy (i.e., adjusted savings, private sector and trade, external funding and income), and national resource accounting (i.e., water and domestic materials, e.g., fossil fuels). The quantifiable metrics include SDG 6.4 (increasing H_2O efficiency across sectors by ensuring sustainable H_2O withdrawals & addressing scarcity in freshwater supplies), SDG 7.1 (ensuring availability and accessibility to modern energy and its services), SDG 7.2 (increasing renewable energy penetration), SDG 7.3 (improving global energy efficiency), SDG 7.4 (enhancing clean energy technologies), SDG 7.5 (infrastructural expansion of sustainable energy), SDG 8.1 (sustained economic growth), SDG 8.4 (decoupling growth from pollution), SDG 9.4 (expansion in resource-efficient and clean technologies that ensure sustainable production and consumption in infrastructures and industries), SDG 12.2 (sustainable and efficient use of natural resources in production and consumption), and SDG 13 (mitigating climate change and its impacts). The adoption of the goals and indicators is based on their usefulness as tools for policy formulation (Taylor et al., 2017). The existing literature assumes a global common shock and spillover effects for anthropogenic emissions, however, the notion appears inconsistent with energy sector dynamics. This implies assuming homogeneous behavior towards energy sustainability will be erroneous, hence, producing biased statistical inferences. Countries appear to have heterogeneous consumption patterns attributable to differences in economic structure, environmental priorities, and commitment towards achieving sustainability. To compare countries from economic level, we further categorized countries into income groups per the existing income convergence of the World Bank. Using the constructed SDG indicators, we address the following research questions: first, are SDG indicators homogeneous or heterogeneous across income groups while accounting for pre-MDGs, MDGs, and SDGs? Second, who are the winners and losers of energy sustainability? Third, what are the global and country-specific spatial-temporal advancements towards achieving energy sustainability? Fourth, how does income convergence affect energy diversity, economic development, and GHG emissions in developing and developed economies? Fifth, what is the impact of income level on energy sustainability indicators while controlling for income inequality? The research questions are addressed by employing statistical techniques to compute the weighted average of indicator-specific effect estimates across income groups classified based on income convergence. Due to differences in economic structure across economies, we use normalization technique to develop scores for the SDG indicators to examine energy sustainability performance. We utilize meta-analysis to assess similar pre-MDG, MDG, and SDG indicators across income groups, while comparing them to global pre-MDGs, MDGs, and SDGs. The adoption of income group-specific fixed-effects in the statistical model controls for heterogeneous effects. Historical changes of energy and its related services are captured and compared from pre-MDGs, MDGs, and SDGs periods. A graphical comparison of performance across economies is presented using linear regression technique that controls for country-specific effects. We find significantly large heterogeneous characteristics of energy sustainability across income groups.

2. Methods

2.1. Data

We employed data from world development indicators—a World Bank database (World Bank, 2020) with collection of reliable data sources including International Monetary Fund (IMF), International Financial Statistics (IFS) and Balance of Payments (BOPs) databases, International Debt Statistics, OECD, Sustainable Energy for All (SE4ALL) database from WHO Global Household Energy database, SE4ALL Global Tracking Framework, IEA Statistics, Food, and Agriculture Organization (FAO), AQUASTAT data, Carbon Dioxide Information Analysis Centre, Environmental Sciences Division—Oak Ridge National Laboratory in the US, Private Participation in Infrastructure Project Database, European Commission, Joint Research Centre—Netherlands Environmental Assessment Agency (PBL), and Emission Database for Global Atmospheric Research (EDGAR). We used weighted average annual frequency data spanning 1960–2019 across 217 countries and territories (Supplementary Table 1). We further used aggregated data at the global level (WLD), and across income groups namely low-income countries (LIC), lower-middle-income countries (LMC), low- & middle-income countries (LMY), middle-income countries (MIC), upper-middle-income countries (UMC), and high-income countries (HIC) (World Bank, 1978). Using over six decades of data across several topics, country-specific and income group dynamics provide broader coverage to capture historical changes in energy sustainability from pre-MDGs (1961–1999), MDGs (2000–2015), and SDGs (2016–2019) epochs.

2.2. Proxy SDG indicators

The energy sector is not standalone but depends on other sectors, thus, our SDG targets and indicators for assessing energy sustainability account for natural resource efficiency, environmental pollution, and economic dynamics. The 11 SDG targets presented herein (Table 1) are adopted from the SDG framework by the United Nations (United Nations, 2015). Owing to the difficulty in retrieving data on exact SDG targets/indicators, we utilized proxy data options. For example, to account for SDG 8.4, "Decoupling growth from pollution by ensuring natural resource efficiency in production and consumption", we utilized adjusted savings: energy depletion, fossil fuel energy consumption, and net energy imports. Adjusted savings: energy depletion denotes the ratio of the rate of coal, crude oil, and natural gas energy resource supply to the unexpended reserve lifetime (World Bank, 2020). Fossil fuel energy consumption entails the utilization of coal, oil, natural gas, and petroleum products whereas net energy imports cover energy utilization less production. Hence, these indicators are used to capture both material footprint and domestic material consumption. Second, SDG 13.0, "Mitigating climate change and its impacts" is assessed and reported using the total greenhouse gas emissions (i.e., include carbon dioxide, methane, nitrous oxide, and Fluorinated gases) as proxy to capture the impact of climate change. In this way, our variable selection is based on several factors including—data availability, and data series that explicitly capture SDG indicators or function as proxy indicators.

2.3. Periodic assessment

To capture and compare historical changes of energy and its related services from pre-MDGs, MDGs, and SDGs periods. We calculate the arithmetic mean of the yearly data across countries and territories expressed as:

$$Y_i = \frac{1}{n}\sum_{x=1}^{n} z_x \tag{1}$$

Table 1
SDG targets, & indicators for energy sustainability assessment.

№	SDG targets	SDG indicators	Our series
1	6.4 Increasing H_2O efficiency across sectors by ensuring sustainable H_2O withdrawals & addressing scarcity in freshwater supplies	6.4.1 Periodic changes in H_2O consumption efficiency 6.4.2 Dynamics of water stress: factors affecting freshwater withdrawals and regeneration of H_2O resources	Total water productivity (constant 2010 US$ GDP/m^3 of total freshwater withdrawal) Annual freshwater withdrawals for industrial use (% of total freshwater withdrawal) Total renewable internal freshwater resources (billion m^3)
2	7.1 Ensuring availability and accessibility to modern energy and its services	7.1.1 Share of population with access to electricity	Access to electricity (% of population) Rural access to electricity (% of rural population) Urban access to electricity (% of urban population)
		7.1.2 1 Share of population relying on clean technologies	Access to clean fuels and technologies for cooking (% of population)
3	7.2 Increasing renewable energy penetration in global energy portfolio	7.2.1 Share of renewables in final energy utilization	Renewable energy consumption (% of total final energy consumption)
4	7.3 Improving global energy efficiency	7.3.1 Energy intensity comprising primary energy and economic growth	Energy intensity level of primary energy (MJ/$2011 PPP GDP)
5	7.a Enhancing clean energy technologies and cleaner fossil fuel technologies	7.a.1 Support of clean and renewable energy production through R&D	Alternative and nuclear energy (% of total energy use) Combustible renewables and waste (% of total energy)
6	7.b Infrastructural expansion of sustainable energy and its related services from external funding	7.b.1 Foreign direct investments in energy efficiency and technologies to achieve sustainable development	Investment in energy with private participation (current US$) Foreign direct investment inflows (% of GDP)
7	8.1 Sustained economic growth	8.1.1 Annual growth rate of GDP per capita	GDP per capita (constant 2010 US$)
8	8.4 Decoupling growth from pollution by ensuring natural resource efficiency in production and consumption	8.4.1 Material footprint 8.4.2 Domestic material consumption	Adjusted savings: energy depletion (% of GNI) Fossil fuel energy consumption (% of total) Net energy imports (% of energy use)
9	9.4 Expansion in resource-efficient and clean technologies that ensure sustainable production and consumption in infrastructures and industries	9.4.1 Industrial-based emissions	CO_2 emissions from electricity and heat production (% of total fuel combustion) CO_2 emissions from gaseous fuel consumption (% of total) CO_2 emissions from liquid fuel consumption (% of total) CO_2 emissions from solid fuel consumption (% of total) Energy related methane emissions (% of total) Nitrous oxide emissions in energy sector (% of total)
10	12.2 Sustainable and efficient use of natural resources in production and consumption	12.2.1 Reducing material footprint 12.2.2 Sustainable domestic material consumption	Adjusted savings: energy depletion (% of GNI) Fossil fuel energy consumption (% of total) Net energy imports (% of energy use)
11	13.0 Mitigating climate change and its impacts	13.3.1 Impact reduction of climate change	Total greenhouse gas emissions (kt of CO_2 equivalent)

Notes: The SDG targets and indicators presented are based on the Sustainable Development Goals (United Nations, 2015). Our series denote global data variables used as proxy to assess the various indicators and classify countries meeting the target.

where Y denotes the calculated arithmetic mean of the data across countries, or territories i, n represents the periods spanning 1961–1999 for pre-MDGs, 2000–2015 for MDGs, and 2016–2019 for SDGs, and z_x denotes the sum of data series under consideration for epoch n. Similarly, we estimate the standard deviation of the data using the expression:

$$S_i = \sqrt{\frac{\sum (z_x - \overline{z})^2}{n-1}} \tag{2}$$

where S represents the estimated standard deviation of the sampled series across countries and territories i, while accounting for pre-MDGs, MDGs, and SDGs. $\overline{z}$ denotes the mean of data series z_x for period n.

2.4. Settings for meta-analysis

Using the expressions in Eqs. (1)–(2), we derive the mean and standard deviation of both experimental and control groups. From here, we compute the effect size of income groups and global measurements—by designating income groups namely LIC, LMC, LMY, MIC, UMC, and HIC as experimental groups whereas the global measurements, viz. WLD represents the control group. The effect sizes for pre-MDGs and MDGs are computed using Hedges' g statistic (Hedges, 1981) with approximate bias correction to control for upward bias in computing for standardized mean difference whereas Cohen's d statistic (Cohen, 2013) is used to control for small sample bias due to small data sample for computing standardized mean difference for the SDG epoch. The specification for the meta-analysis comprises the number of observations, mean, and standard deviation of both experimental and control groups, income group-specific fixed-effects model to capture heterogeneous effects using the inverse-variance estimation technique (Cooper et al., 2019). Existing studies adopt meta-analysis (Glass, 1976) as statistical technique to analyze results from existing studies with related research questions, however, we utilized this technique to assess similar pre-MDG, MDG, and SDG indicators across income groups, by comparing them with the global pre-MDGs, MDGs, and SDGs. In this scenario, we compute the weighted average of indicator-specific effect estimates to validate the possibility of substantial variations across income groups. Thus, using the estimated effect of interest, we can draw useful conclusions to ascertain the causes of variations in energy sustainability across income groups.

2.5. Empirical estimation

Following the Brundtland report titled, “our common future” (Brundtland, 1987), we define energy sustainability as meeting energy demand without compromising the environment and depleting energy resources for the sake of future generations (Tester et al., 2012). Our empirical estimation accounts for three pillars of energy sustainability namely energy demand (i.e., energy access and utilization), energy supply (i.e., energy availability, and affordability), and energy footprint (i.e., energy intensity vs. energy efficiency, and energy eco-capacity). For energy footprint, we investigate energy resource exploitation and utilization by assessing characteristics including renewable (infinite) vs. non-renewable (finite), and sustainable (efficient) vs. unsustainable (inefficient). The energy footprint across countries and territories is examined using the composition of the energy portfolio, level of energy (in) dependence, and rate of environmental degradation (i.e., waste generation, resource depletion, and emissions). Consistent with SDG 6.4 of ensuring H_2O efficiency and sustainable H_2O withdrawals, we estimated H_2O stress dynamics by assessing the role of energy sector production in changing H_2O consumption efficiency and regeneration of H_2O resources. The energy-water stress *EWS* across country *i*, is expressed as:

$$EWS_i = f_N\left[{}^{\mu WP_i}/_{(AWE_i * \mu RFR_i)}\right], AWE_i = (\mu AWI_i * 0.6475) \tag{3}$$

where μ represents the population mean, *WP* denotes water productivity (i.e., estimated as gross domestic product in 2010 US$ prices divided by annual total H_2O withdrawals), *AWE* is the annual freshwater withdrawals for energy production, *AWI* is the annual freshwater withdrawals for industrial use and *RFR* represents total renewable internal freshwater resources. According to UNESCO, industrial water utilization accounts for ~20% of freshwater withdrawals—of which an average of 63% is used for hydro and nuclear power generation, 1.75% (on average) for energy generation via thermal power plants, and the remaining for industrial processes (UNESCO, 2021). Using these approximations, the annual freshwater withdrawals for energy production is calculated by multiplying the annual freshwater withdrawals for industrial use by 0.6475. Though there are variations in water use for energy production, however, due to country-specific data limitations, we assume the global energy-driven water withdrawal value (i.e., 0.6475) is fixed for all countries and territories.

The SDG 12.2 was evaluated to assess the progress of sustainable and efficient use of natural resources in production and consumption. We accounted for material footprint by estimating the sustainability of domestic material consumption expressed as:

$$FS_i = f_N\left({}^{\mu FFE_i}/_{\mu AED_i}\right) \tag{4}$$

where *FS* represents fossil stress, calculated using fossil fuel energy consumption *FFE* divided by adjusted savings of energy depletion *AED*. Fossil fuel encompasses coal, natural gas, oil and petroleum products while energy depletion accounts for the stock of coal, crude oil, and natural gas energy resources compared to its lifetime of remaining reserves.

To examine the long-term impact of energy resource exploitation on future generations (i.e., energy security), we quantify for both energy deficit and energy reserve using our estimated benefit-cost formulation expressed as:

$$BC_i = f_N(\delta_i - \gamma_i) \tag{5}$$

$$\delta_i = \sum(CLN_i, ACC_\mathrm{i}, CLE_i, INV_i) \tag{6}$$

$$\gamma_i = \sum(FS_i, EWS_i, EMI_i, IMP_i, INT_i) \tag{7}$$

where *BC* is the benefit-cost assessment to classify countries and territories into winners and losers of energy sustainability, δ_i represents the summation of SDG indicator scores with positive effects on energy sustainability whereas γ_i denotes score summation of SDG indicators with poor energy sustainability performance. The best energy sustainability performance indicators include access to clean fuels and technologies for cooking *CLN*, access to electricity *ACC*, consumption of nuclear energy, renewable energy, and combustible renewables and waste *CLE*, and investment in energy with private participation *INV*. In contrast, the poor energy sustainability performance indicators comprise fossil stress, energy-water stress, CO_2 emissions from fuel consumption, electricity and heat production, energy related CH_4 emissions, and N_2O emissions in energy sector *EMI*, energy imports *IMP*, and energy intensity *INT*. From Eq. (5), countries can be categorized under either energy deficit—if energy cost exceeds benefits or energy reserve—if energy benefits exceed energy cost.

Due to differences in economic structure, production, consumption, and population dynamics across countries and territories, using a comparable metric, viz. normalization technique is critical for assessing SDG targets (Xu et al., 2020). The function f_N in Eqs. (3)–(5) denotes the normalization function for scoring a specific SDG indicator y' expressed as:

$$f_N \approx y' = 100(y - y_{min})/(y_{max} - y_{min}) \tag{8}$$

where y' represents the score of SDG indicator y via the normalization technique with scores ranging from 0 to 100 across economies over time. Thus, the lower bound (i.e., score 0) represents poor performance whereas the upper bound (i.e., score 100) represents best performance. Countries with score above 50 denotes transformation towards achieving best performance. Using this scoring technique, countries are ranked accordingly from pre-MDGs, MDGs, and SDGs periods—to ascertain the winners and losers of energy sustainability.

2.6. Country-specific effects

Here we use cross-country linear regression technique that controls for country-specific effects. The estimation technique has been used to investigate several within and between effects of economic dynamics on energy sector portfolio across several countries over specified periods (Hsiang, 2010). Contrary to historical periods used in existing literature, we adopt the periodic mean of sampled variables for the ease of graphical comparison across economies. The linear specification of the model can be expressed as:

$$\overline{y}_i = \overline{x}_i + \overline{z}_i \tag{9}$$

where $\overline{y}_i$ denotes the mean target variables [i.e., energy sustainability target (pros & cons), benefit-cost, energy intensity, access to electricity, access to clean technologies, composition of clean energy technologies, and energy-related GHG emissions] across economies *i*, $\overline{x}$ represents the independent variable, namely income level whereas $\overline{z}$ denotes income inequality, the effect size of the regression. The empirical scenario in Eq. (9) allows the assessment of the nexus between the dynamics of energy sustainability and average income level while accounting for the effect of income inequality across countries and territories.

2.7. Income convergence

Income homogeneity occurs in economies with similar economic structure, technology, and factors of production, hence, with the likelihood of achieving economic convergence if growth in poor economies is faster than in wealthy economies (Tamura, 1991). This implies income level and technology spillover play a substantial role in achieving energy sustainability (Nordhaus, 2010). Using the updated version (2020 − 2021) of World Bank's country and lending group, 217 sampled economies are classified into similar income groups (World Bank, 2021b). Thus, using the atlas conversion factor, countries and territories are classified based on gross national income (GNI) per capita. The atlas conversion factor helps to control for domestic and international inflation-driven changes to a country's exchange rate (World Bank, 2021a). The income group classification entails—27 lower-income economies (≤ $1045), 55 lower-middle-income economies ($1046–$4095), 55 upper-middle-income economies ($4096–$12,695), and 80 high-income economies (≥ $12,696). Aside from country-specific rankings, the income convergence allows the assessment of energy sustainability across income groups compared to global ratings. The generic assessment of energy diversity, economic development, and GHG emissions across income groups can be expressed as:

$$g_j^R = \overline{k}_j^R \tag{10}$$

where g_j^R is the output proportion of SDG indicators *R* namely—energy use, global GHG emissions, rural access to electricity, urban access to electricity, GDP per capita, foreign direct investment (FDI) inflows, FDI outflows, renewable energy and fossil fuel energy consumption—across income groups and global ratings *j* (i.e., LIC, LMC, LMY, MIC, UMC, HIC, and WLD). $\overline{k}$ denotes the mean of input of SDG indicators used to calculate income group-specific output proportions.

3. Results

3.1. Comparing pre-MDGs, MDGs, and SDGs

To ascertain the progress towards achieving sustainable development, we compared energy sustainability dynamics from pre-MDG (1961–1999), MDG (2000–2015), and SDG (2016–2019) periods. Because past events foreshadow present and future occurrences, employing these assessment criteria and conceptualization are useful tools for policy formulation. Using meta-analytic statistical technique, we analyzed 20 data series (Supplementary Table 2) by comparing income-specific groups to global ratings. We find that access to electricity (i.e., rural and urban access) has increased substantially across income groups throughout the SDG era compared to both pre-MDG and MDGs (see Supplementary Figs. 1–6). In contrast, energy depletion (i.e., ratio of the stock of energy resources versus lifetime reserves) declined significantly during the SDG period compared to pre-MDG and MDGs. Among income groups, the SDG policies benefited low-income countries more than high-income countries, hence, improving lifetime reserves of energy resources. Failure of the MDGs to clearly highlight energy sustainability in the global policies may have worsened energy depletion, energy sector-related N_2O emissions, energy-related CH_4 emissions, and CO_2 emissions from electricity and heat production during the MDG era compared to pre-MDG periods (see Supplementary Figs. 1–6). To rule out the notion of global common shocks and equality (i.e., cross-section dependence and homogeneity) of energy indicators across income groups, we require energy indicators to be inconsistent across income economies—implying a high level of heterogeneity. In this way, the independence of SDG indicators can be properly examined. To achieve this, we used the inverse-variance estimation technique that captures income group-specific fixed-effects, thus, accounting for heterogeneity (see Methods). The forest plots showing the estimated results were constructed based on means of both experimental and control groups, effect sizes, corresponding confidence intervals, and percentage of overall weight for each data series (Supplementary Figs. 1–6). The test for θ denotes the overall effect sizes—expressed as the weighted average of variable-specific effect sizes with corresponding significance test of $H_0 : \theta = 0$ reported as p-$value < 0.01$. This implies the overall effect sizes of the sampled energy indicators are statistically and significantly different from zero. The homogeneity test between variables, $H_0 : \theta_i = \theta_j$ is statistically significant at p-$value < 0.01$, confirming heterogeneous effects (I^2) across variables. This infers sampled variables for energy sustainability across income groups have large heterogeneous (i.e., I^2>75%) characteristics (Higgins et al., 2003). This confirms the expectation of a reverse output compared to standard empirical results. Thus, >90% variations in effect size estimation can be attributed to between-variable heterogeneity.

3.2. Assessing energy sustainability indicators

Unlike the MDGs, the SDGs (i.e., SDG 7) explicitly highlights the importance of achieving energy sustainability, which mainly comprises a combination of the energy portfolio, economics, and emissions. Using six decades of energy sustainability indicators, we observe the average share of renewables in the energy portfolio is higher in low-income countries (i.e., 68.7%) compared to the global average of 17.5%. However, the penetration of renewables in high-income countries (i.e., 8%) is lower than the global average (see Fig. 1A).

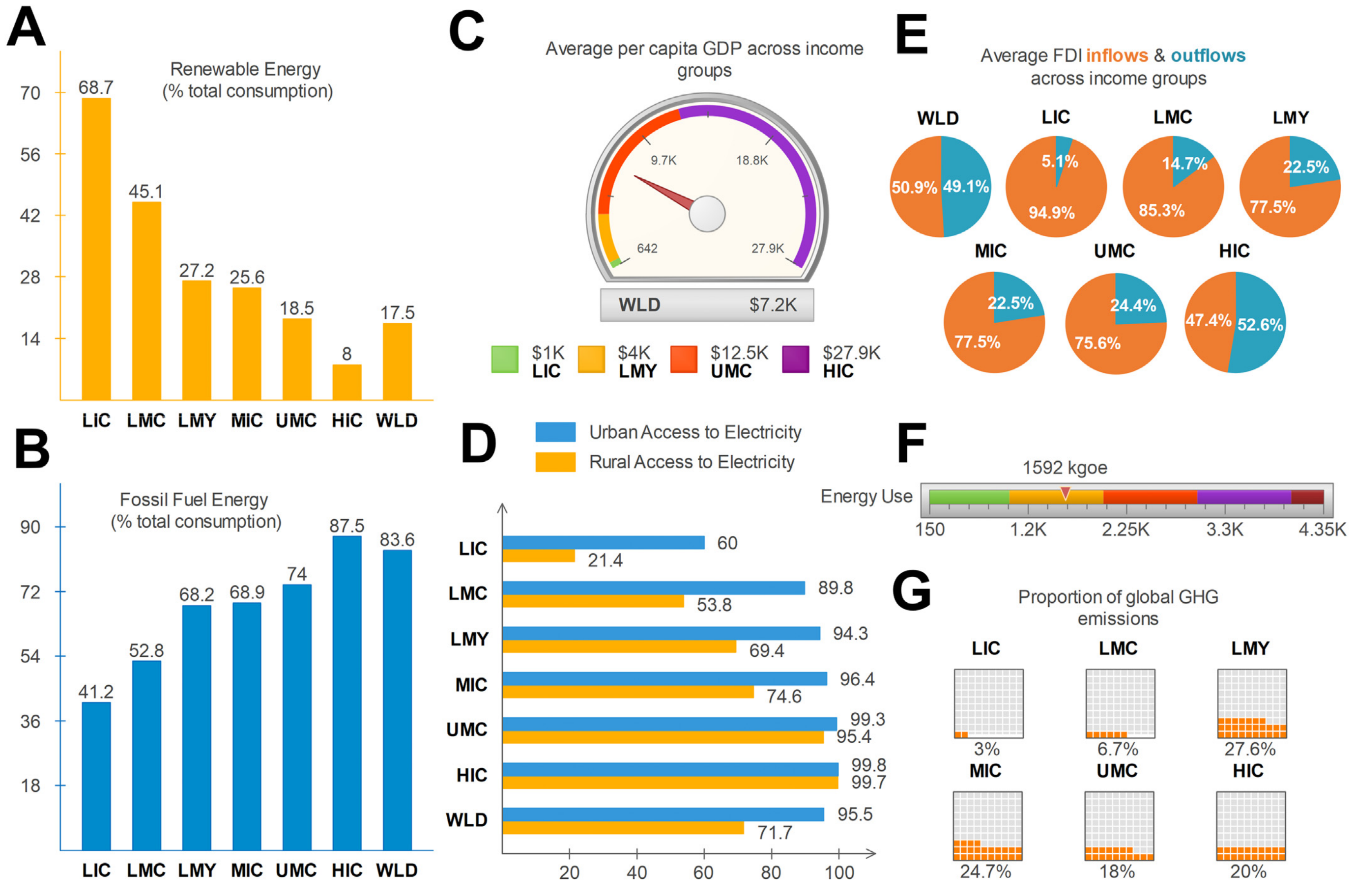

Fig. 1. Trends of energy diversity, economic development, and GHG emissions across income groups. (A) Renewable energy. (B) Fossil fuel energy. (C) Average income level. (D) Access to electricity. (E) FDI inflows and outflows. (F) Energy utilization. (G) Global GHG emissions. The estimates presented across income groups were computed using the mean from 1961 to 2019. *Income group abbreviations—global average (WLD), low-income countries (LIC), lower-middle-income countries (LMC), low- & middle-income countries (LMY), middle-income countries (MIC), upper-middle-income countries (UMC), and high-income countries (HIC).*

Thus, LIC > LMC > LMY > MIC>UMC > WLD > HIC — implying developing countries have higher renewable energy adoption compared to developed countries (Fig. 2B). In contrast, the energy portfolio in high-income countries is dominated by fossil fuel energy (i.e., 87.5%), slightly higher than the global average of 83.6%. This order (i.e., HIC > WLD > UMC > MIC>LMY > LMC > LIC) infers that developed economies consume more fossil fuels compared to developing economies (see Fig. 1B). Urban-rural access to electrification (i.e., 60% & 21.4%) is much lower in low-income economies compared to the global average of 95.5% (urban) and 71.7% (rural) [see Fig. 1D]. Lack of electricity access in low-income countries (Fig. 2C) may have mirrored the low level of income (<$650, Fig. 1C), low energy use (<400 kgoe, Fig. 1F), but high foreign direct investment inflows (Fig. 1E). The high-income level (Fig. 1C) and FDI outflows (Fig. 1E) in high-income economies could have been driven by access to electricity (Fig. 1D), high energy use (Fig. 1F), and dominance of fossil fuels (Fig. 1B) in the energy mix. Yet, the proportion of global GHG emissions is higher in low- & middle-income countries (27.6%) and middle-income (24.7%) countries compared to high-income countries (20%) but lower in low income (3%) and lower-middle-income countries (6.7%) [see Fig. 1G]. The score of population with access to clean fuels and technologies for cooking in high-income countries (score = 98.80) far exceeds low-income countries by 8.5 times (score = 11.60) [see Fig. 2A].

However, energy investment participation by the private sector is more visible in low- & middle-income countries (score = 100) than in high-income countries (see Fig. 2D). Due to dependence on fossil fuels for economic activities, fossil energy stress is relatively high in developed economies than in developing economies (Fig. 2E). Energy-water stress is visibly high in low-income economies that depend on hydropower resources for energy generation (Fig. 2F).

The benefit-to-cost ratio of energy sustainability across income groups is in the order MIC>LMY > UMC > HIC > LMC > WLD > LIC, implying the overall scores of energy sustainability is fairly high in middle-income countries compared to low-income economies (see Supplementary Fig. 7D,E,F).

3.3. Spatial-temporal changes of SDG indicators

Using the country-specific estimated scores from 1961 to 2019, we spatially mapped the SDG indicators to capture energy sustainability performance. In assessing the level of clean fuels and technologies for cooking, we find developed countries have the best performance (score ≥ 92) than most developing countries (Fig. 3A). Contrary, developing countries (i.e., DR Congo, Nepal, Ethiopia, Mozambique, Tanzania, Zambia, Nigeria, Cameroon, Niger, Myanmar, Paraguay, Haiti, Tajikistan, Kenya, Benin, Togo, Gabon, Cambodia, and Zimbabwe) have better performance

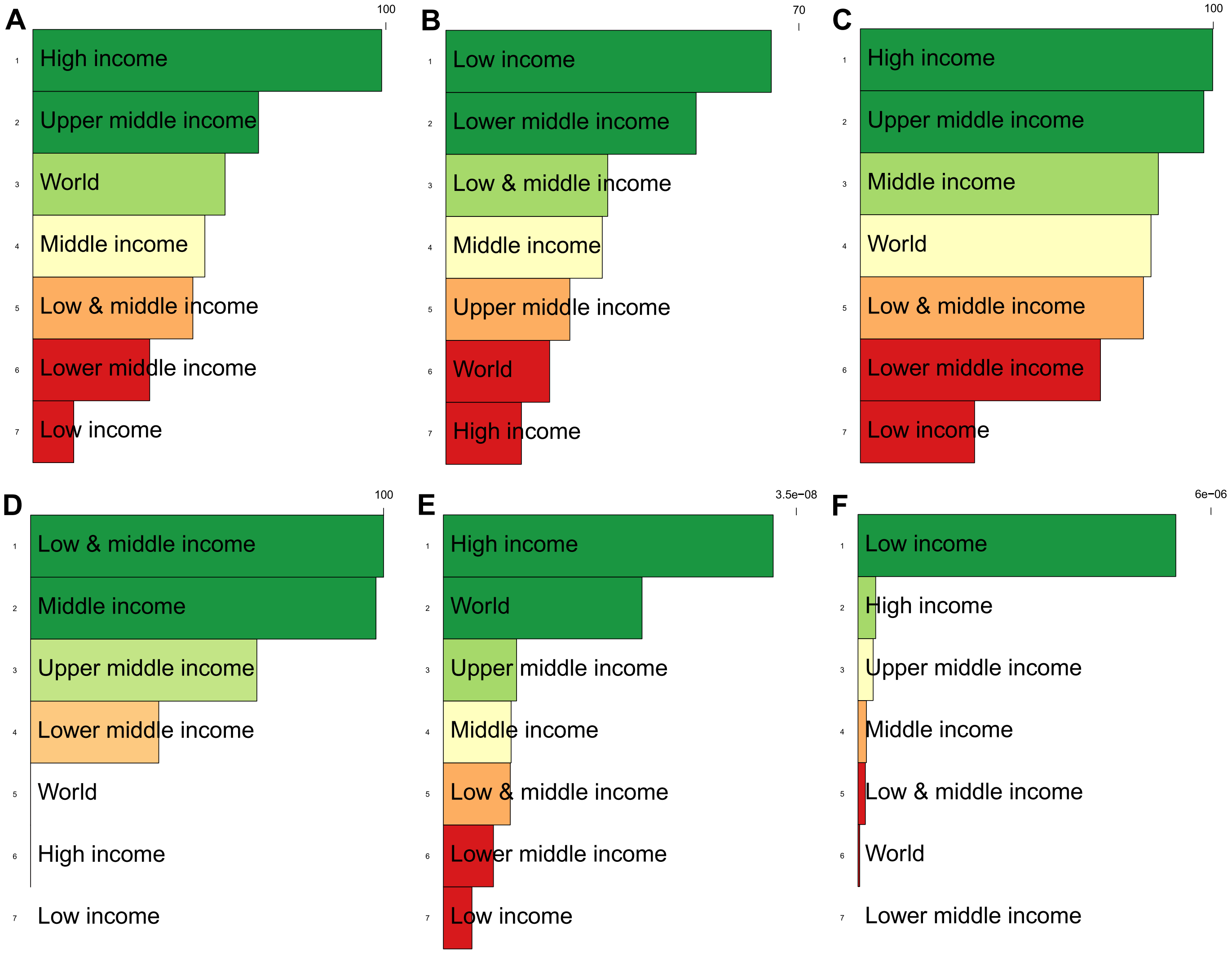

Fig. 2. Sustainability assessment of energy and its services across income groups. (A) Access to clean fuels and technologies. (B) Clean energy technologies. (C) Access to electricity. (D) Energy Investment. (E) Fossil energy stress. (F) Energy-Water stress. Legend: The indicators are estimated using the empirical procedure presented in the methods. Colors ranging from dark-green, lime-green, yellow, orange, and red represent the magnitude of estimated indicators in descending order. Missing filled-rectangular shape with white background (D and F) denotes missing data.

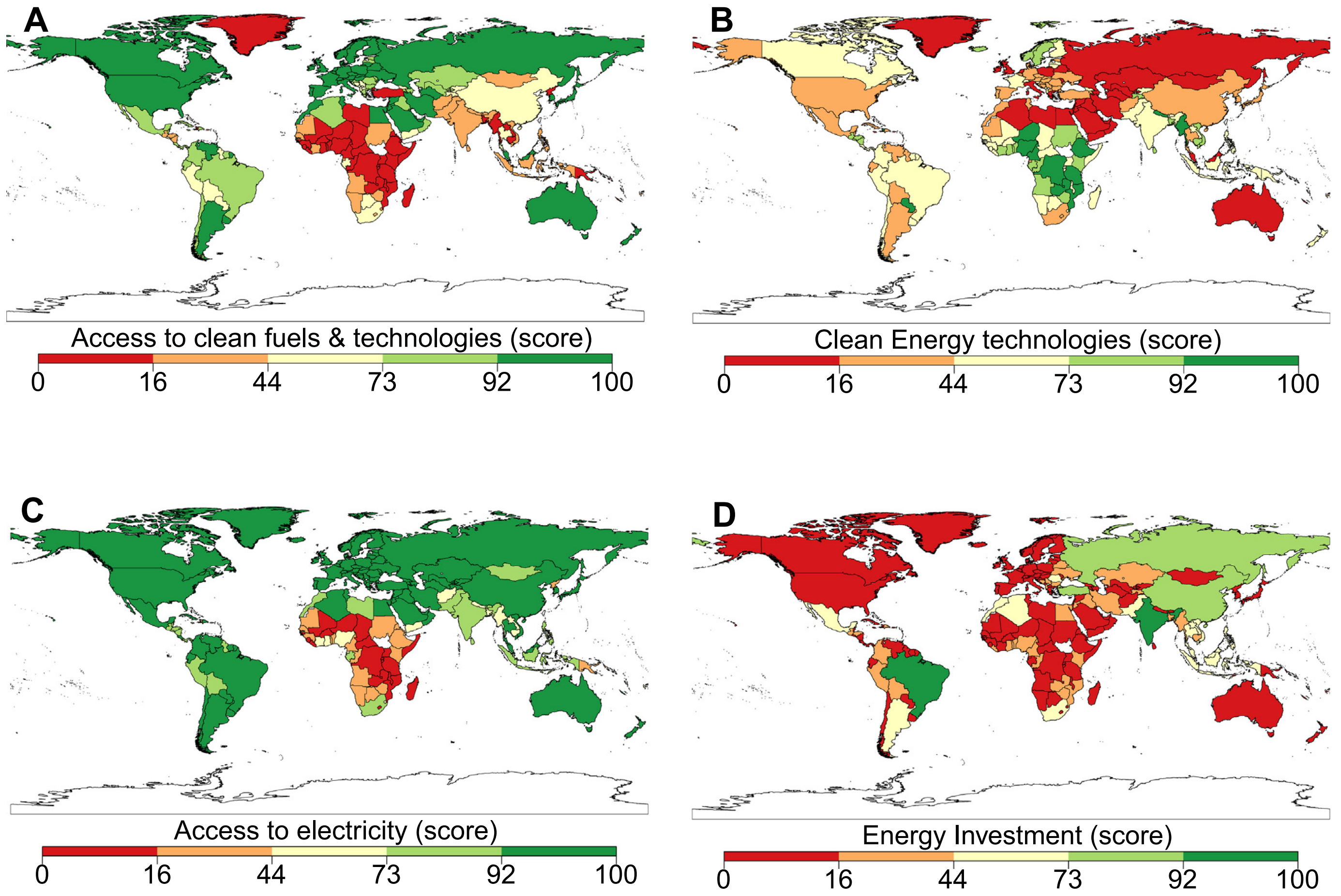

Fig. 3. Global sustainability indicators of energy and its services. (A) Access to clean fuels and technologies. (B) Clean energy technologies. (C) Access to electricity. (D) Energy Investment. (E) Fossil energy stress. (F) Energy-Water stress. Legend: The indicators are estimated using the empirical procedure presented in the methods. Colors ranging from red, orange, yellow, lime-green and dark-green represent the estimated indicators in ratio from 0 to 15.9 (worse), 16–43.9 (bad), 44–72.9 (good), 73–91.9 (better), and 92–100 (best), respectively.

(score ≥ 73) in the adoption and utilization of clean energy technologies (i.e., renewable energy, nuclear energy, combustible renewables, and waste) compared to developed countries excluding Iceland, and Norway (Fig. 3B). However, access to electricity is fairly high (score = 100) in high-income economies compared to low-income countries (Fig. 3C). Private participation in energy investment is limited to few countries including Brazil, India, Turkey, China, Russia, Indonesia, Lao, Mexico, South Africa, Morocco, Argentina, Thailand, Pakistan, Philippines, Romania, Vietnam, Algeria, Malaysia, Belarus, Peru, Bulgaria, Benin, Jordan, Egypt, Colombia, Ghana, Serbia, Zambia, Ukraine, and Nigeria (Fig. 3D). The over six decades of data used to assess fossil stress and energy-water stress show bad and worse performance across all countries and territories—a situation that has energy policy implications (Supplementary Fig. 8). We observe relatively high energy-related emissions (score ≥ 73) in Bahrain, Kuwait, Qatar, Russia, Brunei Darussalam, Trinidad & Tobago, Poland, Saudi Arabia, Estonia, Oman, Libya, UAE, Equatorial Guinea, Hong Kong, Singapore, Kazakhstan, Czech Republic, and Bosnia and Herzegovina (Fig. 4A). The fairly high scores in Fig. 4B reveal the high energy required to produce one unit of output in Somalia (score = 100), Liberia (score = 77.50), Mozambique (score = 74), and Ethiopia (score = 70.10) — whereas the remaining countries and territories have scores below 69. It is evident in Fig. 4C that 117 countries and territories are highly energy-dependent (score ≥ 92), which infers energy importation to supplement domestic generation capacity. The highest energy importers (score = 100) include Singapore, Malta, Hong Kong, Gibraltar, and Curacao (Fig. 4C). Using the sampled SDG indicators, we accounted for both pros (Fig. 4D) and cons (Fig. 4E) of energy sustainability targets before deriving the overall sustainability index, viz. benefit-cost (Fig. 4F). The *pros* element comprises factors that drive the agenda towards energy sustainability whereas the *cons* element derails the progress. Evidence from Fig. 4D shows 3 best-performing countries (Iceland, Norway, and Sweden), 54 better-performing economies, and 88 good-performing economies with SDG indicators that favor energy sustainability. In contrast, 142 economies are good performers (score ≥ 44) of SDG indicators that disrupt the agenda towards energy sustainability (Fig. 4E). The overall sustainability index that examines the pros and cons of energy sustainability targets from 1961 to 2019 shows 13 good-performing economies, 73 bad-performing economies, and 131 worse-performing economies. For example, the winners making progress towards achieving energy sustainability include inter alia, Bahamas, Belize, Monaco, Norway, and San Marino whereas the losers of energy sustainability comprise inter alia, North Korea, Mozambique, Liberia, Hong Kong, and South Sudan (Fig. 4F). We corroborate the robustness of the constructed energy sustainability indicator using between-group visualization with statistical features (Patil, 2021). The output statistics in Fig. 5 show significant (*p-value < 0.01*) mean differences in energy sustainability between income groups. The mean score of energy sustainability increases across income groups (Fig. 5). For example, the average scores in low-income, lower-middle-income, upper-middle-income, and high-income economies are 27.04, 39.52, 48.82, and 55.32. This implies growth in income and/or economic development increases energy sustainability.

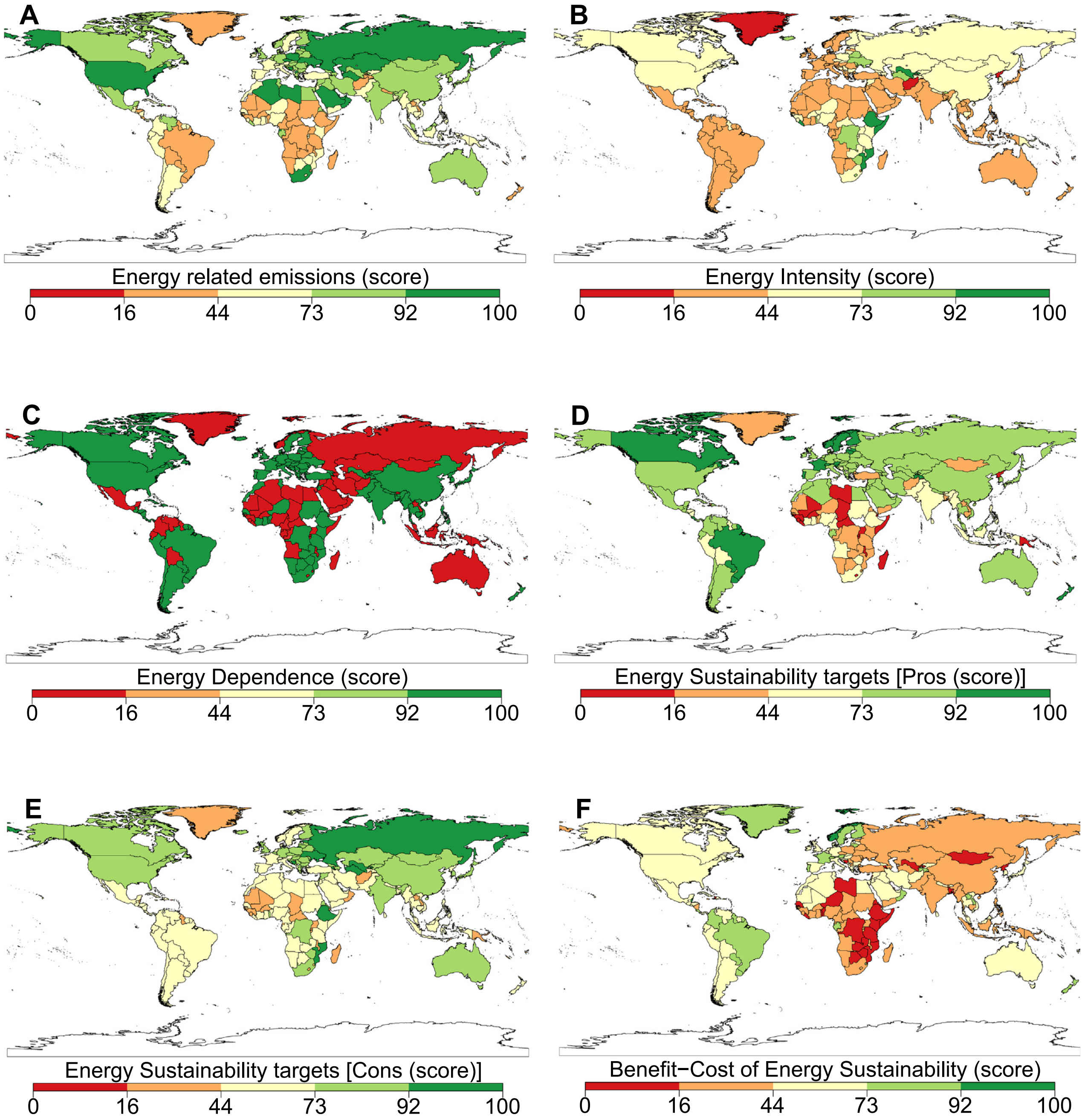

Fig. 4. Global sustainability indicators of energy and its services. (A) Energy-related emissions. (B) Energy intensity. (C) Energy dependence. (D) Pros of energy sustainability target. (E) Cons of energy sustainability target. (F) Benefit-cost of energy sustainability target. Legend: The indicators are estimated using the empirical procedure presented in the methods. Colors ranging from red, orange, yellow, lime-green, and dark-green represent the estimated indicators in ratio from 0 to 15.9, 16–43.9, 44–72.9, 73–91.9, and 92–100, respectively.

3.4. Factors affecting energy sustainability

In line with SDG 8 and 10, we assessed the role of sustained economic development (i.e., income level and income inequality) in achieving energy resource efficiency across global economies. We find a negative monotonic relationship between energy intensity and average income level (Fig. 6A). Developing economies with high-income inequality, typically sub-Saharan Africa (i.e., Ethiopia, Liberia, DR Congo, Burundi, and Zimbabwe) and Asian countries (i.e., Uzbekistan, Bhutan, and Turkmenistan) have high energy intensity with corresponding low-income level. Contrary, developed economies (i.e., Australia, United Arab Emirates, Bermuda, Japan, Liechtenstein, and Canada) with high-income levels and reduced income inequality have low energy intensity (Fig. 6A). The possible *Z*-shape relationship in Fig. 6B shows income level and income inequality have little impact on SDG indicators that disrupt energy sustainability. However, a positive monotonic relationship can be observed between: income level vs. SDG indicators that promote energy sustainability (Fig. 7A); and income level vs. overall sustainability index (Fig. 7B). Low-income level and extreme inequality in developing economies namely Mozambique, South Sudan, Burundi, Burkina Faso, Central African Republic, Liberia, Ethiopia, DR Congo, and The Gambia hamper efforts towards attaining energy resource efficiency, hence, affecting energy sustainability

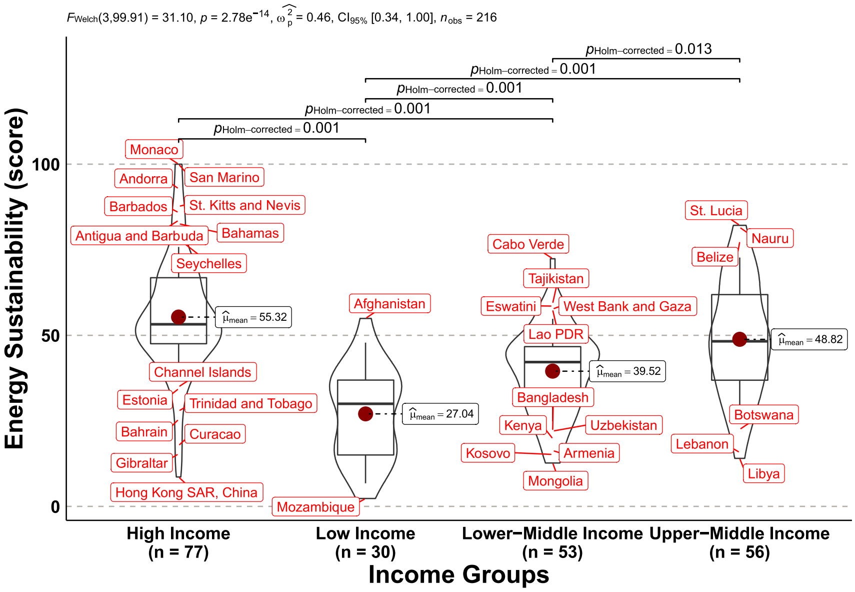

Fig. 5. Comparison of energy sustainability across income groups. The output statistics show significant (*p-value < 0.01*) mean differences in energy sustainability between income groups.

(see Supplementary Fig. 9B,C). Conversely, high-income countries with reduced inequality (i.e., Israel, Norway, Switzerland, Finland, and Austria) have high readiness in fulfilling the SDG targets (Fig. 7A) while achieving energy sustainability (Fig. 7B).

4. Discussion & conclusion

While it appears premature to elucidate winners and losers of energy sustainability, investigating the past, and present state of affairs serves as a key performance indicator for assessing progress towards attaining the SDG targets of the 2030 agenda. Though the MDGs failed to explicitly highlight energy sustainability, yet, energy played a crucial role in the achievement of several goals (Sovacool, 2012). Since the inclusion of energy and its services as the central theme of the 2030 agenda, mitigating climate change and its impacts through energy sustainability has become eminent. Experts argue that the complexity between energy and sustainable development entails systemic, demand, and supply-side management (Grubler et al., 2018). Thus, assessing the complex global energy sector dynamics unveils the energy-SDG synergies and trade-offs. Contrary to the extant qualitative-based literature on SDGs (Nerini et al., 2018), we provide an empirical-based assessment that examines the progress of energy sustainability from pre-MDG, MDG, and SDG periods.

There are over 2.6 billion people globally that depend on either kerosene, solid biomass (i.e., charcoal and fuelwood) or coal for heating and cooking purposes (IEA, 2020). Evidentially, our empirical assessment shows access to clean fuels and technologies for cooking in developing countries is still limited. The estimated 11.6% population in low-income economies with access to clean cooking technologies is below the global adoption, averaging 54.5%. This implies attaining universal access to clean cooking by 2030 requires significant climate policy interventions including shielding poor households from the distributional burden of carbon taxation (Cameron et al., 2016) and cost-effectiveness in switching from solid and carbon-intensive fuels to modern cooking fuels. Consistent with existing literature (Yadav et al., 2021), improving income, access to reliable power supply, and reducing income inequality enhance the adoption of clean cooking options. Global access to electricity in both rural and urban areas has increased significantly on average from 75.3% to 84.7% since the inception of the SDGs. However, electricity access remains relatively low in low-income countries, specifically in rural areas of sub-Saharan Africa, which has affected electricity consumption, hence, leading to energy poverty. Consistent with our empirical findings, the lack of electricity in rural areas is attributable to income and inequality (i.e., sparse population density, high upfront cost, and lack of energy infrastructure like grid extension) (Szabó et al., 2016). This implies the achievement of universal access to electricity, particularly in low-income economies requires both internal and external interventions including political will and commitment, external funding through FDI and technology spillover, and private sector investment (Sachs et al., 2019). Private sector energy investment participation comprising generation, transmission, and distribution is quite evidential in low- & middle-income economies than in high-income countries. However, significant energy investments are still required in developing countries to improve infrastructures, boost power supply and increase access to attain SDG-7 (Foster and Briceño-Garmendia, 2010).

SDG-7 is not a magic bullet to achieving energy sustainability but depends on other SDGs with environmental and economic concerns (Taylor et al., 2017). We find that low-income countries, typically sub-Saharan Africa have the highest renewable energy penetration (68.7%) with corresponding low fossil fuel consumption (41.2%) and low GHG emissions (3%), yet, far below (US$642) the global average income level (i.e., US$7200). Though renewable energy sources are useful haven technologies for market price volatility, environmental and health impacts of climate change (Owusu and Asumadu, 2016), however, experts argue of the challenges of renewables including the risk of resource competition, viz. land and water use intensity (Evans et al., 2009). Decarbonization pathways that rely on nuclear power, concentrating solar power (CSP) deployment, carbon capture, and biofuel production may escalate water stress without robust water-saving and harvesting technologies (IEA, 2016). It is estimated that about ~63% of industrial water utilization (i.e., freshwater withdrawals) is used for hydro and nuclear power generation, whereas 1.75% is used for energy generation via thermal power plants (UNESCO, 2021). While water consumption for renewable energy generation (particularly wind and solar PV) is considerably lower than fossil fuel-based power plants, land-use footprint (i.e., ~1.31–809.74 km^2/TWh) is typically higher for renewables

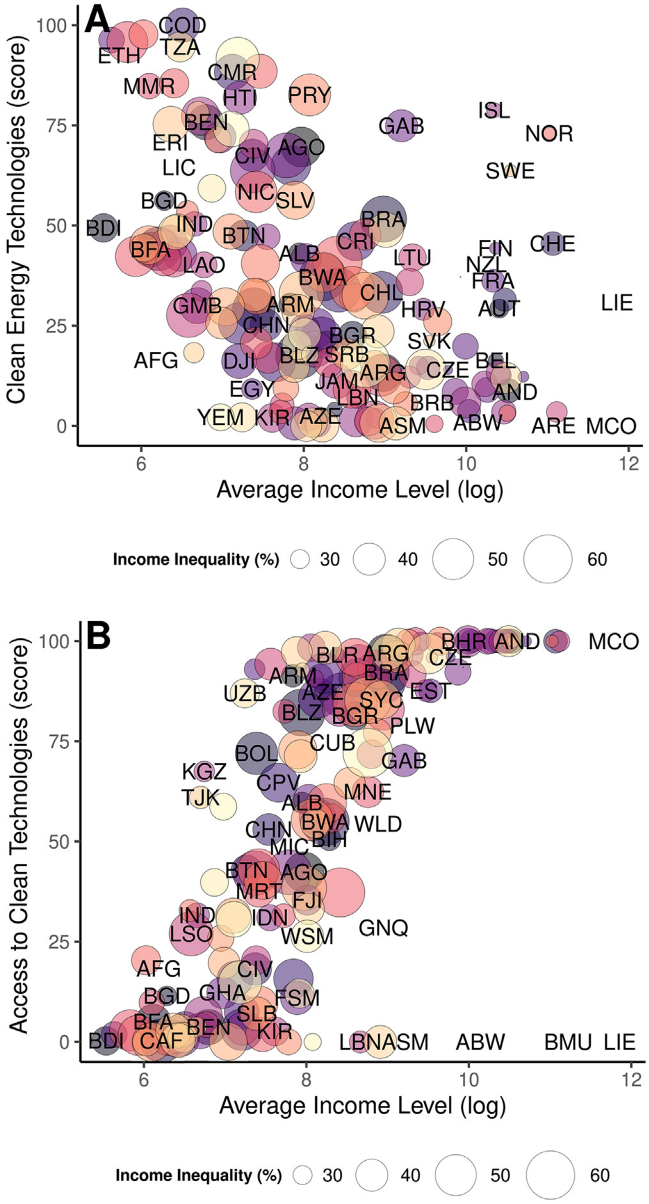

Fig. 6. Global nexus of sustainability indicators of energy and its services in income function while controlling for income inequality (A) Energy intensity. (B) Cons of energy sustainability target. Legend: The trend indicates the relationship between sustainability indicators of energy and its services and average income level whereas the white filled-circles with black outline denotes the magnitude of income inequality. *See Supplementary Table 1 for interpretation of ISO 3166-1 aplha-3 country codes.*

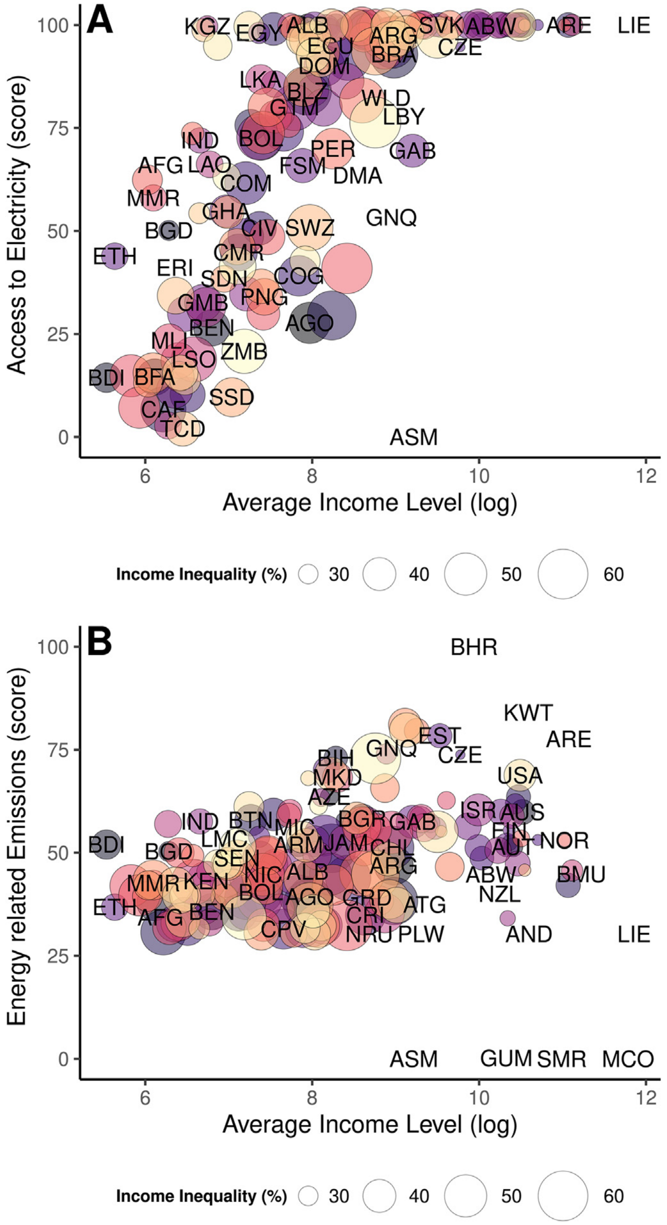

Fig. 7. Global nexus of sustainability indicators of energy and its services in income function while controlling for income inequality. (A) Pros of energy sustainability target. (B) Benefit-cost of energy sustainability target. Legend: The trend indicates the relationship between sustainability indicators of energy and its services and average income level whereas the white filled-circles with black outline denotes the magnitude of income inequality. *See Supplementary Table 1 for interpretation of ISO 3166-1 aplha-3 country codes.*

(Sarkodie and Owusu, 2020; Trainor et al., 2016). Africa produces less emissions but its energy portfolio is more vulnerable to climate change sensitivity and exposure, hence, faces challenging water legacies (i.e., "*hydrological variability and multiplicity of transboundary river basins*") that impede economic development (Foster and Briceño-Garmendia, 2010).

Our empirical analyses underscore the importance of addressing energy system - climate vulnerability that reduces pressure and trade-off between natural resources (i.e., domestic material, food, water, and land resources) and environmental threats (biodiversity loss, transboundary and domestic pollution) (Conway et al., 2015). Though the SDG indicators assessed herein are mere tools and not a finality in itself, yet, provide a snapshot of progress towards attaining sustainable development from energy and environmental perspective—which has long-term policy implications.

CRediT authorship contribution statement

Samuel Asumadu Sarkodie: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing – review & editing.

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 Information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.154945.

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