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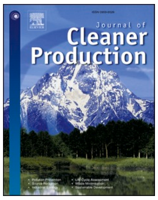

Advancing COP26 climate goals: Leveraging energy innovation, governance readiness, and socio-economic factors for enhanced climate resilience and sustainability

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ABSTRACT

Climate change adaptation and mitigation remain critical to achieving sustainable development while reducing climate vulnerability, particularly among climate-exposed and sensitive regions. Yet, achieving a balance between climate-resilience pathways, high economic productivity, high human development, and energy efficiency appears complex, leading to potential trade-offs. Here, we examine the overarching effect of the diversified energy portfolio, socio-economic drivers, and governance adaptation readiness on Climate change vulnerability across 212 economies. Contrary to the poor conventional panel techniques reported in the existing literature, we employ novel machine learning and dynamic panel estimation techniques that control for chaos, nonlinearity, mutual coupling, and heterogeneity in dynamic systems. The convergent cross-mapping causality technique reveals mutual coupling effects between energy portfolio, governance readiness, socio-economic drivers, and climate change vulnerability. The rapidly increasing population and increasing demand for resources under the business-as-usual society and economic structure that normalizes unsustainable development pathways due to weak governance structures create ineffective climate-resilient policies that lead to unabated emissions with consequences on climate change. The effect of social and governance readiness leads the transformation process to attain sustainable development. Thus, high social and governance readiness spurs climate resilience through climate change adaptation and mitigation to achieve sustainable development. Alternative (renewables) and nuclear energy have displacement effects on fossil fuels, yet, the magnitude of displacement is not large enough to replace future fossil fuel consumption. Conversely, a low-carbon future is still attainable by replacing the fossil energy portfolio with more natural gas and carbon-abatement technologies. Our study demonstrates that energy innovations are useful climate-resilience pathways that lessen climate change vulnerability.

1. Introduction

The recent objectives of COP26 highlight the role of adaptation and mitigation in achieving climate-resilient pathways (UKCOP26, 2022). Climate resilience requires adjustments in socio-ecological and economic structures that can timely and efficiently '*anticipate*,' '*reduce*', '*accommodate*', and/or '*recover*' from the consequences of climate change and its impacts (Denton et al., 2014). Yet, the world's biggest challenge of the 21st century involves meeting the energy demands of a growing population and sustaining economic development while mitigating the effects of climate change (O'neill et al., 2010). There is however a general scientific and political consensus that climate change is already happening, identifying GHG emissions as the single biggest global challenge (WRI, 2008). The GHG emissions over the last four decades have increased by 330% in Asia, 70% in Africa & Middle East, 57% in Latin America, and 22% in OECD countries (Blanco et al., 2014). In 2021, the global CO_2 emissions from emerging and developing countries accounted for two-thirds of the world's CO_2 emissions (IEA, 2021). The alarming increase in emissions is reported to hamper global ambition to limit the average temperature level below 1.5 °C (IPCC, 2018). Thus, global emission reduction strategies will require fundamental changes in energy production and consumption that underpin economic structures (van Vuuren et al., 2018). For example, the emission reduction targets of the European Union include a shift from a

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carbon-intensive economy to a low-carbon economy by increasing renewables by 27% and energy efficiency by 30% efficiency by 2030 (EEA, 2021).

The global CO_2 emissions from fossil fuels and industrial processes have increased consistently in 4 decades (1970–2010) (Blanco et al., 2014), however, the largest absolute decline of 4% in global energy demand since World War II occurred in 2020 due to COVID-19 pandemic (IEA, 2021). The global demand for coal in 2020 dropped by 4%, viz. equivalent to 220 Mt—due to travel restrictions and containment measures. The global energy demand is expected to rebound by 4.6%, pushing the global energy use by 0.5% higher than the pre-pandemic level. For example, there was a rebound effect in 2021, reversing the decline in developed countries, particularly the US and Europe, accounting for half of the global coal demand (IEA, 2021). Global natural gas demand rose by 3900 bcm in 2020 and is projected to increase to ~4600 bcm and 5700 bcm in 2030 and 2050, respectively (IEA, 2021a). The global oil demand is estimated to increase to ~98 MMB/D by 2023 and ~104 MMB/D after 2030 (IEA, 2021a). In contrast, renewable energy increased by 3% (~330 TWh) during the pandemic period, particularly in 2020 due to the surge in electricity generation from wind and solar PV. The global wind and solar PV generation are estimated to grow by 8.3%, increasing the global electricity from renewables to ~30% (IEA, 2021, 2021a). Similarly, global nuclear energy is estimated to grow by 15% between 2020 and 2030, reflecting the expansion in output from emerging markets and developing economies (IEA, 2021a).

Diverse economic structures in developed economies, emerging markets, and developing economies determine the attitude of governments toward climate change (Acemoglu et al., 2008). For example, political ideologies-embedded governance is reported to influence GHG emissions and energy efficiency (Wang et al., 2022). Developed economies are projected to decline CO_2 emissions by almost a third between 2020 and 2050, reflecting the strive to achieve a low-carbon economy through abatement policies including switching to low-carbon fuels and technological advancements to improve energy efficiency (Le Quéré et al., 2019). On the other hand, there is a strong demand for energy in emerging markets and developing economies due to increasing population, economic growth, urbanization, and infrastructure expansion. The 7.7 billion estimated (est. 2020) world population is projected to increase by ~750 million in 2030 and ~2 billion people in 2050 in line with the UN projections—of which a large number of the population growth is in emerging markets & developing economies (IEA, 2021a). The post-COVID-19 pandemic crisis is expected to grow the global economy rapidly, with a 3% average GDP growth rate per annum in line with IMF projections (IMF, 2022). These factors of demand are reported to increase CO_2 emissions by ~20% between 2020 and 2050 due to a limited focus on clean fuels & technologies, and energy efficiency (IEA, 2021a).

There is growing political consensus on mitigating CO_2 emissions to net-zero emissions by 2050 (IPCC, 2018). Nevertheless, global energy consumption is estimated to increase in all major end-user sectors. Yet, the global energy sector based on the Announced Pledges Scenario is predicted to improve its decadal annual intensity by ~2.5% through government support, but still below the ~4.2% target in the Net-Zero Emissions scenario (IEA, 2021a). Aside from improvements in energy efficiency in the industrial sector, the global energy sector transformation cannot be met without social readiness, viz. active public participation (Liu et al., 2018). The populace is the key driver of demand for efficient energy-related goods and services crucial to sustainability (Renn et al., 2020). The deployment of low-carbon technologies and social readiness are projected to decline CO_2 emissions by 55% compared to 40% (require investment and policy support) without the active participation of the public and consumers. However, behavioral changes and improvements in material efficiency reduce CO_2 emissions by 8% (IEA, 2021a). This infers improvement in energy efficiency by reducing energy demand per output is critical to achieving net-zero emissions. Failure of economies to deploy net-zero emission policies including energy efficiency, behavioral changes, and electrification measures is predicted to increase global energy use by ~90% (300 EJ) by 2050 (IEA, 2021a). This scenario implies GHG emissions will increase unabated in 2050, which is injurious to sustainable environment with climate consequences.

Climate change vulnerability (i.e., exposure, climate sensitivity, and adaptive capacity) determines the magnitude of climate consequences across economies (Sarkodie et al., 2022; Sarkodie and Strezov, 2019; Smit and Wandel, 2006). This demonstrates the importance of climate-resilience including adaptation and mitigation in reducing the worst consequences of climate change effects (Smit and Wandel, 2006). Yet, empirical studies that examine drivers, adaptation, and co-benefits of climate change vulnerability through the lenses of diversified energy portfolios are limited. Several studies in the extant literature have examined the energy-growth-emission nexus (see Ozturk, 2010). However, existing literature on energy-growth-climate change (Stern, 2011; Zheng et al., 2020) assumes data exhibit a stochastic process—but in reality, masquerade as such due to poor conventional panel techniques to identify and solve dynamic systems. This implies existing techniques assume the causes of climate change are distinct from the effects (Sugihara et al., 2012). However, there is a strong dynamic coupling between energy, economic growth, and climate change. Thus, we show that the coupling effect among energy, economic development, and climate change vulnerability exhibits dynamic systems that are driven by deterministic processes that cannot be modeled by existing traditional panel models. Here, we employ empirical dynamic modeling techniques, viz. convergent cross-mapping causality, and kernel regularized least-squares that go beyond equilibrium, linearity, and stability assumptions expounded in conventional panel models, yet control for heterogeneous and nonlinear effects.

Our research questions include: First, do energy innovation, social, and governance adaptation readiness offset global climate change

Table 1
Variable selection and description.

Indicator Name	Unit	Data Source
Adjusted savings: energy depletion	% of GNI	World Bank (2020)
Alternative and nuclear energy	% of total energy use	World Bank (2020)
Access to clean fuels and technologies for cooking	% of population	World Bank (2020)
Energy Innovation	Number	OECD (2020)
Energy consumption	ktoe/capita	World Bank (2020)
Energy intensity level of primary energy	MJ/$2011 PPP GDP	World Bank (2020)
Foreign direct investment net inflows	BoP, current US$	World Bank (2020)
Fossil fuel energy consumption	% of total	World Bank (2020)
Gross domestic product	Constant 2015 US$	World Bank (2020)
GHG emissions	ton CO_2eq/capita	EDGAR (2020)
Governance readiness	Score	ND-GAIN (2018)
Human development index	Score	UNDP (2016)
GDP per capita, aka Income level	Constant 2015 US$	World Bank (2020)
Total population	Number	World Bank (2020)
Urban population	Number	World Bank (2020)
Renewable energy consumption	% of total final energy consumption	World Bank (2020)
Social readiness	Score	ND-GAIN (2018)
Climate change vulnerability	Score	ND-GAIN (2018)

vulnerability? Second, do existing country-specific climate profiles and diversified energy portfolios show deterministic processes with policy implications? Third, what are the winners and losers of sustainable development? Fourth, do alternative (renewables) and nuclear energy have displacement effects on fossil fuels? Our research questions are answered in line with COP26 objectives by: first, assessing the global status and drivers of climate change vulnerability, and the impact of diversified energy portfolio, social and governance adaptation readiness. We present the winners and losers of sustainable development including energy sustainability, and human development. Besides, we validate the existence and magnitude of global displacement effects using novel estimation methods. Our empirical models demonstrate interconnectedness (mostly mutual coupling) between energy portfolios, socio-economic drivers, adaptation readiness, and climate change

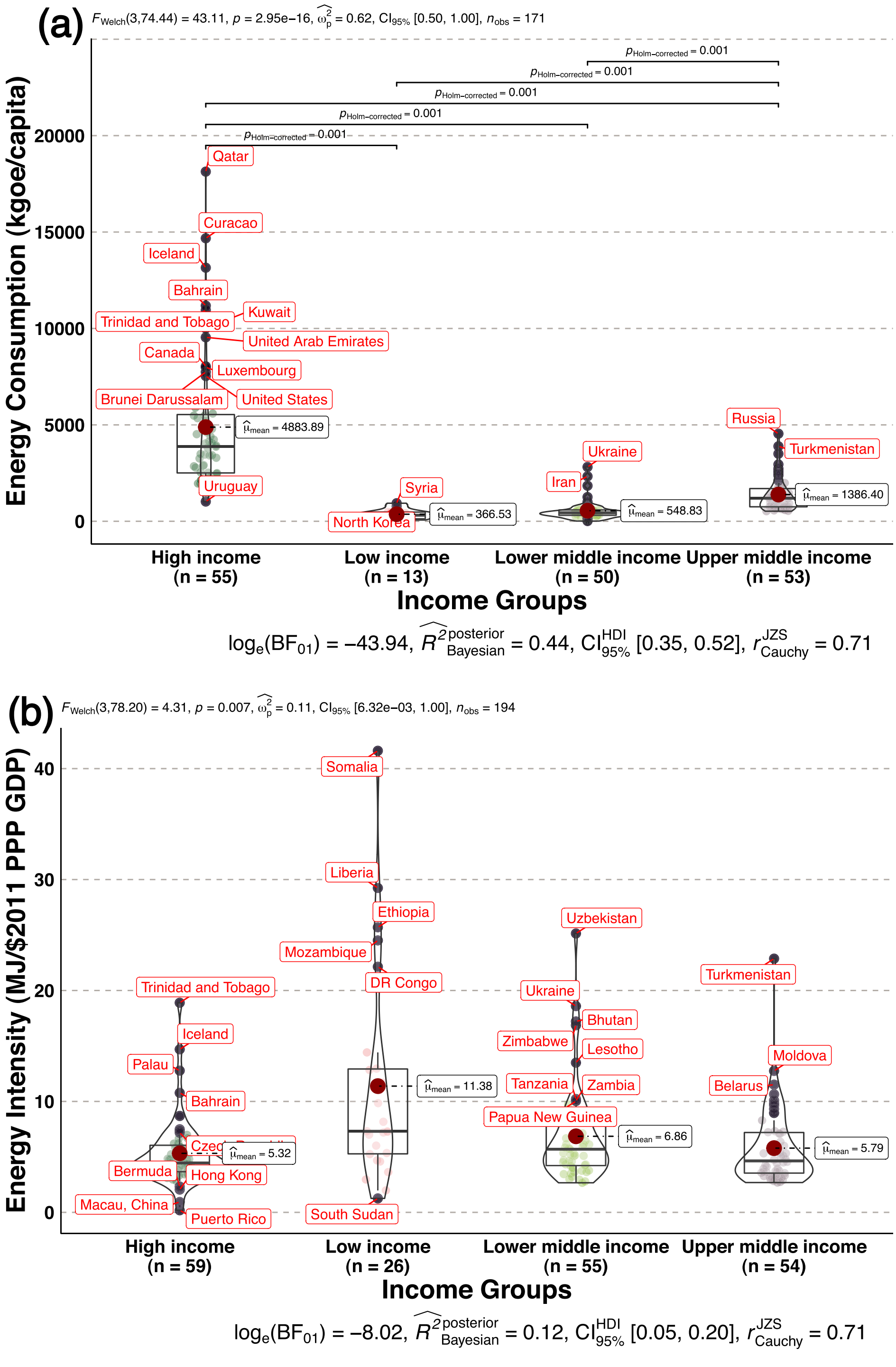

Fig. 1. Historical accounting across income groups (a) energy consumption (b) energy intensity. Pairwise test: Games−Howell test, Comparisons shown: only significant. The statistical details of Bayesian hypothesis testing [log_e (.)] with R^2 estimate of posterior Bayesian $\widehat{R^2}^{posterior}_{Bayesian}$, 95% confidence interval $CI^{HDI}_{95\%}$, and prior type and value r^{JZS}_{Cauchy}. The highlighted countries represent outliers with important policy implications. These countries signify the excesses of data series under consideration.

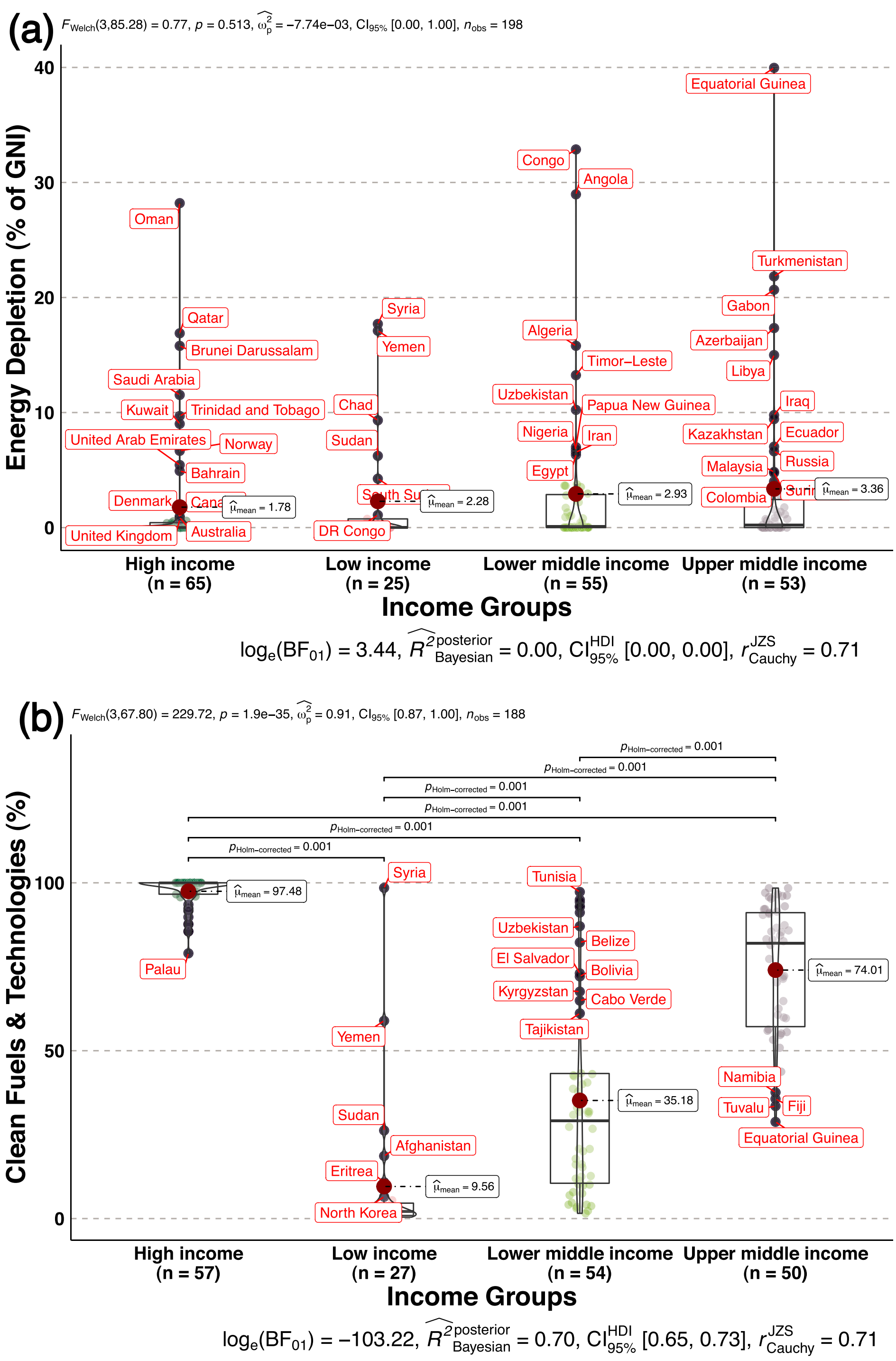

Fig. 2. Historical accounting across income groups (a) energy depletion (b) access to clean fuels and technologies. Pairwise test: Games−Howell test, Comparisons shown: only significant. The statistical details of Bayesian hypothesis testing [log_e (.)] with R^2 estimate of posterior Bayesian $\widehat{R^2}^{posterior}_{Bayesian}$, 95% confidence interval $CI^{HDI}_{95\%}$, and prior type and value r^{JZS}_{Cauchy}. The highlighted countries represent outliers with important policy implications. These countries signify the excesses of data series under consideration.

vulnerability. From a policy perspective, our study suggests the complexity involved in decoupling the above-mentioned dependencies to achieve sustainable development.

2. Methods

To assess the overarching effect between energy portfolio, socio-economic, and climate change vulnerability, we utilized data series spanning 1995–2017 from the World Bank (2020), ND-GAIN (2018), OECD (2020), and EDGAR (2020). While our data were collected from reputable sources, there may still be potential biases including data availability and quality, indicator selection bias, subjective weighting bias, economic bias, time lag bias, contextual bias, and ethical and political bias. These limitations could lead to challenges associated with

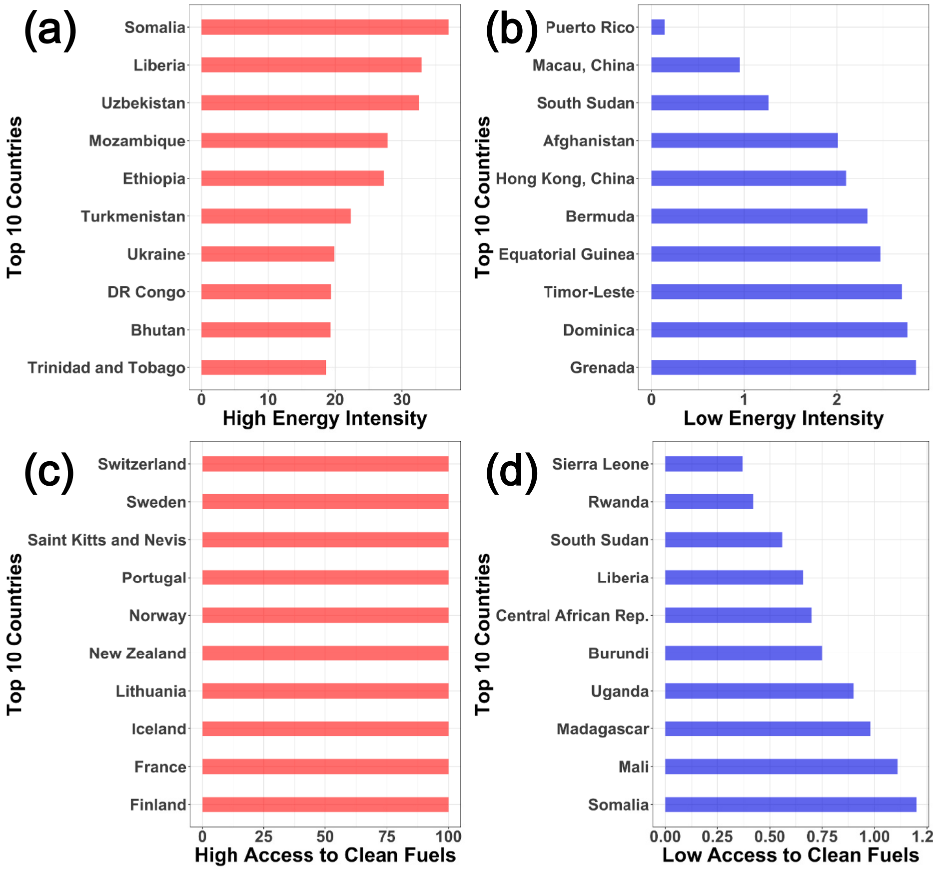

Fig. 3. Top 10 countries with (a) high energy intensity (b) low energy intensity (c) high access to clean fuels and technologies for cooking (d) low access to clean fuels and technologies for cooking.

comparing economies across different geographical regions. Nevertheless, we employ a regularization-based panel technique that can mitigate these potential biases introduced by over-represented features. The time frame of the dataset is in alignment with significant climate policies (such as the Kyoto Protocol [1997] and the Paris Agreement [2015]), and the availability of comprehensive data. Our global data set covers 212 economies across income groups, specifically high-income, upper-middle-income, lower-middle-income, and low-income. Data series presented in Table 1 were strategically selected based on the objectives of COP26 namely emission reduction (fossil reduction and investment in renewables), financing, adaptation, and global partnership (UKCOP26, 2022). The dataset on energy portfolio includes energy depletion, energy innovation, alternative & nuclear energy, access to clean fuels and technologies for cooking, energy consumption, energy intensity level, fossil fuel, and renewable energy consumption (World Bank, 2020). Energy innovation *alias* technology diffusion comprises the number of patents that capture climate change mitigation technologies related to energy generation, transmission, or distribution (OECD, 2020). The socio-economic variables cover foreign direct investment net inflows, gross domestic product, income level, and human development index (this incorporates the three dimensions of human development: knowledge, standard of living, and healthy life) (UNDP, 2016; World Bank, 2020). Besides, demographic and environmental-related indicators include total population, urbanization, GHG emissions, climate change vulnerability, social and governance adaptation readiness (EDGAR, 2020; ND-GAIN, 2018; World Bank, 2020). These sampled variables in line with the Sustainable Development Goals (SDGs) are crucial to assessing the complexity of energy-growth-climate vulnerability nexus.

2.1. Model estimation

Our empirical assessment involves four sections namely historical accounting, structural relationships, cross-mapping causality, and parameter estimations. To account for between-group historical and statistical details, we explored the distribution of diversified energy portfolios (i.e., energy consumption, energy intensity, energy depletion, access to clean fuels and technologies, fossil energy consumption, renewable energy use, alternative energy consumption, and energy innovation) for income groups using the mean indicator from 1995 to 2017. In addition, we further compare the statistically significant mean differences in diversified energy portfolios between income groups using the package presented in Patil (2021). Besides, we visually present the statistical details while highlighting country-specific outliers. The function of the package automates the testing procedure based on the number of groupings (i.e., 4 groups herein). Here, the function optimally selected the parametric and Bayes Factor $[log_e(BF_{01})]$ with Welch's one-way ANOVA for hypothesis testing, and Bayesian R^2 $(\boldsymbol{R}^2_{posterior})$ effect-size estimation. The pairwise comparison test between income groups is examined using the Games-Howell test which considers no equal group variance but depicts only significant test estimates (Welch, 1951).

Second, the structural relationships were assessed by using the normalized average indicators [i.e., (0,1): $y^* = (y_i - y_{min} / y_{max} - y_{min})$] where score *0* represents the minimum value whereas score *1* denotes the maximum value across economies. We investigated the country-specific nexus while accounting for income groups among selected pairs of indicators (i.e., access to clean fuels and technologies for cooking vs. governance and social readiness, climate change vulnerability vs. human development, fossil energy consumption, and

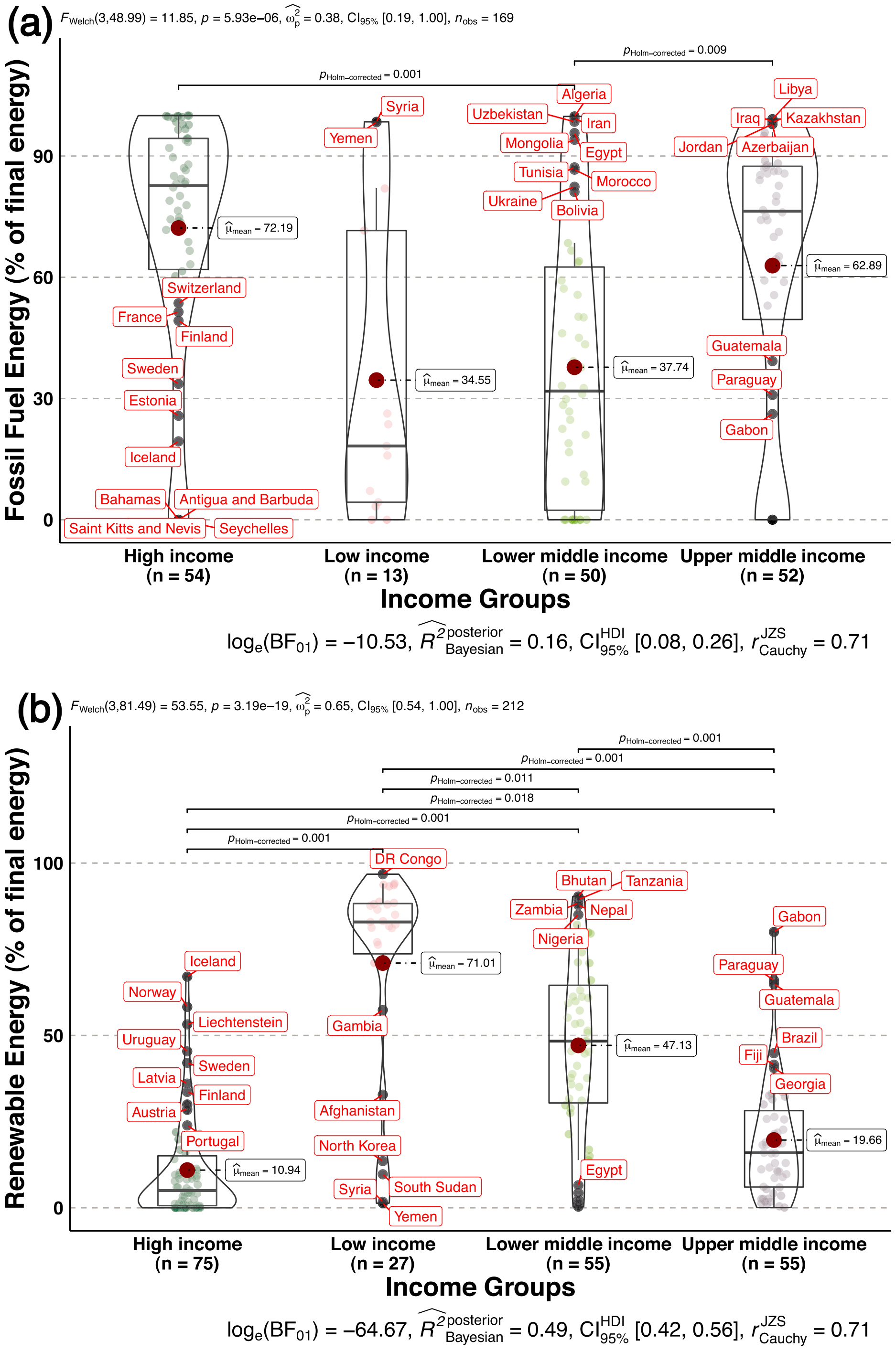

Fig. 4. Historical accounting across income groups (a) fossil energy consumption (b) renewable energy use. Pairwise test: Games−Howell test, Comparisons shown: only significant. The statistical details of Bayesian hypothesis testing [log_e (.)] with R^2 estimate of posterior Bayesian $\widehat{R2}^{posterior}_{Bayesian}$, 95% confidence interval $CI^{HDI}_{95\%}$, and prior type and value r^{JZS}_{Cauchy}. The highlighted countries represent outliers with important policy implications. These countries signify the excesses of data series under consideration.

renewable energy use) visualized using a scatterplot with a second-degree polynomial-based regression fit. Similarly, we used the normalized data to categorize the top 10 hotspots of diversified energy portfolios.

Third, we investigated causal networks in complex systems by employing the convergent cross-mapping causality, a panel dynamic modeling technique that goes beyond equilibrium, linearity, and stability assumptions due to the characteristics of the sampled variables (Li et al., 2021). Convergent cross-mapping is based on a manifold reconstruction—a nonlinear state-space—that differentiates panel causality from correlation (Sugihara et al., 2012). Unlike existing techniques for causation, this technique is useful for non-separable relationships (causal-effects) in deterministic dynamical systems (Tsonis Anastasios et al., 2015). We examined the manifold reconstruction of

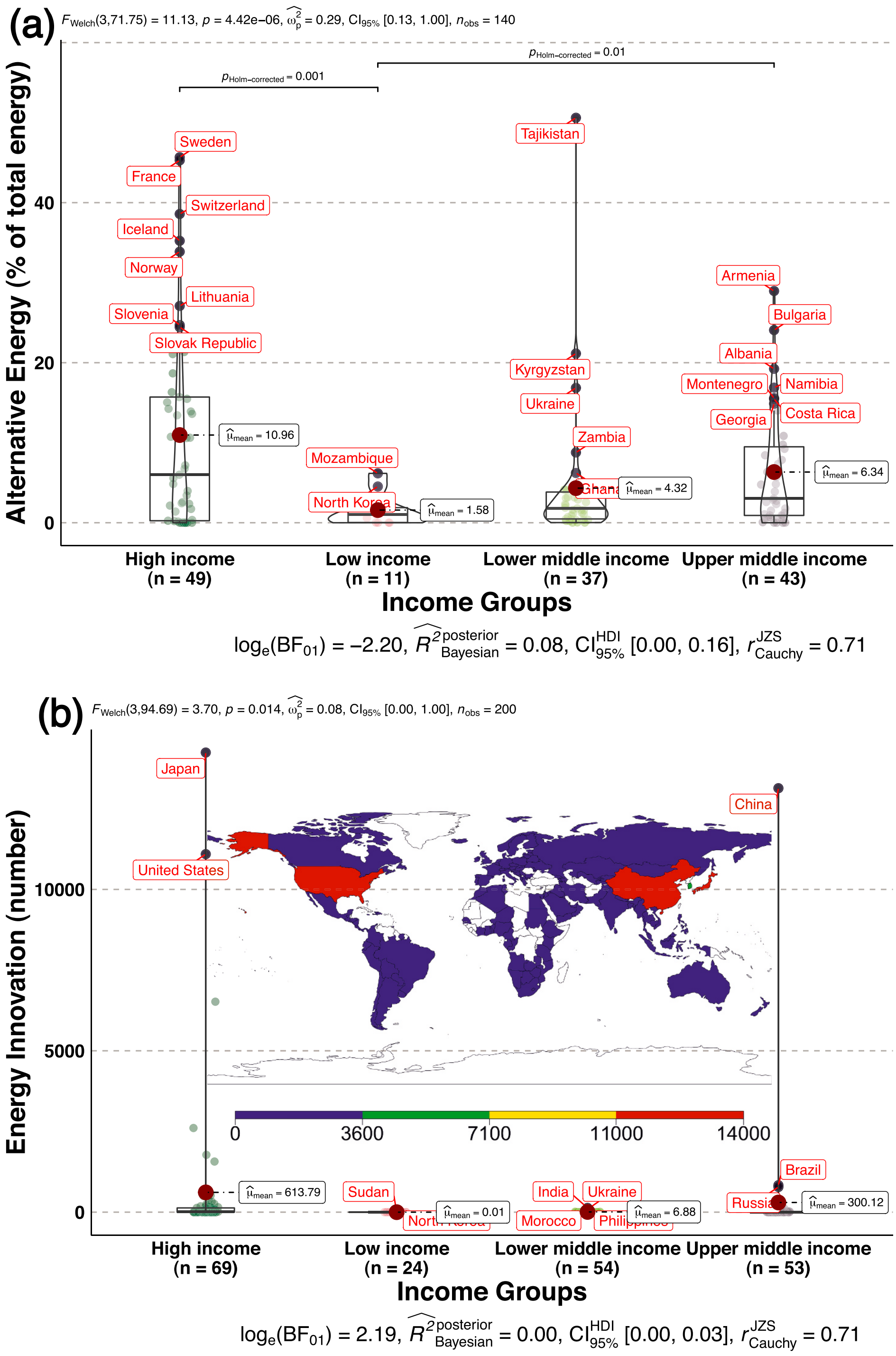

Fig. 5. Historical accounting across income groups (a) alternative energy consumption (b) energy innovation. Pairwise test: Games−Howell test, Comparisons shown: only significant. The statistical details of Bayesian hypothesis testing [log_e (.)] with R^2 estimate of posterior Bayesian $\widehat{R}^{2\,posterior}_{Bayesian}$, 95% confidence interval $CI^{HDI}_{95\%}$, and prior type and value r^{JZS}_{Cauchy}. The highlighted countries represent outliers with important policy implications. These countries signify the excesses of data series under consideration.

data series to ascertain deterministic behavior using the Simplex projection (Sugihara and May, 1990) whereas nonlinearity is assessed with a sequential-locally weighted global linear maps (Hsieh et al., 2008; Li et al., 2021). Using the convergent cross-mapping technique, we evaluated the causal relationship among sampled variables by constructing 41 models, resulting in 82 outcomes presented in Fig. 9.

Finally, we estimated the drivers of climate change vulnerability and global fossil fuel displacement by constructing a panel-fixed effects model that controls for non-linearities and heterogeneous effects across economies using a machine learning approach with kernel regularized least-squares (KRLS) estimator. Advantageously, the KRLS estimator solves complex estimation problems in regression and classification including misspecification bias due to inconsistent functional form used to specify empirical models (Hainmueller and Hazlett, 2014). The KRLS technique

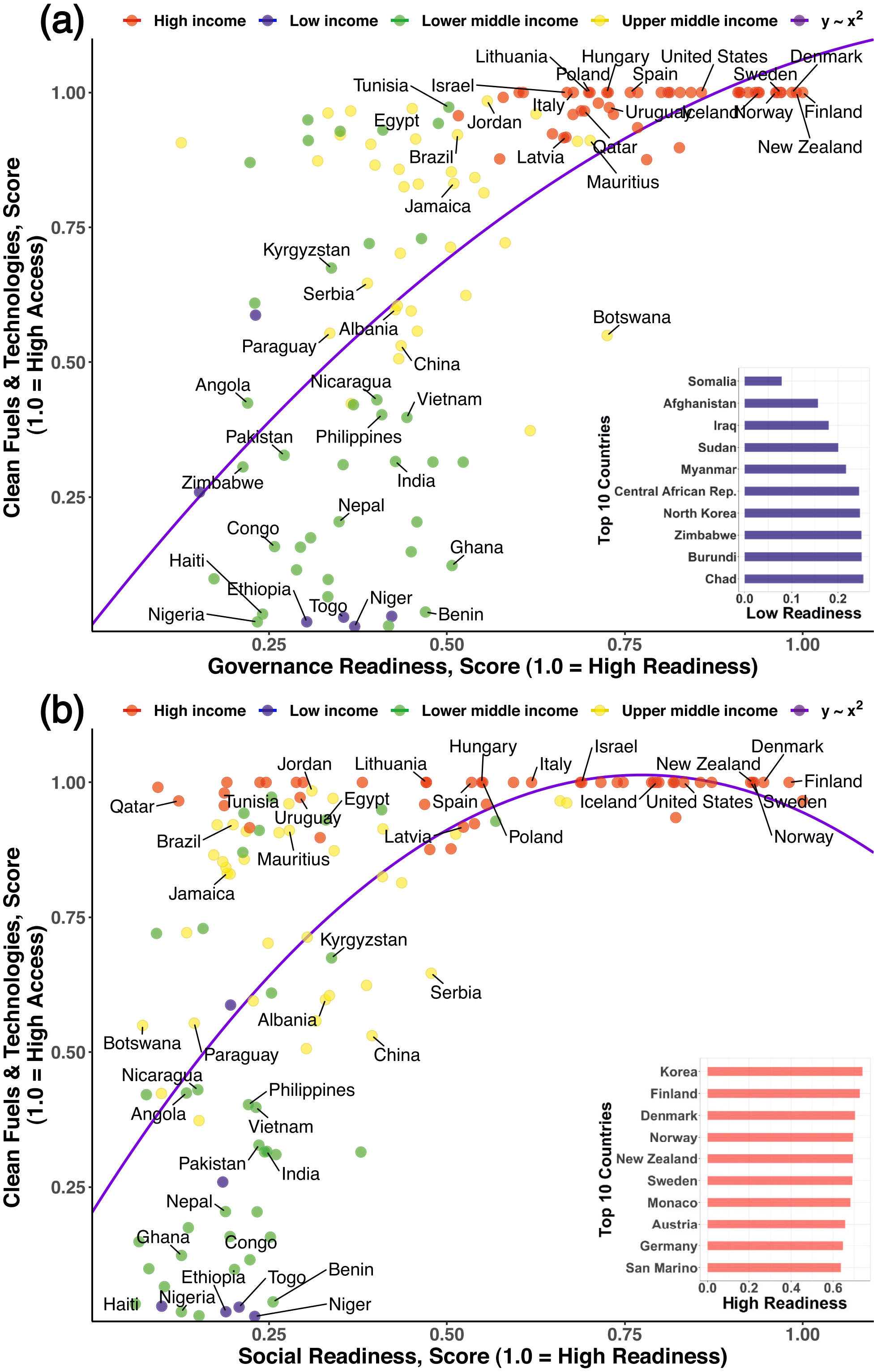

Fig. 6. Country-specific access to clean fuels and technologies for cooking vs. (a) governance readiness and (b) social readiness.

assumes a flexible functional form, zero conditional means, homoscedastic and normally distributed errors, and zero serial correlation, hence, exhibits desirable estimation properties to produce unbiased and consistent empirical models (Ferwerda et al., 2017). The KRLS estimator was used to estimate six models that control for country-specific fixed effects and periodic effects, which capture differences (geographical and economic structure) within economies over the period and the effect of time-driven policy interventions across economies. For example, global climate and developmental policies such as the MDGs (2000–2015), and SDGs (2016-to-date) were periodically-based interventions that could alter climate and energy structure, hence, controlling for periodic effects account for unobserved factors driven by time variations (Sarkodie, 2022). We included the lagged-dependent variable (LDV) in all models to account for omitted-variable bias, which is essential to explain inertia effects and

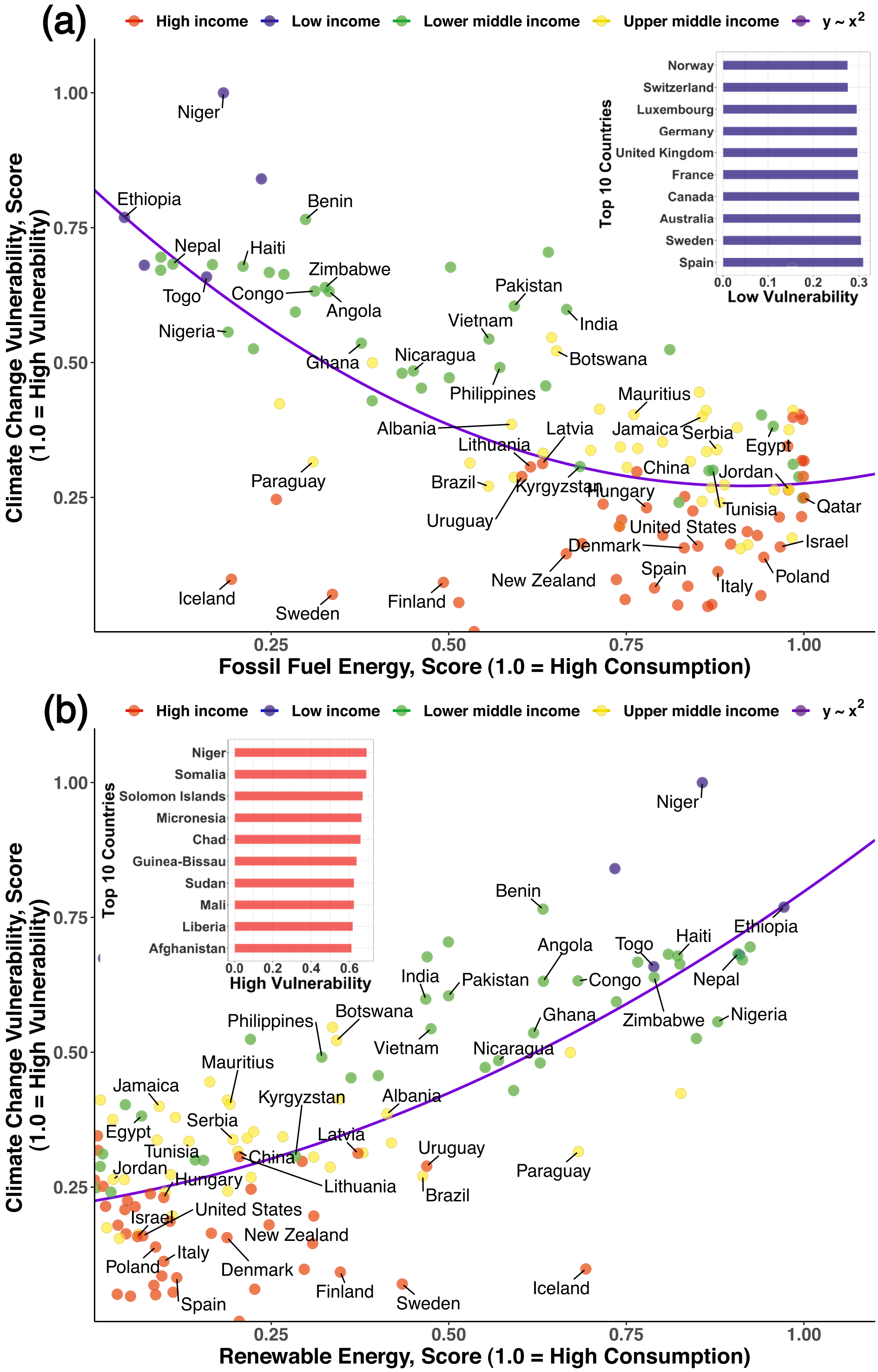

Fig. 7. Nexus between climate change vulnerability and (a) fossil energy consumption (b) renewable energy use.

historical returns (Wooldridge, 2016). In Model 1, we assessed the impact of energy innovation, income level, HDI, and governance readiness on climate change vulnerability. Model 2 investigated the effect of alternative energy sources, energy innovation, FDI, HDI, and governance readiness on climate change vulnerability. In Model 3, we examined the effect of fossil fuels, FDI, access to clean fuels and technologies for cooking, energy innovation, population growth, HDI, and governance readiness on climate change vulnerability. However, Model 4 investigated the nexus between renewables, fossil fuels, HDI, FDI, access to clean fuels and technologies for cooking, energy innovation, population, social and governance readiness on climate change vulnerability. In the global fossil fuel displacement assessment, we examined the impact of income, quadratic income, FDI, urbanization, and renewables on fossil fuel energy consumption in Model 5 whereas renewable energy was replaced with alternative energy sources in Model 6. All six models were validated using pointwise derivatives and conditional quantile specification based on 5th, 50th, and 95th percentiles to examine heterogeneous effects.

2.2. Limitations

Understanding the limitations and uncertainties of both estimation methods is crucial to ensure robust and reliable results. Both convergent cross-mapping and KRLS are more powerful estimation tools for handling nonlinear relationships than traditional techniques. While convergent cross-mapping is useful for validating causal hypotheses in dynamic systems, KRLS is useful in modeling complex relationships. However, convergent cross-mapping is sensitive to embedding parameters (such as time delay and embedding dimension) which may affect the estimated results (Sugihara and May, 1990). Because KRLS is a machine-learning technique, its performance relies heavily on data quality, hyperparameter tuning, and the choice of kernel function (Ye and Sugihara, 2016).

3. Results & discussion

3.1. Historical accounting

The between-income-group comparisons were examined using the Games−Howell test while accounting for historical changes across countries. The visualization shows the statistical assumptions and details for evaluating the Bayesian analysis across income groups (Patil, 2021). Both descriptive and inferential statistical details from the Bayesian hypothesis testing are presented in Figs. 1-2, 4-5. Energy consumption entails domestic primary energy production plus imports excluding exports. The lowest average energy consumption (12.40 kgoe/capita) is reported in Lesotho (i.e., a lower-middle-income country in sub-Saharan Africa) whereas the highest average energy consumption (18133.23 kgoe/capita) occurs in Qatar (i.e., a high-income country in the Middle East & North Africa region). The estimated mean distribution of energy consumption (i.e., 366.53, 548.83, 1386.40, and 4883.89 kgoe/capita) across income groups (low, lower-middle, upper-middle, and high income, *respectively*) significantly ($P_{Holm\text{-}corrected} < 0.01$, n_{obs}: 171) vary from each other (Fig. 1a). This implies disparities in energy consumption across income groups—which may be driven by energy availability, accessibility, and affordability. Energy intensity indicates energy utilized in producing one unit of end product. This infers a decline in energy intensity implies energy efficiency. While the mean distribution of energy intensity in Fig. 1b is not significantly ($P_{Holm\text{-}corrected} > 0.05$, n_{obs}: 194) different across income groups, low-income economies have the highest average energy intensity of 11.38 MJ/$2011 PPP GDP whereas high-income economies have the lowest energy intensity (5.32 MJ/$2011 PPP GDP). The 10 hotspot countries of energy intensity include Somalia, Liberia, Ethiopia, Uzbekistan, Mozambique, Turkmenistan, DR Congo, Trinidad & Tobago, Ukraine, and Bhutan (Fig. 3a) whereas economies with low energy intensity include Puerto Rico, Macau, South Sudan, Afghanistan, Hong Kong, Bermuda, Timor-Leste, Equatorial Guinea, Peru, and Sri Lanka (Fig. 3b). Energy depletion denotes the ratio of energy resources including oil, gas, and coal to its lifetime reserves. The mean energy depletion is not significantly different in Fig. 2a, yet, high-income economies have the lowest average depletion compared to upper-middle-income economies. The 10 hotspot countries of energy depletion comprise Equatorial Guinea (39.96% of GNI), Congo (32.87% of GNI), Angola (28.97% of GNI), Oman (28.20% of GNI), Turkmenistan (21.83% of GNI), Gabon (20.67% of GNI), Syria (17.70% of GNI), Azerbaijan (17.34% of GNI), Yemen (17.11% of GNI), and Qatar (16.89% of GNI).

Clean fuels and technologies represent the share of the population with access to clean fuels and technologies for cooking. This indicator underpins household air pollution and, hence, is crucial to achieving quality of life. The average distribution of clean fuels and technologies is statistically significant ($P_{Holm\text{-}corrected} < 0.01$, n_{obs}: 188), hence varies across income groups (Fig. 2b). While low-income countries exhibit the lowest average accessibility (9.56%) to clean fuels and technologies, high-income economies have the highest average access (97.48%). For example, 37 of the 57 high-income countries have 100% access to clean fuels and technologies for cooking whereas the top 10 countries with low accessibility consist of Rwanda, Sierra Leone, South Sudan, Liberia, Burundi, Central African Republic, Uganda, Mali, and Guinea—originating from sub-Saharan Africa (Fig. 3d). In addition to aggregate energy consumption, we further included disaggregate energy use comprising fossil fuels, renewables, and alternative & nuclear energy. The inclusion of nuclear energy is strategic to develop a comprehensive indicator of clean energy sources which is often ignored in the existing literature (Owusu and Asumadu, 2016), hence, leading to omitted-variable bias. The introduction of this indicator further curtails the under-reporting of clean energy, especially for countries such as France, Hungary, Ukraine, Slovakia, and others whose energy portfolio is dominated by nuclear energy. Fossil energy entails fossil fuels specifically coal, oil, natural gas, and petroleum products in the total energy use whereas renewable energy represents the proportion of renewables in final energy consumption. Fossil fuels contribute an average of 34.55% of total energy in low-income economies but 72.19% in high-income economies (Fig. 4a). Thus, fossil fuels account for an average of >50% in 107 nations. For example, the top 10 fossil fuel dependent economies include Qatar (100% of total energy, average estimate), Brunei Darussalam (100%), Saudi Arabia (99.91%), Gibraltar (99.90%), Oman (99.82%), Algeria (99.80%), Trinidad & Tobago (99.72%), Malta (99.66%), Bahrain (99.41%), and Iran (99.28%). The mean distribution of renewables is statistically significant ($P_{Holm\text{-}corrected} < 0.01$, n_{obs}: 212) across income groups, where the highest mean of 71.01% (of final energy use) occurs in low-income economies while the lowest share of 10.94% occurs in high-income economies (Fig. 4b). Renewable energy contributes to an average of >50% in 54 economies of which 34 are situated in Sub-Saharan Africa. The top 10 economies with high share of renewables in the final energy use include DR Congo (96.78%), Ethiopia (94.05%), Uganda (93.72%), Burundi (93.61%), Somalia (93.25%), Bhutan (90.31%), Tanzania (89.44%), Rwanda (88.80%), Guinea-Bissau (88.46%), and Zambia (88.40%). Alternative and nuclear energy are the clean forms of energy sources (i.e., inter alia hydro, solar, nuclear, and geothermal) with no CO_2 generated (World Bank, 2020) whereas energy innovation represents energy technologies that mitigate climate change (i.e., technology diffusion through patents). The contribution of alternative and nuclear to the energy mix (Fig. 5a) is relatively low in low-income economies (1.58%) compared to high-income countries (10.96%). The top 10 economies with high proportion of alternative and nuclear energy in the total energy portfolio comprise Tajikistan (50.61%), Sweden (45.68%), France (45.29%), Switzerland (38.58%), Iceland (35.23%), Norway (33.87%), Armenia (28.96%), Lithuania (27.09%), Slovenia (24.70%), and Slovak Republic (24.44%). We observe extremely low technology diffusion in low-income economies (0.01) than in upper-middle-income (300), and high-income economies (~614). Thus, economies with a high number of energy innovation patents include Japan (14,241), China (13,137), the United States (11,093), Korea (6521), Germany (2607), Canada (1776), Australia (1569), Chinese Taipei (1503), Brazil (835), and Russia (780) [see Fig. 5b]. The wide variability among diversified energy portfolios (Figs. 1-2, 4-5) within income groups can be attributed to several factors including variations in energy efficiency, energy mix, technological advancements, and policy interventions across economies.

3.2. Structural relationships

We explored the country-specific nexus among selected pairs of indicators using a scatterplot with polynomial-based regression fit presented in Figs. 6–8. The structural relationships were investigated by normalizing [(0,1); where score *0* is the lowest whereas *1* is the highest] the average indicators across countries and territories while accounting for income groups. The country-specific access to clean fuels and technologies for cooking and governance readiness show a positive nonlinear relationship (Fig. 6a), yet an inverted U-shape relationship is

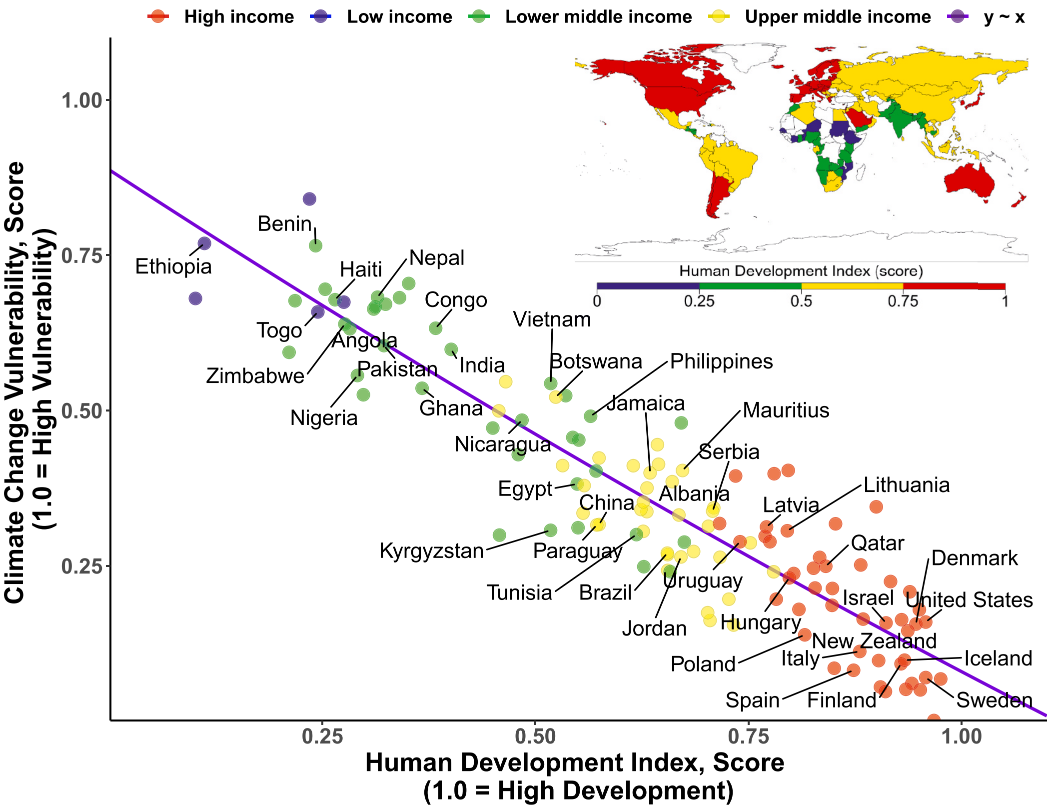

Fig. 8. Nexus between climate change vulnerability, and human development.

more visible when governance is replaced by social readiness (Fig. 6b). In both plots, countries with low access to clean fuels and technologies for cooking exhibit significantly low governance and social adaptation readiness to climate change. Among the top 10 countries with low governance readiness are Somalia, Afghanistan, Iraq, Sudan, Myanmar, Central African Rep., North Korea, Zimbabwe, Burundi, and Chad (Fig. 6a). These countries with similar economic characteristics have unstable political systems and lack social coercion to demand clean fuels. In contrast, economies with high social and governance readiness have high access (nearly 100%) to clean fuels and technologies for cooking. The top 10 countries with high social readiness include Korea, Finland, Denmark, Norway, New Zealand, Sweden, Monaco, Austria, Germany, and San Marino (Fig. 6b). Renewable energy technologies are reported to contribute immensely to climate change mitigation (Owusu and Asumadu, 2016) whereas fossil fuel consumption escalates anthropogenic emissions, yet, we observe contrasting results in terms of climate change vulnerability. While we observe a mitigating effect of fossil fuel energy consumption on climate change vulnerability (Fig. 7a), there is evidence of a positive structural relationship between renewable energy utilization and climate change vulnerability (Fig. 7b). There is both direct and indirect impact of fossil fuel utilization on climate change vulnerability. For example, while fossil fuels appear as a double-edged sword for economic prosperity and driver of anthropogenic emissions, fossil fuels are used as a conduit to finance climate change adaptation and mitigation options in developed countries, hence, declining long-term climate change vulnerability. Besides, economic growth through industrialization predominantly drives the dominance of fossil fuels in upper-middle-income and high-income economies but is significantly lower in low-income countries (see Fig. 4) (Steckel et al., 2015). In contrast, the share of renewable energy dominates the energy portfolio in developing countries compared to fossil fuels (see Fig. 4). The dependency on hydropower in developing countries typically sub-Saharan Africa increases exposure to climate change and its impacts. Hence, climate change effects (i.e., hydrological effects) on rainfall and temperature patterns are predicted to hamper hydropower generation capacity (Hamududu and Killingtveit, 2012). The top 10 economies with high vulnerability include Niger, Somalia, Solomon Islands, Micronesia, Chad, Guinea-Bissau, Sudan, Mali, Liberia, and Afghanistan, whereas Norway, Switzerland, Luxembourg, Germany, United Kingdom, France, Canada, Australia, Sweden, and Spain rank top 10 countries with low climate vulnerability. Aside from the energy system and its related services, we assessed development across income groups using the human development index (i.e., this index has 3 dimensions namely education, income, and life expectancy). We utilized this index to stimulate global debate on country-specific governance policy choices affecting energy dynamics and climate change vulnerability (Ergun et al., 2019; UNDP, 2019). A nearly perfect and negative monotonic relationship is observed between human development and climate change vulnerability in Fig. 8. A similar relationship is reported in some studies, which highlight several factors that explain this pattern including adaptive capacity, economic diversification, international support, governance and institutions, infrastructure and technology, and access to information and healthcare (IPCC, 2014; O'brien et al., 2007). Low-income countries typically in sub-Saharan Africa with low human development are more vulnerable to climate change and its impacts, however, high-income economies with high human development exhibit high adaptative capacity that declines climate change vulnerability (Sarkodie and Strezov, 2019).

3.3. Convergent cross-mapping causality

Both historical accounting and structural relationships highlight several challenges including country-specific complexities across income groups, between-group predictability [see R-squared $\left(\widehat{R^{2}}^{posterior}_{Bayesian}\right)$ estimates of the posterior Bayesian in Figs. 1-2, 4-5], heterogeneous and

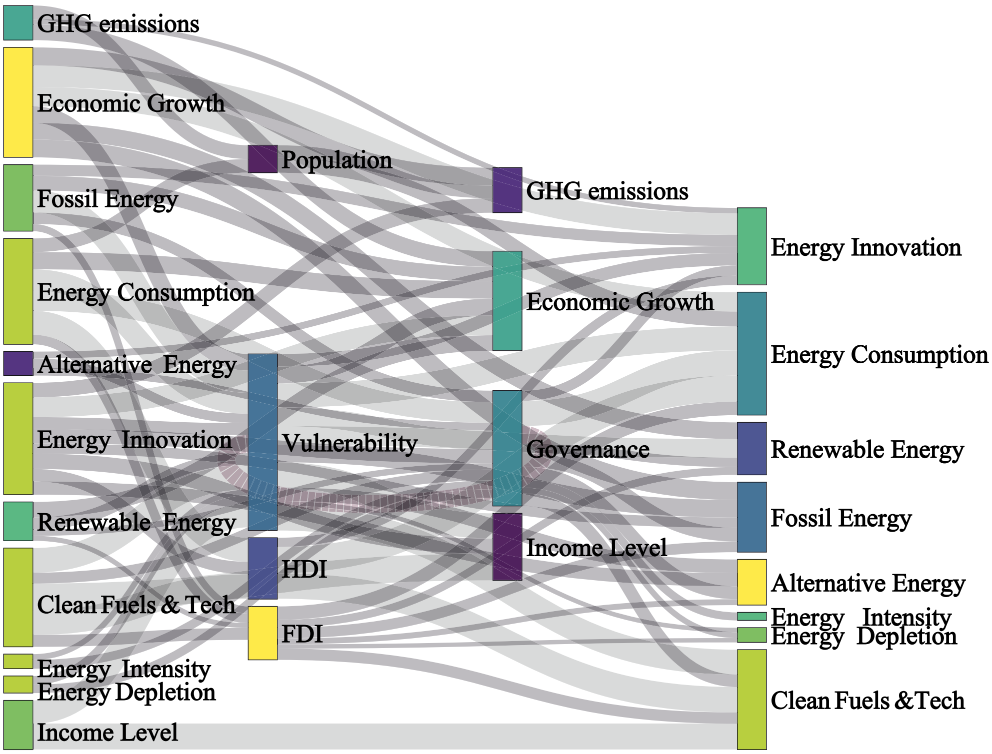

Fig. 9. Convergent cross-mapping causal relationships. Legend: The estimated parameters from 41 models corresponding to 82 networks of empirical relationships are statistically significant at *p-value* < 0.01.[1]

nonlinear effects. These panel challenges in addition to the unequally spaced dataset required panel dynamic modeling techniques that go beyond equilibrium, linearity, and stability assumptions expounded in conventional panel models (Li et al., 2021). Second, the era of a sustainable environment implies a paradigm shift from a brown economy to a circular economy, hence, many developed countries have adopted mitigation options and changes in the economic structure, viz. decoupling economic growth from energy use. However, the business-as-usual scenario remains on course in developing countries as evidenced in the energy intensity level (see Fig. 1b; Fig. 3a). Besides, the Simplex projection confirmed the existence of deterministic processes. The interdependence between energy, emissions, and economic growth in purely deterministic dynamic systems cannot be assessed with standard causality tests (Sugihara et al., 2012), hence, the adoption of convergent cross-mapping causality technique. The estimated parameters from 41 models and 82 empirical results presented in Fig. 9 are statistically significant at *p-value* < 0.01.

The empirical evidence suggests interconnectedness (mostly bidirectional) between energy portfolios, socio-economic drivers, adaptation readiness, and climate change vulnerability. This implies the difficulty of decoupling the dynamic interactions between the cause and effects to achieve sustainable development. The complexity of interconnectedness has significant policy implications, with potential trade-offs. For example, transitioning from fossil fuels to cleaner and more sustainable energy could have economic implications, leading to job displacement in the carbon and energy-intensive industries, specifically the fossil fuel sector (such as oil, coal, and gas) (Pollin and Callaci, 2019). However, prioritization of investments in renewables (such as wind, hydro, and solar) could provide opportunities for new green jobs (Piggot et al., 2019). We observe a feedback effect between economic growth versus vulnerability, GHG emissions, and diversified energy portfolios (i.e., energy innovations, energy consumption, renewables, fossil fuels, and alternative and nuclear energy). Similarly, a bidirectional causality is found between income level against access to clean fuels & technologies for cooking, and energy innovation, *respectively*.

Second, a mutualistic relationship (also known as a bidirectional causal relationship) is observed between climate change vulnerability against governance readiness, income level, and diversified energy portfolios (i.e., access to clean fuels & technologies for cooking, energy innovation, energy intensity, energy depletion, energy consumption, renewables, fossil fuels, and alternative & nuclear energy). In addition, the empirical results find a bidirectional causality between energy innovations versus GHG emissions, HDI, and diversified energy portfolios (i.e., energy intensity, fossil fuels, and alternative and nuclear energy).

Third, we find a feedback effect between governance readiness and diversified energy portfolios (i.e., energy intensity, energy innovation, energy consumption, access to clean fuels & technologies for cooking, energy depletion, renewables, fossil fuels, and alternative and nuclear energy). Besides, a bidirectional causality is found between FDI and diversified energy portfolios (i.e., access to clean fuels & technologies for cooking, energy consumption, energy depletion, renewables, fossil fuels, and alternative and nuclear energy). The convergent cross-mapping causality confirms a feedback relationship between population versus GHG emissions and energy consumption—whereas a similar causality is reported between HDI against energy consumption and access to clean fuels & technologies for cooking.

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[1] The Sankey diagram involves a combination of visual elements by assessing the quantitative information while visually representing the causal flow in the complex system. Each column in the diagram represents a stage in the causal process. The total width of the grey links (bands) entering a node equals the total width of the grey links (bands) leaving that node, representing the conservation of the quantity assessed. The grey links (bands) connect the nodes, indicating the flow of the variable being assessed. The grey links (bands) show the flow direction from left to right whereas the width of the links (bands) represents the quantity of the flow. Thus, the wider the grey links (bands), the larger the quantity.

The mutual coupling effects[2] between energy portfolio, governance, socio-economic drivers, and climate change vulnerability highlight complexities that have significant global policy implications that may either facilitate or thwart efforts toward achieving sustainable development goals. For example, the rapidly increasing population and increasing demand for resources based on a business-as-usual society and economic structure that normalizes unsustainable development pathways due to weak governance structures—create ineffective climate-resilient policies that lead to unabated GHG emissions—with consequences on climate change (Denton et al., 2014).

3.4. Drivers of climate change vulnerability

The recent COP26 prioritizes climate change adaptation and mitigation, which are directly linked to reducing global climate change vulnerability (Sarkodie et al., 2022; UKCOP26, 2022). On this premise, we developed four vulnerability models with estimated parameters presented in Figs. 10 and 11. The goodness-of-fit (R^2) of all the estimated models ranges between 0.960 and 0.996, showing significantly strong predictive power (96–99.6%) of the energy portfolio, socio-economic, and demographic drivers in explaining the complexities of global climate change vulnerability. The coefficient on the lagged-dependent variable (i.e., vulnerability$_{t-1}$) is positive and statistically significant ($p\text{-value} < 0.01$) across the four models, confirming the effect of historical climate change vulnerability in predicting current global trends. We observe a significant ($p\text{-value} < 0.01$) positive nexus between population and climate change vulnerability. Population growth increases human demand caused by livelihood pressures, hence, affecting natural resource supply with limited biological resource capacity which may escalate environmental pressures such as climate change (Fig. 11b). Energy innovation has global emission reduction effects, therefore, declining climate change vulnerability, especially in economies with high technology diffusion. Our empirical estimation shows the expansion and integration of innovation in energy systems decline long-term vulnerability (Figs. 10 and 11). Similarly, increasing clean energy technologies (i.e., access to clean fuels and technologies for cooking, alternative (renewables), and nuclear energy sources) reduces the global burden of climate change whereas dependence on fossil fuels exacerbates climate change vulnerability. This evidence of controlled-energy portfolios among other indicators in the climate change vulnerability models contradicts the bivariate nexus in Fig. 7. This contradiction may be a classic case of omitted variable bias in Fig. 7 that confounds the nexus between fossil fuels/renewables and climate change vulnerability. While the initial exploration of the bivariate relationships provides simpler interpretations, it further led to hypothesis generation and comprehensive analyses. Climate change mitigation technologies related to energy generation, transmission, and distribution are essential to ensure modern and clean energy production and consumption. Investment in energy innovation via Research, Development, and Demonstration (RD&D) is reported to have increased since 2000—with OECD countries spending nearly 16.6 billion USD in 2016 on energy innovation whereas 22 nations and the EU assured to double energy RD&D investments to reduce emissions (Chan et al., 2017). For example, the UK invested £2.5 billion from 2015 to 2021 as part of the Clean Growth Strategy to advance low-carbon innovations and decline climate impacts (GOV.UK, 2022). Public investments in energy innovation remain a mirage in certain developing countries, especially low-income economies, which may rely on technology transfer from developed economies. Consequently, efficiency-seeking FDI from developed countries underpins technology spillover in developing economies in exchange for natural resources. For example, the UK government between 2011-12 and 2016-17 mobilized public and private investments of £2.2 billion and £500 million under the UK international climate finance to support climate change mitigation in developing economies (GOV.UK, 2017). Such external funding improves sustainable development by declining preventable climate change vulnerability in developing countries, particularly in low-income economies. This explains why increasing FDI inflows by 1% lessens climate change vulnerability by 0.003%. Similarly, we find that improvements in income, human development, social and governance adaptation readiness mitigate climate change vulnerability. The impacts of climate change unequally affect developing countries, especially low-income economies, with an additional threat to social justice, and governance readiness that impedes climate change adaptation and mitigation (Levy and Patz, 2015). In contrast, income expansion improves human development by providing access to quality education, ensuring a healthy lifestyle, promoting well-being, and changing consumption patterns (Lamb and Rao, 2015). Besides, increasing levels of income facilitate the mobilization of resources to finance climate change, viz. abatement and

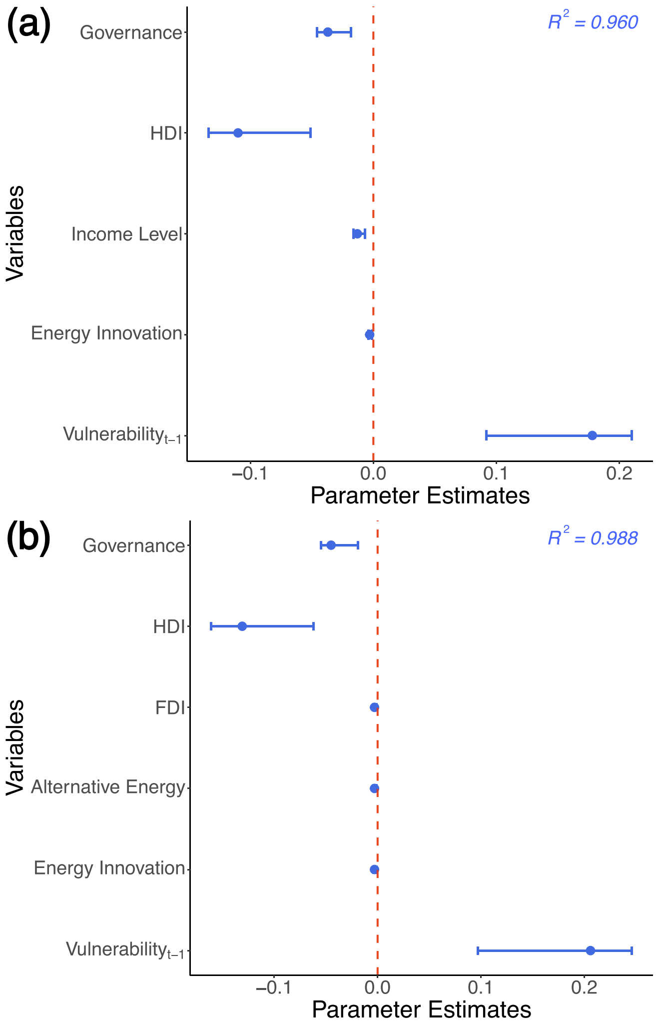

Fig. 10. Parameter estimates of the nexus between climate change vulnerability, energy innovation, income level, alternative energy, FDI, HDI, and governance readiness. (a) Model 1 (b) Model 2. Legend: The estimated parameters are statistically significant at $p\text{-value} < 0.01$. Diagnostics for Model 1 (n_{obs}: 1512, *Lambda*: 2.309, *Tolerance*: 1.512, *Sigma*: 123, *Eff. Df*: 207.3, R^2: 0.960, and *Looloss*: 14.860) and Model 2 (n_{obs}: 1236, *Lambda*: 0.749, *Tolerance*: 1.236, *Sigma*: 117, *Eff. Df*: 348.2, R^2: 0.988, and *Looloss*: 7.253).

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[2] Mutual coupling effects refers to the causal effect relationship between two data series (or variables). In essence, it refers to the dynamic interactions between socioeconomic and energy-related variables that influence each other over time. This infers that changes in one series could instantaneously affect the state or direction of the other variable.

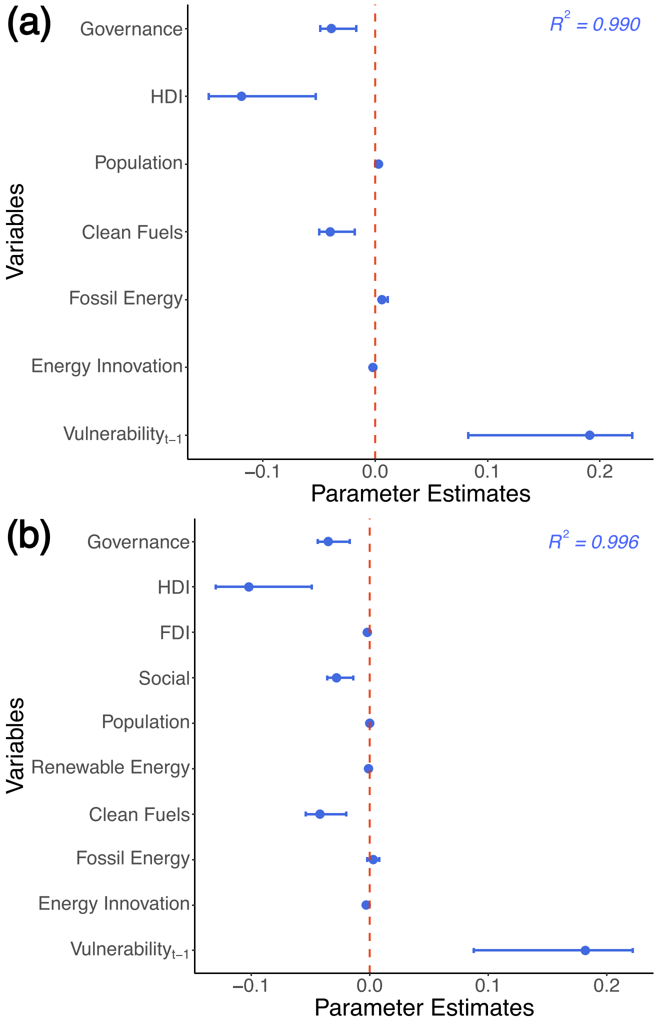

Fig. 11. Parameter estimates of the nexus between climate change vulnerability, energy innovation, fossil energy, renewable energy, clean fuels and technologies, population, FDI, HDI, social and governance readiness. (a) Model 3 (b) Model 4. Legend: The estimated parameters are statistically significant at *p-value* < *0.01*. Diagnostics for Model 3 (n_{obs}: 1059, *Lambda*: 0.592, *Tolerance*: 1.059, *Sigma*: 113, *Eff. Df*: 318.8, R^2: 0.990, and *Looloss*: 6.427) and Model 4 (n_{obs}: 994, *Lambda*: 0.289, *Tolerance*: 0.994, *Sigma*: 115, *Eff. Df*: 446, R^2: 0.996, and *Looloss*: 4.982).

adaptation technologies that wane the sensitivity and exposure to climate change and its impacts. The empirical research demonstrates that an upsurge in income increases environmental awareness, which may lead to social and governance transformation toward reducing pollution levels by shifting from a linear economy to a circular economy through abatement options and environmental regulations (Dasgupta et al., 2002).

3.5. Global displacement of fossil fuels

In line with SDG 12-13 of ensuring sustainable production & consumption, and mitigating climate change and its impacts (United Nations, 2015), we further examined the displacement effect of renewables (Model 5) and alternative energy (Model 6) on global fossil fuel consumption. Models 5-6 controlled for affluence (i.e., per capita GDP, thus, accounting for population growth), quadratic of affluence to capture the nonlinearity in wealth distribution, urbanization (i.e., this influences consumer behavior and preferences), and FDI (i.e., this account for external funding that may alter energy resources and consumption patterns relative to output). The estimated models show an R-square of 0.945 (Model 5) and 0.941 (Model 6), implying ~95% predicted power of controls—including alternative and renewable energy in explaining historical changes in fossil fuel utilization. The pointwise estimates in both models show statistically significant (*p-value* < *0.01*) positive coefficients (i.e., 0.176–0.189) on the lagged-dependent variable (fossil fuels$_{t-1}$), confirming the inertia effects of historical fossil fuel consumption (Fig. 12). This infers the current high level of fossil fuels across countries, particularly upper-middle-income and high-income countries are caused by unobserved factors of past consumption patterns of fossil fuels. External financing in the form of FDI inflows plays a crucial role in achieving sustainable development, especially in developing countries (DiSano, 2002; Sarkodie, 2021). However, the composition of FDI inflows is reported to either improve environmental sustainability through advances in efficiency—research & development, technology, and innovation transfer (pollution-halo hypothesis) or exacerbate anthropogenic emissions through resource exploitation (pollution-haven hypothesis) (Dunning, 1980; Sarkodie, 2021). In our scenario, the composition of FDI inflows across economies intensifies fossil fuel energy consumption by 0.012%. This implies that resource-seeking in developing countries outweighs efficiency-seeking by developed economies. The race to sustained economic development is somewhat characterized by energy intensity, viz. high fossil fuel consumption, predominantly in industrial economies. This scenario of fossil fuel intensity worsens between competing economies for competitive advantage to reduce production costs while improving productivity. However, the escalation effect of fossil fuel-driven emissions is reported to improve green energy innovations in developed countries (Sarkodie and Owusu, 2021). Similarly, we find that a 1% rise in income level increases fossil fuel utilization by 0.03% across economies, however, the intensity of fossil fuel consumption drops to 0.001% at a 1% increase in income. In assessing the turning point, any additional increase in income above 15% would further stimulate fossil fuel consumption. Thus, affluence has an increasing marginal effect on fossil fuel energy consumption across economies. The existing literature reports a strong relationship between wealth creation and urbanization, highlighting the role of urbanization in stimulating richer market structures and economies of scale (Bloom et al., 2008). Similarly, our empirical assessment shows 1% increase in urbanization escalates fossil fuel consumption by ~0.01% (Fig. 12). Urbanization affects the quality of life, and both operational and embodied energy use—industrial, transportation fuel use, and residential energy utilization for heating and cooling, consequently, influencing energy consumer behavior and preferences (Kennedy et al., 2015; Rickwood et al., 2008). Energy remains a crucial driver of anthropogenic emissions, therefore, the displacement of carbon-intensive energy sources (fossil fuels) with clean energy (alternative and nuclear energy) acts as an abatement option to improve efficiency in the energy mix. We observe that a 1% increase in renewable energy consumption declines fossil fuels by 0.04% whereas alternative and nuclear energy decreases fossil fuel consumption by 0.003%. While the displacement effect of renewable energy (Model 5) on fossil fuels is more pronounced than alternative energy sources (Model 6), both energy sources cannot entirely replace fossil fuels in equivalent proportions. This can be attributed to several factors including climatic factors that affect the efficiency of renewable energy sources, renewable energy market failures limiting adoption, cost of industrial production, and utility costs when fossils are replaced with alternative sources (Owusu and Asumadu, 2016; York, 2012). While our empirical analysis shows little likelihood that alternative energy sources can suppress fossil fuels, diversification of the energy portfolio across economies could still help in reducing global emissions.

3.6. Advancing COP26 climate goals

The findings of our empirical analyses align with the objectives and policies of COP26 (COP26, 2021; UNFCCC, 2022). These highlight the

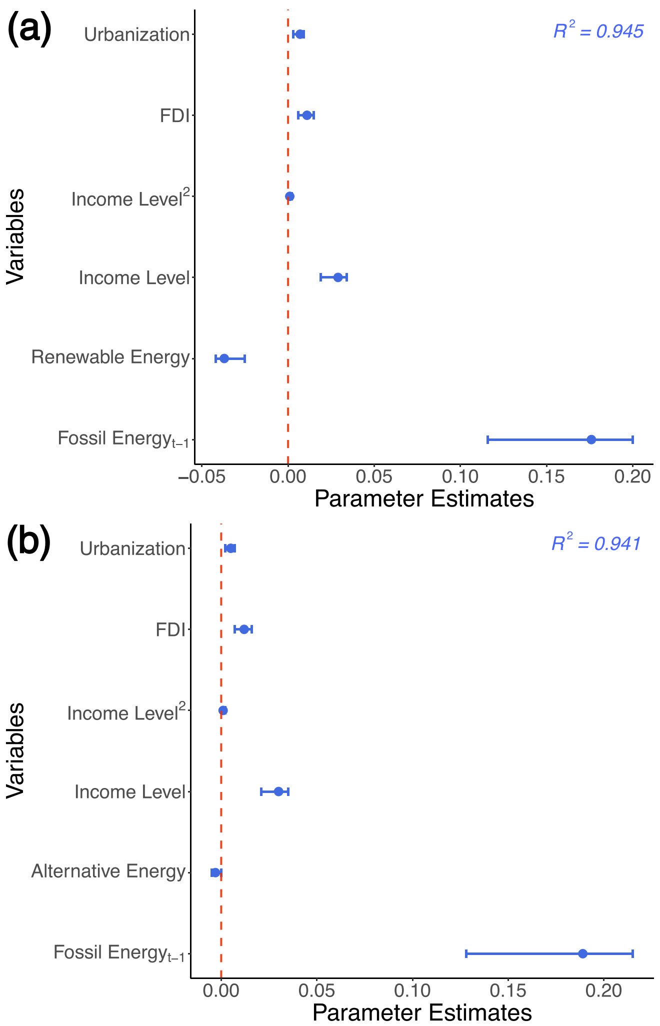

Fig. 12. Parameter estimates assessing global fossil fuel displacement. (a) Model 5 (b) Model 6. Legend: The estimated parameters are statistically significant at *p-value* < 0.01. Diagnostics for Model 5 (n_{obs}: 2272, *Lambda*: 4.24, *Tolerance*: 2.272, *Sigma*: 155, *Eff. Df*: 192.1, R^2: 0.945, and *Looloss*: 103.1) and Model 6 (n_{obs}: 2153, *Lambda*: 4.086, *Tolerance*: 2.153, *Sigma*: 150, *Eff. Df*: 187.9, R^2: 0.941, and *Looloss*: 107.5).

interconnectedness of several factors in addressing climate change and its impacts while emphasizing the benefits of governance, energy transition, and sustainability in achieving climate resilience and a low-carbon future. These findings contribute to the ongoing global debate and decision-making practices related to climate change mitigation and adaptation.

The relationship between our findings and COP26 climate goals can be summarized as follows:

Mutual coupling effects: The validation of mutual coupling effects between energy disaggregate portfolios, socio-economic factors, and climate vulnerability across economies underscores the complexity of addressing climate change and its impacts. This supports the global participatory and collaborative aim of COP26 on climate action, which further acknowledges that climate issues involve multifaceted dimensions including energy, socio-economics, governance, and vulnerability.

Social and governance readiness: Our findings support COP26's discussions on the importance of social and governance readiness in driving sustainability and climate resilience through mitigation and adaptation efforts.

Weak governance structures: Demonstrating the role of weak governance structures in hindering the effectiveness of climate-resilience policies resonates with COP26's debate on the influence of robust governance and policy frameworks in achieving effective climate change mitigation and adaptation measures.

Energy innovations: The empirical findings emphasize the role of energy innovations in enhancing climate resilience pathways, supporting COP26's goal of scaling up clean energy technologies while improving energy innovations.

Energy transition: Our results corroborate COP26's deliberations, by demonstrating the role of renewables and nuclear energy as pathways to climate resilience. This implies the acceleration from fossil fuels to clean and renewable energy sources is crucial to increasing energy efficiency while reducing global emissions.

Unsustainable development and population growth: Our findings align with COP26's discourse of challenges posed by the rapidly increasing population (including urbanization) and the need to transition from business-as-usual growth practices that hamper sustainable development pathways. This highlights the need to address population growth and carbon-intensive economic growth while shifting toward sustainable development.

Carbon abatement technologies: The empirical findings support COP26's discussions that carbon abatement technologies such as clean fuels and technologies for cooking, can play a crucial role in achieving climate change resilience and sustainability.

Low-carbon future: Our findings of achieving a low-carbon future by replacing fossil fuel energy portfolios align with COP26's goals of achieving net-zero emissions while limiting global warming.

4. Conclusion

Mitigating climate change and its impacts remains the central theme of several environmental cooperation, however, the recent COP26 highlights adaptation—which infers coping mechanisms of new and existing systems to modulate the harmful effects of climate change on sustainable development (Denton et al., 2014; UKCOP26, 2022). Against the backdrop, this study assessed the nexus between diversified energy portfolio (i.e., energy innovation, energy use, energy intensity and depletion, fossil fuels, clean fuels and tech for cooking, alternative (renewables) and nuclear energy), socio-economic indicators (population, income, HDI, FDI, urbanization, social readiness, and governance) and climate change vulnerability spanning 1995–2017 across 212 economies. The structural relationship identifies the mitigating effect of fossil fuel energy consumption on climate change vulnerability but finds evidence of a positive structural relationship between renewable energy utilization and climate change vulnerability. This outcome is possible without controlling for other confounding factors expounded in the estimated models. Contrary, the empirical analysis reports the escalation effect of fossil fuels and mitigation effects of renewable energy sources on climate change vulnerability. Besides, access to clean cooking fuels & technologies, and alternative energy sources play a crucial role in reducing climate vulnerability by decarbonizing economic development. Evidentially, the between-group distribution suggests fossil fuel consumption is relatively higher in developed countries whereas developing economies, predominantly low-income economies are heavily dependent on renewables (Sarkodie, 2022). Yet, developing economies exhibit low developmental trajectories including income, educational quality, healthy living, and well-being. Our estimated models validate the role of growing income in reducing climate change vulnerability by improving adaptation readiness. However, the existing literature identifies the compatibility of low emissions, high income, and high human development as difficult or unrealistic—sounding the alarm on potential trade-offs (Steinberger et al., 2012).

The effect of social and governance readiness cannot be ignored regardless of the energy mix and income status. These institutions of change lead the transformation process to attain sustainable development. For example, social readiness affects consumer behaviors, consumption patterns, and willingness to support climate change agendas through adaptation technologies (Bellamy, 2019). Similarly, governance readiness determines political will and environmental regulations to meet sustainable targets, this explains why several international frameworks on climate change have failed (Held et al., 2011). Thus, high social and governance readiness spur climate resilience, viz. climate anticipation, reduction, accommodation, and/or recovery from climate impacts—which combines climate change adaptation and mitigation to achieve sustainable development (Denton et al., 2014).

Do alternative (renewables) and nuclear energy have displacement effects on fossil fuels? Yes, but the magnitude of displacement is not large enough to repeal and replace fossil fuel consumption any time soon [see Sarkodie (2022)]. This implies stringent energy regulations that shift the energy mix to depend entirely on renewables may suffer economic consequences without modern energy innovations to replicate and incorporate the characteristics of fossil fuels. However, a low-carbon future is still attainable by possibly replacing the fossil energy mix with more natural gas than coal and oil and/or integrating carbon-abatement technologies like carbon capture storage to pollution-intensive forms of fossil fuels. This trade-off can ensure sustained economic development while achieving low-carbon targets. Besides, renewables are more susceptible to climate change variability compared to fossils. For example, hydrological systems and solar resources are affected by weather conditions, wind turbines get frozen in harsh winter conditions whereas biomass competes with land and food production systems. Thus, fossils are more stable and efficient energy sources compared to renewables. However, since renewables are localized and somewhat non-tradable, economies become more energy-independent. Coincidentally, we observe that developing countries, particularly low-income countries in Asia and sub-Saharan Africa dependent on renewables are relatively poor, exposed, and sensitive to climate change—with corresponding low economic output compared to developed countries dependent on fossil fuels. Does that mean renewable energy leads to poverty and climate vulnerability? Not really, but perhaps availability, affordability, and accessibility of energy services, low climate change adaptation & mitigation technologies, and other unobserved factors impede economic development and climate resilience.

Energy innovations are useful climate-resilience pathways that lessen climate change vulnerability, however, carbon abatement energy technologies are fairly limited in low-income economies. Ensuring energy innovation that could decline climate change vulnerability across countries and territories will require the six guiding policy principles namely: allowing scientific researchers and experts autonomy over funding decisions, integrating technology diffusion into research institutes, setting targets for demonstration projects on learning, incentivizing international research collaborations, implementing strategies for evaluation and adaptation of innovation programs, and stabilizing innovation funding (Chan et al., 2017).

Future studies could examine the global impact of successful energy transition policies in reducing climate vulnerability. Additionally, the resilience and/or vulnerability of energy infrastructure could be explored in the face of climate change and its impacts, and how it affects other critical sectors. Finally, the synergy between climate change mitigation and adaptation policies in the era of green growth could be investigated.

CRediT authorship contribution statement

Samuel Asumadu Sarkodie: designed the study, collected the data, performed the data analysis, coordinated and supervised the study, Methodology, Software, Validation, Visualization, Writing – review & editing. **Maruf Yakubu Ahmed:** drafted the manuscript. **Phebe Asantewaa Owusu:** drafted the manuscript, All authors reviewed the manuscript and approved it for submission.

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.

Data availability

Data will be made available on request.

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