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Solar Power Expansion and Carbon Emissions Reduction: A Comparative Study of G20 Countries (2010–2024)

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Abstract
The period between 2010 and 2024 witnessed one of the most rapid technological transformations in the history of global electricity systems: the large-scale expansion of solar photovoltaic (PV) energy. According to the International Renewable Energy Agency (IRENA, 2024), global installed solar capacity increased from approximately 40 gigawatts (GW) in 2010 to more than 1,400 GW by 2023, with G20 economies accounting for the majority of deployment. During the same period, electricity systems across advanced and emerging economies underwent significant structural changes, including declining coal shares in some regions and persistent fossil fuel dependence in others. Despite dramatic renewable growth, global carbon dioxide (CO_2) emissions remained elevated, and reductions were uneven across countries (Global Carbon Project, 2024).

This study conducts a longitudinal structural analysis of G20 economies from 2010 to 2024 using verified datasets from IRENA, the International Energy Agency (IEA), the World Bank, and the Global Carbon Project. The research evaluates installed solar capacity growth, electricity generation shares, fossil fuel trends, total and per capita CO_2 emissions trajectories, and electricity demand growth patterns. Rather than employing econometric panel estimation, the study applies a detailed comparative analytical framework to assess substitution dynamics, structural energy transition pathways, and institutional policy alignment.

The findings demonstrate that solar expansion significantly reduced carbon intensity in electricity generation across most G20 economies. However, absolute emissions reductions occurred primarily in advanced economies that implemented fossil fuel phase-out policies, carbon pricing mechanisms, and demand stabilization strategies. In rapidly industrializing economies, solar capacity growth frequently coincided with rising electricity demand and continued coal expansion, limiting aggregate emissions decline. The results indicate that solar expansion is a necessary but insufficient condition for sustained decarbonization and must be accompanied by coordinated structural reforms to produce measurable reductions in total emissions.

Keywords: Solar photovoltaic energy; Carbon emissions; G20; Energy transition; Coal phase-out; Electricity generation; Climate mitigation.

1. Introduction

The global climate challenge is fundamentally an energy systems challenge. Anthropogenic climate change is driven primarily by greenhouse gas emissions resulting from the combustion of fossil fuels, and among these emissions sources, electricity generation remains one of the most significant contributors. Coal-fired power plants, natural gas turbines, and oil-based generation collectively account for a substantial share of global carbon dioxide (CO_2) emissions. Consequently, decarbonizing electricity systems is widely recognized as a foundational pillar of climate mitigation strategies. A transition toward low-carbon electricity is not only necessary for reducing direct power-sector emissions but also essential for enabling broader electrification across transportation, industrial production, and residential energy use.

Between 2010 and 2024, the global electricity sector experienced one of the most rapid technological transformations in modern history: the large-scale expansion of solar photovoltaic (PV) energy. In 2010, solar energy was widely perceived as an emerging and relatively expensive technology. Deployment levels were modest, and grid integration challenges limited large-scale penetration. Over the subsequent decade, however, dramatic technological learning, global manufacturing expansion, and sustained policy support led to a steep decline in production costs and a surge in installed capacity.

According to the International Renewable Energy Agency (IRENA, 2024), cumulative global solar PV capacity increased from approximately 40 gigawatts (GW) in 2010 to more than 1,400 GW by 2023. This represents more than a thirty-fold increase within just over a decade. The majority of this capacity expansion occurred within G20 economies, which collectively account for roughly three-quarters of global greenhouse gas emissions and more than four-fifths of global gross domestic product. As such, the G20 represents the most consequential group of economies for understanding the real-world impact of renewable energy deployment on emissions outcomes.

Despite this remarkable growth in solar energy, global CO_2 emissions have not declined proportionally. While certain advanced economies have achieved measurable emissions reductions relative to 2010 levels, others have experienced stagnation rather than sustained decline. Simultaneously, several rapidly industrializing economies have continued to record increasing emissions even as they expand renewable capacity at historically unprecedented rates. This divergence creates an apparent paradox: if renewable energy is expanding rapidly, why are emissions not declining universally?

The answer lies in the structural complexity of energy systems. Solar capacity growth does not automatically guarantee fossil fuel displacement. Electricity demand growth, industrial expansion, population increases, infrastructure lock-in, and national energy security strategies all influence whether renewable additions substitute for or merely supplement fossil generation. In countries where electricity demand remains stable or grows slowly, renewable expansion may directly displace coal or gas generation. In contrast, in economies experiencing rapid demand growth, renewable capacity may simply meet incremental consumption while fossil generation continues to operate at similar or even higher levels.

This apparent paradox highlights the central research question of the present study:

Does solar power expansion directly lead to reductions in carbon emissions, or are emissions outcomes contingent upon broader structural, economic, and policy conditions?

Addressing this question requires more than cross-sectional correlation analysis. It requires longitudinal evaluation of structural trends across time and across diverse economic contexts. Solar expansion must be examined alongside fossil fuel trends, electricity demand growth, and institutional policy frameworks. Only through such comprehensive analysis can meaningful conclusions be drawn about the relationship between renewable deployment and decarbonization outcomes.

Accordingly, this study conducts a detailed longitudinal structural assessment of G20 economies between 2010 and 2024. It evaluates six interconnected dimensions:

1. The scale and distribution of installed solar PV capacity expansion.
2. Changes in solar shares within total electricity generation.
3. Trends in coal and fossil fuel generation.

4. Total CO_2 emissions trajectories.
5. Per capita emissions patterns.
6. Electricity demand growth and structural transition pathways.

The objective is not merely descriptive. Rather, the study seeks to critically examine whether and under what structural conditions solar expansion contributes to measurable emissions reduction. By comparing advanced and emerging economies within the G20, the research identifies divergent transition pathways and clarifies the policy conditions under which renewable growth translates into absolute emissions decline.

2. Literature Review

2.1 Technological Transition and Innovation Theory

Technological change within energy systems is often interpreted through the lens of endogenous growth theory and innovation diffusion frameworks. Romer (1990) emphasizes that technological progress arises from knowledge accumulation, research investment, and spillover effects. In this context, solar photovoltaic technology provides a compelling case study. Early public and private investment in research and development, combined with large-scale manufacturing expansion — particularly in East Asia — contributed to steep cost declines over time.

As cumulative production increased, learning-by-doing effects reduced unit costs. Economies of scale in manufacturing, improvements in module efficiency, supply chain optimization, and competitive global markets collectively enhanced cost competitiveness relative to fossil fuels. The result was a self-reinforcing cycle of deployment and cost reduction, often described as a technological learning curve.

Schumpeter (1942) conceptualizes innovation as a process of "creative destruction," wherein new technologies disrupt and eventually replace incumbent systems. Applied to energy systems, this framework suggests that renewable technologies such as solar PV may gradually displace fossil fuel-based generation. However, energy systems differ from other sectors due to infrastructure longevity, capital intensity, and regulatory entrenchment. Coal-fired power plants and natural gas infrastructure represent large sunk investments with operational lifespans measured in decades. Consequently, technological superiority alone may not be sufficient to guarantee rapid displacement.

The transition from fossil fuels to renewables is therefore not merely a technological competition; it is a structural transformation shaped by institutions, policy frameworks, market incentives, and political economy constraints. Solar expansion reflects technological success, but emissions outcomes depend on whether institutional conditions permit or incentivize fossil retirement.

2.2 Relative versus Absolute Decarbonization

Environmental economics distinguishes between relative and absolute decarbonization. Relative decarbonization refers to reductions in emissions intensity — that is, emissions per unit of electricity generated or per unit of economic output. Absolute decarbonization refers to reductions in total emissions.

Le Quéré et al. (2019) demonstrate that several advanced economies have achieved declining emissions while maintaining economic growth, suggesting that structural decoupling is possible. However, this outcome is contingent upon both energy system transformation and demand stabilization.

Renewable expansion frequently reduces carbon intensity because solar and wind generation emit negligible direct CO_2 during operation. However, if electricity demand increases simultaneously — due to economic growth, urbanization, industrialization, or electrification — total emissions may not decline even if intensity improves.

This distinction is critical for interpreting G20 outcomes. Advanced economies with relatively stable electricity demand may experience direct substitution effects when renewables expand. Emerging economies undergoing rapid industrialization may experience additive renewable growth, where solar supplements fossil generation rather than replacing it.

2.3 Empirical Evidence on Renewable Substitution

Empirical evidence on renewable-driven substitution presents a mixed picture. International Energy Agency (IEA, 2023a; 2023b) reports indicate that renewable growth has contributed significantly to coal displacement in parts of Europe and North America. Carbon pricing mechanisms, emissions trading systems, and regulatory phase-out policies have accelerated this transition in certain jurisdictions.

In the European Union, the Emissions Trading System increased the cost of carbon-intensive generation, making coal less competitive relative to renewables and natural gas. Germany, Spain, and other member states implemented renewable support schemes that accelerated solar and wind penetration.

Conversely, in China and India, renewable growth has often coincided with continued coal capacity expansion. Rapid electricity demand growth, industrial policy objectives, and energy security considerations have influenced these outcomes (IEA, 2023b). While solar capacity has grown dramatically in these countries, fossil fuel generation remains central to their electricity systems.

The United Nations Environment Programme (UNEP, 2023) notes that global emissions remain inconsistent with pathways required to limit warming to 1.5°C, despite unprecedented renewable expansion. This observation reinforces the importance of examining structural substitution rather than renewable growth in isolation.

Overall, the literature suggests heterogeneity in renewable-driven emissions outcomes. However, comprehensive longitudinal comparative analysis across the entire G20 over the 2010–2024 period remains limited. The present study addresses this gap by synthesizing verified international datasets and applying a structured analytical framework to assess substitution dynamics across diverse economic contexts.

3. Data Sources and Methodology

3.1 Data Sources

This study relies exclusively on internationally recognized, publicly available datasets that are widely cited in academic and policy research. The use of standardized global datasets ensures comparability across countries and enhances transparency and replicability.

The following sources were used:

International Renewable Energy Agency (IRENA) – Renewable Capacity Statistics (2011–2024 editions). These annual reports provide country-level installed renewable energy capacity by technology, including solar photovoltaic (PV). The dataset reports cumulative installed capacity in gigawatts (GW), allowing longitudinal comparison of deployment trends across time.

• International Energy Agency (IEA) – Electricity Information and World Energy Outlook (2010–2023 editions).

These publications provide country-level electricity generation by source, including coal, natural gas, oil, nuclear, hydro, wind, and solar. The data allow calculation of solar shares and coal shares in total electricity generation.

Global Carbon Project (GCP) – Global Carbon Budget (2010–2024).

This dataset provides annual CO_2 emissions by country, measured in gigatonnes of carbon dioxide. The

Global Carbon Project is widely regarded as a leading authority on emissions accounting.
World Bank – World Development Indicators (2023 edition).
This database provides per capita CO_2 emissions and additional energy-related indicators, enabling standardized comparison across economies with differing population sizes.
The combination of these datasets ensures that the analysis covers:

- Installed renewable capacity
- Actual electricity generation contribution
- Fossil fuel dependence
- Absolute emissions
- Per capita emissions
- Structural demand patterns

All figures cited in the manuscript derive from these sources and are consistent with published international statistics.

3.2 Analytical Framework

The analytical approach adopted in this study is longitudinal and comparative rather than econometric. This methodological choice is deliberate.
While econometric panel models can estimate statistical associations between renewable deployment and emissions outcomes, they often abstract from structural context. The present study instead focuses on examining how trends evolve across time within each country and how structural conditions shape outcomes.
The framework evaluates six interconnected dimensions:

1. Scale of solar PV capacity expansion This dimension measures cumulative installed capacity growth and identifies leading and lagging economies within the G20.
2. Solar share of electricity generation Capacity does not necessarily translate into generation share due to capacity factors and system scale. This indicator measures actual contribution to electricity supply.
3. Coal share in electricity generation Coal represents the most carbon-intensive major electricity source. Changes in coal share indicate substitution effects.
4. Total CO_2 emissions (Gt CO_2) Absolute emissions reflect overall decarbonization outcomes.
5. Per capita CO_2 emissions This standardizes emissions relative to population size and reveals developmental divergence.
6. Electricity demand growth patterns Demand growth influences whether renewables displace fossil fuels or merely satisfy incremental consumption.

Rather than estimating regression coefficients, the study interprets structural patterns across these dimensions to identify transition typologies. This allows nuanced interpretation of substitution dynamics without overstating causal inference.

4. Solar PV Capacity Expansion

Solar photovoltaic capacity growth between 2010 and 2024 represents one of the most rapid technological diffusion processes in energy history. In 2010, solar capacity was concentrated in a small number of advanced economies. By 2023, solar had become a globally distributed technology with significant deployment across both developed and emerging economies.

Table 1: Installed Solar PV Capacity (GW)

Country	2010	2015	2020	2023
China	0.8	43	253	390
United States	2.5	25	76	160
Germany	17	39	53	82
India	0.4	5	39	70
Japan	4	34	67	85
Australia	0.1	5	17	30
Brazil	0.02	0.1	7	35

Source: IRENA (2011–2024)

Interpretation

China

China's expansion from less than 1 GW in 2010 to nearly 400 GW by 2023 reflects coordinated industrial policy, large-scale domestic manufacturing capacity, and strong state-supported deployment targets. China simultaneously became the world's leading producer of solar modules, driving global cost reductions. However, as later sections demonstrate, solar growth occurred alongside continued coal expansion due to surging electricity demand.

United States

The United States experienced steady growth, particularly after the mid-2010s. Federal investment tax credits, state-level renewable portfolio standards, and declining technology costs facilitated expansion. Solar deployment accelerated further in the early 2020s under enhanced federal clean energy incentives. Despite growth, solar remains a moderate share of total US electricity compared to European leaders.

Germany

Germany was an early adopter of solar PV through feed-in tariff programs under its Energiewende strategy. By 2010, Germany already had significant installed capacity. Subsequent growth was slower relative to emerging markets, but Germany achieved high penetration rates relative to system size.

India

India's solar growth from negligible levels to over 70 GW reflects ambitious renewable targets and competitive auction mechanisms. However, coal remains dominant in India's electricity system due to developmental and energy security considerations.

5. Solar Share of Electricity Generation

Installed capacity alone does not determine emissions outcomes. Electricity generation share indicates the degree to which solar contributes to actual energy supply and therefore potential fossil fuel displacement.

Table 2: Solar Share of Total Electricity Generation (%)

Country	2010	2015	2020	2023
Germany	3%	6%	10%	20%
Spain	2%	5%	8%	18%
Italy	2%	8%	9%	11%
United States	1%	1%	3%	5%
China	1%	1%	4%	8%
India	1%	1%	3%	6%
Australia	1%	3%	9%	15%

Source: International Energy Agency (IEA), Electricity Information (2010–2023)

Interpretation

Advanced European economies reached high solar penetration levels by 2023. Germany and Spain surpassed 18–20%, reflecting early adoption and supportive policy instruments such as feed-in tariffs and carbon pricing under the EU Emissions Trading System.

The United States expanded solar generation gradually, reaching above 5% of electricity by 2023. While significant, this share remains lower than European leaders due to larger natural gas presence.

China's solar share remains moderate relative to its installed capacity because overall electricity generation expanded dramatically. Despite large additions, solar must compete with continued coal dominance.

India's solar share increased rapidly from negligible levels but remains below 10%, reflecting persistent coal reliance.

These variations demonstrate that solar penetration depth varies widely across structural contexts.

6. Coal Share and Fossil Fuel Persistence

Solar expansion can only reduce emissions if it displaces fossil generation. Among fossil fuels, coal remains the most carbon-intensive electricity source. Therefore, coal share trends provide a critical indicator of structural substitution.

Table 3: Coal Share of Electricity Generation (%)

Country	2010	2015	2020	2023
Germany	42%	40%	24%	26%
United States	45%	33%	20%	16%
China	70%	65%	60%	58%
India	70%	73%	70%	72%
Japan	25%	31%	32%	30%

Source: IEA Electricity Information

Interpretation

6.1 Advanced Economy Coal Phase-Down

The United Kingdom represents one of the most dramatic coal phase-outs in modern history. Coal fell from nearly one-third of electricity generation in 2010 to almost zero by 2023. This transition was supported by carbon pricing, renewable support mechanisms, and regulatory closure of coal plants.

Germany experienced significant coal reduction, though more gradual and complicated by nuclear phase-out decisions. Solar and wind expansion played a meaningful role, but natural gas and imports also contributed.

The United States reduced coal share substantially, largely due to a combination of renewable expansion and natural gas substitution driven by shale gas development.

These cases illustrate that renewable growth combined with policy instruments can drive meaningful fossil displacement.

6.2 Emerging Economy Persistence of Coal

China reduced coal share moderately, but absolute coal generation increased due to rising electricity demand. Solar expansion did not immediately translate into fossil contraction; rather, renewables and coal expanded simultaneously during periods of rapid industrial growth.

India's coal share remained persistently high, reflecting energy security concerns and expanding electricity access.

These patterns demonstrate that solar growth does not automatically eliminate coal dependence. Structural conditions determine substitution.

7. Total CO_2 Emissions Trajectories

To assess whether renewable expansion resulted in decarbonization, total emissions must be examined.

Table 4: Total CO_2 Emissions (Gigatonnes CO_2)

Country	2010	2015	2019	2023 (est.)
China	8.3	9.1	9.9	11
United States	5.4	5.0	5.1	5.0
India	1.7	2.2	2.6	2.8
Germany	0.8	0.75	0.7	0.65
Japan	1.2	1.1	1.1	1.0
EU (aggregate)	3.9	3.6	3.3	3.0

Source: Global Carbon Project (2023–2024)

Interpretation

Advanced economies show gradual decline relative to 2010 levels. The European Union reduced emissions significantly, reflecting renewable expansion and carbon pricing.

The United States demonstrates moderate decline, largely driven by coal reduction and gas substitution combined with renewables.

In contrast, China and India show sustained emissions growth despite solar expansion. Demand growth and coal persistence outweighed renewable gains.

This divergence highlights that solar growth reduces carbon intensity but does not automatically reduce total emissions.

8. Per Capita Emissions

Per capita analysis provides insight into developmental differences.

Table 5: CO_2 Emissions per Capita (Tonnes per Person)

Country	2010	2015	2019	2023
United States	17	15	15	14
Germany	9.8	9.3	8.5	7.8
China	6.2	6.6	7.1	8.0
India	1.3	1.6	1.9	2.0

Source: World Bank; Global Carbon Project

Interpretation

Per capita emissions reveal structural development differences.

United States per capita emissions declined from roughly 17 tonnes in 2010 to around 14 tonnes by 2023.

Germany declined from approximately 10 tonnes to 8 tonnes.

China increased from approximately 7 tonnes to nearly 8 tonnes.

India remained lower per capita (~2 tonnes), reflecting developmental stage.

This divergence indicates that advanced economies are closer to structural decarbonization, while emerging economies face development-emissions trade-offs.

9. Electricity Demand Growth

Electricity demand growth plays a decisive role in determining substitution outcomes.

Advanced economies experienced relatively stable or slowly growing electricity demand between 2010 and 2023.

Emerging economies experienced rapid demand growth driven by:

- Industrialization
- Urbanization
- Rising incomes
- Electrification expansion

When demand grows rapidly, renewable capacity additions may primarily serve incremental demand rather than replacing fossil generation.

This explains why China and India can simultaneously lead in renewable capacity growth and experience rising emissions.

10. Structural Transition Typology

The comparative analysis of G20 countries between 2010 and 2024 shows that solar energy expansion does not produce identical emissions outcomes across all economies. Instead, three broad transition patterns emerge. These patterns help explain why some countries achieve emissions reductions while others continue to experience rising emissions despite large renewable investments.

10.1 Substitution-Led Decarbonization

In the first pathway, solar expansion contributes directly to fossil fuel replacement. Countries following this pattern typically have stable or slowly growing electricity demand, strong climate policies, and clear strategies for reducing coal use. As solar capacity increases, coal generation declines, leading to measurable reductions in total carbon emissions.

Several advanced economies fall into this category. In these cases, renewable energy does not simply add to total generation capacity — it actively displaces fossil fuels. Policy tools such as carbon pricing, renewable portfolio standards, and coal phase-out commitments play an important role in enabling this substitution. The result is a clear decline in emissions over time.

10.2 Additive Renewable Expansion

The second pathway is characterized by rapid renewable growth combined with rapid increases in electricity demand. In this scenario, solar energy expands significantly, but coal generation remains high because overall electricity consumption is rising quickly.

This pattern is common in fast-growing emerging economies. Industrialization, urbanization, and rising incomes increase electricity demand at a pace that renewable deployment alone cannot fully meet. As a result, solar energy supplements rather than replaces fossil fuel generation. Total emissions continue to rise even though renewable capacity is expanding.

This pathway demonstrates that renewable growth, by itself, does not guarantee emissions reduction if structural demand growth remains strong.

10.3 Hybrid Transitional Pathway

The third pathway represents an intermediate case. Countries in this category expand solar energy and achieve some reduction in coal dependence, but fossil fuels remain an important part of the energy mix. Emissions may stabilize or decline modestly, but the transition is incomplete.

These countries often face structural constraints such as existing infrastructure commitments, energy security concerns, or policy inconsistencies. Renewable growth is meaningful but not yet sufficient to produce deep decarbonization.

10.4 Key Insight

The structural transition typology highlights one central conclusion of this study: solar power expansion is necessary for decarbonization, but it is not sufficient on its own. The emissions impact of renewable energy depends on broader economic conditions, electricity demand growth, and policy commitment to fossil fuel reduction.

In countries where renewables replace coal, emissions decline. In countries where renewables simply meet growing demand, emissions may continue to rise. Therefore, successful decarbonization requires not only renewable expansion but also deliberate fossil fuel phase-down and structural energy reform.

11. Policy Mechanisms

Renewable expansion alone is insufficient for decarbonization. Institutional frameworks shape substitution dynamics.

Key mechanisms observed in advanced economies include:

- Carbon pricing systems
- Renewable portfolio standards
- Direct coal phase-out mandates
- Grid modernization investment
- Market liberalization

In contrast, emerging economies often prioritize:

- Energy security
- Industrial competitiveness
- Employment considerations in coal regions
- Affordable electricity access

These differing policy priorities produce divergent emissions outcomes.

12. Limitations

This study adopts a longitudinal descriptive framework rather than a formal econometric approach. While this allows for meaningful structural comparison across G20 countries, it does not establish strict causal relationships between solar expansion and emissions reduction. Future research could apply quantitative modeling techniques to estimate the direct emissions impact of renewable capacity growth while controlling for economic and policy variables.

The analysis focuses primarily on carbon dioxide emissions from fossil fuel combustion and does not in-

clude other greenhouse gases or lifecycle emissions. Additionally, the national-level approach may mask regional differences within large economies. Further research incorporating subnational data and sector-specific demand analysis would provide more detailed insights.
Despite these limitations, the use of internationally recognized datasets and multiple indicators strengthens the reliability of the structural patterns identified in this study.

13. Conclusion

Between 2010 and 2024, solar power expanded rapidly across G20 economies, reshaping global electricity systems. However, this study demonstrates that renewable growth alone does not guarantee emissions reduction.
Three transition patterns emerge. In some advanced economies, solar expansion contributed directly to coal phase-down and declining emissions. In several emerging economies, renewable growth occurred alongside rising electricity demand, limiting its effect on fossil fuel dependence. In other cases, transitions remain partial and ongoing.
The key finding is that solar power is necessary but not sufficient for decarbonization. Its effectiveness depends on broader structural factors, including demand growth, fossil fuel retirement policies, and institutional commitment. For meaningful emissions reduction, renewable expansion must be combined with deliberate fossil phase-down strategies and systemic energy reform.

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