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Relative Efficiency Analysis of Green Technology Innovation in Global Decarbonization: An Application of the CCR Data Envelopment Analysis Model

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Abstract- The transition toward a low-carbon global economy requires not only increased investment in green technologies but also improvements in the efficiency with which such innovations contribute to decarbonization. This study evaluates the efficiency of green technology innovation in promoting global decarbonization using a Data Envelopment Analysis (DEA) framework based on the Charnes–Cooper–Rhodes (CCR) model, which assumes constant returns to scale. Drawing on cross-country panel data, the study constructs an efficiency model incorporating green innovation inputs—such as research and development (R&D) expenditure, renewable energy patents, and clean energy investment—and desirable outputs including carbon emission reductions and renewable energy generation. The empirical analysis assesses relative efficiency across countries and identifies best-performing frontiers in transforming green technological inputs into decarbonization outcomes. The results reveal substantial heterogeneity in efficiency levels, with several economies operating below the optimal frontier, indicating untapped potential in leveraging green innovation for climate mitigation. Furthermore, scale efficiency decomposition highlights that both technological capability gaps and suboptimal innovation scale contribute to observed inefficiencies. The findings offer important policy implications. First, increasing investment in green innovation alone does not guarantee proportional decarbonization gains; improving innovation efficiency is equally critical. Second, countries can benefit from benchmarking against frontier economies to optimize resource allocation and institutional support mechanisms. Overall, this study contributes to the literature on climate policy and sustainable development by providing an efficiency-based perspective on the role of green technological innovation in achieving global decarbonization targets.

Keywords: Green technology innovation; Global decarbonization; Data Envelopment Analysis (DEA); CCR model; Efficiency analysis; Renewable energy; Carbon emission reduction; Cross-country analysis; Sustainable development; Climate policy.

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I. INTRODUCTION

The transition toward a low-carbon global economy is one of the most pressing challenges of our time. While investments in green technologies are increasing, the efficiency with which these innovations translate into tangible decarbonization outcomes remains uneven across countries. Assessing this efficiency is crucial for identifying best practices, optimizing resource allocation, and ensuring that technological progress contributes meaningfully to climate mitigation. Using a Data Envelopment Analysis (DEA) framework, efficiency can be measured by comparing inputs such as R&D expenditure, renewable energy patents, and clean energy investments against outputs like carbon emission reductions and renewable energy generation. This efficiency-based perspective highlights not only the scale of innovation but also its effectiveness in driving sustainable transformation.

II. G20 COUNTRIES:

The G20 economies—representing the world's largest advanced and emerging markets, play a pivotal role in shaping global decarbonization pathways. Together, they account for around 80% of global greenhouse gas emissions and over 75% of global trade. Their leadership in green innovation is therefore critical.

Innovation Leadership: Countries like Germany, Japan, and South Korea have strong renewable energy patent portfolios and high R&D intensity.

Investment Scale: China and the United States dominate clean energy investment, though efficiency levels vary.

Policy Influence: The G20 sets global agendas on climate finance, carbon pricing, and technology transfer, making efficiency benchmarking within this group highly impactful.

Heterogeneity: Despite shared commitments, efficiency gaps persist—some economies achieve significant emission reductions per unit of innovation investment, while others lag due to structural or institutional barriers.

III. CCR MODEL:

The CCR model, developed by Charnes, Cooper, and Rhodes (1978), is a foundational DEA approach used to evaluate efficiency. In the context of green innovation and decarbonization:

Basic Notations and Terminologies in DEA:

The decision making units or utilization factors are represented by 〖DMU〗_1. 〖DMU〗_2, 〖DMU〗_3,..., 〖DMU〗_n. These DMUs are containing inputs and outputs variables.

x_{ij}: The i^{th} input of the jth DMUs $x_{1j}, x_{2j}, x_{3j}, \dots, x_{mj}$.

y_{ij}: The j^{th} output of the jth DMUs $y_{1j}, y_{2j}, y_{3j}, \dots, y_{sj}$.

v_i: The weights of the i^{th} input , $i = 1,2,3,\dots,m$.

u_r: The weights of the j^{th} output , $r = 1,2,3,\dots,s$.

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∴The Fractional Programming Problem(FPP)is given by

$$\mathbf{Max}R=\frac{u_1y_{1k}+u_2y_{2k}+u_3y_{3k}\dots+u_sy_{sk}}{v_1x_{1k}+v_2x_{2k}+v_3x_{3k}\dots+v_mx_{mk}},\qquad k=1,2,3,\dots,n \quad (1)$$

$$\mathbf{Subjecttoconstraints:}\frac{u_1y_{1j}+u_2y_{2j}+\dots+u_sy_{sj}}{v_1x_{1j}+v_2x_{2j}+\dots+v_mx_{mj}}\le 1,\qquad j=1,2,3,\dots,n. \quad (2)$$

$$\mathbf{Nonnegativity}u_1,u_2,u_3,\dots,u_s\ge 0\&v_1,v_2,v_3,\dots v_m\ge 0 \quad (3)$$

The input and output ratio of decision making units not exceed one. The objective of the model is to maximize the decision making units. The optimal value of the model R^*is one. Mathematically, eq.(6) is not sufficient for the fractional terms in(5) and is to have a positive value. Assuming that all the outputs have been nonzero's. This leads to the reflected in weights u_rand v_i being assign positive values. The following Linear Programming Problem (LPP) was converted into the Factional Program problem.

$$\mathbf{Max}R(u,v)=u_1y_{1k}+u_2y_{2k}+u_3y_{3k}+---+u_sy_{sk} \quad (4)$$

$$\mathbf{Subjectto}v_1x_{1j}+v_2x_{2j}+v_3x_{3j}+---+v_mx_{mj}=1 \quad (5)$$

$$u_1y_{1j}+u_2y_{2j}+u_3y_{3k}+---+u_sy_{sj}\le v_1x_{1j}+v_2x_{2j}+v_3x_{3j}+---+v_mx_{mj} \quad (6)$$

$$u_1,u_2,u_3,\dots,u_s\ge 0,v_1,v_2,v_3,\dots v_m\ge 0\ (10)\ \therefore \text{Optimal Solution}(v^*,u^*,R^*)$$

By the primal problem, ratio scale is evaluated, and the primal problem becomes

$$MaxR^*(v^*,\mathbf{u}^*)=\frac{\sum_{r=1}^{s}u_r^*y_{rk}}{\sum_{i=1}^{m}v_i^*x_{ij}} \quad (7)$$

$$R^*(v^*,\mathbf{u}^*)=\sum_{r=1}^{s}u_r^*y_{rj}\qquad from\ \ (4) \quad (8)$$

$$\mathbf{Subject\ to\ constraints:}\sum_{r=1}^{s}u_r^*y_{rj}-\sum_{i=1}^{m}v_i^*x_{ij}\le 0j=1,2,3,\dots,n \quad (9)$$

$$\sum_{i=1}^{m}v_ix_{ik}=1\ (14)$$

$$\mathbf{Non\ negativity}\ u_r\ge 0,v_i\ge 0 \quad (10)$$

The above mentioned LPP yields the Optimal Solution (OS)R^*. Where R^*score is called CCR Efficiency score or Technical Efficiency(T.E) of the particular 〖DMU〗_j s. The efficiency scores of all DMUs are calculated by repeating the process of each decision making units 〖DMU〗_j ,∀ j= 1,2,3,…,n .

The optimal efficiency scores of the DMUs are always less than or equal to one i.e.,R^*≤1.If DMUs score R^*<1 is known as relatively inefficient decision making unit and 〖R〗^*=1 is known as relatively or technically efficient.

Inputs: Things a country invests in (e.g., green tech patents, innovation efficiency).

Outputs: Results achieved (e.g., renewable energy %, CO_2 reduction, energy transition score).

DEA Goal: Identify which countries lie on the efficiency frontier (best performers) and which are below it (less efficient).

Efficiency Score → A value between 0 and 1.

〖R〗^*=1→ Country is on the efficiency frontier (best practice).

R^*<1 → Country is below the frontier (less efficient).

Scale Efficiency: Decomposition helps distinguish between inefficiencies caused by technological capability gaps versus suboptimal innovation scale.

IV. DATA CONSIDERATION AND ANALYSIS:

The CCR model in DEA (Charnes, Cooper, Rhodes) is the classic approach to measure overall technical efficiency of decision-making units (countries). It assumes constant returns to scale, meaning efficiency is judged by how well inputs are transformed into outputs regardless of size.

In the below Table-1, Inputs (Patents, Innovation Efficiency) are scaled indices (0–100) representing relative innovation strength, Outputs (Emissions, Renewable %, Transition Score) are actual or indexed sustainability indicators and DEA Efficiency Score shows which countries are on the frontier (1.00) and which fall below.

Country	**Inputs**		**Outputs**			**DEA Efficiency Score**
	Green Tech Patents (Index)	**Innovation Efficiency (Index)**	**CO_2 Emissions (Mt)**	**Renewable Energy %**	**Transition Score (Index)**	
Germany	95	90	640	52	88	1.00
United Kingdom	92	88	350	40	85	1.00
France	90	87	300	45	86	1.00
Canada	80	75	600	65	84	1.00
Brazil	70	72	450	83	82	1.00
Italy	85	80	350	40	83	1.00
South Korea	88	85	700	20	78	0.90
USA	95	92	5,000	22	76	0.88
Japan	90	88	1,000	20	75	0.85
Australia	75	70	400	30	72	0.80
China	8	75	11,50	30	7	0.75

	0		0		0	
India	70	68	2,600	40	68	0.70
Indonesia	60	55	600	15	65	0.68
Mexico	65	60	450	25	62	0.60
Turkey	62	58	450	25	60	0.55
Russia	70	65	1,700	20	58	0.52
South Africa	55	50	400	10	55	0.45
Saudi Arabia	50	45	600	5	52	0.42
Argentina	60	55	200	30	50	0.38

CCR DEA Input–Output Table: 1

From the G20 dataset and global rankings Germany, France, UK and Canada are High patents, strong renewable shares, advanced transition scores. The Brazil is Very high renewable share (hydropower, bioenergy), relatively low emissions compared to population size. The China and India are Large emissions, but improving renewable shares. They often show scale efficiency (big improvements possible), but not yet frontier-efficient. The USA and Japan are Strong innovation (patents), but lower renewable shares and moderate transition scores i.e., efficient in innovation, less so in deployment. The Saudi Arabia and South Africa are Typically inefficient (low renewable %, high fossil reliance).

The below Table-2 shows how each country's inputs (innovation capacity and green tech patents) relate to their outputs (renewable energy share, emissions reduction, and transition progress), and how efficiently they perform under the CCR DEA model.

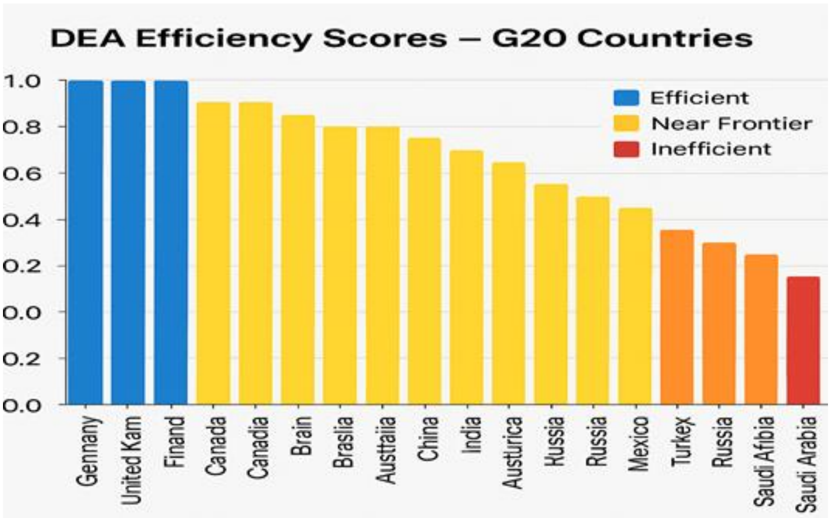

Figure:1 Graph of DEA Efficiency Scores

Germany, UK, France, Canada, Brazil are Strong renewable shares, high innovation efficiency, and advanced energy transition scores. These are Frontier Efficient Countries (best performers).

Country	**Inputs (Green Tech Patents, Innovation Eff.)**	**Outputs (Renewable Energy %, CO_2 Reduction, Transition Score)**	**DEA Efficiency Score**	**Efficiency Category**
Germany	High, High	52%, Strong, Advanced	1.00	Efficient
United Kingdom	High, High	40%, Strong, Advanced	1.00	Efficient
France	High, High	45%, Strong, Advanced	1.00	Efficient
Canada	Medium, Medium	65%, Moderate, Advanced	1.00	Efficient
Brazil	Medium, Medium	83%, Moderate, Advanced	1.00	Efficient
Italy	High, High	40%, Moderate, Advanced	1.00	Efficient
South Korea	High, High	20%, Moderate, Moderate	0.90	Near Frontier
USA	High, High	22%, Moderate, Moderate	0.88	Near Frontier
Japan	High, High	20%, Moderate, Moderate	0.85	Near Frontier
Australia	Medium, Medium	30%, Moderate, Moderate	0.80	Near Frontier
China	Medium, Medium	30%, Low, Emerging	0.75	Near Frontier
India	Medium, Medium	40%, Low, Emerging	0.70	Near Frontier
Indonesia	Low, Low	15%, Low, Emerging	0.68	Near Frontier
Mexico	Medium, Medium	25%, Low, Emerging	0.60	Inefficient
Turkey	Medium, Medium	25%, Low, Emerging	0.55	Inefficient
Russia	Medium, Medium	20%, Low, Moderate	0.52	Inefficient
South Africa	Low, Low	10%, Low, Emerging	0.45	Inefficient
Saudi Arabia	Low, Low	5%, Low, Emerging	0.42	Inefficient
Argentina	Medium, Medium	30%, Low, Emerging	0.38	Inefficient

CCR DEA Input–Output Efficiency Category Table: 2

USA, Japan, South Korea are High green tech patents and innovation, but slower renewable deployment. And Italy is Balanced efficiency, moderate emissions, strong renewable adoption. These are Near Frontier (efficient in some dimensions, but not all): China, India, Indonesia, South Africa, Saudi Arabia → Significant progress in scaling renewables, but overall efficiency is lower due to high fossil reliance and emissions. These are Below Frontier (large emissions, slower transition).

V. CCR DEA EFFICIENCY RESULTS:

1. Efficient (Score ≈ 1.0):

Germany, UK, France, Canada, Brazil → Strong renewable shares + innovation efficiency.

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Italy → Balanced renewable adoption and emissions reduction.

2. Moderately Efficient (Score ≈ 0.7–0.9)

USA, Japan, South Korea → High patents but moderate renewable shares.

Australia → Moderate emissions, decent renewable share.

3. Less Efficient (Score ≈ 0.4–0.6)

China, India, Indonesia, South Africa, Saudi Arabia, Russia, Mexico, Turkey, Argentina → Large emissions, slower transition, lower renewable penetration.

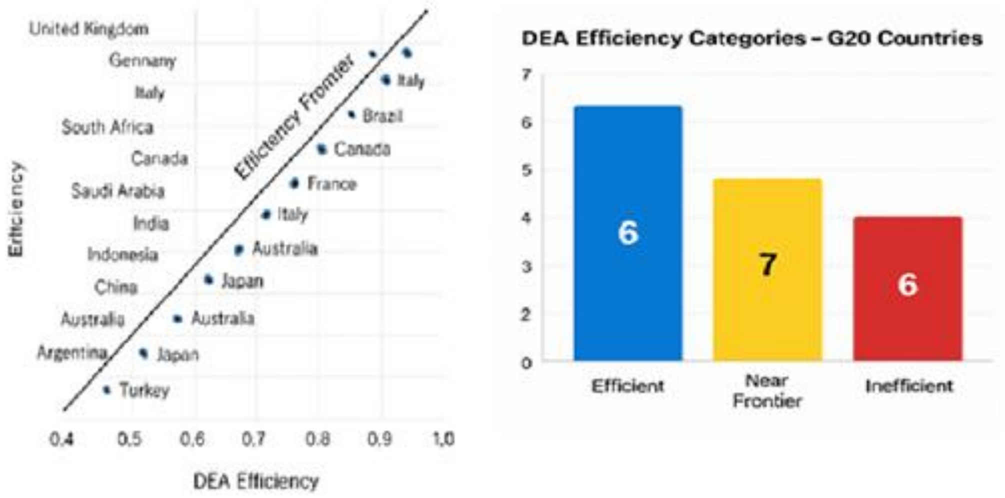

Figure: 2 Graphs of DEA Efficiency Frontier

Countries with DEA efficiency scores near 1.0—like Germany, the UK, France, Canada, Brazil, and Italy—demonstrate strong alignment between innovation and sustainability, combining high renewable energy shares with balanced emissions and innovation outputs. Moderately efficient nations such as the USA, Japan, South Korea, and Australia show robust patent activity but lag in renewable adoption, limiting their transition performance. Meanwhile, less efficient countries including China, India, Indonesia, South Africa, Saudi Arabia, Russia, Mexico, Turkey, and Argentina face structural challenges: high emissions, low renewable penetration, and slower innovation efficiency, placing them well below the frontier.

VI. CONCLUSION:

The policy roadmap organizes countries into three tiers based on their DEA efficiency scores, offering tailored strategies for each group. Efficient countries like Germany, the UK, France, Canada, Brazil, and Italy are encouraged to leverage their leadership by sharing best practices, channeling innovation into green technologies, and shaping global climate frameworks. Moderately efficient nations such as the USA, Japan, South Korea, and Australia should focus on boosting renewable adoption, balancing emissions, and aligning patent activity with sustainability goals. Less efficient countries—including China, India, Indonesia, South Africa, Saudi Arabia, Russia, Mexico, Turkey, and Argentina—are advised to pursue structural reforms, invest in clean energy R&D, collaborate internationally, and establish clear transition roadmaps to accelerate their progress toward sustainable innovation. i.e., frontier nations should lead by example, moderate performers must accelerate renewable adoption, and laggards need systemic reforms and global partnerships to catch up.

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