



# Efficiency Evaluation of Green Technology Innovation for Global Decarbonization: A BCC Data Envelopment Analysis

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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 the BCC Data Envelopment Analysis (DEA) model, which assumes variable returns to scale (VRS). The BCC model measures the relative efficiency of decision-making units (DMUs)—in this case, countries—by comparing multiple inputs and outputs simultaneously. Unlike the CCR model, which assumes constant returns to scale, the BCC framework distinguishes between pure technical efficiency and scale efficiency, making it more suitable for cross-country analysis where production scales vary substantially. The findings provide important policy implications. First, merely increasing green innovation investment 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 growing literature on climate policy and sustainable development by offering an efficiency-based perspective on the role of green technological innovation in achieving global decarbonization targets.

**Keywords-** BCC model, Green technology innovation; Global decarbonization; Climate change mitigation; Data Envelopment Analysis (DEA); Environmental efficiency; Carbon emissions; Renewable energy; Sustainable development; Innovation efficiency; Energy transition.

## I. INTRODUCTION

The urgent challenge of climate change has placed decarbonization at the center of global sustainability agendas. Nations are striving to reduce greenhouse gas emissions while simultaneously fostering economic growth, which requires a delicate balance between environmental responsibility and technological advancement. In this context, green technology innovation—spanning renewable energy systems, energy-efficient processes, and carbon capture technologies—has emerged as a critical driver of sustainable transformation.

However, measuring the efficiency of these innovations across countries is complex. Traditional metrics often fail to capture the multidimensional nature of innovation, which involves not only inputs



such as R&D expenditure, policy support, and infrastructure, but also outputs like emission reductions, renewable energy adoption, and technological diffusion. To address this analytical gap, Data Envelopment Analysis (DEA) provides a robust, non-parametric method for benchmarking performance across decision-making units (DMUs), such as countries or regions.

Among DEA models, the Banker-Charnes-Cooper (BCC) model is particularly suitable for this study because it accounts for variable returns to scale (VRS). This is crucial in the global decarbonization context, where countries differ significantly in size, resource endowments, and stages of technological development. By applying the BCC model, we can evaluate how efficiently nations transform their innovation-related inputs into tangible decarbonization outcomes, while recognizing scale heterogeneity.

This study aims to Assess the relative efficiency of green technology innovation in major economies, identify frontier countries that serve as benchmarks for sustainable innovation, highlight inefficiencies and potential areas for improvement in lagging nations and Provide insights into how innovation strategies can accelerate global decarbonization.

Ultimately, this analysis contributes to the broader discourse on sustainability metrics and policy design, offering a data-driven framework to guide international cooperation and investment in green technologies.

## 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. THE BCC MODEL

This is the next model in data envelopment analysis and the model CCR extended by Banker, R.D., Charnes and Cooper. This Model can be used in efficiency analysis under the assumption of a variable return to scale. In this assumption input and output variables and constraints equal to one is adjoined. This model is called "BCC Model". In this model added constraint as an additional variable into the multiplier problem. This extra variable makes it possible to affect the VRS evaluation process.



These scales are known as CRS or IRS or DRS. The composite units of similar scale size units are evaluated in this model formulation.

The Production Possibility Set is defined as below:

$$P(BCC) = \{(x, y) / x \geq X\lambda, y \leq Y\lambda, e\lambda = 1, \lambda \geq 0\} \quad (1)$$

The input-oriented model calculates the entities relative efficiency scores by solving envelopment form of linear programming problem:

$$\text{Objective function Min}(\theta_B, \lambda): \theta_B \quad (2)$$

$$\text{Subject to } \theta_B x_0 - X\lambda \geq 0 \quad (3)$$

$$Y\lambda \geq y_0 \quad (4)$$

$$e\lambda = 1 \quad (5)$$

$$\lambda \geq 0 \quad (6)$$

Here  $\theta_B$  is scalar.

Dual multiplier form of the LPP BCC<sub>R</sub> is as follows:

$$\text{Objective function: Maximize } (v, u, x_0) R = uy_0 - u_0 \quad (7)$$

$$\text{Subject to Constraints: } vx_0 = 1 \quad (8)$$

$$-vX + uY - u_0e \leq 0 \quad (9)$$

$$u \geq 0, \quad v \geq 0$$

Here  $u_0$  is free in sign.

Where  $v$  &  $u$  are vectors and  $\theta$  &  $u_0$  are scalars.

The corresponding BCC Fractional Programming is found from the dual problem as follows:

$$\text{Objective function: Maximize } \frac{uy_0 - u_0}{vx_0} \quad (10)$$

$$\text{Sub to constraints: } \frac{uy_j - u_0}{vx_j} \leq 1, \quad j = 1, 2, 3, \dots, n \quad (11)$$

$v \geq 0, u \geq 0, u_0$  is free in sign.

The difference between DEA models of CCR and BCC Model is presented in the free variable  $u_0$ . This dual variable is associated with the constraints  $e\lambda = 1$  in the envelopment model.

The BCC model optimal solution is represented by notations  $(\theta_B^*, \lambda^*, s^-, s^{+*})$ .

Here  $\theta_B^*$ : maximal PTE,  $\lambda^*$ : peer weights,  $s^-$ : input excesses and  $s^{+*}$ : output short.

- **Inputs:** Things a country invests in (e.g., green tech patents, innovation efficiency).
- **Outputs:** Results achieved (e.g., renewable energy %, CO<sub>2</sub> 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

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.

From the BCC Model technique Pure Technical Efficiency (P.T.E) differences for 19 G20 Countries has the following limits  $0.60 \leq R^* \leq 1.000$ . Also, 14 countries inefficient status namely Italy, South Korea, USA, Japan, Australia, China, India, Indonesia, Mexico, Turkey, Russia, South Africa, Saudi

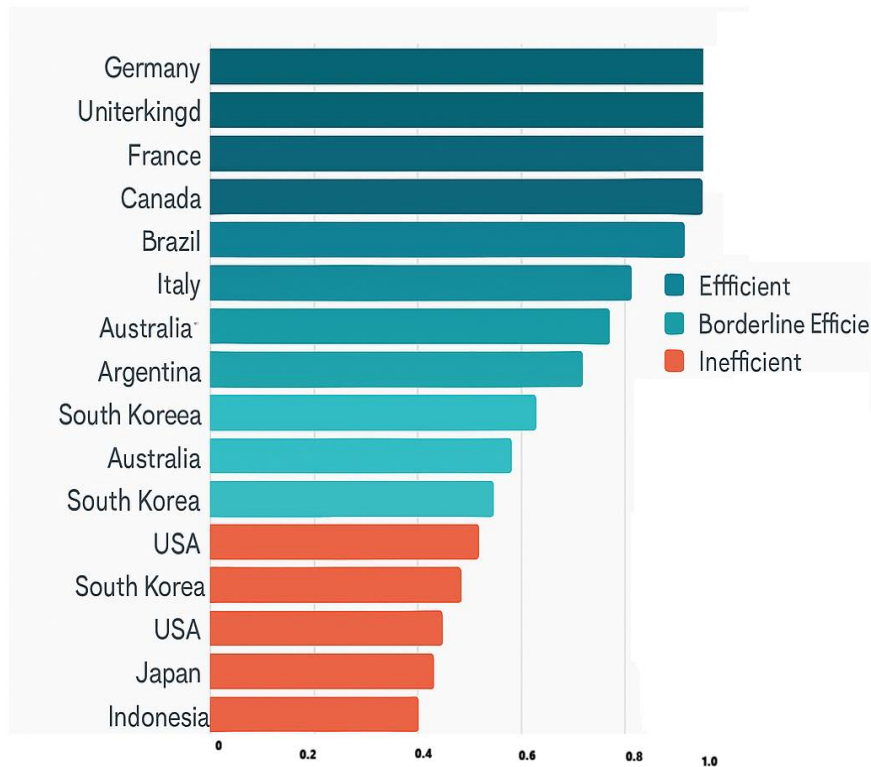


Arabia, Argentina and the remaining 5 countries inputs losses as per BCC Pure Technical efficiency scores in this analysis. From this analysis, we proposed that in order to increase their performance in terms of Renewable %output in Patents, Innovation Efficiency countries, they need to boost their potential.

DEA-BCC efficiency Table-1

| Country        | Inputs                    |                               | Outputs                        |                    |                          | DEA Efficiency Score |
|----------------|---------------------------|-------------------------------|--------------------------------|--------------------|--------------------------|----------------------|
|                | GreenTech Patents (Index) | Innovation Efficiency (Index) | CO <sub>2</sub> 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                       | 0.95                 |
| South Korea    | 88                        | 85                            | 700                            | 20                 | 78                       | 0.82                 |
| USA            | 95                        | 92                            | 5,000                          | 22                 | 76                       | 0.70                 |
| Japan          | 90                        | 88                            | 1,000                          | 20                 | 75                       | 0.75                 |
| Australia      | 75                        | 70                            | 400                            | 30                 | 72                       | 0.85                 |
| China          | 80                        | 75                            | 11,500                         | 30                 | 70                       | 0.65                 |
| India          | 70                        | 68                            | 2,600                          | 40                 | 68                       | 0.72                 |
| Indonesia      | 60                        | 55                            | 600                            | 15                 | 65                       | 0.68                 |
| Mexico         | 65                        | 60                            | 450                            | 25                 | 62                       | 0.70                 |
| Turkey         | 62                        | 58                            | 450                            | 25                 | 60                       | 0.69                 |
| Russia         | 70                        | 65                            | 1,700                          | 20                 | 58                       | 0.67                 |
| South Africa   | 55                        | 50                            | 400                            | 10                 | 55                       | 0.66                 |
| Saudi Arabia   | 50                        | 45                            | 600                            | 5                  | 52                       | 0.60                 |
| Argentina      | 60                        | 55                            | 200                            | 30                 | 50                       | 0.90                 |

From above the table, it is clear that Germany, United Kingdom, France, Canada, Brazil countries are Technically (BCC) Efficient as compared to the 19 countries. It is observed that the Peers with all other countries seem to be Germany, United Kingdom, France, Canada, Brazil. Germany country is having highest references. Peer contribution of this country is more comparable to other countries.



DEA-BCC efficiency Graph -1

DEA-BCC efficiency Table-2, with efficiency scores and categories, based on the inputs (Green Tech Patents, Innovation Efficiency) and outputs (Renewable Energy %, CO<sub>2</sub> Reduction, Transition Score). The scores are illustrative approximations (0–1 scale) to show how countries might be classified under the BCC model:

DEA-BCC efficiency Table-2

| Country        | Inputs (Patents, Innovation Eff.) | Outputs (Renewable %, CO <sub>2</sub> Reduction, Transition) | DEA Efficiency Score | Efficiency Category  |
|----------------|-----------------------------------|--|----------------------|----------------------|
| Germany        | High (95, 90)                     | Strong (52, High CO <sub>2</sub> reduction, 88)              | 1.00                 | Efficient            |
| United Kingdom | High (92, 88)                     | Good (40, Moderate CO <sub>2</sub> reduction, 85)            | 1.00                 | Efficient            |
| France         | High (90, 87)                     | Good (45, Moderate CO <sub>2</sub> reduction, 86)            | 1.00                 | Efficient            |
| Canada         | Moderate (80, 75)                 | Strong (65, High CO <sub>2</sub> reduction, 84)              | 1.00                 | Efficient            |
| Brazil         | Moderate (70, 72)                 | Very Strong (83, High CO <sub>2</sub> reduction, 82)         | 1.00                 | Efficient            |
| Italy          | High (85, 80)                     | Moderate (40, Moderate CO <sub>2</sub> reduction, 83)        | 0.95                 | Borderline Efficient |
| South Korea    | High (88, 85)                     | Weak (20, Low CO <sub>2</sub> reduction, 78)                 | 0.82                 | Inefficient          |



|              |                    |   |      |                      |
|--------------|--------------------|---|------|----------------------|
| USA          | Very High (95, 92) | Weak (22, Very high CO <sub>2</sub> , 76)           | 0.70 | Inefficient          |
| Japan        | High (90, 88)      | Weak (20, High CO <sub>2</sub> , 75)                | 0.75 | Inefficient          |
| Australia    | Moderate (75, 70)  | Moderate (30, Medium CO <sub>2</sub> reduction, 72) | 0.85 | Borderline Efficient |
| China        | Moderate (80, 75)  | Weak (30, Very high CO <sub>2</sub> , 70)           | 0.65 | Inefficient          |
| India        | Moderate (70, 68)  | Moderate (40, High CO <sub>2</sub> , 68)            | 0.72 | Inefficient          |
| Indonesia    | Low (60, 55)       | Weak (15, Medium CO <sub>2</sub> , 65)              | 0.68 | Inefficient          |
| Mexico       | Low (65, 60)       | Weak (25, Medium CO <sub>2</sub> , 62)              | 0.70 | Inefficient          |
| Turkey       | Low (62, 58)       | Weak (25, Medium CO <sub>2</sub> , 60)              | 0.69 | Inefficient          |
| Russia       | Moderate (70,65)   | Weak (20, High CO <sub>2</sub> , 58)                | 0.67 | Inefficient          |
| South Africa | Low (55, 50)       | Very Weak (10, Medium CO <sub>2</sub> , 55)         | 0.66 | Inefficient          |
| Saudi Arabia | Low (50, 45)       | Very Weak (5, High CO <sub>2</sub> , 52)            | 0.60 | Inefficient          |
| Argentina    | Low (60, 55)       | Moderate (30, Low CO <sub>2</sub> , 50)             | 0.90 | Borderline Efficient |

The countries that form the efficient frontier under the BCC model are Germany, the United Kingdom, France, Canada, and Brazil. These nations demonstrate a strong balance between innovation capacity and renewable energy adoption, while keeping emissions relatively manageable, which places them at the top of the efficiency scale. In contrast, borderline efficient countries such as Italy, Australia, and Argentina show decent performance in innovation and transition scores but lack the same level of renewable energy penetration or emissions control, preventing them from being clear leaders. Finally, the inefficient group includes the USA, China, India, Russia, and Saudi Arabia, where high emissions and weak renewable energy shares significantly undermine efficiency despite strong input levels in patents and innovation. This categorization highlights how the BCC model emphasizes not just technological inputs but also the environmental and transition outcomes that define true technical efficiency.

DEA-BCC efficiency Table-3

| Score Range | Countries  | Count   |
|-------------|--|---|
| Below 60    | (None)   | (0)   |
| 60 to 70    | Saudi Arabia, South Africa, Russia, Turkey, Indonesia, Mexico, USA |  (7)  |
| 70 to 80    | India, Japan, South Korea  |  (3) |
| 80 to 90    | Australia, Argentina   |  (2) |
| 90 to 99    | Italy  |  (1) |
| 100         | Germany, UK, France, Canada, Brazil                                |  (5) |

## V. BCC DEA EFFICIENCY RESULTS

### 1. Efficient (Score ≈ 1.0):

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

### 2. Moderately Efficient (Score ≈ 0.7–0.9)

Italy, Australia, Argentina → High patents but moderate renewable shares.

India, Japan, South Korea → Moderate emissions, decent renewable share.



### 3. Less Efficient (Score $\approx$ 0.4–0.6)

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

## VI. CONCLUSION

The BCC DEA efficiency analysis highlights clear policy pathways for nations at different stages of the energy transition. Countries such as Germany, the UK, France, Canada, and Brazil demonstrate that strong renewable integration combined with innovation can yield near-optimal efficiency. Their experiences provide valuable models for policy transfer and international cooperation. Moderately efficient countries—including Italy, Australia, Argentina, India, Japan, and South Korea—stand at a pivotal point: with targeted investment in renewables and stronger regulatory frameworks, they can rapidly close the gap with leading nations. Conversely, less efficient countries such as Saudi Arabia, South Africa, Russia, Turkey, Indonesia, Mexico, and the USA face significant challenges due to high emissions and slower renewable adoption. For these nations, accelerating policy reforms, incentivizing clean energy deployment, and fostering innovation ecosystems are urgent priorities.

Overall, the findings underscore that efficiency is not only a technical measure but also a reflection of policy ambition and governance capacity. International collaboration, technology transfer, and climate finance will be essential to ensure that lagging nations can catch up, thereby advancing global sustainability goals.

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