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A KRLS-Based Incremental Analysis for Disaggregated Energy Security Risk Effect on Energy Transition in the USA

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In light of recent developments in energy security and energy transition, this study examines the effects of disaggregated energy security risk (ESR) on the energy transition index (ETI). Economic ESR reduces ETI, while environmental ESR increases it. Geopolitical and reliability ESRs have no significant impact on ETI. Additionally, the marginal effects of these variables differ across percentiles. Therefore, the study uncovers both average and percentile-based variations in the marginal effects of ESR on ETI.

I. Introduction

Combating climate change and environmental problems has been pursued by enhancing the energy transition to clean sources (Ulussever et al., 2023). Accordingly, the negative effects of fossil fuel-based energy on the environment can be reduced as more clean energy is incorporated into the total energy mix. In addition to environmental concerns, the recent energy crisis also highlights the importance of energy transition, as increasing geopolitical tensions have imposed high risks on energy supply and prices. The *ESR* of countries has increased under this high-risk geopolitical environment. For this reason, both total *ESR* and *ESR* sub-types can be affected by such conditions. Thus, achieving energy transition has become critical.

Consistent with developments in environment and energy-related fields, the literature on *ETI* and *ESR* has been evolving. Some studies have focused on *ETI*. For example, Zhang et al. (2023) examine the USA and conclude that geopolitical risk negatively and insignificantly affects *ETI*. Kartal et al. (2024) study Nordic countries and determine the time- and frequency-based varying effect of *ETI* on decarbonization across countries. Lamnatou et al. (2024) highlight the role of renewable energy sources in the energy transition for France. Other studies have addressed *ESR*. For instance, Doğan et al. (2023) consider newly industrialized countries and state that *ESR* increases emissions. Iyke (2024) examines 25 countries and finds that climate change increases *ESR*. Moreover, some studies have considered both *ETI* and *ESR* simultaneously. Aslam et al. (2024) examine BRI countries and determine that *ETI* has a declining effect on *ESR* where renewable resources are used. Kartal et al. (2024) analyze the USA and state that *ETI* is not effective in easing *ESR* across time lags. Although the literature on *ESR* and *ETI* is growing, it remains limited. Some studies on the USA examine the effect of *ETI* on *ESR* (e.g., Kartal, Taşkın, et al., 2024); however, these studies have not considered *ESR* sub-types or addressed the incremental effect, which refers to the changing impact of independent variables (*ESR* sub-types) on the dependent variable (*ETI*) across percentiles. Hence, there is a gap in the literature: the incremental effect has not been considered, and *ESR* sub-types have not been used for the USA case. This study aims to fill this gap and differentiate itself from existing studies.

Because ensuring energy transition is critical, especially for larger economies due to their high energy consumption, empirical examination of such countries is appropriate, and this analysis can serve as a guide for other countries. Therefore, the USA is an ideal case for empirical analysis because it is the largest economy, uses high levels of energy, and faces environmental challenges (WB, 2024). Additionally, the USA has the most up-to-date data for both *ETI* and *ESR* (UNCTAD, 2024; USC, 2024), which enables researchers to conduct analyses using recent data.

Considering the literature gap, this study focuses on the USA in examining the incremental effect of *ESR* sub-types on *ETI*. To do this, the study uses *ETI* as a proxy for energy transition, as developed by UNCTAD (2024), considers *ESR* sub-types for a disaggregated analysis, and applies a Kernel regularized least squares (*KRLS)* approach. Thus, this study seeks to answer the following research questions: (i) How

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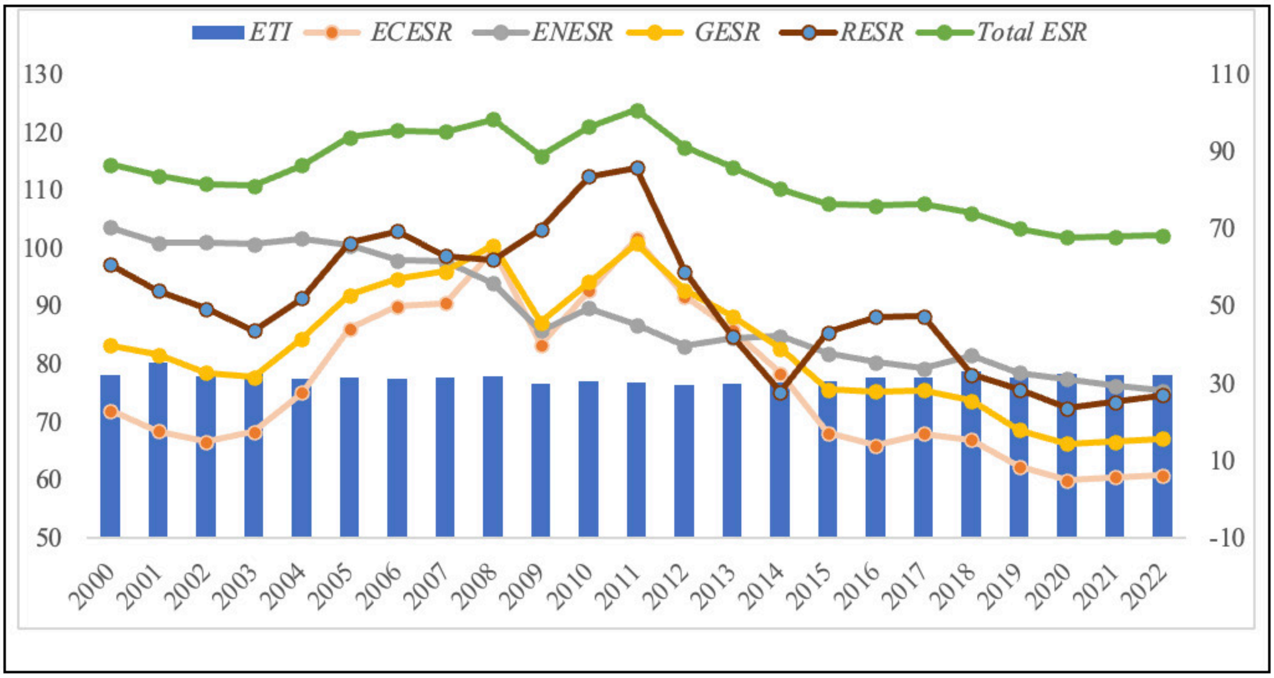

Figure 1. Progress of *ETI* and *ESR* in the USA

Note: Total *ESR* is shown on the right axis.

do *ESR* sub-types marginally affect *ETI*? (ii) Do the effects of *ESR* sub-types on *ETI* differ between average marginal effect (*AME*) and pointwise marginal effect (*PME*)?

This study offers three key contributions. First, it is a pioneering study for the USA that examines the effect of *ESR* sub-types on *ETI*. Although there are various studies on *ETI*, none have investigated *ETI* in the USA by considering *ESR* sub-types. Second, the study investigates the incremental effect of *ESR* sub-types on *ETI*, distinguishing it from prior research. Third, unlike other studies, this study employs a *KRLS* approach to uncover *AME* and *PME*.

The reminder of the paper is structured as follows. The methodology is presented in Section II, empirical outcomes in Section III, and the conclusion in Section IV.

II. Methodology

A. Data

Figure 1 presents the progress of *ETI* and *ESR* sub-types. *ETI* has exhibited a horizontal trend over the years, indicating an unsuccessful energy transition policy. In contrast, *ESR* has shown a time-varying structure. Total *ESR* increased until 2011 and then decreased after that point. A similar pattern is observed in *ESR* sub-types, except that reliability *ESR* experienced an increase between 2014 and 2017.

This study reveals the marginal effect of *ESR* sub-types on *ETI*. Therefore, the USA is examined because it offers extensive data, including data on *ESR* sub-types. In this context, the study uses *ETI* as a proxy for energy transition and considers *ESR* sub-types, consistent with the evolving literature. Additionally, the study analyzes data from 2000 to 2022, which represents the full range of available data. Data for *ETI* is sourced from UNCTAD (2024), while data for *ESR* sub-types is obtained from USC (2024). A summary of variable details are provided in Table A in the appendix.

B. Empirical Process

The study applies a five-steps process for empirical analysis. Firstly, descriptive statistics are analyzed. Secondly, correlations are examined. Thirdly, the nonlinearities are examined using the Broock, Scheinkman, Dechert, and LeBaron (BDS) test (Broock et al., 1996). Lastly, the *KRLS* approach (Hainmueller & Hazlett, 2014) is performed to investigate *AME* and *PME* of *ESR* sub-types on *ETI*, *respectively*. The study uses Equation (1) to uncover the effects:

$$ETI_{it} = a_0 + a_1 ECESR_{it} + a_2 ENESR_{it} + a_3 GESR_{it} + a_4 RESR_{it} + \varepsilon_{it} \quad (1)$$

where *ETI, ECESR, ENESR, GESR*, and *RESR* denote energy transition index, economic *ESR*, environmental *ESR*, geopolitical *ESR*, and reliability *ESR*, respectively.

III. Empirical Outcomes

A. Preliminary statistics

ETI has a mean value of 77.76, ranging from 76.4 to 80.3. *ESR* sub-types have relative volatilities between 60.02 and 75.49. Among all sub-types, *RESR* has the highest mean and maximum values, followed by *ENESR*, *GESR*, and *ECESR*, in that order. Moreover, *ECESR* exhibits the highest volatility, followed by *RESR*, *GESR*, *ENESR*, and *ETI*, respectively. Furthermore, *ETI* has a non-normal distribution, whereas the *ESR* sub-types have normal distributions.

Table 1. ***KRLS*** **outcomes**

Variable	Coefficient	SE	t	P>t	P25	P50	P75
ECESR	-0.0139	0.0039	-3.5920	0.0020	-0.0268	-0.0174	-0.0042
ENESR	0.0228	0.0067	3.3830	0.0030	0.0135	0.0193	0.0357
GESR	-0.0054	0.0043	-1.2430	0.2290	-0.0138	-0.0043	0.0055
RESR	-0.0029	0.0073	-0.4020	0.6920	-0.0121	-0.0044	0.0054

Note: SE is the standard error; P25, P50, and P75 represent the 25th, 50th, and 75th percentiles, respectively.

ETI exhibits medium- and low-level correlations with the *ESR* sub-types. Specifically, *ETI* has a medium-level negative correlation (-0.51) with *ECESR*. Similarly, there are medium-level negative correlations between *ETI* and both *GESR* (-0.40) and *RESR* (-0.30). On the other hand, there is a positive and low-level correlation between *ETI* and *ENESR*.

All variables are non-stationary at the level; however, all variables become stationary at first differences.

Table B in the appendix demonstrates the nonlinearity test outcomes. *ETI* displays a mixed condition across the dimensions. Similarly, both *GESR* and *RESR* have mixed conditions. However, both *ECESR* and *ENESR* exhibit a completely nonlinear structure.

B. AME Outcomes

Table 1 shows the *AME* outcomes of *ESR* sub-types on *ETI*. *ECESR* has a statistically significant negative effect on *ETI* (p-value: 0.0020). Conversely, *ENESR* has a statistically significant positive effect on *ETI* (p-value: 0.0030). In contrast, both *GESR* (p-value: 0.2290) and *RESR* (p-value: 0.6920) have statistically insignificant effects on *ETI*. These outcomes suggest that increasing economic *ESR* reduces *ETI*, while increasing environmental *ESR* raises *ETI*. Therefore, U.S. policymakers can rely on *ENESR* to support improvements in *ETI*.

C. *PME* Outcomes

Figure 2 demonstrates the PME of *ESR* sub-types on *ETI*.

In Figure 2a, *ECESR* has a positive marginal effect on *ETI* at low levels, specifically when *ETI* is below 77. However, if this threshold is exceeded, *ECESR* has a completely negative marginal effect on *ETI*, and this negative effect becomes much stronger as *ETI* increases.

In Figure 2b, *ENESR* has a consistently positive marginal effect on *ETI* across all levels. Notably, the increasing marginal effect is much stronger when *ETI* is between 76 and 77.5. Once this threshold is surpassed, particularly between 77.5 and 80, the increasing effect of *ENESR* on *ETI* becomes much weaker. If *ETI* exceeds 80, the increasing effect of *ENESR* becomes stronger again.

In Figure 2c, *GESR* has a positive marginal effect on *ETI* at low *ETI* levels, up to approximately 77. However, *GESR* exhibits a completely negative marginal effect on *ETI* at higher levels. This negative effect intensifies when *ETI* is between 77 and 79, while the effect becomes slightly weaker when *ETI* exceeds 79.

In Figure 2d, *RESR* has a negative marginal effect on *ETI* at low *ETI* levels, specifically between 76 and 79.5. However, *RESR* has a positive marginal effect on *ETI* at higher levels, with the effect becoming much stronger when *ETI* exceeds 79.

Finally, Figure 3 provides a summary of these outcomes.

D. Policy Implications

Considering the results, U.S. policymakers should view rising environmental *ESR* as an opportunity to implement measures that expedite the energy transition. In this context, policymakers should continue supporting the shift from fossil fuels to renewable sources by promoting public awareness campaigns and providing financial subsidies to both companies and consumers. Additionally, enacting stricter policies (such as emissions limits, reduction targets, and emission trading systems) and pursuing long-term benefits from clean energy in response to environmental disasters (e.g., hurricanes) can further stimulate the energy transition by leveraging environmental *ESR*.

Furthermore, U.S. policymakers should aim to reduce economic *ESR* due to its negative impact on the energy transition. To address this, they should focus on decreasing investment volatility, maintaining stable energy prices to avoid adverse public reactions, securing supply chains and critical minerals through long-term purchasing agreements, and stabilizing policies to minimize policy instability. They should also recognize that *ESR* sub-types exhibit varying *PME*, which is crucial for formulating effective energy transition policies. Assuming that incremental increases will yield similar effects could lead to misguided policy decisions.

The findings suggest that both *ESR* and its sub-types should be considered in formulating the U.S. energy transition policy. Moreover, average and marginal incremental effects of *ESR* sub-types should be taken into account. This approach will help the U.S. develop a more robust energy transition policy. The outcomes are largely consistent with the current literature (e.g., Kartal, Taşkın, et al., 2024), while providing a unique perspective by considering *ESR* sub-types and their incremental effects.

IV. Conclusion

This study focuses on the USA, utilizes the most up-to-date data, and employs a *KRLS* approach. Accordingly, the study uncovers both the average marginal effect (*AME*) and the percentile marginal effect (*PME*) of *ESR* sub-types on

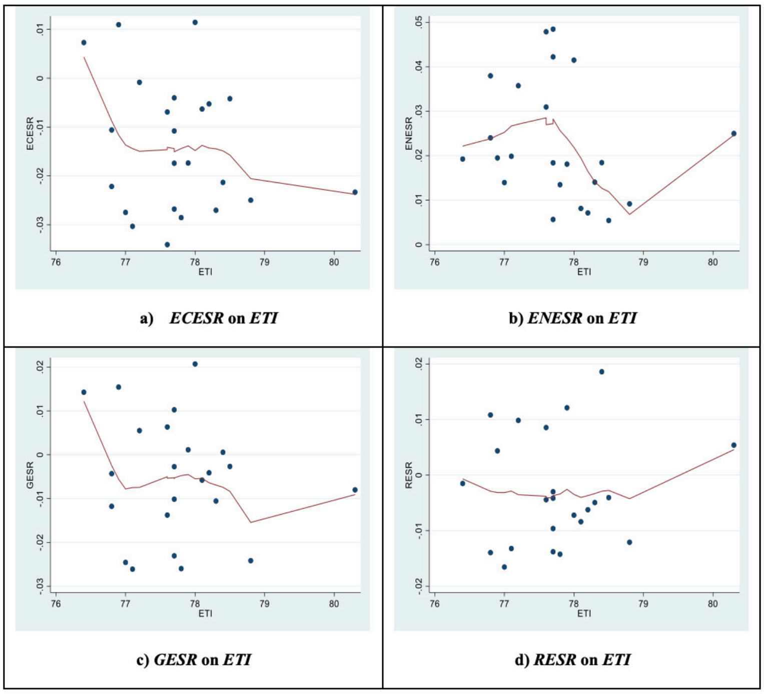

Figure 2. ***PME*** **outcomes for** ***ESR*** **sub-types on** ***ETI***

Note: In the above graphs, the x-axis denotes *ETI* and the y-axis denotes the marginal impact of the *ESR* sub-types.

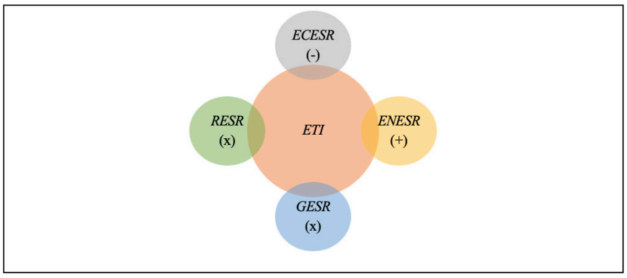

Figure 3. Summary of the outcomes

Note: +, -, and x denote the increasing, decreasing, and insignificant effects, respectively.

ETI in addressing the research questions. In summary, it reveals both average and percentile-based variations in the marginal effects of ESR on ET.

While the study aims to provide a comprehensive analysis, it has some limitations. Since the study focuses on the USA, future research could examine other developed countries as well as developing countries with varying levels of *ESR* and *ETI*. Comparative studies between fossil-dependent and renewables-led states could also be considered. Additionally, as this study primarily addresses *ESR* sub-types, future research might explore other recent issues such as geopolitical risk, climate, and trade policy uncertainty. Furthermore, new studies could apply other novel econometric methods as well.

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Appendix

Table A. Details of the Variables

Symbol	Definition	Measurement Unit	Data Source
ETI	Energy Transition Index	Index	UNCTAD (2024)
ECESR	Economic *ESR*	Index	USC (2024)
ENESR	Environmental *ESR*		
GESR	Geopolitical *ESR*		
RESR	Reliability *ESR*		

Table B. Nonlinearities of the Variables

Variable	D2	D3	D4	D5	D6	Decision
ETI	0.1290	0.0029	0.0040	0.0008	0.0280	M
ECESR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
ENESR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
GESR	0.0000	0.0000	0.0000	0.0006	0.0575	M
RESR	0.0000	0.0000	0.0000	0.0138	0.7139	M

Notes: Values show the p-values. D, M, and NL represent dimension, mixed, and nonlinear, respectively.