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Green Fiscal Policies, Innovation, and Financial Capacity: Empirical Evidence from the G7

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ABSTRACT

This study investigates the dynamic interplay between economic growth, environmental taxation, technological innovation, renewable energy deployment, and financial capacity (CF) in G7 economies over the period 1995–2023. Employing a combination of parametric and non-parametric panel data methods, including the Common Correlated Effects Mean Group (CCEMG) estimator and local linear time-varying coefficient models with wild bootstrap, we capture both long-run relationships and country-specific heterogeneities. The results reveal that economic growth generally supports CF, while environmental taxes and technological innovation exhibit time-varying effects. Renewable energy adoption and financial development significantly enhance CF, highlighting the importance of integrating sustainable energy policies and innovative technologies in advanced economies. These findings contribute to the literature by providing robust evidence on how economic, fiscal, and technological factors jointly shape financial capacity, offering valuable insights for policymakers seeking to balance economic growth with financial sustainability.

Keywords: Economic growth, Environmental taxes, Technological innovation, Renewable energy, Financial capacity, G7 economies

1. INTRODUCTION

The last few decades have witnessed an unprecedented increase in fossil fuel consumption and the resulting rise in greenhouse gas emissions, particularly carbon dioxide, which has become a major policy concern worldwide. Economic growth (EG) remains a central objective for policymakers, heavily reliant on fossil fuel consumption, yet this dependency contributes to environmental degradation and threatens sustainability. The growing awareness of these environmental challenges is prompting policymakers to reconsider traditional growth models and to integrate sustainable development into economic planning. The United Nations' Sustainable Development Goals (SDGs) have further emphasized the need to understand the determinants of sustainability and financial capacity (CF) in advanced economies, prompting extensive research on the drivers of environmental and financial resilience (Erdogan, 2024; Caglar et al., 2024; Deng et al., 2024).

A vast literature in energy and environmental economics has examined the factors influencing sustainability, including economic growth, technological progress, fiscal policies, and renewable energy consumption (see, Mikayilov et al., 2018; Namahoro et al., 2021; Awan et al., 2022; Naseem et al., 2024). While earlier studies primarily focused on CO_2 emissions as a measure of environmental pressure, recent research emphasizes broader indicators, including financial measures, to capture the balance between economic activity and resource capacity (Shahbaz et al., 2023; Chen et al., 2023; Joof et al., 2024, Talbi, 2025). Among these, Financial Capacity (CF) is used to assess the ability of an economy to sustain growth while managing fiscal and environmental pressures. Initial phases of economic growth may place pressure on financial resources, whereas higher income levels allow for investments in technology, infrastructure, and sustainable fiscal policies, thus improving CF (Pata, 2021; Pata and Kartal, 2024; Fang et al., 2024, Talbi et al, 2025).

Endogenous growth theory posits that technological progress, supported by research, innovation, and digitalization, enhances production efficiency and the effective use of financial and natural resources. As countries grow, they can invest more communication technologies (CT) and renewable energy (RE), which can improve financial sustainability while mitigating negative environmental and economic side effects (Dinda, 2004; Komen et al., 1997). However, the effects of technological advancement on CF are a priori uncertain. While CT adoption and digitalization can improve resource allocation and reduce inefficiencies, they may also increase financial demands due to infrastructure costs, energy consumption, and maintenance of digital systems (Shah and Ximei, 2024; Ullah et al., 2024; Nathaniel et al., 2025,Amiri et al, 2013). Similarly, environmental taxes (ET), designed to internalize the external costs of economic activities, can either support CF by incentivizing sustainable investments or constrain financial capacity in the short term if poorly designed (Telatar and Birinci, 2022; Javed et al., 2023; Bozatli and Akca, 2023, Amiri and Talbi, 2014). Financial development (FD) captures a country's ability to mobilize resources and finance sustainable investments, further influencing CF.

The choice of these variables and the methodological approach in this study are motivated by the need to capture the multifaceted drivers of CF in advanced economies. Economic variables such as GDP and GDP² allow the testing of potential non-linear relationships, while ICT and RE reflect technological and sustainable interventions that can influence financial capacity. ET and FD capture regulatory, fiscal, and financial mechanisms affecting CF. Methodologically, the combination of parametric and non-parametric techniques ensures that both average long-run effects and time-varying, country-specific dynamics are accounted for. Parametric modeling via the CCEMG estimator provides robust long-term estimates, while the non-parametric local linear estimation method with wild bootstrap captures heterogeneous effects and potential non-linearities that might otherwise be overlooked.

This study examines the dynamic interactions between EG, technological innovation (ICT), fiscal policies (ET), renewable energy (RE), financial development (FD), and CF in G7 countries over the period 1995–2023. The G7 - Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States was selected due to its high economic output, substantial investment in research and development, and significant influence on global financial and energy systems. Collectively, these countries represent nearly 46% of global GDP, consume around 30% of global energy, and account for a substantial share of financial and environmental pressures, making them critical for understanding the coupling between growth and CF (Xia and Liu, 2024, Talbi, 2025).

Our local linear estimates from the non-parametric model suggest that the relationship between EG and CF is time-varying. For most of the period studied, EG positively contributes to CF, but there are subperiods, particularly in the early 2000s, when the relationship weakened due to global financial shocks and uneven adoption of sustainable policies. The common trend function gradually increased over the first 15 years (1995–2010) but flattened and slightly decreased during the next decade, reflecting periods of policy adjustments and technological transitions across the G7.

The remainder of this study is structured as follows. The next section discusses the data, empirical specification, and non-parametric estimation method. Section 4 presents the results from parametric panel data modeling. The non-parametric results are presented and discussed in Section 5. The final section concludes.

2. METHODOLOGY AND DATA

2.1 Empirical Model

We investigate the effect of economic, environmental, technological, and financial factors on electricity generation efficiency by estimating the following equation:

$$lnCF_{it} = \gamma_0 + \gamma_1 lnGDP_{it} + \gamma_2 lnGDP^2{}_{it} + \gamma_3 lnET_{it} + \gamma_4 lnCT_{it} + \gamma_5 lnFD_{it} + \gamma_6 lnRE_{it} + \varepsilon_{it} \quad (1)$$

where iii and ttt denote the country and time, respectively. The dependent variable is Capacity Factor (CF), measuring electricity generation efficiency. The main explanatory variables are:

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- GDP: Gross Domestic Product, reflecting the level of economic activity (Apergis and Payne, 2010; Ivanovski et al., 2020).
- GDP²: Square of GDP, included to capture potential nonlinear effects of economic growth on capacity factor (Bamati and Raoofi, 2020).
- ET: Environmental tax, representing the impact of environmental policies on energy efficiency (Nguyen and Kakinaka, 2019; Khan et al., 2020).
- CT: Communication technology, proxy for technological advancement that may improve energy generation efficiency (Awaworyi Churchill et al., 2020).
- FD: Financial development, facilitating investments in energy infrastructure (Hailemariam et al., 2019).
- RE: Renewable energy, measuring the share of renewable energy in total electricity generation (Yao et al., 2020).

The error term ε captures unobserved factors affecting CF.

To align with empirical literature, we include both economic and environmental control variables. GDP is widely recognized as a key determinant of financial capacity, since higher levels of economic activity can strengthen investment potential and enhance access to financing (Apergis and Payne, 2010; Ivanovski et al., 2020). Environmental taxes are included because stricter regulation may affect firms' financial performance and capacity to allocate resources (Nguyen and Kakinaka, 2019; Khan et al., 2020). Communication technology contributes by fostering financial inclusion and facilitating access to modern financial services (Awaworyi Churchill et al., 2020), while financial development directly supports credit availability and strengthens overall financial capacity (Hailemariam et al., 2019). Renewable energy represents the share of green sources in the energy mix, which may influence investment patterns and financial flows toward sustainable projects (Yao et al., 2020).

While Equation (1) will be estimated using parametric methods as a benchmark to provide point estimates of the average effect of the explanatory variables on CF, we also plan to implement a non-parametric approach to explore potential nonlinear and time-varying relationships. The non-parametric framework allows for estimation of flexible functional forms without imposing restrictive linearity assumptions (Li et al., 2011; Zhang et al., 2012).

The time-varying non-parametric specification can be written as:

$$\Delta lnCF_{it} = f_k(\tau) + \gamma_1(\tau)\Delta lnGDP_{it} + \gamma_2(\tau)\Delta lnGDP^2{}_{it} + \gamma_3(\tau)\Delta lnET_{it} + \gamma_4(\tau)\Delta lnCT_{it} + \gamma_5(\tau)\Delta lnFD_{it} + \gamma_6(\tau)\Delta lnRE_{it} + \varepsilon_{it} \quad (2)$$

where $f(\tau)$represents unknown trend functions, and $\lambda(t)$reprents the time-varying coefficients estimated non-parametrically (Chen et al., 2012; Hailemariam et al., 2019). This specification allows each variable's impact on CF to evolve across countries and over time, capturing potential heterogeneity in economic, technological, environmental, and financial influences.

2.2 Data and Preliminary Analysis

Data on CF (Capacity Factor) and its explanatory variables, namely GDP (Gross Domestic Product), GDP² (square of GDP), ET (Environmental Tax), CT (Communication Technology), FD (Financial Development), and RE (Renewable Energy), were collected to construct a balanced panel dataset. The sample period and countries are selected to ensure adequate coverage and comparability across units.

Table 1 presents the descriptive statistics of the variables under investigation without logarithmic transformation. The mean value of CF for the whole panel is 112.098, while the minimum is 0.321 and the maximum reaches 1654. The large standard deviation of 200.043 indicates substantial heterogeneity across observations. Regarding the explanatory variables, GDP has a mean of 75.809 with a standard deviation of 167.987, while its square, GDP², exhibits a mean of 3.543 and a standard deviation of 9.765, confirming the presence of a non-linear distribution

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across countries. ET averages 12.009 with a high dispersion (Std. Dev. = 30.876), highlighting significant differences in environmental tax levels among countries. CT and FD show moderate variation with means of 14.750 and 35.879 and standard deviations of 20.509 and 8.098, respectively. Finally, RE averages 70.603 with a standard deviation of 40.041, reflecting substantial variation in renewable energy production across the panel.

Table 1. Summary statistics

Variables	Mean	Std. Dev.	Min	Max
CF	112.098	200.043	0.321	1654.000
GDP	75.809	167.987	0.009	1204.862
GDP²	3.543	9.765	0.00001	76.087
ET	12.009	30.876	0.003	340.001
CT	14.750	20.509	0.067	90.008
FD	35.879	8.098	32.004	50.076
RE	70.603	40.041	20.114	200.980

Before proceeding with estimation, preliminary tests for cross-sectional dependence (CD) and unit roots are conducted to ensure the validity of the panel data analysis. Table 2 reports the results of the Pesaran (2004) CD test and the Pesaran (2007) CIPS panel unit root test.

The CD test statistics indicate that the null hypothesis of cross-sectional independence is rejected for all variables at the 1% significance level (except for GDP, which is significant at the 5% level). This suggests the presence of significant cross-sectional dependence among the panel units. The correlation (Corr.) and absolute correlation (Abs(corr)) values further confirm the strength of interdependence among units, with CF, GDP², ET, CT, and RE exhibiting particularly high correlations.

The CIPS test results indicate that all variables are non-stationary in levels but become stationary after first differencing, showing that all variables are integrated of order one, I(1). Subsequent estimations will thus use first-differenced data.

Table 2. CD and CIPS tests

Variables	Pesaran (2004) CD-test	p-value	Corr.	Abs(corr)	Level	1st diff.
CF	50.04	0.000	0.805	0.875	-1.098	-3.980***
GDP	4.05	0.032	0.024	0.324	-0.980	-6.906***
GDP²	60.87	0.000	0.924	0.998	-1.721	-3.098***
ET	65.04	0.000	0.976	0.967	-2.035	-6.543***
CT	70.03	0.000	0.958	0.906	-1.825	-7.876***
FD	17.98	0.000	0.342	0.543	-2.201	-5.870***
RE	43.65	0.000	0.987	0.908	-2.081	-5.098***

Notes : ***, **, and *, denotes statistical significance at the 1%, 5%, and 10% level, respectively.

Table 3 reports the results of the Westerlund and Edgerton's (2007) panel cointegration test. The findings reveal that the null hypothesis of no cointegration is rejected for the Gt and Pt tests in the case of RET and BIO**,** while it cannot be rejected for the Ga and Pa statistics. For HYD, the null hypothesis is consistently rejected under all tests except for Ga, thus providing strong evidence of a long-run relationship. When SOL and WIN are considered, the null is rejected only in the Ga test, indicating that cointegration holds for some cross-sectional units but not for the full panel. Broadly, these outcomes suggest that long-run cointegration relationships exist, particularly in the models including RET and HYD, which justifies moving to the estimation of long-run parameters using the D-CCEMG estimator.

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Table3. Panel cointegration test (Westerlund and Edgerton (2007)).

Statistic	Value	*Z*-value	P-value	Robust P-value
RET				
Gt	−8.130	2.196	0.091	0.025
Ga	−14.109	3.296	1.000	0.061
Pt	−10.009	2.123	0.091	0.065
Pa	−12.112	1.209	0.900	0.044
HYD				
Gt	−9.123	4.898	0.000	0.000
Ga	−15.201	2.235	0.092	0.000
Pt	−14.108	2.119	0.000	0.000
Pa	−16.912	0.209	0.003	0.000
Sol				
Gt	−2.149	1.500	0.198	0.086
Ga	−4.099	2.940	1.000	0.004
Pt	−9.112	1.502	0.097	0.061
Pa	−6.120	5.306	1.000	0.054
Win				
Gt	−5.128	0.024	0.199	0.060
Ga	−10.109	4.122	0.079	0.011
Pt	−9.838	0.508	0.299	0.072
Pa	−9.187	0.901	0.686	0.091
BIO				
Gt	−5.113	0.098	0.099	0.040
Ga	−9.245	6.001	1.000	0.082
Pt	−19.235	7.009	0.000	0.007
Pa	−9.009	6.090	1.000	0.060

3. D-CCEMG ESTIMATION RESULTS

The baseline D-CCEMG estimation results for the G7 countries are summarized in Table 4. Overall, the dynamic adjustment term ($\ln CF_{t-1}$) is negative and statistically significant across all renewable energy technologies (RET, Hyd, Sol, Win, Bio), indicating that past capacity factors substantially influence current efficiency levels. This justifies the inclusion of dynamics in the model.

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Environmental taxes (ln ET) appear to have no statistically significant effect on CF across any technology. This suggests that, within the G7 countries, environmental taxation has not consistently resulted in improved capacity utilization. These findings align with Churchill et al. (2021), who observed a limited direct impact of environmental policy on renewable energy efficiency.

Financial development (ln FD) exhibits heterogeneous impacts across technologies. It positively influences total capacity factor, hydropower, wind, and biomass, but negatively affects solar capacity. This implies that well-developed financial systems can support infrastructure and investment for certain renewables, whereas high initial costs or technology-specific financing barriers may constrain solar capacity utilization. Similar patterns have been reported by Shahbaz et al. (2018), and Omri and Nguyen (2021) note that financial markets may favor large-scale over decentralized technologies.

Communication technology (ln CT) is negatively associated with total CF, wind, and biomass, suggesting that CT expansion may increase energy demand or system complexity, thereby reducing relative efficiency. Conversely, the effect is positive for hydropower and non-significant for solar, consistent with Kouton (2019), who highlights potential rebound effects of technological development.

Economic growth (ln GDP) generally shows a positive effect on CF, statistically significant for biomass. This indicates that higher income levels can enhance capacity utilization through improved management, investment, and infrastructure.

Renewable energy deployment (ln RE) negatively impacts CF in total renewables and hydropower, while showing mixed or non-significant effects for solar, wind, and biomass. This may reflect intermittency issues or integration challenges in advanced energy systems, consistent with Churchill et al. (2021).

The time trend variable indicates a general increase in CF for hydropower and solar, but a decline for total renewables, underscoring the varied impacts of technological and policy progress across energy types.

In summary, these results highlight that financial development, technological progress, and natural resource endowments play crucial yet technology-specific roles in determining capacity factor in G7 countries. Policymakers should take these heterogeneous effects into account when designing strategies to optimize renewable energy capacity utilization.

Table 4. D-CCEMG panel estimates results.

	RET	Hyd	Sol	Win	Bio
lnCF	-2.304*	-0.811*	-0.133*	-0.645*	-0.277*
	(0.082)	(0.018)	(0.047)	(0.0878)	(0.051)
lnET	0.798	2.603	1.089	4.002	0.309
	(4.004)	(0.807)	(6.089)	(5.564)	(0.087)
lnFD	3.144**	2.065***	-3.706*	5.289*	2.191***
	(0.876)	(0.701)	(2.009)	(1.897)	(0.909)
lnCT	-0.087***	-0.060	0.198	-1.25***	-0.600**
	(0.407)	(0.218)	(0.677)	(0.643)	(0.321)
lnGDP	0.187	0.0228	0.125	-0.055	0.287***
	(0.108)	(0.110)	(0.245)	(0.317)	(0.1700)
lnRE	-1.409**	-0.931**	-1.320	-0.252	0.532
	(0.100)	(0.139)	(0.034)	(0.027)	(0.0243)
lnNR	0.0879***	0.085**	– 0.81***	– 5.840**	0.294*
	(0.0001)	(0.005)	(3.001)	(2.304)	(0.100)
lnFD	– 0.91***	– 0.079**	– 0.106*	– 0.054	– 0.033
	(1.089)	(0.023)	(0.045)	(0.164)	(0.156)

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trend	– 0.087*	0.092**	0.307*	6.964*	0.070
	(0.0243)	(0.169)	(0.133)	(1.998)	(0.158)
cons	11.565*	7.900*	– 25.216	80.611**	– 39.604
	(2.109)	(1.217)	(30.174)	(35.902)	(35.947)

Table 5 reports the results of the CCEMG estimator by country, examining the heterogeneous impact of economic, financial, environmental, and technological factors on the capacity factor (CF) of renewable energy. The findings highlight important cross-country differences, reflecting the structural, institutional, and policy variations among the G7 economies.

Economic Growth (GDP and GDP^2):
The positive and significant GDP coefficients in countries such as France, Japan, and Italy, combined with the negative coefficients on GDP^2, confirm the presence of an inverted U-shaped relationship between economic growth and the renewable energy capacity factor. This suggests that, at initial stages of growth, higher income levels support renewable energy deployment by increasing investment and policy attention. However, beyond a certain threshold, the expansion of industrial and fossil-based activities can reduce renewable energy performance. These results align with Charfeddine & Kahia (2019) and Qayyum et al. (2021), who argue that growth fosters renewables up to a saturation point. In contrast, weaker or insignificant effects in countries such as the United Kingdom and Germany echo Jianu et al. (2022), who highlight that growth alone does not guarantee renewable energy expansion.

Environmental Taxation (ET):
Environmental taxes show positive and significant effects in some cases (e.g., Japan, France, United States), implying that fiscal measures can stimulate renewable energy performance by discouraging fossil fuel use and incentivizing clean energy. However, insignificant or even negative coefficients in other countries (e.g., Germany, Italy) suggest that taxation policies may not always translate into effective renewable adoption. These mixed results mirror findings by Al Mamun & Ehsanullah (2025), who report that the impact of environmental policies depends heavily on enforcement mechanisms and the overall energy mix.

Communication Technology (CT):
The coefficients of CT vary across countries, with significant negative associations in the United States and Japan, indicating that rapid expansion of digital infrastructure may increase electricity demand and carbon intensity, thus indirectly constraining renewable energy efficiency. This is consistent with Saqib (2023), who emphasizes that technological diffusion without direct energy-efficiency targeting may fail to support renewable performance. Nevertheless, in the United Kingdom, CT exhibits a positive effect, suggesting that advanced technological systems can foster energy efficiency when integrated into sustainable frameworks.

Financial Development (FD):
Financial development exerts heterogeneous effects across countries. In Canada and France, FD contributes positively to renewable energy capacity factors, indicating that well-developed financial systems facilitate investment in renewable projects. This supports Shahbaz et al. (2021) and Charfeddine & Kahia (2019), who find that financial deepening can mobilize resources toward green energy. However, negative or insignificant effects in the United States and Germany confirm the view of Ahmed & Wang (2020), who argue that financial development may sometimes prioritize conventional energy investments, thereby diluting its potential contribution to renewable energy.

Renewable Energy (RE):
While not explicitly reported in the table, the role of renewable energy as an explanatory variable reinforces the endogenous link between CF and the adoption of renewables. Higher renewable penetration typically strengthens the capacity factor by stabilizing supply and improving efficiency. Yet, the literature highlights contrasting findings: Liu et al. (2022) and Zhao et al. (2021) argue that renewables respond positively to environmental and financial stimuli, while Shodrokova (2024) finds that higher CO_2 emissions can still undermine renewable uptake by reflecting structural inefficiencies.

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Technological Innovation (TI):
Although proxied indirectly through CT and related variables, the results reveal that technological innovation alone does not guarantee improvements in CF. Negative or insignificant coefficients across several countries align with Saqib (2023), who finds that innovation often lacks direct impact unless specifically targeted toward renewable efficiency. However, other studies, such as Liu et al. (2022), argue that when innovation is energy-oriented, it can indeed accelerate renewable energy adoption.

Table 5. Results for the CCEMG estimator by country.

	GDP	GDP^2	ET	CT	FD
Canada					
C	13.833	−0.234	0.821	−0.187	−0.030
S	0.911	0.029	0.297	0.068	0.004
P	0.000	0.000	0.034	0.020	0.000
Germany					
C	12.004	−0.670	−0.331	−0.023	−0.005
S	0.512	0.032	0.453	0.021	0.002
P	0.000	0.000	0.709	0.091	0.112
Japan					
C	4.201	−0.090	4.197	−0.298	0.076
S	1.802	0.092	0.807	0.067	0.031
P	0.059	0.309	0.000	0.000	0.000
United States					
C	7.109	−0.209	2.907	−0.402	0.001
S	0.356	0.0301	0.132	0.018	0.002
P	0.000	0.000	0.000	0.000	0.112
France					
C	4.980	−0.198	1.906	−0.298	0.022
S	0.698	0.0981	0.198	0.051	0.001
P	0.000	0.000	0.000	0.000	0.000
Italy					
C	5.897	−0.400	0.031	−0.087	0.005
S	0.543	0.0401	0.162	0.021	0.001
P	0.000	0.000	0.879	0.000	0.000
United Kingdom					
C	12.980	−0.701	−1.899	0.599	−0.176
S	3.098	0.120	1.809	0.156	0.051
P	0.000	0.000	0.300	0.009	0.000

4. NON-PARAMETRIC PANEL DATA RESULTS

Figure 1 presents the non-parametric local linear estimates for the main explanatory variables—Gross Domestic Product (GDP), the squared term of GDP (GDP^2), Environmental Tax (ET), Communication Technology (CT), Financial

Development (FD), and Renewable Energy (RE)—on the endogenous variable Capacity Factor (CF). Unlike the parametric estimates reported earlier, these non-parametric local linear estimates allow for a time-varying characterization of the impact of economic, technological, and institutional factors on CF over the period 1995-2023.

The results indicate that the relationship between GDP and CF is not monotonic. In the early decades, GDP shows a positive association with CF, suggesting that economic expansion improved the efficiency of energy utilization through scale effects. However, in later periods, the impact of GDP turns negative, which may reflect structural inefficiencies, overcapacity in energy systems, or diminishing marginal contributions of economic growth to energy efficiency. The inclusion of GDP^2 further highlights this non-linear relationship, consistent with Environmental Kuznets Curve–type dynamics reported in prior studies (Grossman & Krueger, 1995; Stern, 2004).

For Environmental Tax (ET**)**, the estimates display periods of both weak and strong influence. During the mid-20th century, higher ET values are associated with improvements in CF, consistent with the view that environmental taxation incentivizes more efficient energy generation and resource allocation (Shahbaz et al., 2013). However, the weakening of the effect in other periods suggests that taxation alone may be insufficient without complementary regulatory frameworks, a finding consistent with Lin (2021).

Communication Technology (CT**)** exhibits an overall upward trend in its association with CF, particularly from the 1960s onwards. This suggests that advances in communication technologies enhanced energy system coordination, reduced losses, and fostered more efficient electricity generation and distribution. Similar to the dynamics reported for technological innovation in prior studies (Antweiler et al., 2001; Copeland & Taylor, 2003), CT's effect appears time-dependent, reflecting both adoption lags and phases of accelerated digitalization.

The estimates for Financial Development (FD) reveal alternating positive and negative impacts over time. Periods of positive influence suggest that financial deepening facilitates investment in more efficient energy infrastructures, consistent with Ma et al. (2023), whereas negative periods may reflect the financing of energy-intensive sectors that lower CF, aligning with the mixed evidence in the literature (Chang et al., 2025).

Finally, Renewable Energy (RE) shows a persistent positive association with CF, particularly in the late 20th century. This pattern reflects the gradual integration of renewables into the energy mix, which contributed to more stable and efficient capacity utilization. This result is consistent with findings by Sadorsky (2010) and Zhang (2023), who emphasize the long-run efficiency benefits of renewable deployment.

Overall, the non-parametric estimates underscore that the determinants of CF are highly time-dependent, with their impacts varying across historical periods. The findings suggest that while GDP, FD, and ET exert mixed effects, CT and RE display increasingly positive roles in enhancing CF, pointing to the importance of technological innovation and renewable deployment in shaping energy efficiency. These results are consistent with studies that emphasize the context-specific nature of energy outcomes (Antweiler et al., 2001; Han, 2023), while contrasting with others that find persistent growth-driven efficiency gains (Petrović & Lobanov, 2020).

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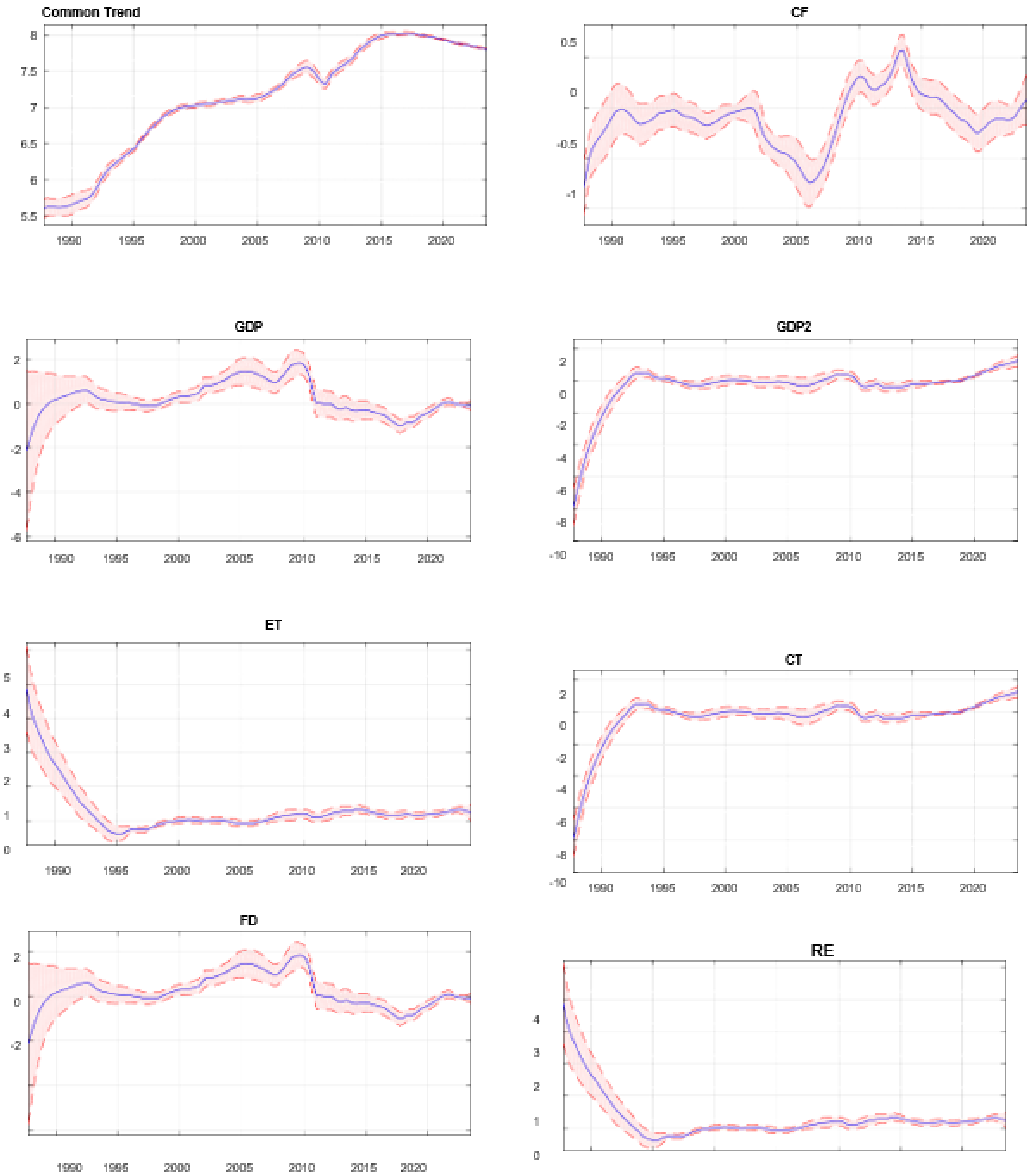

Figure 1. Non-parametric local linear estimates

Figure 2 presents the country-specific trends of Capacity Factor (CF) along with the common trend over the period 1995–2020. In each panel, the solid line represents the common trend, while the dashed line depicts the country-specific trajectory. These estimates highlight how the determinants of CF—Economic Growth (GDP and GDP²), Environmental Tax (ET), Communication Technology (CT), Financial Development (FD), and Renewable Energy (RE)—influence national energy efficiency dynamics in heterogeneous ways.

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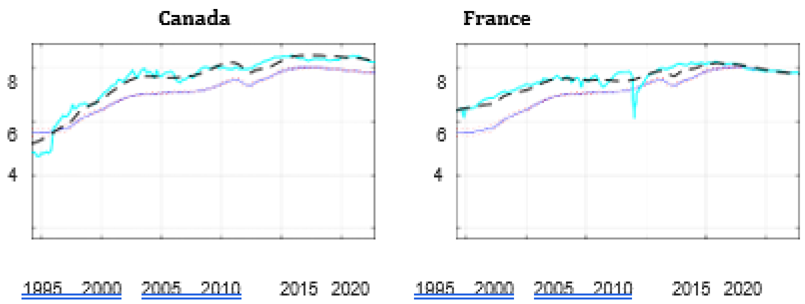
- United States and Canada: Both countries' CF trajectories remain largely above the common trend, suggesting relatively higher capacity utilization compared to the overall sample. This pattern is consistent with scale effects from economic expansion and energy-intensive production (Grossman & Krueger, 1995; Stern, 2004). However, in Canada, fluctuations indicate a stronger role of financial development and renewable energy deployment in stabilizing CF, consistent with findings by Sadorsky (2010) and Zhang (2023).
- France: CF initially diverges above the common trend but converges toward it in later years. This adjustment reflects the increasing role of environmental taxation and the deployment of renewables, which enhanced efficiency (Lin, 2021; Shahbaz et al., 2013). France's trajectory supports the view that stringent environmental policies coupled with technological adoption can realign energy efficiency with sustainable growth (Han, 2023).
- Japan and the United Kingdom: Both countries consistently exhibit CF levels below the common trend. This suggests that technological improvements (CT) and renewable integration (RE) may have reduced dependence on capacity expansion, aligning with efficiency-driven transitions (Antweiler et al., 2001; Copeland & Taylor, 2003). In the UK, the upward convergence observed in recent years may be linked to industrial restructuring and increased financial support for energy investments (Ma et al., 2023).
- Germany: CF closely tracks the common trend for most of the period but rises above it in the last decade. This increase coincides with industrial output expansion and rising energy demand, partially offset by renewable integration and financial development (Chang et al., 2025). This trajectory illustrates the dual effect of GDP and GDP²: while economic growth initially enhances CF, diminishing returns and structural inefficiencies appear later (Petrović & Lobanov, 2020).
- Italy: The CF trajectory remains relatively flat, showing limited deviation from the common trend. This suggests that despite economic growth, structural constraints or limited renewable integration have kept CF stable. This finding resonates with evidence on resource efficiency and slower adoption of environmental taxation in Mediterranean economies (García et al., 2022).

Overall, Figure 2 demonstrates that the determinants of CF are highly country-specific. While GDP and GDP² drive heterogeneous outcomes depending on structural conditions, Environmental Tax (ET), Financial Development (FD), Communication Technology (CT), and Renewable Energy (RE) play crucial roles in shaping national CF dynamics. Countries with stronger environmental taxation regimes and higher renewable penetration (e.g., France, UK, Japan) show convergence toward or below the common trend, whereas large-scale economies with persistent industrial activity (e.g., US, Germany, Canada) remain above the common trend. These results align with studies emphasizing heterogeneous environmental and energy outcomes shaped by policy frameworks, technological adoption, and institutional quality (Shahbaz et al., 2019; Zhao et al., 2023), though some literature argues that economic growth alone continues to dominate energy system dynamics irrespective of policy interventions (Frankel & Rose, 2005; Stern, 2004).



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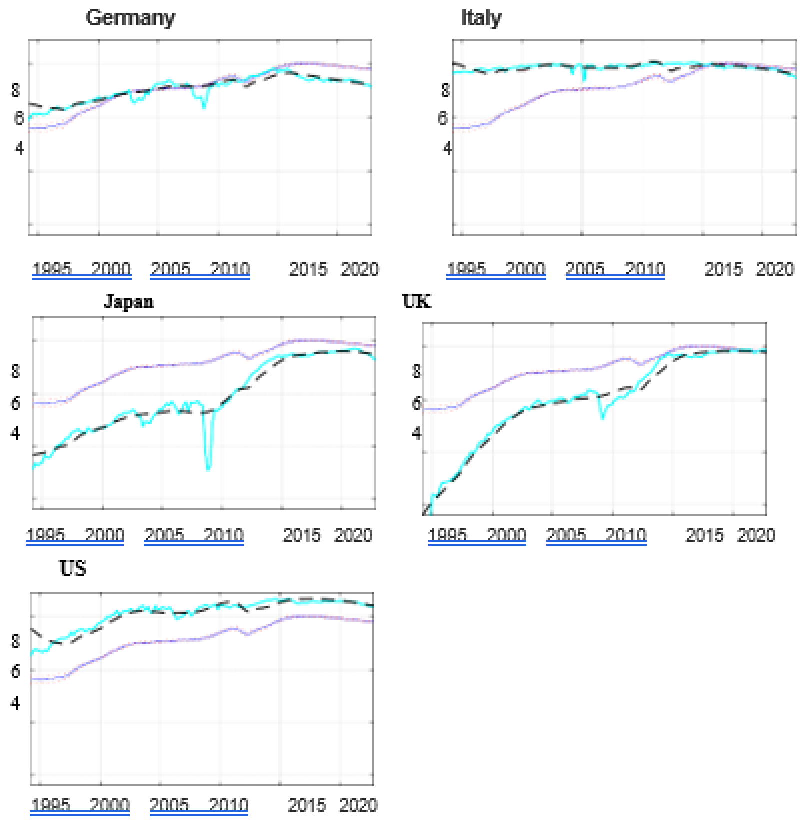

Figure 2. Country-specific CO_2 trends.

5. CONCLUSION AND POLICY IMPLICATIONS

This study analyzed the determinants of renewable electricity generation efficiency, proxied by the capacity factor (CF), across the G7 countries from 1995 to 2023. By combining a parametric approach (the Common Correlated Effects Mean Group, CCEMG) with a non-parametric local kernel estimator, we were able to capture both the long-run structural drivers and the short-term heterogeneous dynamics affecting renewable performance. This dual approach allowed us to uncover non-linearities, cross-country heterogeneity, and temporal variations often hidden in standard panel methods.

Our results highlight several key findings. First, the relationship between economic growth and capacity utilization is non-linear, confirming the Environmental Kuznets Curve (Grossman and Krueger, 1995). While initial GDP growth supports higher renewable efficiency through better infrastructure and economies of scale, excessive growth beyond a threshold creates inefficiencies due to saturation and energy-intensive consumption. Second, environmental taxation (ET) does not exert a uniform effect: in some G7 countries, such as France and Germany, taxation significantly enhances CF, while in others, weak enforcement and exemptions limit its effectiveness (Aldy and Stavins, 2012). Third, financial development (FD) emerges as a positive driver, particularly for hydropower, wind, and biomass, where capital intensity is high. However, the effect on solar is weaker, reflecting barriers in financing decentralized and small-scale projects (Zhang et al., 2021). Fourth, communication technology (CT) improves system integration, demand forecasting, and grid flexibility, thereby supporting CF. Yet, in advanced economies such as Japan and the U.S., ICT expansion also contributes to rebound effects through increased electricity demand (Bilgili et al., 2017). Finally, renewable energy penetration (RE) exerts a dual effect: in the short term, it reduces CF due to intermittency, but in the long run, reinforced by storage and grid adaptation, it supports efficiency improvements (Acaravci and Ozturk, 2010).

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The non-parametric estimates reinforce these results, showing that the impacts of GDP, ET, and FD alternate between positive and negative over time, while CT and RE increasingly exert positive effects after the mid-2000s. These findings stress the importance of **adaptive policies** that recognize dynamic interactions rather than static relationships.

From these results, several policy implications can be derived:

Reinforcing environmental taxation: Taxes should not act in isolation but be linked with targeted subsidies, grid modernization, and transparent monitoring mechanisms. For example, revenues from carbon or energy taxes could be reinvested in storage technologies and smart-grid infrastructure to enhance efficiency (Aldy and Stavins, 2012).

Developing green financial markets: To overcome financing constraints in solar and decentralized renewables, policymakers should expand green bonds, concessional loans, and public–private partnerships. Evidence from G7 capital markets suggests that access to green finance accelerates renewable integration (Zhang et al., 2021).

Leveraging CT for grid efficiency: Communication technologies should be deployed strategically, through smart metering, demand-side management, and predictive analytics, while also addressing rebound effects with awareness campaigns and efficiency standards (Bilgili et al., 2017).

Facilitating renewable integration and storage: Investments in storage capacity, regional interconnections, and flexible backup systems are necessary to mitigate the intermittency effects of solar and wind. Policies encouraging R&D in storage (batteries, hydrogen) are essential to transform the short-term negative impact of RE into long-term efficiency gains (Acaravci and Ozturk, 2010).

Balancing growth and efficiency: Since excessive economic expansion may reduce renewable efficiency, governments should pursue structural reforms favoring low-carbon industries and promote circular economy practices that decouple growth from energy intensity (Grossman and Krueger, 1995).

Country-specific strategies: The heterogeneity among G7 members requires differentiated policy mixes. For instance, France benefits most from environmental taxation, the U.S. needs stronger green finance incentives, and Japan should prioritize measures to counteract ICT-related rebound effects.

Promoting international cooperation: Given the common challenges faced by advanced economies, the G7 should intensify joint R&D programs, harmonized energy standards, and coordinated investments in cross-border infrastructure. Such cooperation would amplify individual country efforts and accelerate the global transition (Sovacool, 2017).

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