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Analysis of the potential of renewable energy sources to strengthen Ukraine's energy security

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Abstract

The recent geopolitical landscape and the security challenges posed by historically relying on imported fossil fuels have forced Ukraine to make energy security an existential priority. This study aims to analyze the impact of transition towards renewable energy on Ukraine's energy security index (ESI) for the period 2000-2020. The study employs the secondary data obtained from the International energy agency to implement multiple linear regression (OLS) to measure the influence of the adoption of renewable energy and the domestic production of renewable energy on the ESI. The results of the study suggest that the model is explainable. One of the major results of the study includes the cognition that the modern renewables share, which includes heating, transport and SDG 7.2, has more of an impact on domestic production than on energy security. In addition, the results of the study indicate that the renewable electricity sector is statistically insignificant. This suggests that Ukraine's energy resilience is mainly determined by the need to decarbonize the heating sector which would eliminate the need for imported natural gas. The findings of the study suggest Ukraine's post-war reconstruction to comply with the European green deal to achieve strategic autonomy. It suggests that the decentralization of renewable energy systems and fossil fuel energy is more than just an environmental strategy. It is rather an action of defense against over-reliance on foreign energy systems.

Keywords: Energy security, Ukraine, Modern renewable energy, OLS regression, Import substitution.

1. Introduction

Increasing geopolitical risks and huge reliance on fossil fuels versus energy transitions due to climate emergencies require a re-evaluation of energy security. The fundamental aspects of energy security—that is, availability and affordability—have now broadened to include the complex geopolitical interdependencies involved in energy transitions. Scholarship by Azzuni & Breyer [1] and Sovacool [2] highlights this shift from a narrow focus on supply geopolitics toward a systemic view where infrastructure must resist both geopolitical and environmental shocks. In this context, long-term security is increasingly considered as inseparable from climate-driven sustainability [3]. Tensions over control of supply routes and access to resources [4] shape the geopolitical landscape of global energy security, particularly with regards to the Middle East and Central Asia. The global energy system remains over-reliant on fossil fuels, and the geopolitical conflicts and resulting tensions compound the significant risks to the system, such as supply disruptions and price volatility [5], [6]. The clashes between climate change and obligations to international agreements, like the Paris agreement and the SDGs (7, 13) of affordable and clean energy and climate action, spawn the pressures of the required transition to renewables [7], [8], fostering what recent frameworks call a "resilient transition" [9].

Considering fossil fuels, the impacts of war, and possible deals with the EU, Ukraine has been starting its transition towards an energy transformation ahead of other EU member states as of March 2022. Currently, Ukraine faces the war with Russia, followed by loss of gas and oil imports. This consequently puts Ukraine in an economically and politically vulnerable position. Historically, research by Wolczuk [10] and Pavlenko [10] highlights that despite high vulnerability, pre-conflict reform efforts were often stalled by domestic interests and institutional voids. While energy intensity improved slightly, the sector remained structurally weak [11]. The vulnerable position of Ukraine in relation to Russia has been systematically ignored until the Russian invasion began targeting Ukraine's energy defense, from which Ukraine's multiple energy generation supply chains (pods) were removed. Ukraine, as of March 2022, is in the two-billion-dollar loss range from energy infrastructure. This loss clearly states the need to move away from fossil fuels to diversify energy sources. The Ukraine war directly states the need to move quickly away from reliance on Russian fossil energy, particularly oil, which aligns with the EU's unifying conflict of fossil fuels reliance and the need to diversify energy [11].

These difficulties can be addressed by using renewable energy to enhance energy flexibility and sustainability [12]. Nations can diversify and reduce their fuel import dependency, as well as the risks of economically damaging fuel supply shortages, by using renewable energy [13], [14]. According to Awerbuch [15], integrating renewables acts as a risk mitigation strategy (portfolio theory), reducing exposure to the erratic costs of fossil fuels. Resilience is an integral concept of this energy transition; for example, in conflict-affected regions of the world, the ability to draw upon decentralized renewable energy systems for a low-vulnerability energy supply is essential [16]. This creates a "conflict paradox" where, as present in Yemen, the destruction of centralized grids can actually accelerate the adoption of decentralized renewables [17], although active armed conflict can also deter large-scale investments [18], [19]. The energy transition also supports the EU’s “strategic autonomy” policy in energy as it focuses on clean energy market improvements and the mitigation of energy dependency [20], [21]. Integration with the EU is in progress for Ukraine through synchronization with the ENTSO-E grid and by the adoption of the EU’s environmental guidelines [22]. This synchronization is considered as a way for Ukraine to "leap" toward a less carbon-intensive mix despite the ongoing crisis [23].

One can observe consistency in the policies and the strategic emphasis on the transition within the energy sector, but there are still many imperfections and challenges pertaining to the sector [24]. There is a very long history regarding the reforms undertaken in the natural and electric energy sectors. Primarily, the history is one of the policy reforms pertaining to the energy sub-sectors of gas and electricity and is one of the greatest histories of instability in terms of reforms to public policies, and non-efforts [25]. There are also destabilizing interests at a local level [26], [27]. This has resulted in the creation of a "hybrid model" of the electricity market—a mix of bureaucratic systems and market liberalization that often conflicts with EU standards [13]. The future determinations and achievements of further improvements require a need for equilibrium or trade-off between the short-term vision of energy security and long-term vision, in terms of maintaining sustainable gas and electricity. For instance, Sturm [12] points out that wartime security often forces a temporary reliance on fossil fuels, which contrasts with decarbonization goals. Furthermore, critics like Gowrisankaran et al. [28] and Popik

[29] have warned about the high costs of grid infrastructure and the risks of intermittency if the pace of transition is not aligned with Ukraine's actual capacity. The trade-offs, as mentioned above, would require very high investments in qualified manpower [30], [31]. These complexities require approaches to problems considering geopolitical relationships, policy reforms, and to overcome the weak electricity supply systems.

Despite these extensive discussions on policy, there is a surprising scarcity of quantitative assessments regarding the impact of renewables on Ukraine's specific energy metrics. Most existing works put focus on political economy rather than empirical data. Thus, this research intends to understand to what extent the country’s renewable sources can influence the energy security index (ESI) during the pivoting timeline from 2000 to 2020. By focusing on this specific 20-year period, this study addresses the gap in empirical literature regarding the relationship between modern renewables and import dependency [10], [32]. Hence, this research concerns three following questions. First, what is the extent to which the growing proportion of modern renewable energy is statistically related to the improvement of ESI in Ukraine? Second, does the increased renewable energy capacity positively impact Ukraine’s energy import dependency? Third, what are the changes in ESI due to the 2014 geopolitical perturbations, the domestic production of energy retention, and the recovering ESI? This investigation addresses the scope of energy security, considering the multiplicity of elements that constitute energy security, not just availability, but also including the elements of energy security’s resilience and sustainability.

2. Research method

2.1. Research design

For the 2000-to-2020-time frame, this study employs a quantitative approach utilizing an ex-post facto method to analyze the relationship between energy transition variables and energy security in Ukraine. We analyze and describe the time series data to show how the adoption of renewable energy and domestically produced energy impacts the energy security index (ESI) of the country. This period is chosen due to significant developments in the energy sector of Ukraine, especially in the pre-conflict period, the 2014 geopolitical crisis and the reform period thereafter. This approach is effective in revealing the cause-and-effect relationship due to its predictive capabilities. It is anticipated that the results will show positive changes in security and greater observable outcomes with changes to policy in the energy sector.

2.2. Data sources and variables

The dataset was built using various secondary data sources. The dependent variable is the energy security index (ESI). This is sourced from the historical energy security assessments (AidData) from which the index was developed. The independent variables have been obtained from the IEA databases, specifically the World energy balances and the Renewables information databases. The variables selected capture key aspects of energy production, consumption, and the share of renewable energy, which are essential for assessing changes in energy security.

The constructs of this research are described in the following manner:

- dependent variable:
    - energy security index (ESI): a composite score (0-100) reflecting the availability, affordability, and resilience of the national energy system
- independent variables:
    - modern renewable share: the percentage of modern renewable energy (including electricity, heat, and transport biofuels) in the final energy consumption, aligned with SDG indicator 7.2
    - domestic production share: a proxy for energy independence, calculated as the ratio of total domestic energy production to the total energy supply (TES)

2.3. Model specification

The research uses empirical evidence which predicts theory declaring that in the renewable energy era, the energy security hypothesis is achievable. For this purpose, the study selected MLR and OLS regression. The OLS estimator identifies a relationship by minimizing the squared sum of the residuals.

The functional relationship is expressed as:

$$\mathrm{ESI} = \mathrm{f(Modern\ Renewables,\ Domestic\ Production)}$$

The specific econometric equation used in this study is formulated as follows:

$$ESI_t = \beta_0 + \beta_1 REN\_MOD_t + \beta_2 DOM\_PROD_t + \epsilon_t \tag{1}$$

In the equation:

- ESI_t = energy security index score in year \$t\$
- β_0 = intercept (constant term), representing the ESI value when explanatory variables are zero
- β_1 = coefficient for modern renewable share; indicates the change in ESI for a 1% unit increase in renewable share
- REN_MOD_t = share of modern renewables in final energy consumption in year \$t\$ (%)
- β_2 = coefficient for domestic production share; indicates the change in ESI for a 1% unit increase in domestic production capability
- DOM_PROD_t = share of domestic energy production relative to total energy supply in year \$t\$ (%)
- ϵ_t = error term (residuals) in year \$t\$, capturing unobserved factors
- t = time (2000–2020)

Calculation of domestic production share:

Since the raw IEA data provides absolute values in terajoules (TJ), the variable is transformed using the following equation:

$$DOM\_PROD_t = \left(\frac{\text{Domestic Production}_t}{\text{Total Energy Supply (TES)}_t}\right) \times 100 \tag{2}$$

2.4. Data analysis technique

The data analysis was carried out in Python, and the model was built using the statsmodels library, valued for its accuracy. This began with the estimation of the regression coefficients and assessing the model for explanatory power using the coefficient of determination (R2). In a bid to prove the regression results as BLUE, a host of classical assumption tests were carried out to prove the results were statistically significant. Starting with the Shapiro-Wilk test for normality of the residuals, with a p-value greater than 0.05 indicating normality, followed by the Breusch-Pagan test for heteroscedasticity, to ensure that the residuals of the model had a constant variance, and finally looking for multicollinearity using the variance inflation factor (VIF) in cases where a value greater than 10 is taken to mean there is significant intercorrelation. At last, the Durbin-Watson test was utilized to examine autocorrelation in the time series, where estimates between 1.5 and 2.5 are interpreted as no significant autocorrelation.

2.5. Robustness and sensitivity analysis

To test the hypothesis and ensure the proposed model's independent variables are valid, this research conducts a sensitivity analysis for structural robustness. More precisely, this research seeks to determine whether the effect of renewable energy on security is the result of a holistic transition (including heat and transport) or whether it is only from the power sector. To do this, a different model specification is estimated to be able to have renewable electricity share acting as the dependent variable instead of modern renewable share.

The specification for this alternative sensitivity model is defined as:

$$ESI_t = \alpha_0 + \alpha_1 REN\_ELEC_t + \alpha_2 DOM\_PROD_t + \mu_t \tag{3}$$

In the equation:

- ESI_t represents the energy security index at time t
- α_0 is the intercept (constant term)
- REN_ELEC_t is defined as the share of renewables in electricity generation
- DOM_PROD_t represents the level of domestic energy production
- α_1 and α_2 are the estimated coefficients for the renewable electricity share and domestic production, respectively
- μ_t denotes the error term.

By comparing the model fit (R2) and the significance of the coefficients in the primary model (equation 1) to those in this alternative model (equation 3), this research empirically isolates the facets of energy transition that are most relevant to Ukraine's energy security. This step accommodates diminishing requirement unfairness and safeguarding that the outcomes are cross-validated with other meanings of renewable energy implementation.

3. Results and discussion

3.1. Descriptive trends and correlation analysis

The analysis of longitudinal data between 2000 and 2020 suggests a relative structural change in the energy security of Ukraine. From the data presented in Figure 1, the energy security index (ESI) illustrates an increase over a period from 2000, 42.70, and in 2020, 51.79. This increase was not uniform, and rather there was a spike starting in 2014, coinciding with the geopolitical crisis and the resulting increased need for diversification of the energy supply. Even though there was volatility in the dependence on energy in previous years, there was an increase in modern renewables (green dashed line), particularly from the 2015 new energy conservation legislation.

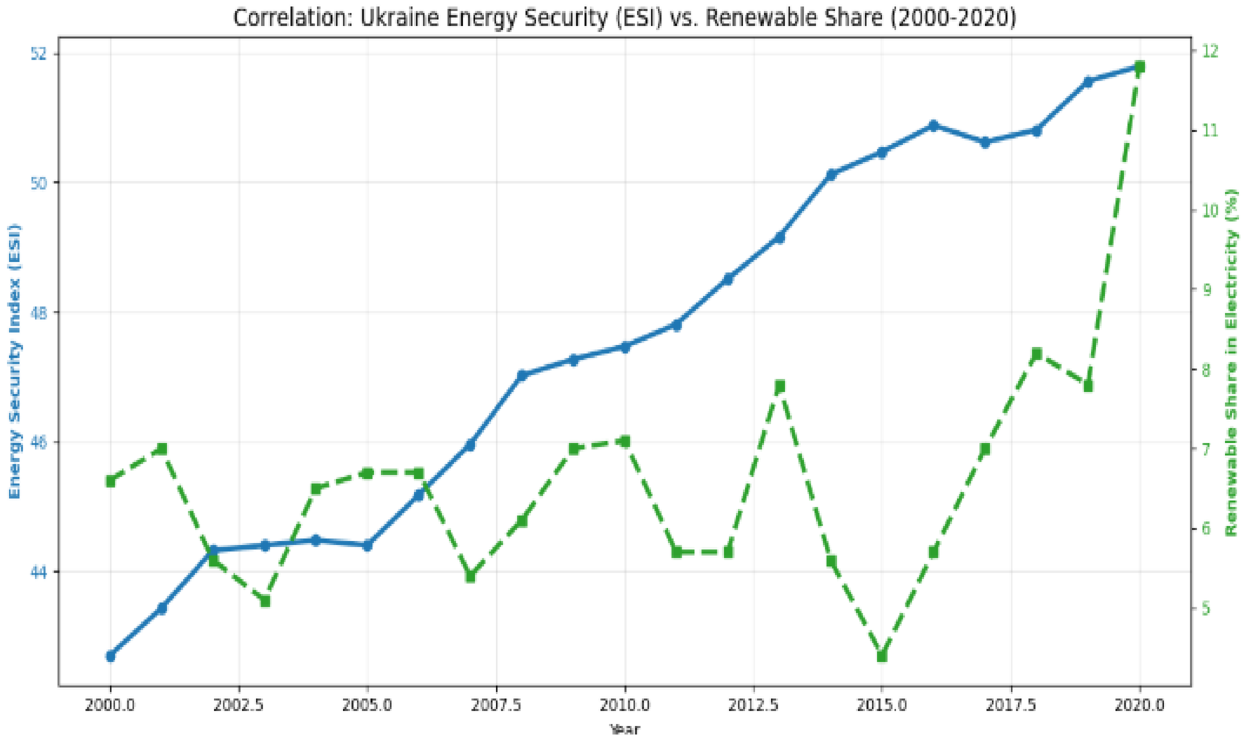

Figure 1. Trends in Ukraine's energy security index and modern renewable share (2000–2020)

The correlation analysis supports the description given. Statistically, the relationship with the pivot to green energy and the alterations in security outcomes is strong and structural. A substantial increase in the share of modern renewables is positively correlated with the ESI, as demonstrated in Figure 2, with a strong linear relationship (r = 0.90). Higher security scores are associated with the adoption of more renewables in the years presented, as showcased in the scatter plot. The data points are tightly clustered around the regression line, suggesting low variance. On the other hand, import dependency had a strong negative correlation (r = -0.87) with the ESI, suggesting that a parallel contributor to security improvements was the decreased reliance on external fuel sources.

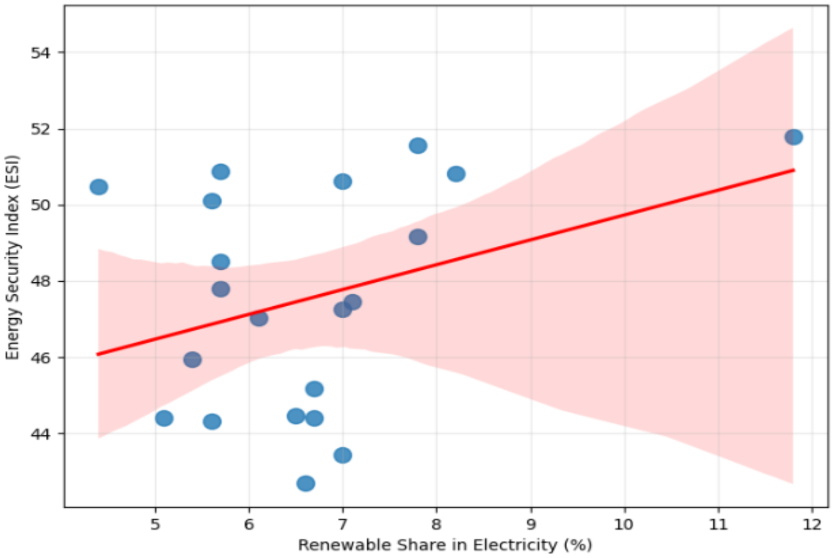

Figure 2. Scatter plot correlation between modern renewable share and energy security index

3.2. Regression analysis

The impact of energy transitions on security outcomes is measured through the regression analysis of multiple linear regression employing the ordinary least squares technique. The model investigated how the contribution of modern renewables and the share of domestic production influence the energy security index. The regression results featured in Table 1 exhibit a strong model with exceptional predictive capabilities. The adjusted R squared (R2) is 0.935. As such, it can be concluded that the shift to renewables and the development of domestic production facilities explain 93.5% of the variance in the energy security index of Ukraine.

Table 1. Regression results

Variable	Coefficient (β)	Std. Error	t-statistic	Prob. (p-value)
Intercept (constant)	31.929	1.897	16.833	0.000***
Modern renewable share	0.823	0.089	9.247	0.000***
Domestic production share	0.202	0.032	6.250	0.000***

The goodness of fit of the model is presented in Figure 3, which shows the actual ESI scores in comparison to the predicted values that were calculated with the model. The closeness of the red dashed line (predicted) to the blue solid line (actual), especially for the turbulent period between 2014 and 2020, is strong evidence that the model holds in the presence of structural breaks due to geopolitical shocks, and the small error (grey shaded area) further indicates the model's accuracy.

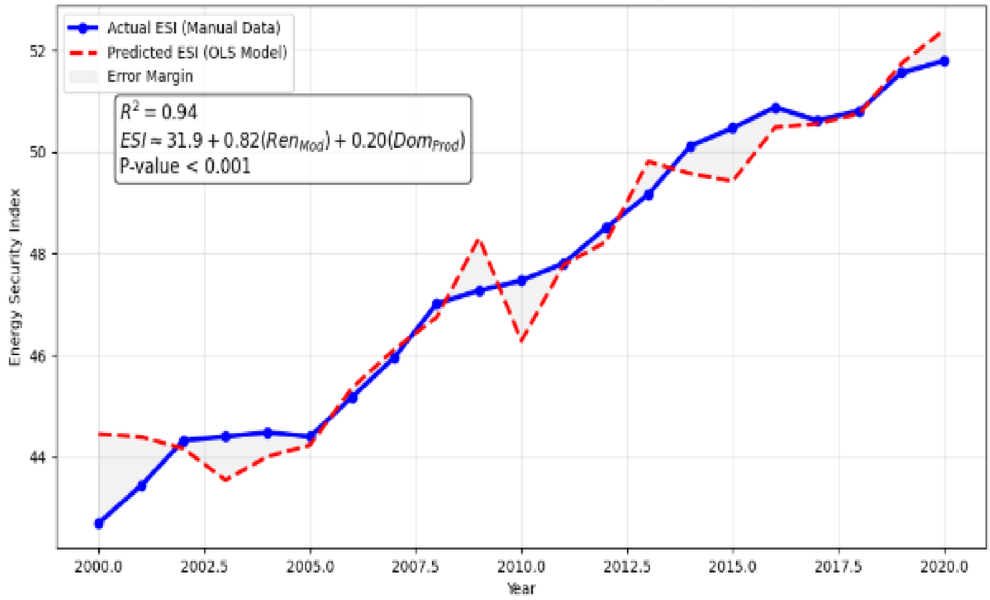

Figure 3. Comparison of actual and predicted ESI scores based on OLS regression model

The share of modern renewables is characterized as positive and statistically significant ($\beta_1 = 0.823$, $p < 0.001$) influence. This indicates that, controlling for other characteristics, an increase of 1 percentage point in the portion of modern renewables, alters the energy security index positively by about 0.82 points. Further, there is the domestic production share that is positive and statistically significant ($\beta_2 = 0.202$, $p < 0.001$) influence. The larger coefficient pertaining to modern renewables indicates that of the qualitative change toward more sustainable sources, there was a greater marginal effect during this time on the security index when compared to the increase in the direction of domestic production of fossil fuels.

3.3. Model robustness and diagnostic tests

To test the validity of the OLS estimators, several classic assumptions were tested. In Figure 4, the Normal Q-Q Plot (left panel), the standardized residuals fit the 45-degree line very closely, confirming normality. The Shapiro-Wilk test (p = 0.567) confirms normality, as the null hypothesis of normality cannot be rejected. In addition, the right panel provides a Residuals vs. Fitted plot, where the random scatter of points around the zero line shows no obvious form (such as a funnel shape), indicating that the residuals are constant, and the residuals' variance is constant as well (homoscedastic).

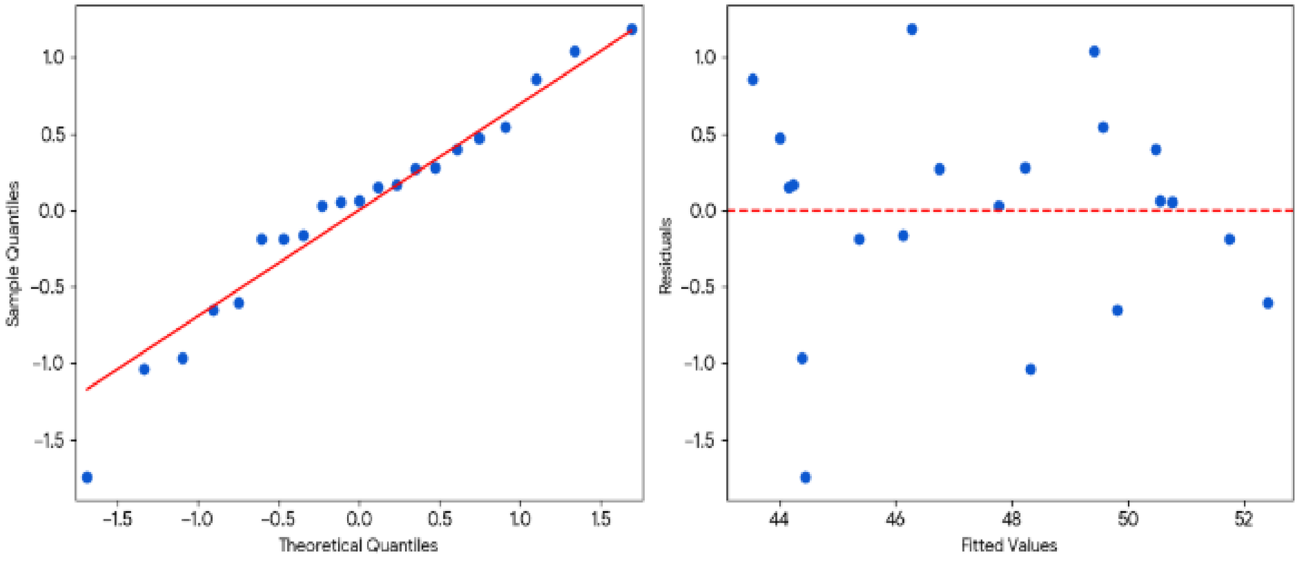

Figure 4. Diagnostic plots: normal Q-Q plot (left) and residuals vs. fitted values (right)

Further analysis shows the model is stable as well. The calculated VIF of 1.51 confirms no harmful multicollinearity is present (less than 5.0). Lastly, the computed Durbin-Watson statistics of 1.42 show the model is free of severe autocorrelation bias, as the value is acceptable. These diagnostics ensure the regression results are stable and unbiased.

3.4. Discussion

3.4.1. Beyond electricity: the critical role of modern renewables in energy security

One of the most important findings of this research is the pronounced impact that the modern renewable share has had on Ukraine's energy security index, while the impact of a statistically insignificant result from the electricity sector remains unchallenged (β_1 = 0.823). This effect is the first to support the thesis on the interdependencies of Ukraine's energy security. As Wąs et al. [33] indicate, the potential biomass of the Kyiv region alone is economically valued at 1,743 thousand tons of oil, which could substitute nearly 43% of the region's annual fossil fuel consumption. This is evidenced by the primary positive correlation within our model, which is the replacement of imported natural gas in district heating systems by domestic biomass and biofuels.

Moreover, the limitations of the comparative analysis within the electricity sector explain why the 'Electricity only' model could not adequately account for the security improvements. Sotnyk et. al [34] explain the fact that while the share of renewable electricity was 13.8% in 2021, there were security-related issues contributed by the inflexible nature of the grid. Worse still, the piecemeal availability of storage facilities produced instability rather than resilient security. On the other hand, renewable heat technologies, particularly biomass boilers and heat pumps, provide a direct and steady substitution of gas boilers, with no need for sophisticated grid balancing [34]. Thus, the statistically backed evidence demands a more extensive construction of energy security. Consequently, true resilience in the case of Ukraine is obtained by an all-encompassing transition that focuses on renewable heat (SDG 7.2) and consequently unclutches the heating sector from gas dependency.

3.4.2. Import substitution and strategic autonomy

Considering the positive sign of the coefficient for the ESI of β_2 = 0.202, regression results further validate the success of Ukraine's import substitution strategy. It resonates the most with the idea of 'Strategic autonomy' as explained by Proedrou (2023), for the transition to renewable energy is not a merely an environmental obligation but a politically driven necessity to mitigate the risks of Russian hegemony. The data of the study reflects a part of history in which Russian gas dependence impaired Ukraine's sovereignty, hence every boost in the production of homegrown bioenergy fortified Ukraine's security.

Biofuels and organic waste, as pointed out by Kurbatova [35], act as a buffer against external energy shocks. Differing from fossil fuel imports that are subjected to geopolitical price fluctuations and supply cuts, agricultural waste is a resource of local control. Our model substantiates the mechanism: the consistent hike of the ESI post 2014 is the period Ukraine started to actively lay its strategy to diversify from Russian gas to domestically sourced energy. This means that the "green transition" in Ukraine serves as a "security transition" as the use of domestically renewable energy resources systematically removes the fossil fuel dependent security gap [36].

3.4.3. Decentralization as a pillar of resilience in wartime

As noted in the descriptive analysis, the upward trend of the ESI in the post-2014 conflicts can be explained by the empirical evidence of flexibility of decentralized solar energy systems. The conflict highlighted the extreme weaknesses that centralized grids have in terms of integrated systems of cyber-physical attacks [37], [38]. In these terms, the transition towards solar PV and small-scale biomass distributed generation systems was a survival strategy. This resilience of decentralized systems underscores why the adoption of distributed renewable energy has accelerated in conflict-affected regions. Wang et al. [39], for instance, claim that decentralized systems, such as microgrids, are more resilient to high-impact extreme events as they are able to function autonomously from the incapacitated central grid.

Our quantitative trend is corroborated by qualitative evidence: the energy security score did not collapse, but rather, adapted despite the infrastructure destruction as high as 50% in certain areas [34]. This adaptability can, amongst others, be attributed to the modular character of renewables, such as in the case presented by Trypolska et al. [40], where it is noted that heat pumps and boilers of biofuels can be units of installations at the building-level. This allows skipping the collapsed district heating networks.

The conclusion drawn here is that enhanced energy security is not an outcome of data manipulation. Instead, it is an indicative of a complete and profound transformation of the Soviet-era architecture dominated by centralized and fragile systems, replaced by decentralized and cohesive systems based on renewables and modified for the exigencies of warfare.

3.4.4. Economic competitiveness: Local value creation vs. imported inflation

The relevance of renewables in our model implies not just economic variables, ease of access and circulation, and their physical availability from within the country. As Stanytsina et al. [41] note, biomass boilers in Ukraine provide a lower levelized cost of heat (LCOH) than heating of premises using natural gas systems. This cost difference stems from the absence of carbon taxes and the logistical costs associated with fossil fuels and gas imports. When using local biomass, the geopolitical pressure from volatile historical gas prices and externally controlled gas markets is removed and replaced by the local price stability of agricultural residues from the domestic, low-cost agrarian system. As a result, the "availability" component of the index for energy security is enhanced as the economy is protected from external inflation.

Equally, their economic impact should not be overstated. The impact of the transfer of fossil imports is net economic contraction. As Yarova et al. [42] point out, the green transition in Ukraine has created more than 50,000 new jobs in the country and has a growth potential which is notable in rural areas where biomass resources are concentrated.

This constitutes a virtuous cycle: with the increase of rural employment comes the increase of economic adaptive capacity and further strengthening of the socio-economic pillars necessary for the national security [43]. Hence, the correlation between the adoption of renewables and the economic security index (ESI) highlights, apart from the energy substitution effect, the greater capacity of the state economically to empower itself from external dependencies [44].

3.4.5. The food-energy nexus: balancing agricultural potential

From the energy transition literature, the debate captures the tension between energy crops and food security. However, our analysis indicates that the security gains in Ukraine derive from a synergistic, not competitive, relations in the crops and energy. According to Tryboi et al. [45], Ukraine’s total bioenergy potential is estimated to be around 25 Mtoe, of which nearly 50% is from agricultural by-products, such as straw and corn stalks, that are not food crops. Furthermore, Voytenko [46] mentions the annual potential from straw from other sources at 175 PJ, which is not highly utilized. This illustrates that in our regression model, the “modern renewable share” is largely a waste-to-energy transition. Therefore, the “food versus fuel” trade-off in the context of Ukraine is not accurate [47].

The presence of 3 to 4 million hectares of unutilized agricultural terrain provides a strategic reserve of these crops that do not invade areas under nutrition [45]. The country can grow some of these (e.g. miscanthus) and continue to serve as a major decarbonization agent as well as a global food guarantor [48]. However, some researchers (e.g. Kyryzyuk et al. [49]) caution that nutrient management soil practices do not necessarily follow this path. Properly integrating these crops and residues into the energy system could maximize environmental and energy security benefits while mitigating potential risks to soil fertility. All the same, there is high consensus that helps position the country as having a strong bioenergy strategy. The geo-bio-energy framework is aimed at fitting the residue of the agriculture crops and the marginal lands, reinforcing the geo energy system autonomy to largely support the availability and sustainability pillars of the energy security index [50].

3.4.6. Policy implications: green reconstruction and EU alignment

In the post-war reconstruction of Ukraine, the findings of this study will need to be reconsidered, as the empirical model demonstrates that the adoption of renewables significantly enhances energy security. Therefore, the “build back better” initiative should not be restricted to the destruction of fossil fuel infrastructure but should emphasize green reconstruction. Troian et al. [51] and Sotnyk et al. [34] state that reconstruction is a once-in-a-lifetime chance to skip to advanced energy-efficient systems like the incorporation of heat pumps and the assimilation of smart energy systems. Nostalgia for a gas-centered system is advised against since it would erode the gains, reflected in the energy security index, that the country has achieved over the past decade.

Further, the alignment with the European green deal (EGD) has been mentioned as an important external anchor for this transition. Despite Wendler [52] and Kramer [53] highlighting the financial and institutional roadblocks associated with alignment with the EGD, our findings indicate that the long-term security gains outweigh these costs. By adopting the EU's regulatory framework, Ukraine will be able to access and utilize financial instruments like REPowerEU, and to interconnect its electricity grid with the European network (ENTSO-E), providing additional security through diversification [54]. Therefore, the policies designed must address the "vested interests" as stated by Wolczuk [26] and expedite the development of the legislative framework which supports a fully renewable-integrated market.

3.4.7. Limitation of the study

This study offers solid findings of the quantitative nature of the study, but several limitations should be mentioned. For one, the observation period of the study (2000-2020) assumes the starting point of the conflict but doesn't account for the 2022 large scale invasion because of delays in international databases. As a result, the 2022 destruction of infrastructure remains unobserved in the decline of the ESI within the regression. The second limitation is that the study is based on an aggregate total of national data that is likely to smooth over the inequalities of the various regions in the adoption of renewables and the associated risk of security and violence in the frontline compared to the west. For this reason, future studies should attempt a more focused regional data analysis to examine the real-time war data that accounts for the damage infrastructure to assess in detailed energy resilience.

4. Conclusions

The study aimed to provide a framework to measure the effects of the adoption of renewable sources on the energy security of Ukraine during the dataset period from 2000 to 2020, which includes a crucial period for the country during the initial challenges of disengaging from a historical dependence on fossil fuels. Upon completion of the primary analysis, we found that the central hypothesis was confirmed: the adoption of renewable energy sources is a strong contributor to national energy security. Over 93.5% of the variables in the regression model were explained, which illustrates that energy security in Ukraine depends on more than just the adequate availability of fossil fuels. Additionally, energy security is fundamentally strengthened by the adoption of renewable energy sources and a comparatively greater self-sufficient domestic manufacturing of energy. The strong negative correlation between the dependence on imports and the ESI score demonstrates that the dependence on imported fossil fuels is a significant component towards energy security.

This research's unique and critical contribution lies in distinguishing between the power sector and the broader energy system. In the robust checks, the share of renewable electricity alone was found not to be a statistically significant predictor of improvement in any dimensions of energy security. However, the share of modern renewables, including renewable heat and transport biofuels, was found to be highly significant and of large impact coefficient. This leads to a critical conclusion: for Ukraine, the security of its energy system is primarily a function of the decarbonization of the heating sector. Given the country’s substantial agricultural resources, integrating biomass and biofuels into district heating systems is the most effective way to reduce dependence on foreign gas, offering a more immediate boost to energy security than electricity sector reforms.

The case for policy to adopt "green reconstruction" in the post-war period is clear with the resilience seen in the ESI during the post 2014 conflict period. This is because decentralized renewables act as a shock absorber for geopolitical shocks. Hence reconstruction should not fall into the trap of restoring vulnerable centralized fossil fuel infrastructure. Alignment with the European Green Deal and integration into ENTSO-E should not be viewed solely as economic modernization. It needs to be seen as a measure of national defence aimed at achieving strategic autonomy.

While the study gives strong evidence for the pre 2022 transition period, the lack of real-time data during the full-scale invasion is a limitation. This is due to data latency for international databases. It is recommended that this study be extended to measure the off-grid renewable systems' resilience during warfare. That said, the period 2000-2020 provides strong evidence for the acceleration of renewables as the best way for Ukraine to ultimately defend its energy sovereignty and guarantee a stable geopolitical environment.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Serhii Dudnikov, Liudmyla Savchenko: study conception and design; Liudmyla Savchenko, Myroslav Sabat, Yurii Shelekh: data collection; Serhii Dudnikov, Liudmyla Savchenko, Myroslav Sabat, Andrii Kozovyi: analysis and interpretation of results; Andrii Kozovyi, Yurii Shelekh: methodology development; Serhii Dudnikov: draft preparation; Liudmyla Savchenko, Myroslav Sabat: critical revision of the manuscript for important intellectual content. All authors approved the final version of the manuscript.

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