The Energy Efficiency Dilemma: CO_2 Mitigation and the Economy-wide Rebound Effect in European Nations

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Abstract— **In today's world, climate change is a reality that affects everyone, though the severity and nature of its impact varies across different regions. Energy efficiency is often viewed as a pivotal strategy for reducing CO_2 emissions and mitigating climate change. This research explores the dual nature of energy efficiency improvements, particularly focusing on the unintended economy-wide rebound effect, which can offset anticipated reductions in CO_2 emissions. While advancements in energy efficiency are designed to lower energy consumption, they often result in reduced costs that increase energy demand across various sectors. This paper examines empirical evidence from various European countries, using the 2000-2021 period. Conclusions show that there is a backfire rebound effect in the short run and a partial rebound effect in the long run; that is, in the short run, energy demand is offset by energy efficiency, but in the long run, actual resource savings are less than expected.**

Index Terms-- **carbon emissions; climate policy, CO_2 mitigation, economy-wide impact, energy efficiency, European countries, rebound effect.**

I. INTRODUCTION

Climate change is a real and pressing issue, though its effects differ in intensity and nature depending on the region. Strategies to reduce carbon dioxide (CO_2) emissions and mitigate climate change mainly involve the transition to renewable energy (investment in sources such as solar, wind, hydroelectric, and biomass) and energy efficiency (improving the use of electricity in industries, homes, and transport) [1].

An identified problem with energy efficiency is the energy rebound effect, which can occur when gains in energy efficiency led to an increase in energy consumption, reducing or even canceling out the expected benefits of energy savings. This can happen because reducing the cost of using a resource encourages greater consumption of that resource [2] . Types of Rebound Effect (see [3]) can be pointed as the Direct Rebound, which occurs when greater efficiency reduces the cost of using technology, leading to an increase in its use; the Indirect Rebound, which happens when the money saved by an efficient technology is spent on other goods or services that also require energy; and the Economic (or Macroeconomic) Rebound, that occurs when energy efficiency reduces production costs and generates economic growth, which can increase the overall demand for energy. The effect can be partial, total, or Super-compensating (Backfire) when the increase in energy consumption exceeds the efficiency gains, resulting in higher energy consumption than before [4].

The rebound effect can also be decomposed into four effects [5]: (i) substitution effect, when more energy is used when its price is lower; (ii) output effect, when producers use monetary energy savings to increase production, and consequently labor, capital, and raw materials, increasing energy consumption; (iii) compositional effect, as relatively energy-intensive products benefit more when energy prices fall; (iv) competitiveness effect, that occurs when commodities prices go down because cheaper energy is used in their production process; (v) income effect, as energy prices fall, and households have the more available income to be spent in commodities, including energy (direct and indirectly).

Some studies were to estimate the extension of this effect applied to some specific places or policies. For instance, Wang et al. [6] developed a double logarithm energy demand model and an error correction model to examine how changes in electricity prices asymmetrically affect residential electricity consumption in Beijing. They assumed that a decrease in electricity prices was comparable to an increase in energy efficiency. Their findings indicated that residential electricity consumption experiences a partial rebound effect, with long-term direct and indirect rebound effects ranging from 46% to 56%. In comparison, the short-term direct rebound effect falls between 24% and 37%. However, they found no evidence of a backfire effect in either the short or long term, suggesting that improvements in energy efficiency still contribute to reducing household electricity consumption in Beijing.

Given that China is the world's largest consumer of fossil fuels, Chen et al. [7] analyzed the rebound effects of both fossil and non-fossil energy using the DEA-Malmquist index and the LMDI approach for the period between 1992 and 2013. Their study found that the average rebound effect for total energy, fossil fuels, and non-fossil fuels was approximately 47.16%, 48.50%, and 29.20%, respectively. Through econometric analysis, they confirmed that China's technological advancements primarily aimed at enhancing fossil fuel efficiency, which explains why the fossil fuel rebound effect represented the largest share of the total energy rebound effect. Moreover, by applying the Slutsky equation, the researchers introduced a novel method to break down the rebound effect into substitution and output effects without assuming specific production functions. Their findings revealed that the substitution effect accounted for over 80% of the rebound effect for both fossil and non-fossil energy sources.

Brookes [8] examined the broader impact of efficiency improvements on economic growth and highlighted an "efficiency fallacy." He suggested that increasing efficiency would stimulate industrial expansion and economic growth, ultimately resulting in higher energy consumption. Also, Robaina and Arshad [4] estimated the economy-wide rebound effect in ASEAN countries and concluded that in the short run, there is a backfire effect; that is, all efficiency gains are offset by increased demand for energy. But in the long run, there is only a partial rebound. Only in Vietnam does energy efficiency gain stimulate a more than proportionate decrease in energy consumption in the long run. Mashhadi Rajabi [9] states that, despite over forty years of research on the topic, the literature on the energy rebound effect has yet to provide sufficient explanations regarding its origins, underlying mechanisms, and impacts. This knowledge gap presents a major challenge in formulating effective policies to limit energy consumption and lower greenhouse gas emissions.

In European economies, where stringent climate policies and emission reduction targets are in place, understanding the rebound effect is critical to accurately estimate the net impact of energy efficiency measures on CO_2 mitigation [10]. For instance, Karakaya et al [11], compare material and energy efficiency and their rebound effects, providing insights into their implications for sustainability and climate change policies, for the European Union member countries and their major trading partners from 1995 to 2019. They found that developed EU countries and affluent trading partners exhibit higher material and energy efficiency scores, while less developed members and partners rank lower. Moreover, they found a positive correlation between efficiency improvements and rebound effects, suggesting that policymakers should take the rebound issue seriously.

The present paper examines empirical evidence from various European countries, analyzing their energy efficiency and calculating energy efficiency elasticities and rebound effects. First, it adds knowledge about this issue for European countries, as literature is scarce in the European region; second, it distinguishes from previous literature, as it calculates the effects in the short and in the long run. This is particularly important as in the long run, the rebound effect could be dissipated. We particularly focus on the unintended economy-wide rebound effect. The economy-wide rebound effect is increasingly relevant for understanding the true impact of energy efficiency improvements and designing effective climate policies. While micro-level rebounds (e.g., individual households using savings from LED bulbs to buy more electronics) are important, economy-wide analysis captures systemic interactions that determine net energy savings. In the next section, we present the methodology and variables used, the third section presents the results, and section four concludes.

II. METHODOLOGY AND VARIABLES

This study explores the intricate relationship between energy consumption, energy price, carbon emissions, and some macroeconomic variables as economic growth, spanning 2000-2021 in Europe. The sample (cross-sections and time) was selected based on the data availability with World Development Indicators [12] and the United Nations [13] datasets. As the EU commits to achieving carbon neutrality by 2050, it faces the challenge of balancing economic growth and further development with environmental sustainability and planetary boundaries. This paper critically analyzes the implications of different energy sources on economic prosperity and carbon emissions, aiming to provide actionable insights for policymakers and stakeholders.

Methodologically, standard tests and techniques are employed, including descriptive analysis, correlation, cross-sectional dependence, unit root, and co-integration tests. Further, there are three stages to achieve the aim of the current study. In the first stage, the study employed Stochastic Frontier Analysis (SFA), which was introduced by Aigner et al. [14] to calculate energy efficiency scores. To do so, we used the aggregate energy demand function introduced by Filippini and Hunt [15]. In the second stage, the economy-wide rebound effect is estimated using a two-step GMM proposed by Arellano and Bond (1991) and developed by Arellano and Bover (1995). Finally, in the third stage, the GMM dynamic model is also used to estimate the short—and long-run energy efficiency elasticities.

The Filippini and Hunt demand function is as follows:

$$ED_{it} = f(P_{it}, EG_{it}, POP_{it}, Area_{it}, SH_{it}, VA_{it}, ET_{it}) \qquad (1)$$

Where ED_{it} is final aggregate energy consumption (Ktoe), P_{it} the real energy price (in constant 2015 US$), EG is the real GDP (in constant 2015 US$), POP is the population size, Area is the size of the country (in square km), SH is the share, and VA is the value added of the industrial and agriculture sectors (in % GDP), respectively. ET represents the energy demand trend. The subindexes of each variable are *i* for country and *t* for year.

Applying the natural log, the equation of the demand function is as follows:

$$ED_{it} = \alpha_0 + \alpha_1 P_{it} + \alpha_2 EG_{it} + \alpha_3 POP_{it} + \alpha_4 Area_{it} + \alpha_5 SH_{it} + \alpha_6 VA_{it} + \alpha_7 ET_{it} + \in_{it} \quad (2)$$

Whereas the intercept is α_0 and $\in_{it}$ stands as an error term. In addition, the error term is divided into two components: μ_{it} is an idiosyncratic error term, independent and identically distributed, and technical efficiency ϑ_{it} (see equation 3). ϑ_{it} symbolizes waste energy and is assumed to be one-sided, non-negative disturbances that follow the half-normal distribution [16] in the true fixed effect model.

$$\in_{it} = \mu_{it} - \vartheta_{it} \quad (3)$$

$$\vartheta_{it} \sim N(0, \sigma^2) \quad (4)$$

$$\mu_{it} \sim N(0, \sigma^2) \quad (5)$$

Technical energy efficiency (EE) can be determined by the guidelines of Jondrow et al.[17], and can be measured by SFA.

$$EE_{it} = \frac{ED_{it}^{f}}{ED_{it}} = \exp(\vartheta_{it}) \quad (6)$$

The maximum efficiency (=1) happens when the dependent variable ED is equal to the frontier of technical efficiency (ED^f) [17]. Thus, the new equation, after adding technical efficiency is:

$$ED_{it} = \alpha_0 + \alpha_1 P_{it} + \alpha_2 EG_{it} + \alpha_3 POP_{it} + \alpha_4 Area_{it} + \alpha_5 SH_{it} + \alpha_6 VA_{it} + \alpha_7 ET_{it} + \alpha_8 EE_{it} + \mu_{it} - \vartheta_{it} \quad (7)$$

In the second stage, the economy-wide rebound effect is estimated using a two-step GMM proposed by Arellano and Bond [18], and developed by Arellano and Bover [19]. The estimated model in log form for the second stage is as follows:

$$lnED_{it} = \alpha_1 + \delta lnE_{it-1} + \alpha_p lnP_{it} + \alpha_e lnEG_{it} + \alpha_f lnEE_{it} + \alpha_t\, t + \alpha_{pf}\, P * EE_{it} + \alpha_{yf} EG * EE_{it} + \alpha_{yp} EG * P_{it} + \emptyset_{it} + \tau_{it} \quad (8)$$

Where $lnED_{it}$ and lnE_{it-1} reflect total energy consumption and lag term, respectively. In addition, EE stands for energy efficiency, which is measured in stage one. $\alpha's$ are the parameters to be estimated by the model, and the values of $\alpha's$, will be used to compute the elasticity of energy demand with respect to changing energy efficiencies. *t* is time. The nonlinearity is considered by interacting energy efficiency with energy prices and income.

Additionally, the rebound effect can be quantified as Saunders [20] suggested.

$$R = 1 + \rho^E \quad (9)$$

Where, ρ^E is the energy use's elasticity with respect to changes in energy efficiency.

Moreover, according to Saunders [20], there are five possibilities for the rebound effect: (1) super conservation or negative rebound ($RE < 0$), indicates that actual resource savings exceed anticipated savings; (2) zero rebound ($RE = 0$), which fully realizes the improvement in energy efficiency; (3) partial rebound ($0 < RE < 1$), when the actual resource savings are less than anticipated, also known as the 'take-back' effect, the most common result of empirical studies on individual markets; (4) Full rebound ($RE = 1$), when the actual resource savings are equal to the increase in consumption and (v) Backfire (RE > 1), when an increase in energy demand exceeds the gain in energy efficiency. This situation is commonly known as the Jevons paradox.

In the third stage, the GMM dynamic model is also used to estimate the short-and long-run energy efficiency elasticities. It is expected that both elasticities to be negative since energy efficiency and energy generation sources such as crude oil have an inverse relationship. This means that improved energy efficiency will most likely reduce the fuel required to deliver a given level of energy service.

III. RESULTS AND DISCUSSION

Table I presents the ranking of the top ten countries based on energy efficiency for 2000-2021, determined by using equation 6. The highest energy efficiency score is from Luxembourg, followed by Germany and Ireland. All values are below 0.8, which are not low scores, but not very close to 1 (total efficiency).

Moreover, Table II presents the findings from the estimated two-step GMM. Except for the price coefficient, most of the computed coefficients seem to have the expected sign and are statistically significant, at least at the 5% level of significance.

TABLE I. TOP TEN ENERGY EFFICIENT COUNTRIES

Countries	Energy efficiency Score	Rank
Luxembourg	0.80	1
Germany	0.74	2
Ireland	0.71	3
Latvia	0.65	4
Denmark	0.64	5
Spain	0.60	6
Poland	0.58	7
France	0.57	8
Estonia	0.56	9
Greece	0.55	10

TABLE II. GMM RESULTS

Dependent Variable: Energy Demand	**Coefficients**
$\boldsymbol{E_{t-1}}$	0.74^{b} (0.04)
Price ($\boldsymbol{P_{it}}$)	0.15^{c} (0.09)
Economic Growth ($\boldsymbol{EG_{it}}$)	0.28^{b} (0.05)
Energy Efficiency ($\boldsymbol{EE_{it}}$)	0.12^{a} (0.01)
Time (t)	0.80 (0.15)
Economic Growth* price	0.05^{b} (0.06)
Price *Energy Efficiency	-0.08^{c} (0.08)
Economic Growth *Energy Efficiency	0.006^{a} (0.01)
Number of Instruments	27
AR (1)	0.000
AR (2)	0.36
Hansen Test	0.46

Note: a, b, and c represent 1%,5%, and 10%, respectively. P-values reported in parenthesis

Energy Efficiency has a positive estimated coefficient, which shows that it can increase energy consumption. The positive coefficient of energy prices and economic growth shows that there is a direct relationship between existing energy prices and economic growth with energy consumption. Furthermore, it is generally accepted that rising energy prices stimulate technological development, which in turn leads to increases in energy efficiency and a consequent decline in energy use [21]. Moreover, to meet the instant energy demand, nations rely on non-renewable sources, especially fossil fuels, which deteriorate the environment [22]. These non-renewable energy sources increase prices. Moreover, economic growth and energy efficiencies positively influence energy demand in the sample EU economies.

Moreover, the negative sign of the estimated coefficients of the interaction term between energy prices and efficiency suggests that this is the case in developed countries. In advanced countries like the EU, economies have a more stable energy supply and higher prices, which can mitigate the rebound effect. Moreover, the interaction between energy prices and energy efficiency means that technological investment initially increases prices. However, technological advancements in investment result in energy efficiency and decreased energy demand.

In addition, the interaction terms between price, income, and efficiency allow for the separation of price or income-induced effects from other exogenous efficiency effects, thus eliminating the issue of overestimated efficiency elasticity. Later, it can explain the statistically insignificant coefficient of the time trend since some of the exogenous effects may have been captured from the interaction terms.

Moreover, AR(1) and AR(2) confirmed the absence of first- and second-order autocorrelation. In addition, the AR (2) test is more important in detecting the second order of autocorrelation and identifying the system's two-step GMM to be valid. Given 0.46 p-value of the Hansen test and chi-square values implying that the instrument is valid, which is supported by the two-step GMM model. Moreover, the Sargan test result (0.61) indicates that the over-identifying limits in System GMM's estimates were valid for all parameters.

Following the analysis, both the short—and long-term energy efficiency elasticities can be computed using the estimated coefficient from the GMM dynamic panel data energy model, as explained in the preceding section. Additionally, point efficiency elasticities are computed for each country in the panel to calculate the rebound effect.

Table III results show that the estimated efficiency elasticities vary between 6% to 8% in the short run and 3.5% to 5% in the long run. This means that raising energy efficiency in 1% raises energy consumption in 8% in the short run, for instance, for Luxembourg, and in 5% in the long run. Elasticities in the long run are lower than in the short run. The elasticity is higher for countries with higher energy efficiency scores.

The rebound effect of the top 10 sampled economies varies between 1.09 to 1.65 in the short run and from 0.09 to 0.40 in the long run. In the short run, there is backfire (RE > 1), which means an increased demand for energy offsets energy efficiency gains. This rebound effect is higher for countries with higher energy efficiency scores. In the long run, there is a partial rebound; that is, actual resource savings are less than expected.

TABLE III. ESTIMATED ELASTICITIES AND REBOUND EFFECT

	Elasticities		Rebound Effect	
Countries	Short run (%)	Long run (%)	Short run	Long run
Luxembourg	8	5.0	1.65	0.40
Germany	7.4	4.9	1.64	0.25
Ireland	7.0	4.6	1.60	0.26
Latvia	6.9	4.3	1.52	0.36
Denmark	6.8	4.1	1.52	0.20
Spain	6.4	4.1	1.40	0.18
Poland	6.3	3.9	1.37	0.16
France	6.2	3.8	1.26	0.15
Estonia	6.2	3.6	1.12	0.12
Greece	6.0	3.5	1.09	0.09

Indeed, this is in accordance with Karakaya et al [11] that concluded that developed EU countries and their affluent trading partners generally ranked higher in material and energy efficiency scores, while less developed members and partner countries ranked lower. They justify this as developed countries tend to have more time and resources to invest in improving their production processes and technologies than developing countries. They also conclude about the existence of rebound effects, which are generally overlooked by countries, organizations, and stakeholders. Moreover, as our study, they found that this rebound effect is higher in more resource-efficient countries. This indicates that rebound effects can offset some of the benefits of resource efficiency improvements, particularly in high-income countries. Therefore, policymakers should be cautious when implementing resource efficiency measures and consider potential rebound effects to ensure that they are effective and sustainable.

IV. CONCLUSIONS

The present study examines the contribution of energy efficiency improvements to mitigating CO2 emissions through the estimation of the "rebound effect" for a panel of European countries in the period 2000-2021. In the first step, the SFA is applied to calculate energy efficiency. Secondly, two-stage GMM is applied for the short—and long-run energy efficiency elasticities. Furthermore, the rebound effect is calculated using energy efficiency elasticities.

Results showed that Luxembourg, Germany, and Ireland are the most efficient countries, although their efficiency values are not too close to one another.

The GMM results show that past trend growth in energy consumption improves present energy consumption. Moreover, economic growth also has a positive coefficient, showing that economic activity growth needs more energy, but in a proportion lower than one, which could mean a lower energy intensity or energy efficiency. The positive coefficient of energy prices could be explained as rising energy prices stimulating technological development, which in turn leads to increases in energy efficiency. As we found, a rebound effect led to a rise in energy consumption. Furthermore, the coefficient of energy efficiency is positive, showing that an increase in efficiency will increase energy consumption, although the coefficient is lower than one. These results were also confirmed by [8]. Accordingly, we concluded that there is a backfire rebound effect in the short run and a partial rebound effect in the long run; that is, in the short run, energy demand is offset by energy efficiency, but in the long run, actual resource savings are less than expected. This effect is stronger in more energy-efficient countries. Similar conclusions were found in [4] for ASEAN countries.

Given that the rebound effect tends to be stronger in the short run than in the long run, policies for European countries should focus on measures that mitigate this initial impact and ensure effective reductions in energy consumption in the long term. Indeed [23] provides a nuanced view of rebound effects and their implications for energy efficiency policies, emphasizing the need for careful analysis and consideration of both micro and macroeconomic factors in policy design. It emphasizes that policymakers need reliable information about the magnitude of the rebound effect to design effective energy efficiency policies. Some strategies should include pricing and regulatory policies, such as carbon and energy taxation, applying taxes on fossil fuel and energy consumption to discourage increased use even after efficiency gains. Furthermore, the European Emissions Trading System (EU ETS) should be strengthened to ensure that reduced energy demand translates into lower CO_2 emissions. Stricter standards and regulations, like the imposition of minimum energy efficiency standards for equipment, buildings, and industries, preventing increased consumption due to new demands, could also diminish the long-run rebound effect.

But the increase in energy consumption, namely electricity, could not mean necessarily more emissions, as incentives for renewable energy could ensure that any increase in energy consumption is supplied by clean sources, reducing environmental impact.

Additionally, campaigns about behavioral change and conscious consumption can be relevant to encourage the population to not only seek efficiency but also reduce energy waste. In fact, [24] examines various policy strategies, including carbon taxes and changes in consumption patterns, to offset rebound effects while maintaining economic benefits. The authors emphasize that a more complex policy strategy with coordinated measures could provide the desired results in offsetting energy and carbon rebound effects while maintaining economic benefits. Combining these policies can help mitigate the rebound effect and ensure that energy efficiency gains actually result in reduced total energy consumption and greenhouse gas emissions.

This study has certain limitations, particularly regarding the period analysis, limited to 2021, which restricts its generalizability. Once comprehensive data becomes available, future research directions could expand the scope with the latest information. Moreover, the studied period comprises the COVID-19 pandemic that has created a complex and dynamic energy landscape. While some factors may temporarily suppress rebound effects, others could amplify them in the long term. Policymakers will need to carefully consider these evolving dynamics when designing energy efficiency policies and assessing their effectiveness. The pandemic initially led to a dramatic reduction in energy consumption across most sectors, particularly in transportation and services. This unprecedented drop in demand temporarily masked potential rebound effects. So, its relevant to extend the period of study, as the crisis has heightened awareness of energy efficiency. EU countries enhanced LNG capacities and diversified suppliers, potentially leading to more efficient energy use and altering rebound dynamics.

Additionally, this study employs a single method to examine short- and long-run elasticities. Future studies could enhance robustness by incorporating alternative methodologies for calculating energy efficiency and applying advanced econometric techniques, such as ARDL-CS, GMM system, and GMM difference, to refine elasticity estimates.

Furthermore, integrating additional economic variables—such as trade openness, technological advancements, and carbon intensity—into the model could provide deeper insights into the broader implications of energy efficiency for climate change and economic sustainability.

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