Assessing energy transition vulnerability over nations and time

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Article

Keywords:

Posted Date: March 28th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1440213/v1

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This Version: 2022.03.26

Abstract: While achieving the Paris climate goals and sustainable development goals (SDGs) are two major global challenges of our time, energy transition that plays an essential role in achieving climate targets may create socio-economic hardship. A quantitative assessment of the vulnerability of energy transitions is a prerequisite for national and international policymakers to advance a just energy transition that looks after coordination between energy transitions and socio-economic development. This study proposes to measure energy transition vulnerability from the dimensions of *exposure*, *sensitivity*, and *adaptive capacity.* The results of energy transition *vulnerability* index (ETVI) scores for 135 nations reveal a huge inequality across nations; moreover, the COVID-19 pandemic has interrupted the decade-long continuous improvement of energy transition vulnerability. Developed countries usually have low energy transition vulnerability than developing countries and the gaps even have been widened. The existing global transition vulnerability could be mitigated by 12.3 p.p and 5.2 p.p if each nation could follow the path of global or climate party group frontiers in achieving the SDGs, despite the scale and drivers of mitigation vary across countries. The study also suggests that heterogeneous transition policies that consider both emissions and vulnerability are required. Our framework and findings could advise policymakers to formulate policies and cooperation strategies to reduce vulnerability, protect vulnerable countries, and make fair energy transition policies nationally and internationally.

1 Introduction

While the energy transition plays an essential role in achieving climate change targets, it also creates socio-economic challenges. A transformation in the energy and associated systems is needed to achieve the dual goals of mitigating climate change impact while meeting increasing energy needs for human well-being and economic development. Since access to affordable and clean energy are basic human rights, ‘energy justice’ has increasingly become a hot topic in energy transitions as the energy transition could lead to extreme price shocks, energy supply disruption, and even social-economic hardship. Notably, such social-economic effects are unevenly distributed across individuals, communities and nations (Carley and Konisky, 2020). Their adverse impacts could be disproportionally strong on remoted or disadvantaged regions where mining communities are often located, or fossil fuel producers and less developed countries that has limited capability to respond to these challenges. As countries are urged to make immediate and more ambitious transitions to limit global warming of 1.5°C and 2°C (IPCC, 2021), they urgently need to understand their vulnerability in the process of energy transitions.

Understanding the energy transition vulnerability can help policy development at both national and international levels. Learning their vulnerability is a prerequisite for national governments to make plans that protect their economies and people during the energy transitions--a just energy transition (Jenkins et al., 2016), and for international community to mitigate climate change while contributing to their sustainable development goals (SDGs) (Fuso Nerini et al., 2019; Soergel et al., 2021). A conceptual framework on energy transition vulnerability could also help national governments to formulate strategies to enhance their adaptive capacity and resiliency to reduce their vulnerability to energy transitions. Understanding the energy transition vulnerability of climate negotiations groups can deepen our understanding of one of the critical concerns of those groups that will shape global climate negotiations, which may further help to design the global decarbonization roadmap. While energy transition plays an essential role in achieving the climate change target of Sustainable Development Goals (SDG 13), achieving overall SDGs may also enhance energy transition resilience and thus show synergy effects. Understanding the relationship is critical for world leaders who are responsible for achieving both SDGs and the Paris climate goals. The revealed information on energy transition vulnerability across countries and the synergy effects between the energy transitions and SDGs can help the international policymakers negotiate fair energy transition policies across countries and between the current and future generations. Understanding countries' vulnerability in the energy transition can help global leaders to identify countries that could increase their commitments, face potential challenges, or need significant assistance. The international community can also prepare aid to these vulnerable countries to achieve inclusive and just energy transitions.

Measurement of energy transition vulnerability for nations is urgently needed, but notably absent in the literature. While there are growing literature on energy justice and just energy transition, there is insufficient quantitative study on the distributional effect of energy transitions (Carley et al., 2018). Despite of increasing attention to just energy transition across regions, e.g. Shi et al., (2021), there is a lack of a comprehensive study to quantify the vulnerability of energy transitions that can support national policy-making and international climate cooperation. Most of recent studies on energy transition vulnerability, although covering various scales, including nations (Bouzarovski et al., 2017), cities (Calvo et al., 2021), counties (Snyder, 2018), communities (Axon and Morrissey, 2020), households (Streimikiene et al., 2021), and power generations sectors (Van Vliet et al., 2016), are still using qualitative methods, such as questionnaires, interviews, and focused groups discussions. Existing quantitative studies on the distributional impact of energy transitions often investigate among income groups (Blonz et al., 2012), among sub-national regions (Carley et al., 2018) or among sectors (Sovacool et al., 2021), but are silent on a robust, systematic and transparent method of measuring energy transition vulnerability for each country.

Here we propose a framework to quantify national energy transition vulnerability and evaluate the justice and equity dimensions of the energy transition for 135 nations (Figure 1, more details, see Methods). We adopt the framework of Vulnerability Scoping Diagram (VSD) that is originated from climate change adaption literature (Polsky et al., 2007) and analyze the transition vulnerability from three dimensions: *Exposure*, *Sensitivity*, and *Adaptive Capacity*. To operationalize our energy transition vulnerability scoping diagram with data, we adopt the composite index analysis and extract an energy transition vulnerability index (ETVI) score for 135 nations over the period of 2010-2020 (See **Methods**). We investigate spatio-temporal patterns of transition vulnerability by exploring the evolution of the index for each country and climate party group in the recent decade. We shed light on the global decarbonization roadmap by linking energy transition vulnerability to global carbon emission patterns. We also apply the framework to explore the synergy effects between the energy transition and SDGs achievements.

We contribute to the literature on energy transition vulnerability by proposing a conceptual framework to analyze national energy transition vulnerability that could inform policymakers, analysts, organizations on countries that are vulnerable to energy transitions. A country level study that is close to ours is the energy transition indexes published by the World Economic Forum (Bocca, 2020). However, their study focuses on measuring the overall progress of energy transitions, instead of justice and equity dimensions and, therefore vulnerability in the energy transition process. The only quantitative assessment of energy transition vulnerability is at the US subnational level (Carley et al., 2018). To the best of our knowledge, we provide the first quantitative assessments of energy transition vulnerability for 135 nations, which account for 98% of the global GDP and 98% of the global carbon emissions. The revealed spatio-temporal patterns of energy transition vulnerability and its drivers could serve as a basis for policymakers to formulate policies and cooperation strategies to reduce vulnerability, protect vulnerable countries, and make fair energy transition policies nationally and internationally.

We also contribute to national and international policy development by revealing the synergy between SDGs achievement and vulnerability reduction. While energy transition plays an essential role in achieving the climate change target of Sustainable Development Goals (SDG 13), achieving overall SDGs may also enhance energy transition resilience. Such synergies have increasingly been recognized as critical to achieving the Paris climate targets and SDGs (Soergel et al., 2021). Some studies have suggested that energy transition initiatives, such as progress in renewable and clean energy, investment in energy infrastructures, could assist the realization of SDGs (Barrington-Leigh et al., 2019; Pachauri et al., 2021; Rosenthal et al., 2018), and the implication of the integrated SDGs can facilitate the simultaneous achievement of energy transition targets (Allen et al., 2019; Sachs et al., 2019; Spillias et al., 2020). The alternatives to the reality inform governments what interventions are required to achieve the synergies (Editorial, 2019) and which they could achieve from the energy transition vulnerability perspective if relevant SDGs goals were achieved.

Following this introduction, the results are presented in the next section, including the spatial and dynamic characteristics of vulnerability score, climate country group analysis, and scenario analysis. We discuss implications and conclude our analysis in the Discussion section. The Methods section details our data, national energy transition vulnerability framework, quantification approach, and uncertainty method.

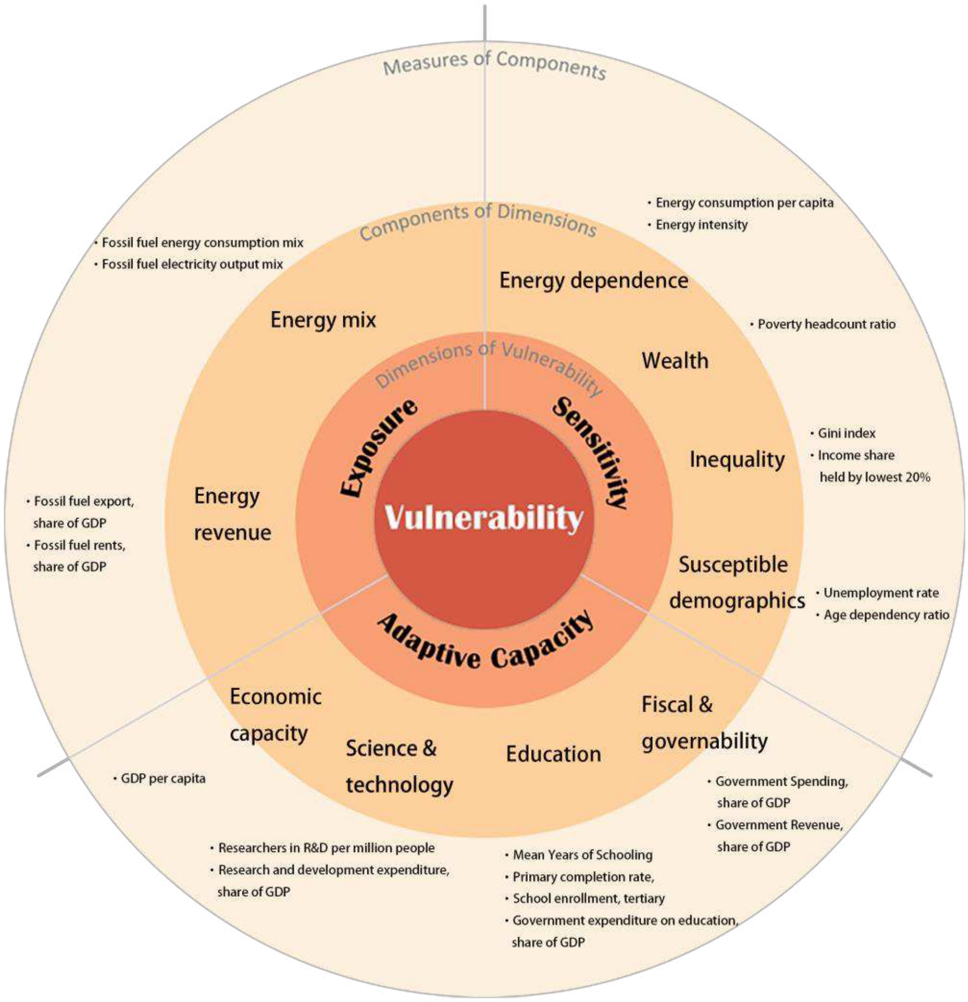


Figure 1. Energy transition vulnerability scoping diagram for nations

Notes: Vulnerability of energy transition is defined as a function of the underlying magnitude of changes in economic structure due to energy transition for each country (exposure); the susceptibility of a country to the impacts of these changes (sensitivity); and the capability of a country to attenuate, cope with or mitigate the negative effects (adaptive capacity). For each dimension, related concepts (components of dimensions) and measures of components can be identified. Our conceptual framework and each dimension build on a pioneer study of Carley et al. (2018), which investigates energy transition vulnerability at the US county level due to renewable portfolio standard policy. Credit of VSD graph template: Brent Yarnal.

2 Results

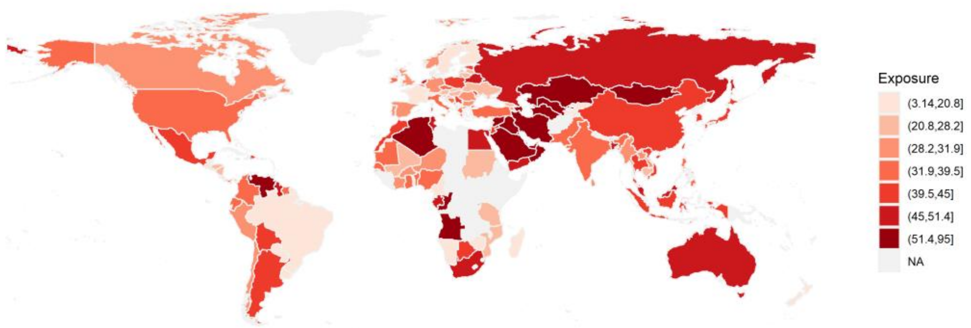
The energy transition vulnerability index (EVTI) is an assessment of each country's overall magnitude on energy transition vulnerability compared with the best global and all-time possible outcome by summarizing the country's performance from the dimensions of exposure, sensitivity, and adaptive capacity. The score signifies a country's position between the least vulnerable (0) and the most vulnerable (100) to the energy transition. A lower score means the nation is more immune to adverse impacts of energy transitions. For example, Iceland's overall index score in 2019 (10.86) suggests it is, on average, 11 percentage points away from the globally and overtime best possible outcome in energy transition vulnerability.

We study energy transition vulnerability for 135 economies from 2010 to 2020. We report the 2019 EVTI score (Figure 2) as the baseline results to reflect the current status of energy transition vulnerability for each economy. This also avoids the unusual impacts of Covid-19 and missing data for 2020 in some countries. The impacts of Covid-19 will be discussed when investigating the time trend of transition vulnerability.

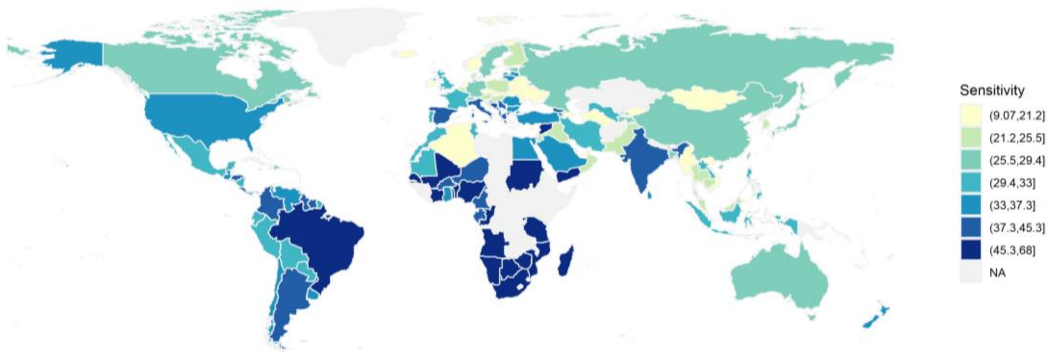
2.1 Energy transition vulnerability patterns show a large spatial difference

The list of the least vulnerable countries is dominated by developed countries (**Figure 2, Table S2**). All countries in the top 20, except Uruguay, are OECD countries. Three Nordic countries top the 2019 vulnerability Index: Iceland, Sweden, and Denmark (**Table S2**). Nordic countries outperform other countries not only because of their advanced economic development levels, but also due to their less dependence on fossil energy. For example, Iceland's total energy has 56% of wind or solar power and an additional 16% of hydropower, which reflects the fact that Iceland is highly unlikely to be negatively affected in the energy transition process of removing fossil fuels. However, even economically developed OECD countries could face significant challenges in achieving inclusive energy transitions. Many OECD countries, such as Australia, Japan and South Korea, are exposed to the energy transition due to a significant amount of fossil fuels in their energy mix. Furthermore, the energy crisis that occurred in 2021 delays the phase-out process of fossil fuels, evidenced by EU's inclusion of gas projects in their green investment rules (EU, 2022).

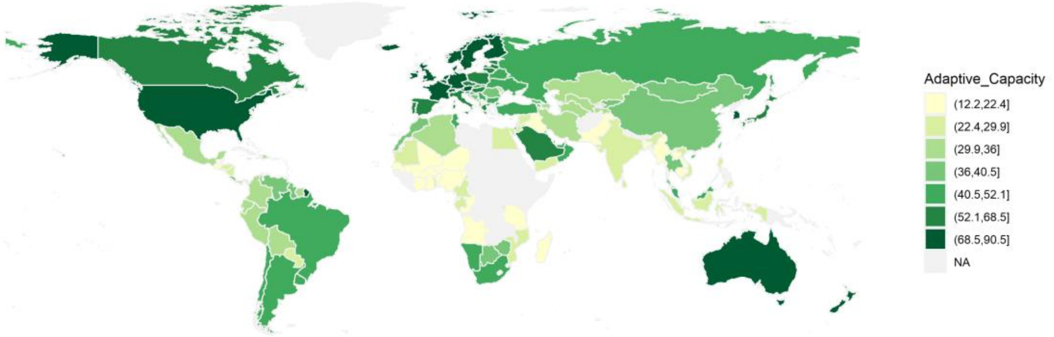
a. Exposure



b. Sensitivity



c. Adaptive Capacity



d. Vulnerability Index

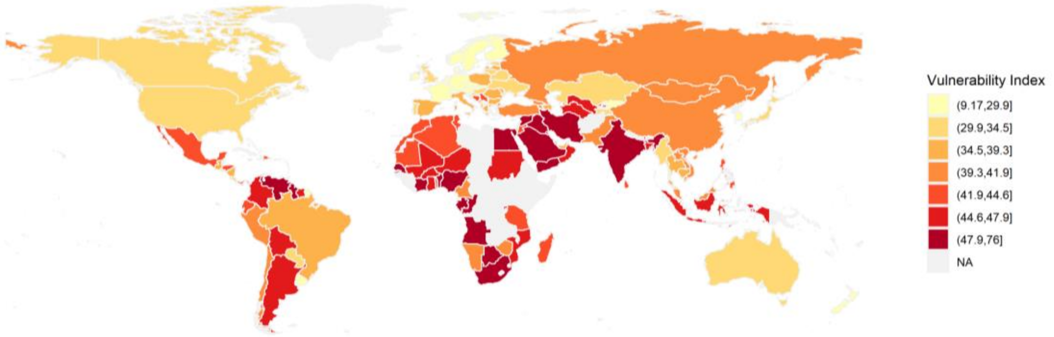


Figure 2. Vulnerability index scores in 2019

Notes: Maps **a**–**c** show exposure (**a**), sensitivity (**b**) and adaptive capacity (**c**) to energy transitions, using a quantile classification scheme so that each category has an equal number of observations. Map **d** show vulnerability scores. A lower vulnerability score means the nation is more immune to adverse impacts of energy transitions.

In contrast, low-income countries tend to have a higher level of vulnerability to energy transitions. This is partly due to the nature of vulnerability in the energy transition process. Assuming a similar level of transition exposure, poorer countries tend to have higher sensitivity and lack adequate infrastructure and mechanisms to adapt to key social-economic challenges induced by energy transitions. The Republic of the Congo, Angola, Iran, Iraq, Syria are the top 5 vulnerable countries in energy transitions. These countries are not only highly dependent on fossil energy and are highly sensitive to the energy transition, but also has limited social and economic capability to adapt to the challenges. Due to socio-economic development status, the global north is generally less vulnerable than the global south, indicating the north-south division is also persistent in terms of the energy transition vulnerability.

Energy exporting countries have diversified levels of vulnerability. Middle East countries can be mainly divided into two types. Although with large exposure, countries like the United Arab Emirates have the better adaptive capacity and are less vulnerable to energy transitions. However, for countries like Saudi Arabia, Kuwait, Nigeria, Iran and Iraq, their extremely high exposure combined with the at best moderate adaptive capacity lead to significant vulnerability to energy transitions.

2.2 The improving trend of energy transition vulnerability was interrupted recently

The world's average energy transition vulnerability has been declining in the last decade, but the trend has been interrupted by COVID-19 (Figure 3). The reverse trend is largely driven by a surge in sensitivity due mainly to increased poverty and unemployment rates, followed by declined adaptive capability (mainly caused by slower GDP growth) and slightly higher exposure. Given the relatively new and ongoing nature of COVID-19, it is not possible to tell whether such a reversal in trend is temporary. Meanwhile, aggregated exposure score also shows significant reverse during the 2016-2018 period, which is mainly caused by the increase in energy revenue for energy exporting countries due to a surge in global energy prices.

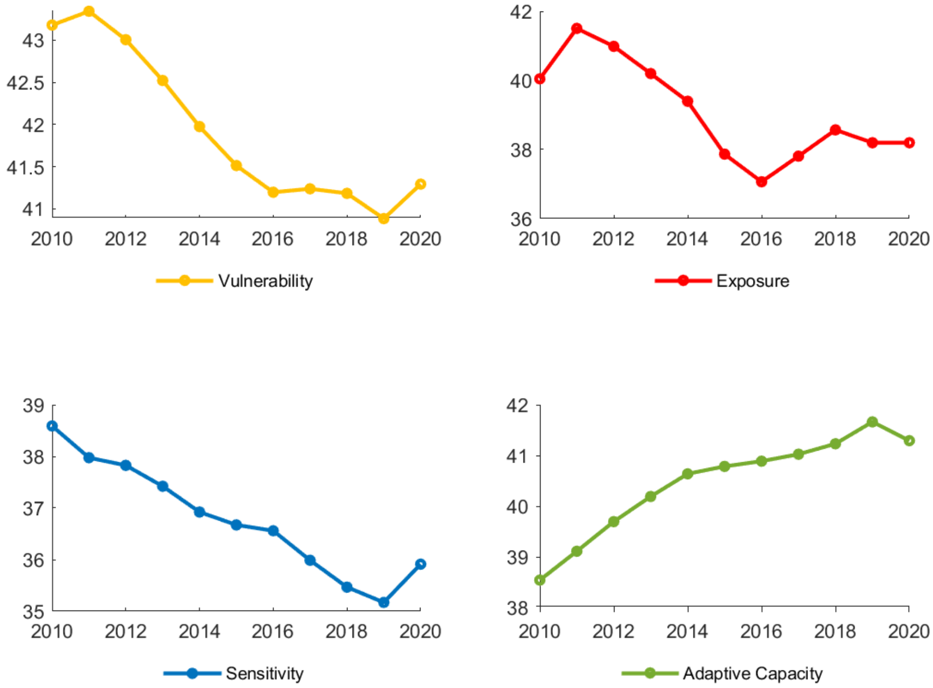


Figure 3. World average vulnerability index over time

Notes: The world average energy transition vulnerability index score and its three dimensions are measured by equally-weighted average across nations.

Under the overall reduction of energy transition vulnerability, there are several disturbing facts. Most significantly, we found that 30 countries, or 22% of assessed countries, experienced increasing vulnerability during the study period of 2010-2019. By dimensions, 43 countries (32%) experienced increased exposure to energy transition vulnerability, 43 countries (32%) had increased sensitivity to energy transition vulnerability, while 16 countries (12%) recorded declined adaptive capacity (**Figure 4**).

The disparity among countries has not been narrowed down but even widened. The vulnerability performance shows significant persistence. Those countries with low initial ETVI in 2010 have been continuously reduced their vulnerability, while those with poor vulnerability index stayed in a poor situation (**Figure S2**). Lithuania, Estonia and China recorded the fastest reduction in the energy transition vulnerability due to improvement from all three dimensions. On the contrary, Lao PDR, Mozambique, and Ghana, which have high initial energy transition vulnerability, experienced the worst deterioration of energy transition vulnerability, due mainly to increased exposure (**Figure 4**).

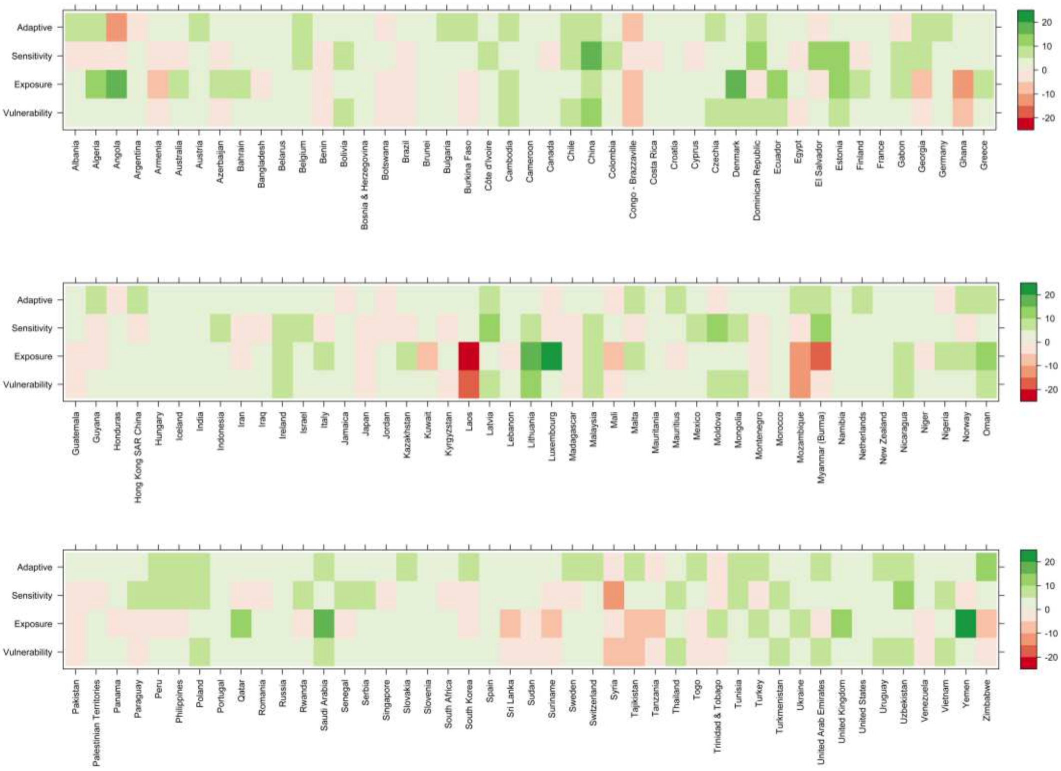


Figure 4. Changes in vulnerability index scores between 2010 and 2019

Notes: The color scale shows the changes in vulnerability index scores and their three dimensions. A positive value (green) indicates an improvement in the score from 2010 to 2019, while a negative value (red) indicates a deterioration in the score from 2010 to 2019.

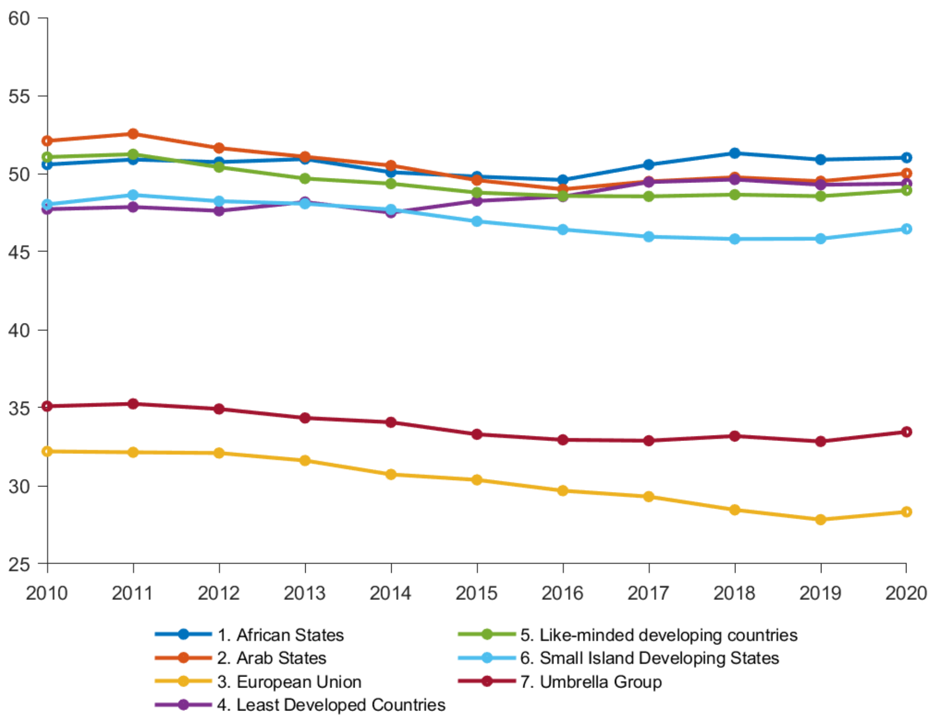
2.3 Energy transition vulnerability by climate party groups

We analyze the different energy transition vulnerabilities across the seven major party groups in the international climate change negotiations defined by the UNFCCC (**Table S3**). **The energy transition is a key method to reduce emissions and fight climate change while climate party groups represent the substantive common interests of different groups for climate negotiations** (UNFCCC, 2022)**.** Understanding the energy transition vulnerability of climate negotiations groups can deepen our understanding of one of the critical concerns of those groups that will shape global climate negotiations, which may further help to design the global decarbonization roadmap.

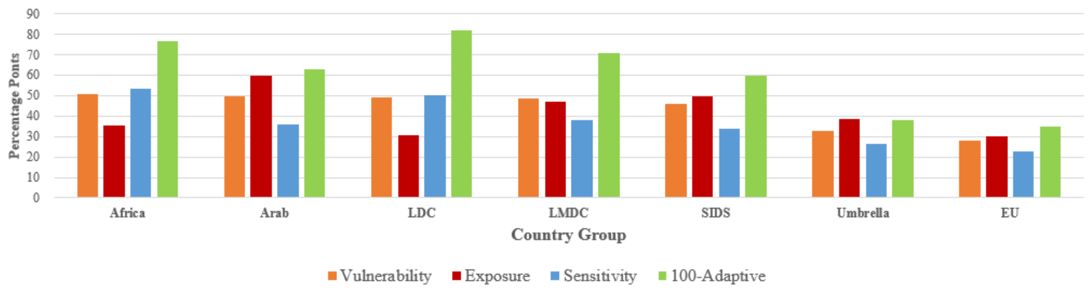
The ETVI shows significant heterogeneity across the climate part groups (**Figure 5**). The EU and umbrella countries, the two economically-developed climate party groups, perform significantly better than other groups (**Figure 5.a, 5.b**) and EU' vulnerability shows the greatest decline over time

(**Figure 5.c**). Among the rest five groups, the small island developing states (SIDS) has the lowest vulnerability scores majority of the time. Despite of their relatively high exposure due to their reliance on fossil fuels in the energy mix, their vulnerability index is much less than the other four groups due to their relatively better status in dimensions of transition sensitivity and adaptive capacity (**Figure 5.b**). The African Group and least developed countries (LDCs) face probably the most challenge in energy transitions: their ETVI has a high value and has been deteriorated in the past ten years, mainly due to their increased exposure to fossil fuels dependence (**Figure 5.c**). In contrast, although with the highest exposure level, the Arab countries have significantly reduced their reliance on fossil fuels over the decade thus achieving a lower ETVI score. Like-minded developing countries (LMDCs) consistently reduced their vulnerability through relatively balanced improvements in all three dimensions despite their high initial ETVI.

a. Dynamics of EVTI scores for climate party groups



b. Components of EVTI scores for climate party groups in 2019



c. Change in EVTI scores for climate party groups from 2010 to 2019

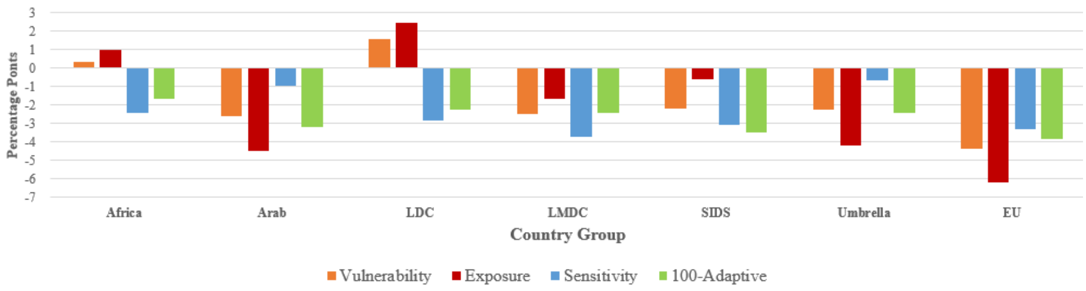
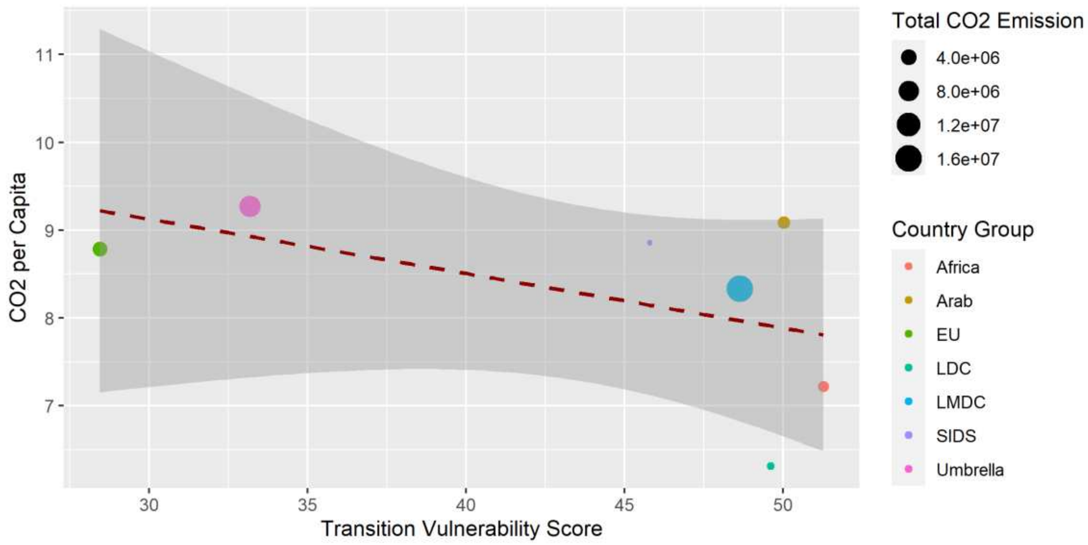


Figure 5. Vulnerability score for climate party groups

Notes: (**a**) Average energy transition vulnerability index (ETVI) score at climate party group level from 2010 to 2020. (**b**) Average EVTI score and its components for each climate party group in 2019. (**c**) Change in EVTI score and its components for each climate party group between 2010 to 2019. Abbreviations: least developed countries (LDCs), like-minded developing countries (LMDCs), small island developing states (SIDS).

Linking energy transition vulnerability to carbon emissions reveals a clear negative relationship, suggesting accounting for energy transition vulnerability when designing the global decarbonization roadmap (Figure 6). Taking transition vulnerability into account, following the World Energy Transition Index report (Bocca, 2020), we divide all the countries into four quadrants (types) to reflect their relative resilience in energy transition and account in global carbon emission patterns: stressful countries, leapfrog countries, painless countries, potential challenges countries. The EU and most umbrella countries have low vulnerability and high emission (Quadrant II, leapfrog countries) and thus can afford faster energy transition. The majority of LDC group have high vulnerability scores with relatively low emissions (Quadrant IV, potential challenge countries). Unfortunately, few countries achieve low ETVI and low emissions simultaneously (Quadrant III, painless countries), which is the most desirable status to meet the dual goals of energy transition and decarbonization. The LMDC group generally have a serious vulnerability to energy transitions, but their emissions could be either relatively low or high. The Arabian and SIDS group need particular attention as they are mainly located in the least desirable quadrant--relative high ETVI and high emissions (Quadrant I, stressful countries). The negative relationship between energy transition vulnerability and emissions per capita and possibly synergies suggest that potential tradeoffs between climate initiatives and SDGs (Cameron et al., 2016) should be minimized so that developing countries can reduce their energy transition vulnerability through economic development. These heterogeneities among countries and climate groups suggest that an inclusive and just energy transition that accounts for regional conditions are highly needed.

a. Climate party groups



b. Positions for different countries

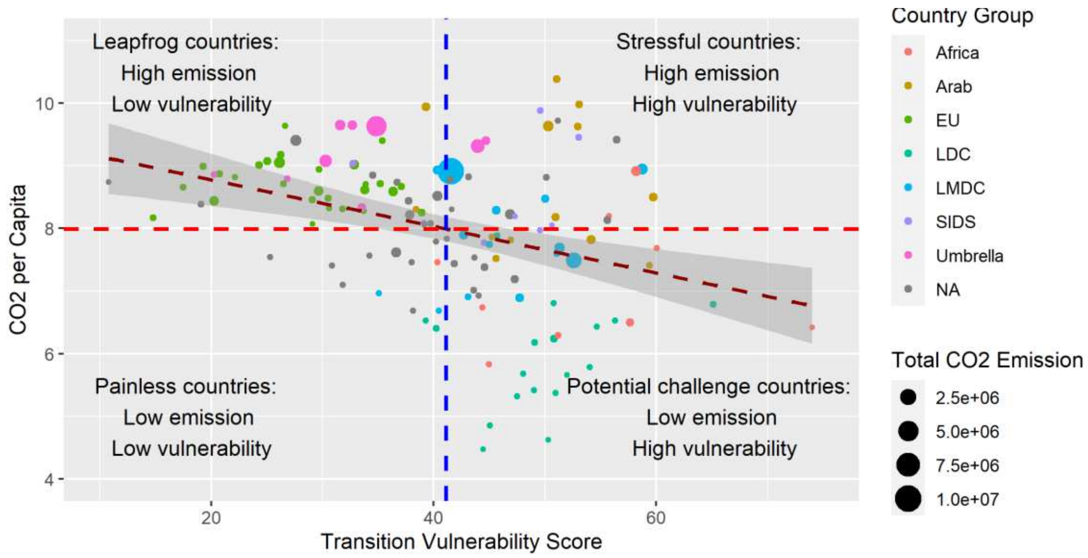


Figure 6. Transition vulnerability and carbon emission in 2019

Notes: The relationship between transition vulnerability and CO2 emission per capita at (**a**) the climate party group and (**b**) national level. We report the results in 2019 to reflect the current status of each economy. The vertical and horizontal line is the mean value for x and y axis variable, respectively. The dark red line stands for the fitted linear curve for the country group and full sample regression with 95% confidence intervals, which confirms a negative relationship between energy transition vulnerability and carbon emission. The logarithmic transformation has been applied for CO2 emission per capita data to avoid extreme volatility.

2.4 Impacts of SDG achievements on energy transition vulnerability

While energy transition plays an essential role in achieving the climate change target of Sustainable Development Goals (SDG 13), achieving overall SDGs may also enhance energy transition resilience and thus show synergy effects. Understanding the relationship is critical for world leaders who have the responsibility to achieve both goals. In this section, we examine how achieving SDGs may affect energy transition vulnerability, and provide estimators in different SDGs achievement scenarios.

To assess how achieving SDGs will affect the energy transition vulnerability, we select five representative indicators in our conceptual framework that are also directly related to SDG and are used to construct the UN country level SDG index (Sachs et al., 2021; The United Nations, 2021). We consider three scenarios. **Global frontier scenario (S1)** assumes all countries' SDG indicators are converged to the global top 20% counterparts in the sample; **group frontier scenario (S2)** assumes countries in a climate party group move up to their top 20% counterparts within their group; and **group catch-up scenario (S3)** modestly assumes that the countries below the average in a party group catch up with the average of their group. The five selected SDG indicators and their targeted values in each scenario are summarized in **Table 1**.

Overall, we found that achieving SDGs has a synergy with a reduction in energy transition vulnerability, but the magnitude is quite different under different SDGs achievement scenarios. At the global level, achieving SDGs will reduce ETVI by 12.3 p.p. and 5.2 p.p., respectively, in the global and group frontiers scenarios (**Figure 7.a, World**). However, catch-up of lagged behind countries to group average will only deliver a small proportion of the benefits by 2.5 p.p. This suggests all governments should do more in terms of SDGs achievement as much of the vulnerability reduction potential can be achieved by learning from their group frontiers that have significant similarities. In the modest scenarios of achieving group frontiers (S2), the least desirable country types that have high emissions and high vulnerability index scores (stressful countries in **Figure 6**), will account for 9% of the total countries, down from 19% currently (**Figure S3**).

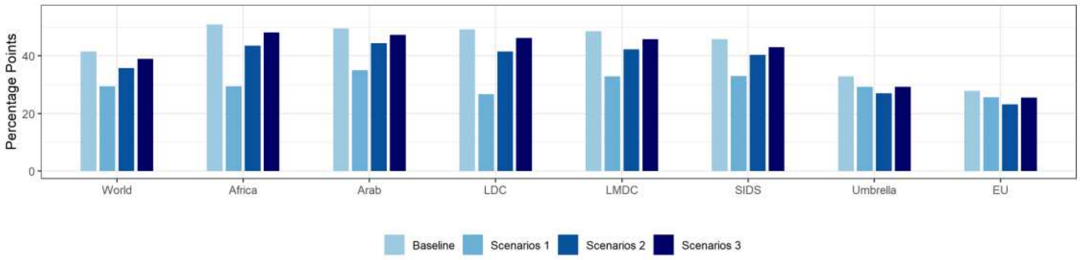
The impact of SDG achievement on vulnerability, however, has significant heterogeneity among different climate party groups (**Figure 7.b**)**.** For example, the SDG achievements will have a large impact on vulnerability in African countries and LDCs, but has little effect on the vulnerability of EU and Umbrella countries. This is largely due to the high level of development in the EU and Umbrella groups and thus achieving SDGs has little relevance. The drivers of vulnerability reduction have also shown disparity among groups. For the EU, the key driver of their vulnerability reduction is improvement in the Science and Technology capability (SDG9); while for the Umbrella countries, the largest reduction in the vulnerability is a result of better Science and Technology capability (SDG9) and lower energy intensity (SDG7). For the developing party groups, poverty reduction (SDG1), reduced inequality (SDG10) and education (SDG4) are the top three drivers of vulnerability decline. The different major drivers we identified for different countries suggest the handles that policy makers could control to mitigate vulnerability during the energy transition.

Table 1. Scenarios for EVTI scores in achieving SDGs

Dimension	Variable	Related SDG	Country Group	Data in 2019	Scenarios 1 target (World Top 20)	Scenarios 2 target (Top 20 in each Group)	Scenarios 3 target (Mean in each Group)
Energy Dependence	Energy Intensity (toe/1000 USD (2010 PPP))	SDG 7	World	0.17	0.08	0.10	0.13
			Africa	0.23	0.08	0.13	0.18
			Arab	0.18	0.08	0.12	0.15
			EU	0.09	0.08	0.06	0.07
			LDC	0.24	0.08	0.12	0.19
			LMDC	0.19	0.08	0.12	0.15
			SIDS	0.18	0.08	0.07	0.12
			Umbrella	0.17	0.08	0.06	0.08
Wealth	Poverty headcount ratio at $3.20/day (%)	SDG 1	World	17.60	2.36	8.74	13.39
			Africa	36.86	2.36	18.72	30.31
			Arab	9.47	2.36	5.14	7.05
			EU	2.54	2.36	2.09	2.27
			LDC	51.05	2.36	22.53	37.05
			LMDC	12.74	2.36	6.45	8.78
			SIDS	7.73	2.36	3.96	5.91
			Umbrella	2.79	2.36	2.26	2.38
Inequality	Gini coefficient	SDG 10	World	37.60	30.10	33.24	35.40
			Africa	44.81	30.10	38.60	41.37
			Arab	39.16	30.10	36.59	37.63
			EU	29.74	30.10	26.18	28.12
			LDC	41.41	30.10	37.42	39.53
			LMDC	39.75	30.10	35.57	37.46
			SIDS	42.34	30.10	38.72	40.26
			Umbrella	30.91	30.10	26.40	29.87
Science & Technology	Researchers (per 1,000 employed population)	SDG 9	World	1.02	1.98	1.60	1.20
			Africa	0.32	1.98	0.86	0.35
			Arab	0.56	1.98	0.94	0.65
			EU	1.99	1.98	2.75	2.32
			LDC	0.31	1.98	0.90	0.33
			LMDC	0.43	1.98	0.89	0.52
			SIDS	0.98	1.98	1.22	1.16
			Umbrella	1.99	1.98	2.82	2.49
Education	Mean years of Schooling (years)	SDG 4	World	8.92	12.10	10.19	9.50
			Africa	5.78	12.10	7.68	6.63
			Arab	7.53	12.10	9.24	8.27
			EU	11.89	12.10	12.69	12.36
			LDC	4.14	12.10	6.60	5.55
			LMDC	7.67	12.10	9.60	8.44
			SIDS	9.45	12.10	10.51	9.87
			Umbrella	12.41	12.10	12.90	12.72

Notes: Five indicators for related SDGs is suggested by the UN global indicator framework and are used to construct the UN country level SDG index (Sachs et al., 2021; The United Nations, 2021). We assign each indicator with the same weight when conducting the scenario analysis to avoid the scaling effects. State differently, we treat five indicators equally important, which can also fully represent the corresponding component in our conceptual framework.

a. Estimators of EVTI scores



b. Drivers of changes in transition vulnerability

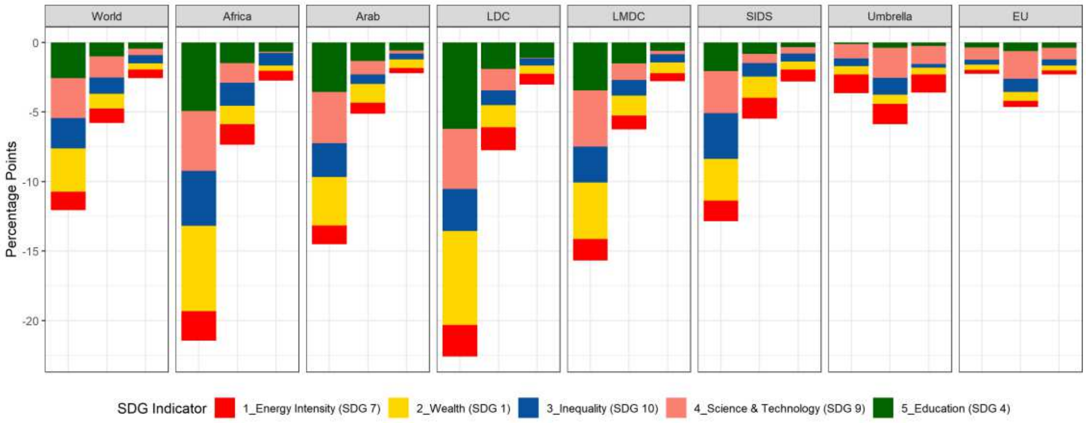


Figure 7. Estimators of EVTI scores in different SDG achievement scenarios

Notes: Indicators for related SDGs is suggested by the UN global indicator framework and are used to construct the UN country level SDG index (Sachs et al., 2021; The United Nations, 2021). We assign each indicator with the same weight when conducting the scenario analysis to avoid the scaling effects. State differently, we treat five indicators equally important, which can also fully represent the corresponding component in our conceptual framework.

3 Discussion

Achieving just energy transitions and sustainable international cooperation need monitoring energy transition vulnerability across nations. However, measurement of energy transition vulnerability for nations is notably absent in the literature. This study proposes a framework to quantify energy transition vulnerability and provides a temporal assessment of energy transition vulnerability for 135 nations. The methods outlined in our paper are of value to global monitoring efforts in energy trainstion. Our approach might also lay a foundation for analyzing spatio-temporal patterns of the distributional impacts of energy transition from subnational to global levels.

Our analysis reveals that the gap between the developed and less developed countries maintain persistent in terms of energy transition vulnerability, provided better performance of developed countries. The persistent inequality of energy transition vulnerability across countries suggests that further policy interventions by national governments and the international community are required to protect those vulnerable nations during the process of energy transitions. Among party groups for international climate negotiations, the developed groups have low and consistently improved vulnerability indices, while others face significantly high vulnerability, including less developed countries and oil-exporting countries, despite different drivers for vulnerability behind. International assistance, through instruments such as climate finance, could deliver double benefits because of the potential synergies between emissions and vulnerability reduction.

The impact of COVID-19 on energy transitions needs close attention. While overall energy transition vulnerability had declined globally in most time of last decade, there is an interruption in the exciting trend after 2019 due to the COVID-19. Even worsen, the COVID-19 might widen the gaps among nations in the energy transition (Quitzow et al., 2021) and fossil fuel producers tend to follow dirty recovery paths (Le Billon et al., 2021). As a reference, COVID-19 was projected to reverse the declining trend of the international poverty headcounts (The World Bank, 2020). The unclear dynamic impacts of COVID-19 on energy transition vulnerability calls for continuous monitoring and further study of the energy transition vulnerability in the post pandemic period.

Global decarbonization and energy transition plans are more likely to succeed if they are inclusive, gradual, and tailored to the needs of each nation (Shi et al., 2021). While energy transition plays an essential role in achieving climate targets, over ambitious energy transition plans could backfire, in particular for those vulnerable nations. While the high emission per capita suggests that the stressful countries (**Figure 6**) might need to set faster transitional plans, their high vulnerability suggests that the steps should not be too ambitious. Instead, the leapfrog countries that have high emissions and low vulnerability, should try their best to achieve fast energy transitions. Those with low emissions, i.e. painless countries and potential challenge countries, should prioritize economic growth. Continuous development of developing countries is a key means to achieve inclusive and just energy transitions, which is a principle of the Paris Agreement (UNFCCC, 2015) and much needed to create a fair and cooperative climate regime (Barrett, 2011). Those low emission countries, however, need to promote energy efficiency and other green growth technologies to minimize their emissions.

Although we demonstrate that achieving SDGs is a means to reduce the energy transition vulnerability, achieving SDGs under an emission constraint needs extra effort. More investment (McCollum et al., 2018) and additional initiatives such as international climate finance, carbon pricing revenue redistribution, and clean energy access, are required to achieve the SDGs (Soergel et al., 2021). As catch-up of lagged behind countries will only deliver a small proportion of the benefits, all governments should do more in terms of SDGs achievement and vulnerability reduction. Much of the vulnerability reduction potential can be achieved by learning from their group frontiers that share significant similarities. In particular, developing groups can deliver more benefits by aligning their SDGs achievement with those best players from their groups even in the absence of additional external assistance.

4 Methods

4.1 Data

We aim to provide a comprehensive global analysis of energy transition vulnerability. We collect the energy data from the World Energy Balance Table of the International Energy Agency (IEA), socio-economic and environmental data from the World Development Indicators of the World Bank and the Demographic and Social Statistics of United Nations Statistics Division, which are reputed global data providers. Our dataset covers 135 economies, which represent more than 97.81% of the world's GDP, 92.16% (7.08 billion) of the world's population, 92.96% of world's energy consumption and 97.97% of world's emissions in 2019, according to our data sources. The summary statistics are presented in **Table S1.**

4.2 Energy transition vulnerability scoping diagram for nations

According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability "encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2014). A recent review found various frameworks that qualify or quantify the vulnerability from climate change-related disasters in the literature and the frameworks are diversified across disciplines (Carley et al., 2018). Based on the IPCC definition, the vulnerability scoping diagram (VSD) unifies the diversified conceptions of vulnerability and define vulnerability from three dimensions: exposure, sensitivity and adaptive capacity (Polsky et al., 2007). The VSD has been used primarily in the context of natural hazards, disaster management and climate change adaptation (Coletti et al., 2013; Howe et al., 2013), and later in the US energy policies (Carley et al., 2018).

Based on the three-dimensional VSD framework, we further advanced the literature by proposing an energy transition vulnerability framework for world economies. Our conceptual framework and each dimension build on a pioneer study of Carley et al. (2018), which investigate energy transition vulnerability at the US county level due to renewable portfolio standard policy. However, we use different sets of indicators as our measurement is at the national level and thus need adjustments. Specifically, our energy transition vulnerability index (ETVI) includes three dimensions: exposure, sensitivity and adaptive capacity, each of which contains at least two components, which are further measured by several indicators (**Figure 1**).

The exposure dimension is positively related to ETVI. The exposure dimension is reflected in two components: energy mix and energy revenue. Countries that have a higher share of fossil fuels in their energy and electricity generation mix are more vulnerable than otherwise as they have more significant infrastructure and associated labor that will need to be upgraded in the future. Similarly, countries that draw a larger share of rents or export revenues from the fossil fuels sector are also more vulnerable than those with fewer shares (Ansari and Holz, 2020; Jin et al., 2021). Their economy will face more socio-economic challenges when the fossil fuels sector declines.

However, our framework suggests that the exposure effects are different among countries with the same ETVI level because ETVI also depends on a country's sensitivity to the exposure and adaptive capacity to mitigate the exposure when facing energy transitions. Given a level of exposure, countries that have higher energy dependency, higher poverty ratio, large inequality, and a higher share of susceptible demography will be more sensitive than those with lower numbers at any given levels of exposure (Hubacek et al., 2017; Wu et al., 2017) . Similarly, a country with lower economic, science and technological capability, lower education level, and less fiscal and financial resources will feel more challenges to attenuate, cope with or mitigate those negative exposure than otherwise when facing the same exposure level (Kuhl, 2020; Lesnikowski et al., 2016).

4.3 Quantitative method: a composite index analysis

To operationalize the VSD with data and extract an energy transition vulnerability index (ETVI) score for a specific country, we adopt the geometric mean of three normalized and arithmetic averaged dimensional indices of exposure, sensitivity and adaptive capacity. In particular, we introduce the following equation:

$$V = \sqrt[3]{\left(\frac{1}{I}\sum_{i=1}^{I} \mathrm{E}_i\right) * \left(\frac{1}{J}\sum_{j=1}^{J} \mathrm{S}_j\right) * \left(100 - \frac{1}{K}\sum_{k=1}^{K} \mathrm{A}_k\right)}$$

where V is the vulnerability score, E is an assessment of exposure with i components associated with energy transition, S is an assessment of the sensitivity with j components, and A is an assessment of adaptive capacity with k components.

The geometric mean method has been utilized by international organizations to generate the cross national comparable index, e.g. Human Development Index (HDI) and Sustainable Development Goals (SDG) index published by the United Nations (UN). Following the way of the UN in constructing the SDG index, within the vulnerability score calculation, we arithmetically average across each component of exposure, as well as the sources of sensitivity and adaptive capacity. Within each component each measure is equally weighted since there is no a priori reason to give one measure greater weight than another. The standard min-max method has been adopted to normalize the original data, with top and bottom 2.5th-percentile performer as upper and lower bounds for the baseline results (**Table S1**).

In our study, beyond as the standard method to conduct composite index analysis, the geometric mean of three dimensions also has a clear economic meaning. More specifically, S and A are both multiplied by E, since the set of sensitivity and adaptive capacity measures, respectively, are both specific to an exposure. Stated differently, the exposure only matters if a nation is sensitive to it or is able to adapt to it, or not. The same level of exposure will have different negative impacts among countries with different level of sensitivity: more fragile countries will feel more pain when facing the same level of exposure. The product of exposure and sensitivity measures the magnitude of direct vulnerability given the energy transition. This direct impact could be mitigated or discounted by the adaptive capacity of each country, which yields an overall assessment of the energy transition vulnerability highlighted in this study.

4.4 Sensitivity analysis

The robustness of the ETVI scores can be tested by taking uncertainty factors into consideration and conducting a sensitivity analysis. Different scenarios were tested to identify the composite index's level of sensitivity to the change in parameters – different upper and lower bounds, weighting schemes, aggregation methods and a successive exclusion of indicators. The resulting variation of countries' scores and rankings are depicted in **Figure S1**. Overall, our results are in general robust to reasonable changes in the way we construct the index.

Data availability

The energy data were retrieved from the International Energy Agency (IEA)'s World Energy Balance Table (https://www.iea.org/reports/world-energy-balances-overview). The socio-economic and environmental data were retrieved from the World Bank's World Development Indicators (https://databank.worldbank.org/source/world-development-indicators) and Demographic and Social Statistics of United Nations Statistics Division (https://unstats.un.org/unsd/demographic-so). The climate party group information was taken from the UNFCCC (https://unfccc.int/process-and-meetings/parties-non-party-stakeholders/parties/party-groupings). More details of data extraction can be provided by the corresponding authors upon request.

Code availability

Code developed for data processing in R and MATLAB is available upon request.

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Supplementary information

Supplementary note 1: Data

Table S1. Descriptive statistics

Dimensions	Components	Measurements	Mean	Std	Upper bound	Lower bound
Exposure	Energy mix	Fossil fuel in energy supply mix	0.67	0.27	1.00	0.00
		Fossil fuel in electricity output mix	0.60	0.33	1.00	0.00
	Energy revenue	Fossil fuel export, share of GDP	0.07	0.13	0.49	0.00
		Fossil fuel rents, share of GDP	0.05	0.11	0.42	0.00
Sensitivity	Energy dependence	Energy consumption	0.33	0.25	0.94	0.07
		Energy intensity	0.21	0.17	0.65	0.05
	Wealth	Poverty rate	22.47	27.47	85.51	0.01
	Inequality	Gini index	38.52	8.16	55.80	24.80
		Bottom 20% income share	6.64	1.80	9.80	2.90
	Susceptible demographics	Unemployment rate	7.67	5.51	22.08	0.75
		Age dependency ratio	58.70	17.50	98.22	32.32
Adaptive Capacity	Economic capability	GDP per capita	21305.02	20703.14	71496.60	1400.80
	Science & technology	R&D expenditure, share of GDP	0.80	0.85	3.25	0.04
		Researchers in R&D	1471.30	1727.78	6375.55	17.08
	Education	Mean Years of Schooling	8.46	3.04	12.90	2.20
		Education education, share of GDP	4.35	1.50	7.59	1.78
		Primary completion rate	89.38	16.56	109.14	44.69
		School enrollment rate, tertiary	39.05	28.08	94.78	2.70
	Fiscal & governability	Government spending, share of GDP	15.63	4.92	25.74	6.27
		Government revenue, share of GDP	25.66	9.91	44.79	9.76

Notes: Data is nation-level data from 2010 to 2020, covering 135 economies. We collect the energy data from the World Energy Balance Table of the International Energy Agency (IEA), and socio-economic and environmental data from the World Development Indicators of the World Bank Demographic and Social Statistics of United Nations Statistics Division, which are reputed global data providers. These economies cover more than 97.81% of the global GDP, 92.16% (7.08 billion) of the world's population, 92.96% of world's energy consumption and 97.97% of world's emissions in 2019, according to our data sources.

Supplementary note 2: Vulnerability score of 135 nations in 2019

Table S2. Vulnerability score of 135 nations in 2019

Rank	Country Code	Year	Vulnerability	Exposure	Sensitivity	Adaptive
1	Iceland	2019	10.86	3.14	23.65	82.72
2	Sweden	2019	13.93	8.50	33.42	90.50
3	Denmark	2019	17.99	20.72	27.09	89.62
4	Finland	2019	20.69	16.33	30.54	82.23
5	Switzerland	2019	21.24	12.48	27.18	71.74
6	France	2019	22.81	14.60	29.57	72.51
7	Norway	2019	23.06	31.85	25.39	84.83
8	Austria	2019	23.65	22.97	30.78	81.29
9	Belgium	2019	25.97	30.31	25.98	77.76
10	Slovenia	2019	26.03	25.26	20.90	66.59
11	Uruguay	2019	27.02	10.93	30.42	40.70
12	New Zealand	2019	27.36	19.90	34.29	69.98
13	Luxembourg	2019	27.56	24.06	29.61	70.60
14	Netherlands	2019	28.63	46.52	23.35	78.39
15	Slovakia	2019	29.16	22.18	23.29	52.02

16	Ireland	2019	29.61	37.12	23.91	70.74
17	South Korea	2019	29.93	40.02	23.43	71.41
18	Germany	2019	30.10	31.65	29.90	71.17
19	Czechia	2019	30.11	31.92	22.07	61.26
20	Costa Rica	2019	30.56	12.58	38.04	40.36
21	Paraguay	2019	30.97	10.55	36.66	23.18
22	United Kingdom	2019	31.14	31.54	31.54	69.64
23	Hungary	2019	31.75	27.50	27.77	58.10
24	Canada	2019	32.93	28.95	35.36	65.11
25	Ukraine	2019	32.98	28.05	23.73	46.12
26	Australia	2019	33.04	47.67	27.69	72.69
27	Lithuania	2019	33.11	21.81	37.20	55.27
28	Portugal	2019	33.20	30.84	28.85	58.89
29	Israel	2019	33.80	48.85	27.59	71.36
30	Malta	2019	33.85	49.33	19.91	60.53
31	Singapore	2019	33.94	46.99	29.39	71.68
32	Japan	2019	34.17	40.37	27.68	64.28
33	Albania	2019	34.46	15.77	38.17	32.05
34	Croatia	2019	35.07	27.13	32.22	50.68
35	Kyrgyzstan	2019	35.12	20.07	34.93	38.22
36	Tajikistan	2019	35.41	19.40	32.66	29.92
37	El Salvador	2019	35.62	21.27	29.21	27.26
38	Cyprus	2019	35.74	47.38	21.46	55.12
39	United States	2019	36.01	37.26	40.70	69.20
40	Latvia	2019	36.08	27.60	37.28	54.33
41	Poland	2019	36.11	43.67	23.12	53.35
42	Spain	2019	36.28	29.01	37.45	56.05
43	Estonia	2019	36.69	40.05	32.37	61.90
44	Thailand	2019	36.86	41.35	18.94	36.04
45	Brazil	2019	37.04	18.81	46.64	42.07
46	United Arab Emirates	2019	37.19	83.02	12.63	50.95
47	Lebanon	2019	37.24	47.84	16.71	35.38
48	Belarus	2019	37.87	50.89	19.65	45.72
49	Greece	2019	37.94	36.58	35.75	58.24
50	Namibia	2019	38.15	17.14	57.65	43.80
51	Cambodia	2019	38.21	25.09	26.36	15.65
52	Malaysia	2019	38.25	51.00	18.89	41.90
53	Chile	2019	38.48	31.63	31.39	42.61
54	Bulgaria	2019	38.71	29.34	37.76	47.66
55	Italy	2019	39.13	35.05	40.82	58.11
56	Nicaragua	2019	39.35	21.24	39.69	27.74
57	Azerbaijan	2019	40.30	74.07	12.70	30.44
58	Mauritius	2019	40.43	41.09	25.94	38.00
59	Peru	2019	40.73	29.72	34.65	34.40

60	Myanmar (Burma)	2019	40.75	30.11	27.65	18.68
61	Hong Kong SAR China	2019	40.98	47.91	34.96	58.91
62	Cameroon	2019	41.02	18.84	47.27	22.52
63	Romania	2019	41.12	28.61	39.95	39.17
64	Moldova	2019	41.22	43.75	24.14	33.66
65	Turkey	2019	41.36	35.17	35.65	43.58
66	Rwanda	2019	41.82	21.49	44.60	23.68
67	China	2019	41.95	39.70	30.25	38.52
68	Georgia	2019	42.02	25.35	47.51	38.40
69	Vietnam	2019	42.09	39.67	25.13	25.20
70	Zimbabwe	2019	42.11	20.41	60.08	39.09
71	Madagascar	2019	42.16	17.52	50.05	14.54
72	Armenia	2019	42.21	28.71	41.14	36.33
73	Guatemala	2019	42.68	20.33	46.68	18.10
74	Montenegro	2019	43.07	28.93	46.42	40.50
75	Panama	2019	43.14	32.68	36.99	33.57
76	Togo	2019	43.19	20.63	53.08	26.44
77	Palestinian Territories	2019	43.36	36.57	34.80	35.95
78	Ecuador	2019	43.38	34.18	35.87	33.42
79	Jordan	2019	43.48	44.91	26.09	29.84
80	Kazakhstan	2019	43.83	63.14	20.21	34.04
81	Serbia	2019	43.84	40.13	37.59	44.15
82	Laos	2019	43.94	30.95	35.30	22.32
83	Morocco	2019	43.99	42.41	32.34	37.95
84	Mali	2019	44.11	23.55	43.54	16.27
85	Tanzania	2019	44.13	20.85	48.28	14.67
86	Dominican Republic	2019	44.31	44.83	28.92	32.90
87	Honduras	2019	44.39	24.87	47.24	25.56
88	Bosnia & Herzegovina	2019	44.48	37.02	38.47	38.23
89	Russia	2019	44.53	50.34	36.00	51.28
90	Sri Lanka	2019	44.58	31.04	37.24	23.35
91	Mozambique	2019	44.62	21.67	56.82	27.84
92	Tunisia	2019	44.70	47.50	32.70	42.50
93	Pakistan	2019	45.36	33.18	34.89	19.37
94	Philippines	2019	45.45	36.52	34.79	26.11
95	Mongolia	2019	45.47	59.11	24.87	36.05
96	Mexico	2019	45.96	43.50	32.94	32.22
97	Argentina	2019	45.97	40.37	40.71	40.90
98	Sudan	2019	46.23	24.88	45.21	12.16
99	Colombia	2019	46.24	32.19	45.78	32.92
100	Burkina Faso	2019	46.33	29.68	41.13	18.54
101	Niger	2019	46.64	30.84	40.88	19.53
102	Bolivia	2019	47.05	44.98	33.25	30.35
103	Mauritania	2019	47.24	38.21	36.00	23.36

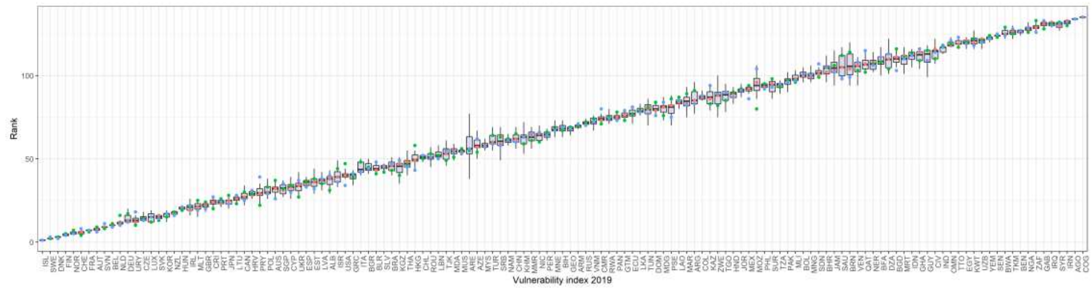
104	Suriname	2019	47.41	38.78	41.64	33.99
105	Ghana	2019	47.92	34.48	40.22	20.65
106	Côte d'Ivoire	2019	47.95	28.23	47.95	18.56
107	Jamaica	2019	48.41	48.87	36.62	36.62
108	Algeria	2019	48.64	66.40	26.61	34.88
109	Turkmenistan	2019	48.74	71.39	24.73	34.42
110	Qatar	2019	48.78	82.20	30.64	53.91
111	Brunei	2019	48.87	84.76	31.05	55.65
112	Trinidad & Tobago	2019	49.00	68.55	26.96	36.35
113	Guyana	2019	49.00	47.63	40.18	38.52
114	Oman	2019	49.04	83.94	25.80	45.56
115	Indonesia	2019	49.37	42.15	36.94	22.71
116	Bangladesh	2019	49.51	45.00	32.45	16.85
117	Saudi Arabia	2019	49.68	73.63	34.90	52.28
118	Venezuela	2019	49.79	52.94	36.50	36.14
119	India	2019	50.15	39.24	42.39	24.20
120	Bahrain	2019	50.21	59.87	33.25	36.41
121	Senegal	2019	50.77	39.47	42.15	21.36
122	Egypt	2019	51.33	49.68	37.05	26.54
123	Uzbekistan	2019	51.57	52.57	39.15	33.39
124	Benin	2019	52.50	35.66	51.71	21.53
125	Yemen	2019	53.30	48.81	42.64	27.22
126	Botswana	2019	53.62	44.58	57.82	40.19
127	Nigeria	2019	54.13	35.47	54.10	17.36
128	South Africa	2019	54.74	47.26	63.39	45.24
129	Kuwait	2019	55.22	95.02	31.22	43.24
130	Gabon	2019	56.42	47.32	49.56	23.43
131	Syria	2019	57.74	62.95	41.40	26.13
132	Iraq	2019	57.83	85.00	29.27	22.28
133	Iran	2019	58.28	66.85	42.58	30.44
134	Angola	2019	61.22	51.53	52.56	15.27
135	Congo - Brazzaville	2019	72.65	81.15	56.24	15.97

Notes: We report the 2019 EVTI scores the baseline results to reflect the current status of energy transition vulnerability for each economy. The EVTI scores for other years are available upon request.

Supplementary note 3: Sensitivity analysis for energy transition vulnerability index

The robustness of the energy transition vulnerability index (ETVI) can be tested by taking uncertainty factors into consideration and conducting a sensitivity analysis. Different settings were tested to identify the composite index's level of sensitivity to the change in parameters – different upper and lower bounds, aggregation methods and a successive exclusion of indicators. The resulting variation of countries' scores and rankings are depicted in **Figure S1**. The countries are ordered according to their median and the original value of ETVI is marked in red. The results based on alternative upper and lower bounds of 0.01 and 0.99, 0.05 and 0.95 are marked in blue and green, respectively.

a. Sensitivity analysis results for rankings.



b. Sensitivity analysis results for scores.

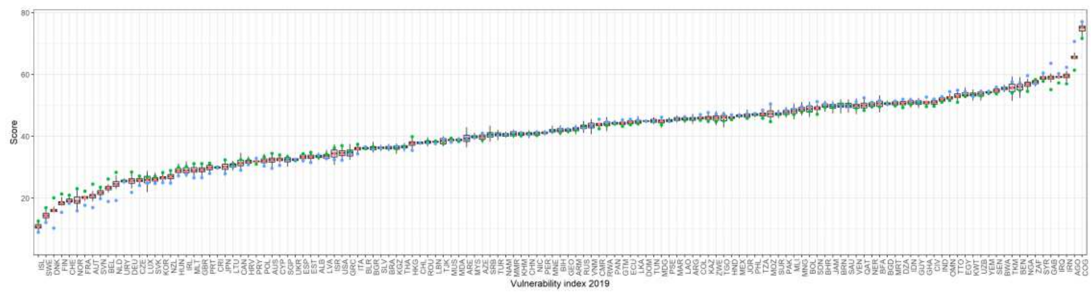


Figure S1. Sensitivity analysis for energy transition vulnerability index

Notes: The robustness of the energy transition vulnerability index (ETVI) is tested by taking different upper and lower bounds, aggregation methods and a successive exclusion of indicators. The countries are ordered according to their median and the original value of ETVI is marked in red. The results based on alternative upper and lower bounds of 0.01 and 0.99, 0.05 and 0.95 are marked in blue and green, respectively. In each box plot, the central rectangle spans the first quartile Q1 to the third quartile Q3, which is the interquartile range (IQR) (IQR = Q3 to Q1), while the line segment inside the rectangle shows the median. When the maximum observed ETVI scores are greater than Q3 + 1.5 × IQR, the upper whisker is Q3 + 1.5 × IQR. Otherwise, the upper whisker is the maximum observed ETVI score. When the minimum observed ETVI scores are less than Q1 − 1.5 × IQR, the lower whisker is Q1 − 1.5 × IQR. Otherwise, the lower whisker is the minimum observed ETVI score.

The ranking of countries is very robust for economies in the top and bottom quintiles of the scale. Although the countries that are listed between those tails reveal a wider interquartile range, the original ETVI ranking remains very close to the median. More than half of the economies only shifted by a maximum of one position from the median rank. Major differences in scores and ranks are usually witnessed when an indicator that represents a country's comparative advantage or weakness in transition vulnerability is excluded. However, testing alternative results by excluding indicators showed that both EVTI rankings and scores are not likely to be driven by the outlier in any single dimension in energy transition vulnerability.

Supplementary note 4: Vulnerability Index over time

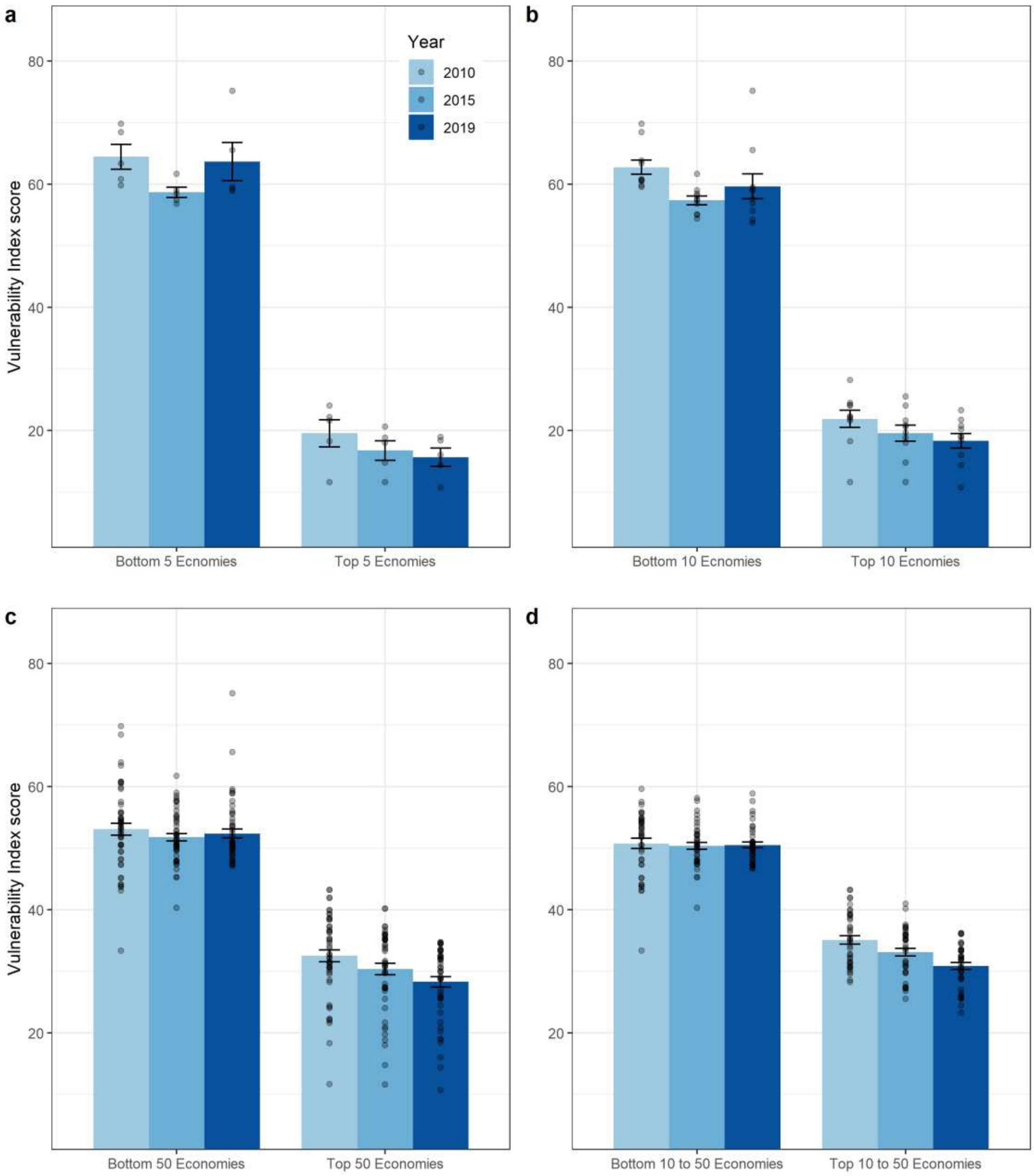


Figure S2. No catching up effects in transition vulnerability

Notes: a, the top five (best ETVI score) countries and the bottom five (poorest ETVI score) countries in 2010, 2015 and 2019 are compared. **b**, the top ten (best ETVI score) countries and the bottom ten (poorest ETVI score) countries in 2010, 2015 and 2019 are compared. **c**, Top and Bottom 50. d, Top and Bottom 10 to 50. The vertical lines within the bar indicate the standard error in ETI Index scores.

Supplementary note 5: By party groups for international climate negotiations

We analyze the different energy transition vulnerabilities across seven major party groups in the international climate change negotiations defined by the UNFCCC (**Table S3**). Since each party group shares similarities in climate change, which is the motivation of energy transitions, their energy transition vulnerability may also have common characteristics and dynamics. For example, less developed countries (LDC) have suggested it is unfair that they should bear responsibility for solving a problem they did not cause, while developed nations such as the US wanted to avoid commitments to avoid burdening their economies. The African Group and the least developed countries group are active in and supportive to all aspects of the climate change negotiating process, with a particular focus on vulnerability and adaptation, both campaign to prioritize the issue of financial support (UNFCCC, 2022). The EU is well-known as a club of developed countries that strongly advocate for climate ambition both in international fora and in its bilateral relations with non-EU countries. While the Umbrella Counties also consists of several developed countries (Australia, Canada, Iceland, Japan, New Zealand, Norway, the United States) plus several former Soviet Union countries (Belarus, Israel, Kazakhstan, the Russian Federation, and Ukraine) are more conservative on the climate issues. Therefore, understanding different dynamics in their energy transition vulnerability may inform further international climate negotiations.

Table S3. Party groups for international climate negotiations

African States	Arab States	European Union	Least Developed Countries	Like-minded developing countries	Small Island Developing States	Umbrella Group
Angola	United Arab Emirates	Austria	Angola	Argentina	Bahrain	Australia
Benin	Bahrain	Belgium	Benin	Bangladesh	Dominican Republic	Canada
Burkina Faso	Algeria	Bulgaria	Burkina Faso	Bolivia	Guyana	Japan
Botswana	Egypt	Cyprus	Bangladesh	China	Jamaica	Kazakhstan
Ivory Coast	Iraq	Czechia	Cambodia	Algeria	Mauritius	Norway
Cameroon	Jordan	Germany	Laos	Ecuador	Singapore	New Zealand
Republic of the Congo	Kuwait	Denmark	Madagascar	Egypt	Suriname	Russia
Algeria	Lebanon	Spain	Mali	Indonesia	Trinidad & Tobago	Ukraine
Egypt	Morocco	Estonia	Myanmar (Burma)	India		United States
Gabon	Mauritania	Finland	Mozambique	Iran		
Ghana	Oman	France	Mauritania	Iraq		
Morocco	Palestinian Territories	United Kingdom	Niger	Jordan		
Madagascar	Qatar	Greece	Rwanda	Kuwait		
Mali	Saudi Arabia	Croatia	Sudan	Sri Lanka		
Mozambique	Sudan	Hungary	Senegal	Mali		
Mauritania	Syria	Ireland	Togo	Malaysia		
Mauritius	Tunisia	Italy	Tanzania	Nicaragua		
Namibia	Yemen	Lithuania	Yemen	Pakistan		
Niger		Luxembourg		Saudi Arabia		
Nigeria		Latvia		Sudan		
Rwanda		Malta		El Salvador		
Sudan		Netherlands		Syria		
Senegal		Poland		Venezuela		
Togo		Portugal		Vietnam		
Tunisia		Romania				
Tanzania		Slovakia				
South Africa		Slovenia				
Zimbabwe		Sweden				

Notes: The classification of each party group for international climate negotiations is defined by UNFCCC (2022).

Supplementary note 5: Scenario analysis

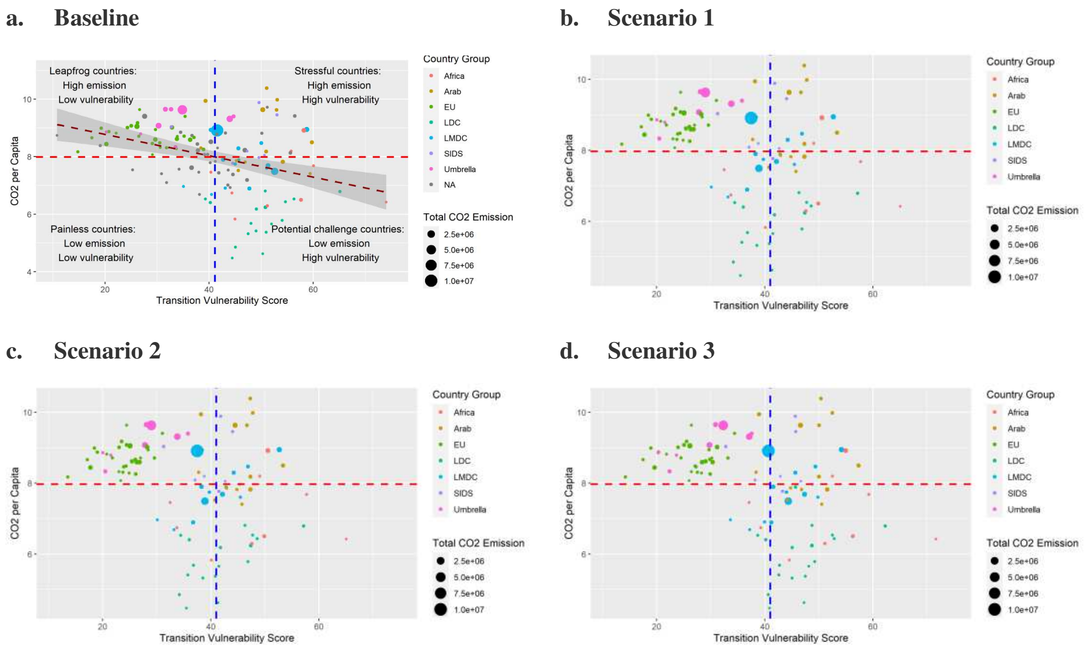


Figure S3. Change in country types in different SDG achievement scenarios

Notes: The relationship between energy transition vulnerability index and CO_2 emission at the climate group and national level in baseline and different SDG achievement scenarios. The vertical and horizontal line is the mean value in the baseline case for x and y axis variable.