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Assessing Rwanda's National electrification strategy: Impact and trade-offs[☆]

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ABSTRACT

Like many African countries, Rwanda faces challenges with high biomass reliance and low electricity access, impeding sustainable development. To address this, the 2016 National Electrification Strategy (NES) was launched, promoting both on-grid and off-grid renewable solutions. This study assesses the impact of the NES on electricity access, renewable energy consumption share, and greenhouse gas (GHG) emissions using the Synthetic Control Method (SCM). The key findings reveal a multifaceted outcome: the NES significantly boosted electricity access by approximately 17 percentage points. However, it led to a decrease in the share of renewable energy consumption by more than 4 percentage points. Total GHG emissions exceed the synthetic control by about 1070 kilotons of CO_2 equivalent. These results highlight crucial trade-offs between rapid electrification and environmental sustainability. Robustness checks confirm our findings. The study provides valuable quantitative evidence on the complex outcomes of a major electrification policy in a developing economy. The results underscore the critical need for integrated policy frameworks that simultaneously pursue electrification goals while implementing measures to preserve renewable energy usage and mitigate adverse environmental impacts, offering insights for policymakers seeking to balance these objectives.

1. Introduction

Rwanda has emerged as a beacon of economic resilience and transformation in sub-Saharan Africa since political stability was restored after the tragic genocide in 1994, enabling the government to set ambitious targets for social and economic development. Rwanda achieved a real GDP growth rate of 8% per annum in the period 2001–2015 (Sandwell et al., 2017) and aspires to become a middle-income country by 2035 and a high-income country by 2050 (World Bank, 2020). These ambitions are founded upon strong policy frameworks aligned to the UN's Sustainable Development Goals (United Nations, 2015).

Despite economic progress, lack of universal access to electricity has impeded Rwanda's sustainable development trajectory. The Government of Rwanda is committed to advancing access to affordable, reliable, sustainable and modern energy for its citizens in line with SDG 7 and in accordance with the goals of the Paris Agreement on Climate Change (United Nations Framework Convention on Climate Change (UNFCCC), 2015). Expanding access to electricity has increased consumption and labour force participation in Rwanda (Adom and Nsabimana, 2022) which in turn enhance the quality of human life. But greater electricity access can also raise greenhouse gas emissions, either directly through increased energy use or indirectly through economic growth. Using renewable sources of energy can help to reduce these impacts and is recognized in SDG7 through the inclusion of targets on renewable energy and energy efficiency. A particular challenge in Rwanda is the use of biomass, which accounts for approximately 85% of Rwanda's total energy consumption (Republic of Rwanda, 2015b) and is comprised mainly of traditional biomass (wood fuel) that poses not only environmental concerns but also hampers socio-economic advancement. This study addresses the fundamental problem of whether increasing electricity access is sustainable in climate change terms by examining the impact of a set of major policy initiatives, collectively called the National Electrification Strategy (NES).

This is an important problem because the extent to which large-scale electrification is compatible with climate sustainability is not clear a priori and can depend upon the nature of the policies that are implemented. The electricity mix, and related CO_2 emissions, largely depend on the extent of on-grid and off-grid electricity access, which reflects the spatial distribution of population densities. In sparsely populated rural areas, where many households have low incomes and therefore low levels of electricity consumption, off-grid systems can play a vital

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role in providing electricity access at reasonable cost (Bisaga et al., 2021). Renewable power generation technologies, particularly solar and wind, have become increasingly competitive relative to fossil fuels due to a reduction of their cost, largely driven by innovation in technology and policy (Dagnachew et al., 2018).

Recognizing these challenges, the Rwandan government created a set of policies for the extraction, development and use of Rwanda's energy resources, the foundation for which was laid out in the 2003 Constitution, which made it incumbent upon the government to formulate an energy policy to promote technology and improve social welfare. This objective is guided by a high-level strategic policy called the National Energy Policy (NEP) (Republic of Rwanda, 2015b). A new NEP, with a broader focus on sustainable development, private sector involvement, and longer-term goals, was not approved by the Rwandan Cabinet until March 2015. The principles of the NEP are operationalized through the Ministry of Infrastructure's Energy Sector Strategic Plan (ESSP). Established in 2012, it sets electrification goals and was revised in 2015 to cover the period until 2018 (Republic of Rwanda, 2015a). The 2015 ESSP outlined several high-level target objectives cutting across all key energy sub-sectors, generating an investment boost in 2016 when public funds poured into transmission and distribution systems (Sustainable Energy for All and Climate Policy Initiative, 2020).

Goals for the provision of on-grid electricity services across the country are set by the Electricity Access Rollout Program (EARP), launched in 2009, which aimed to increase electricity access from 6% to 16% by 2013 (World Bank, 2020). While the EARP extended the national grid, it was realized that this approach is not cost-effective for electrifying remote areas where grid extension is not economically viable (International Renewable Energy Agency, 2019). Furthermore, Rwanda's topography (famously known as the land of a thousand hills) poses a significant challenge to achieving centralized coverage at an affordable cost (Brunet et al., 2021). This set the stage for the launch of the Rural Electrification Strategy (RES) by the Ministry of Infrastructure in 2016 (Republic of Rwanda, 2016), offering a range of electrification options from standalone solar systems through to mini-grids. The strategy aimed to ensure that by 2018, 70% of Rwandans would have access to electricity, with full coverage targeted by 2020. In line with the terminology used in a report prepared by international consultants for the Rwanda Energy Group (REG) Electricity Distribution Company Limited (Group, 2016) we refer to the NEP, the ESSP and the RES collectively as the National Electrification Strategy (NES) and pinpoint 2016 as a pivotal year for the country's electrification efforts, and the basis for our study.

Studying and evaluating electricity access in Rwanda remains critically important, not only due to the country's rapid progress toward universal electrification, but also due to the complex trade-offs it faces between expanding access, maintaining sustainability, and meeting climate goals (Brunet et al., 2021; Adom and Nsabimana, 2022). The RES recognized that a mix of on-grid and off-grid systems, particularly renewable solar home systems and mini-grids, is essential to achieve rural electrification. This strategic shift toward decentralized energy solutions aligns with global best practices and theoretical models that advocate for renewable-based, decentralized electrification in regions with dispersed populations (Bhattacharyya and Palit, 2016). However, challenges remain in ensuring the long-term sustainability of off-grid solutions. Issues such as the affordability of maintenance services, the durability of equipment, and the need for continuous capacity building are critical areas that require ongoing attention (Blimpo and Cosgrove-Davies, 2019). Additionally, there is a need to integrate off-grid systems with future grid expansion plans to avoid redundancy and ensure efficient use of resources (Moner-Girona et al., 2016).

The set of policy initiatives that comprise the NES redefined Rwanda's approach to electrification and introduced several key components to facilitate its objectives. It streamlined regulatory frameworks to attract private sector investment in off-grid solutions, provided incentives such as tax exemptions for renewable energy equipment and simplified licensing procedures for mini-grid operators (Mukeshimana et al., 2021). To address the high upfront costs of renewable technologies, it established financial mechanisms for end-users, including subsidies and micro-financing options. Partnerships with international donors and development banks were instrumental in mobilizing the necessary funds (Rolffs et al., 2015). Moreover, the NES aimed to reduce reliance on traditional biomass and kerosene, thereby helping to decrease indoor air pollution and greenhouse gas emissions (Barron and Torero, 2017). It also contributed to Rwanda's commitments under the Paris Agreement by promoting low-carbon development pathways (Republic of Rwanda, 2017).

We evaluate the impact of the NES using the Synthetic Control Method (SCM), which compares Rwanda's renewable energy outcomes to a synthetic control group of countries with similar socio-economic profiles but without a targeted electrification strategy. This method allows for a robust analysis of the NES's effectiveness by isolating the policy's impact from other external factors (Abadie et al., 2010). We use data from the World Bank to assess the policy and regulatory frameworks put in place by countries to support the achievement of SDG7.

Our empirical findings indicate that the NES significantly increased electrification rates in Rwanda compared to our control group. This is reflected in statistics reported by the Rwanda Utilities Regulatory Authority (RURA) showing that the electrification rate rose from 20% in 2016 to over 50% by 2020, with off-grid connections accounting for a substantial portion of this growth (Rwanda Utilities Regulatory Authority, 2020). Studies have shown that households with access to off-grid solar systems experience improved quality of life, increased income-generating opportunities, and enhanced educational outcomes due to extended study hours (Grimm et al., 2017). Our results also show that electricity expansion in Rwanda occurred in tandem with a reduction in renewable energy consumption as a percentage of total energy use, compared to our group of control countries. The expansion of electricity access from on-grid sources seems to have had more of an impact compared to off-grid sources, as the energy consumption mix had fewer sources of renewable energy. The growth of electricity access also occurred alongside an increase in GHG emissions, which suggests that the infrastructure projects involved in electrification, and associated construction activities, resulted in higher emissions.

The contribution of this paper to the literature is fivefold. First, we provide a direct policy-specific evaluation of Rwanda's 2016 National Electrification Strategy, distinguishing it from broader assessments of the country's energy sector. While previous studies have investigated Rwanda's electrification progress (Bisaga et al., 2021; Mukeshimana et al., 2021; Adom and Nsabimana, 2022), none have isolated the NES as a distinct policy intervention. Our work fills this gap by directly assessing the strategy's causal impact using a counterfactual approach. Second, our study examines the interplay between electricity access, renewable energy consumption, and total greenhouse gas emissions as key outcome variables. This integrated analysis builds on and extends prior research that has typically focused on one or two of these dimensions (Lenz et al., 2017; Dagnachew et al., 2018), offering a more holistic understanding of energy transitions in low-income settings. Third, we apply the Synthetic Control Method to a Sub-Saharan context, demonstrating its utility in evaluating national energy policies. The SCM has been used widely in policy evaluation (Tang et al., 2024), but its application to electrification strategies in Africa remains limited. Our robustness checks, including leave-one-out tests and placebo tests, reinforce the credibility of our causal claims and contribute to methodological advancements in energy policy evaluation. Fourth, our analysis is grounded in an implicit theory of change framework, complemented by political economy and institutional theory. This theoretical triangulation allows us to interpret the NES not only in terms of outcomes, but also in terms of the institutional arrangements, power dynamics, and policy mechanisms that shaped its implementation. This builds on and contributes to the literature on energy governance and institutional capacity in Sub-Saharan Africa (Dagnachew et al., 2020). Fifth, our findings reveal a critical sustainability paradox: while the NES accelerated electricity access, it coincided with a decline in the share of renewable energy consumption and a rise in GHG emissions. These findings highlight the need for integrated policy designs that balance access, affordability, and environmental sustainability. We offer policy recommendations grounded in our theoretical framework to guide future electrification strategies in developing economies. The rest of the paper proceeds as follows. In Section 2 we review the relevant literature and construct a theoretical framework to evaluate the impact Rwanda's electrification efforts. In Section 3 we describe the energy policy in Rwanda and in Section 4 we explain our data and methodology and then report our findings in Section 5. In Section 6 we present our conclusions and policy recommendations.

2. Literature review

Electrification outcomes, defined here as electricity access, renewable energy consumption, and greenhouse gas (GHG) emissions, are shaped by a constellation of structural, socioeconomic, institutional, market, and policy factors. These determinants interact with national strategies such as Rwanda's National Electrification Strategy (NES), influencing both the direction and magnitude of change. Understanding these underlying drivers is essential for interpreting causal impacts and designing credible counterfactual analyses. We review the key factors influencing electrification outcomes and develop a theoretical framework to understand how these outcomes are shaped by Rwanda's NES.

2.1. Determinants of electrification outcomes

2.1.1. Structural and socioeconomic determinants

Household income is one of the most consistently cited determinants of electricity access and consumption. Blimpo et al. (2020) show that income levels affect both the ability to afford connection fees and the perceived value of electricity relative to traditional fuels. High upfront costs can create threshold effects, where even modest income gains do not translate into electrification unless mitigated by targeted subsidies or financing mechanisms. Chapel (2022) and Rolffs et al. (2015) highlight how international support and pay-as-you-go models can reduce affordability constraints, a strategy reflected in Rwanda's NES through micro-financing and donor-backed subsidies. Education and awareness also play a critical role. Ye et al. (2018) and Blimpo et al. (2020) find that higher education levels correlate positively with electricity consumption and productive use, suggesting that electrification outcomes are partly shaped by household capacity to recognize and leverage the benefits of modern energy. Geographic and infrastructural constraints introduce fundamental cost asymmetries. Lower population density in rural areas makes grid extension economically unviable in many contexts (Blimpo et al., 2020; Byaro et al., 2024). Alola (2024) documents a persistent urban–rural clean energy access gap, driven by the rising marginal cost of reaching dispersed populations. Rwanda's hilly terrain and scattered settlements exacerbate these challenges, making conventional grid expansion particularly expensive (Brunet et al. 2021). These geographic realities informed the NES's emphasis on off-grid and mini-grid solutions, which are more adaptable to Rwanda's topography.

Natural resource endowments also influence energy accessibility. Studies by Xia et al. (2023) and Liu and Lu (2023) show that mineral and fossil fuel rents can support electricity access and renewable energy development, but their impact depends on governance quality and energy policy alignment. In Rwanda, where domestic fossil fuel reserves are limited, renewable energy development has relied more heavily on institutional capacity and external financing.

2.1.2. Institutional and market determinants

Governance capacity and institutional coherence are frequently cited as critical enablers of successful energy reforms. Dagnachew et al. (2020) and Falchetta et al. (2021) argue that weak institutions and fragmented governance structures often pose greater barriers to electrification than resource scarcity. In contrast, Rwanda's relatively strong governance – characterized by policy coherence, performance-based management, and regulatory clarity – has facilitated the implementation of its NES. Mukeshimana et al. (2021) highlight how Rwanda's streamlined licensing procedures and tax incentives for renewable energy equipment have supported private sector participation and decentralized energy deployment. Regulatory frameworks and environmental policy stringency also play a decisive role. Hassan et al. (2024) and Zhao et al. (2025) show that stringent environmental policies enhance the impact of renewable energy on carbon emissions reduction. These findings suggest that Rwanda's NES, which emphasized renewable energy sources such as solar and hydro, may have benefited from its broader policy environment, although the observed decline in renewable energy share post-NES indicates potential misalignments between electrification goals and sustainability outcomes. Market dynamics and financial mechanisms are equally influential. Appiah et al. (2023) find that financial development and fiscal policy can either support or hinder renewable energy development, depending on institutional quality. In Sub-Saharan Africa, foreign capital has been shown to positively contribute to renewable energy expansion, but its effectiveness is contingent on transparency and governance (Guo et al., 2024). Rwanda's NES leveraged donor partnerships and concessional financing to overcome high upfront costs, aligning with best practices identified in the literature. Energy pricing and consumer behaviour further shape energy outcomes. Ye et al. (2018), and (Byaro et al., 2024) note that nonlinear tariffs and prepaid meters can discourage electricity uptake if not carefully designed. Rwanda's relatively high electricity tariffs (Chemouni and Dye, 2024) may create tensions between cost recovery and access objectives, particularly for low-income households. Political and social factors, including gender representation and public preferences, also influence energy transitions. Opoku et al. (2021) and Gozgor et al. (2025) find that women's political empowerment is positively associated with renewable energy consumption and energy efficiency. In Rwanda, where governance is relatively inclusive, such dynamics may have contributed to the NES's initial success in expanding access, even if renewable energy outcomes were mixed.

2.1.3. Policy-driven determinants

While structural and institutional factors influence energy transitions, deliberate policy interventions often serve as the most decisive catalysts for change. A growing body of literature evaluates the impact of national electrification strategies and donor-supported programs on electricity access, renewable energy adoption, and environmental outcomes. Programs such as Kenya's Last Mile Connectivity Project, Ghana's National Electrification Scheme, and Rwanda's Electricity Access Rollout Program (EARP) have demonstrated that well-designed public interventions can significantly expand access, particularly when coupled with private sector engagement and concessional financing (Lenz et al., 2017; Blimpo and Cosgrove-Davies, 2019; Chapel, 2022). However, the effectiveness of such programs varies widely depending on implementation capacity, regulatory coherence, and the alignment of incentives across stakeholders. Rwanda's 2016 NES marked a strategic shift from grid-centric expansion to a hybrid model integrating off-grid and mini-grid solutions. The strategy introduced regulatory reforms, financial mechanisms, and capacity-building initiatives aimed at accelerating electrification while promoting renewable energy technologies (Mukeshimana et al., 2021). Despite these efforts, the observed decline in renewable energy share and rise in GHG emissions post-NES suggest that electrification goals may have outpaced sustainability safeguards. Empirical evaluations of similar policy interventions often rely on quasi-experimental methods such as difference-in-differences

(DiD) or panel regressions. However, these approaches face limitations when policies are implemented nationwide or when suitable control groups are unavailable. In such contexts, the SCM offers a robust alternative by constructing a counterfactual trajectory from a weighted combination of comparison units that did not implement the policy in question (Abadie et al., 2010). Recent studies have applied the SCM to diverse energy and climate policies. For instance, Arcila and Baker (2022) reassess British Columbia's carbon tax and find that CO_2 emissions and gasoline consumption rose relative to the synthetic control, challenging theoretical expectations. Crichton et al. (2023) show that Austria's climate strategy led to sustained increases in renewable energy consumption without compromising economic output. Similarly, evaluations of the U.S. Regional Greenhouse Gas Initiative (RGGI) reveal both positive impacts and unintended consequences, such as increased electricity imports and emissions leakage (Lee and Melstrom, 2018; Murray and Maniloff, 2015). These findings underscore the importance of context-specific analysis and the potential for policy spillovers, especially in interconnected energy markets. Beyond infrastructure and regulation, financial inclusion plays a critical role in expanding energy access. Barry et al. (2025) demonstrate that mobile money adoption significantly increases the likelihood of solar panel uptake in Tanzania, particularly among poor households and migrants. Their findings highlight the role of digital finance in overcoming affordability barriers and enabling decentralized electrification. In China, Tang et al. (2024) show that smart energy policies alleviate energy poverty through mechanisms such as improved supply capacity, payment ability, and energy cleanliness. These insights offer valuable lessons for Sub-Saharan Africa, where off-grid and mini-grid solutions are increasingly central to electrification strategies.

Policy interventions to improve electricity access may involve trade-offs with renewable energy adoption and environmental outcomes. Perhaps the most contentious area concerns the impact of electrification programs on greenhouse gas emissions, as the relationship is theoretically ambiguous: expanding electricity access can reduce emissions by displacing traditional biomass and kerosene (Barron and Torero, 2017) but can also increase emissions through higher energy consumption and fossil fuel generation. Brunet et al. (2021) examine Rwanda's challenge of balancing rapid electricity access growth with climate targets. When electrification outpaces renewable generation deployment, the gap is often filled by fossil fuel sources, leading to higher emissions even as access expands (Galeazzi et al., 2024). Greater electricity access can raise emissions both directly through increased energy use and indirectly through economic growth effects, with the net impact depending on whether new electricity consumption displaces higher-emission alternatives or represents additional energy use (Adom and Nsabimana, 2022).

Furthermore, electrification programs that promote clean energy such as solar power may be financed by unsustainable income sources in rural areas that exacerbate deforestation. Chanda et al. (2025) analyse this clean energy-deforestation trade-off in Zambia where they find that solar PV systems are financed through activities such as charcoal burning, bark harvesting, and land clearing. Their evidence that clean energy adoption can be linked to environmentally damaging financing strategies points to the need for integrated policies that provide affordable credit or subsidies to align energy access with environmental conservation.

2.1.4. Synthesis and implications for policy evaluation

The literature reviewed across structural, institutional, market, and policy dimensions reveals a complex and interdependent set of factors shaping electrification outcomes. Household income, education, geographic dispersion, and infrastructure costs consistently emerge as key determinants of electricity access. Meanwhile, institutional quality, regulatory coherence, and financial mechanisms influence the feasibility and sustainability of renewable energy adoption. However, the evidence also highlights persistent tensions and trade-offs — particularly between affordability and cost recovery, centralized grid expansion and decentralized systems, and electrification and environmental sustainability.

Recent empirical studies underscore the importance of rigorous causal evaluation in understanding the true impact of energy policies. While many analyses rely on correlational or cross-sectional approaches, a growing number of studies employ quasi-experimental designs and the SCM to isolate policy effects. For instance, the SCM has been used to evaluate carbon taxation in British Columbia (Arcila and Baker, 2022), climate strategy in Austria (Crichton et al., 2023), and emissions trading under the Regional Greenhouse Gas Initiative in the U.S. Lee and Melstrom (2018), Murray and Maniloff (2015). These studies reveal both intended and unintended consequences, such as emissions leakage, price effects, and sectoral shifts, emphasizing the need for context-sensitive policy design.

In Sub-Saharan Africa, emerging research highlights the role of financial inclusion and digital innovation in expanding access. Barry et al. (2025) show that mobile money adoption significantly increases solar panel uptake in Tanzania, particularly among poor and migrant households. Similarly, Tang et al. (2024) demonstrate that smart energy policies in China alleviate energy poverty through improved supply, affordability, and cleanliness — offering valuable insights for decentralized electrification strategies. Despite these advances, there remains a gap in causal evidence on the impact of national-level electrification reforms in low-income countries. This gap is particularly salient in the case of Rwanda's 2016 National Electrification Strategy (NES), which was implemented as a nationwide reform without an internal control group. To address this, our study applies the SCM, constructing a counterfactual trajectory by matching Rwanda to a weighted combination of countries with similar pre-intervention characteristics. This approach enables us to estimate the causal impact of the NES on electricity access, renewable energy share, and greenhouse gas emissions, offering new insights into the trade-offs and effectiveness of electrification strategies in rapidly transforming economies.

2.2. Theoretical framework for Rwanda's National Electrification Strategy

Our study is anchored in an integrated theoretical framework that combines a Theory of Change (ToC) approach with insights from political economy and institutional theory.

The ToC illustrates how and why a specific change is expected to occur (The Center for Theory of Change, 2025). It connects a program's activities to its long-term goals by identifying the necessary steps and conditions that must happen along the way to produce outcomes. We construct an implicit ToC framework (Fig. 1) to trace how Rwanda's National Electrification Strategy (NES), through inputs such as public investment, institutional reform, and donor-private sector engagement, activates mechanisms like infrastructure rollout, private sector participation, and regulatory enforcement to produce measurable outcomes. This framework is grounded in the growing use of ToC in development economics as a tool for unpacking causal pathways and evaluating complex policy interventions (see, e.g., Bunte et al., 2018; Hout et al., 2022; Hughes et al., 2020; McCarthy and Krause, 2024).

In this study, a ToC is tailored to three key outcome variables: the percentage of the population with electricity access, total greenhouse gas (GHG) emissions, and the share of renewable energy in national consumption. Political economy theory helps explain how Rwanda's centralized governance model facilitates rapid implementation and alignment with donor priorities, while institutional theory highlights the role of technocratic planning and performance-based management in shaping policy coherence. The framework also incorporates trade-offs, such as electricity access versus GHG emissions and affordability versus sustainability, that may emerge as the electrification strategy scales.

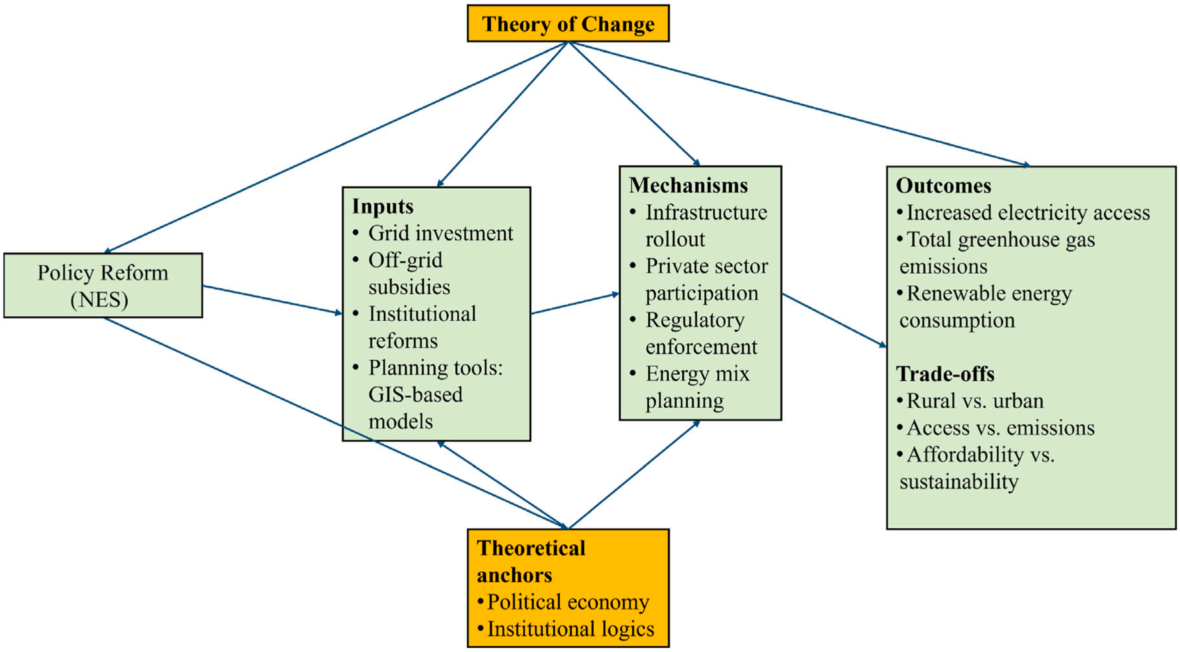

Fig. 1. A theory of change framework for Rwanda's National Electrification Strategy (NES).

To interpret the implementation dynamics of the NES, we also draw on political economy perspectives and institutional theory. Political economy is a well-established and evolving field of enquiry. It is concerned with the structural and institutional features of a country or region and how these interact with politics and economics (Andreas et al., 2022). For example, Chang and Berdiev (2011) consider how government ideology, institutional fragmentation, and political constraints shape regulatory outcomes. Centralized and cohesive governance structures, such as those in Rwanda, are found to facilitate rapid policy implementation and alignment with donor priorities (Trotter, 2016). Chang and Berdiev (2011) find that less politically fragmented institutions are more likely to pursue deregulation and reform in energy markets, while left-leaning governments tend to favour greater regulation and state involvement. In their analysis of energy transition in Mozambique, Power and Kirshner (2019) argue that rural electrification and grid extension constitute a means through which the state demonstrates its presence to rural citizens.

Becker (1983) adds further nuance, suggesting that regulatory outcomes are shaped not only by ideology or institutional design, but also by the power and efficiency of interest groups. In Rwanda, where civil society and private sector lobbying are relatively weak, state-led initiatives dominate, potentially skewing regulation toward elite or donor-aligned interests (Trotter, 2016).

Recent evidence from Al Mamun et al. (2024) highlights the role of political representation, particularly female political empowerment, in shaping environmental and financial regulation. Women are poorly represented in national parliaments, holding only 27% of parliamentary seats worldwide in 2024.[1] However, Rwanda is an outlier. Its Constitution mandates that 30% of seats be reserved for women in all decision-making positions. Following the 2024 elections, women occupied 63.8% of the Chamber of Deputies (lower house) and 53.8% of the Senate (upper house). This could support stronger regulatory frameworks for sustainable energy and climate finance.

Institutional theory complements political economy by highlighting how formal rules, norms, and routines influence behaviour. Organizations are embedded in social systems and shaped by institutional pressures – regulatory, normative, and cognitive – that drive them toward conformity and legitimacy (DiMaggio and Powell, 1983; Scott, 1987). Greenwood et al. (2011) emphasize that conflicting logics – such as market efficiency versus social equity – create complexity that requires hybrid or decoupled responses. In Rwanda, the focus on technocratic planning, performance-based management, and centralized coordination reflects an institutional logic prioritizing efficiency and accountability (Dye, 2020b). Organizations also navigate overlapping demands from government, donors, and market logics.

Institutional factors are central in studies on energy access in SSA. Dagnachew et al. (2020), using stakeholder interviews and expert workshops in Ghana, Nigeria, Ethiopia, and Tanzania, identify poor governance, fragmented institutions, unclear policy, and lack of coordination as key barriers to universal electricity access — often outweighing resource availability. Falchetta et al. (2021) introduce an Electricity Access Governance Index (EAGI) based on data from the World Bank's Regulatory Indicators for Sustainable Energy (RISE) and conclude that governance and institutional reform are essential to lower finance costs, mobilize private finance, and scale-up decentralized systems.

Together, these theoretical perspectives help explain not only the effectiveness of the NES in expanding electricity access and promoting renewables, but also the trade-offs it generates — such as between access and GHG emissions, or affordability and sustainability. By integrating a ToC with political economy and institutional theory, our framework supports a nuanced evaluation of both the impact and the structural dynamics underpinning Rwanda's electrification efforts.

3. Renewable energy policy in Rwanda

Rwanda is gifted with an abundant supply of renewable energy resources, including solar, hydro, geothermal, and biomass. Due to its location near the equator in eastern Africa, it receives abundant sunshine throughout the year: mean monthly solar radiation ranges from 4.3 to 5.2 kWh/m^2 per day across all regions, but remains largely unexploited (Hagumimana et al., 2021). Rwanda's weather is relatively stable, with annual temperatures ranging from 16 to 24 degrees Celsius, so solar power generation is possible during the country's dry and hot seasons. Rwanda usually experiences two annual rainy seasons, supplying water to the country's various river systems, so it also has rich hydropower potential, especially in hilly areas. Although

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[1] See https://data.worldbank.org/indicator/SG.GEN.PARL.ZS.

hydropower is a major source of electricity, the drawdown of lake waters at hydro power stations is sometimes not replenished due to lower-than-average rainfall, causing a drop in energy generation (Safari, 2010). Wind potential has been proven to be abundant in eastern Africa (Mandelli et al., 2014) but has not yet been fully developed in Rwanda (Mukeshimana et al., 2021).

Forests cover around 28% of Rwanda's landmass (Republic of Rwanda, 2017), providing an ample supply of wood that is mainly used for cooking and heating. Other biomass resources available in Rwanda are biogas, and agriculture residues and wastes. Biomass energy resources represent 85% of the energy balance: firewood represents 57% of all energy use, charcoal represents 23%, with agriculture residues and wastes representing 6% (Republic of Rwanda, 2015a).

We identify several factors that affect Rwanda's ability to generate renewable energy based on our theoretical framework outlined in Fig. 1. In terms of the inputs to our ToC model, there are different ways in which an existing electricity grid can be expanded. The sparse population in rural areas of Rwanda makes it expensive to connect power from the national grid. Therefore, off-grid access to electricity through renewable sources, including solar home systems, can be a cost-effective way to connect those living in rural areas.

Access to electricity can also be achieved using standalone distribution networks not connected to the national grid, known as mini-grids, designed to supply power to a few hundred people. They can be based on a range of renewable technologies: solar, wind and hydro have the advantage of very low operating costs, but have high upfront costs, and the availability of power is intermittent. Hybrid mini-grid systems are used to solve the problem of intermittency of renewable energy sources by employing diesel generators to produce power when needed, but have significant operational costs (Mugisha et al., 2021). Mini-grids in Rwanda are owned and operated by private micro-utility companies. The deployment of mini-grids to date is limited because connecting a community requires a higher upfront cost, so a threshold of initial customers is required to make it worthwhile. Off-grid solar systems are more widespread partly due to the flexibility of acquiring customers one at a time, with a modular approach allowing their expansion if demand grows.

An important mechanism to ensure that electrification outcomes are achievable is private sector participation. The Government of Rwanda recognized the need to support private companies working in the rural electrification sector to encourage investment and minimize risk, to meet the targets set out in 'Vision 2020', the country's long-term development blueprint launched by President Kagame in 2000, and revised in 2012 (Republic of Rwanda, 2012). The Rural Electrification Strategy (RES) published by Rwanda's Ministry of Infrastructure in 2016 puts the private sector in the lead in financing and delivering off-grid and mini-grid energy access (Republic of Rwanda, 2016). It encourages private sector participation by "de-risking" investment through the provision of risk-mitigation facilities that enable solar products to be affordable to the population. Another key element of the RES is a revised approach to the measurement of energy access, which had previously been measured as the percentage of households connected to the national grid.

Most people living in rural areas, where the national grid has not reached, are financially-challenged, so the RES provides government financial support in the form of targeted subsidies to bridge affordability gaps for the lowest earning households. The widespread use and availability of mobile payment in Rwanda allows micro-utilities to operate a power usage-based business model with streamlined payment collection (Sandwell et al., 2017). Another input to electrification expansion is the use of Geographic Information System (GIS) data to plan electricity roll-out. Integrating spatial data with energy mix modelling, and policy frameworks, can facilitate the optimal deployment of energy infrastructure, while decreasing dependence on fossil fuels (Isihak et al., 2022).

Private sector participation in Rwanda's energy sector is facilitated by Power Purchase Agreements (PPAs) that serve to "de-risk" private sector involvement in electrification. PPAs provide long-term agreements for the sale of electricity, typically spanning 20 to 25 years, which are essential for Independent Power Producers (IPPs) to secure the large-scale financing required for capital-intensive projects (Republic of Rwanda, 2015a). IPPs sell their electricity to the Energy Utility Corporation Limited (EUCL), a subsidiary of the Rwanda Energy Group (REG) established by the government in July 2014 to enhance efficiency in utility operations. PPAs normally include a "take or pay" clause, tying EUCL to pay for typically 90% of the power it receives, regardless of whether it is used (Dye, 2020a). EUCL recovers this cost through the electricity tariff paid by its customers. Rwanda contracted most of its new plants using PPAs, on terms described by Dye (2020a) as "generous", exacerbated by the fact that PPAs were priced in US dollars. Rwanda's electricity tariffs, at 0.21 USD per kWh in 2018, were among the highest in sub-Saharan Africa, and not helped by the appreciation of the US dollar against the Rwandan franc (Chemouni and Dye, 2020).

Turning to the theoretical anchors in Fig. 1, the ability of a state to govern effectively is an important political economy factor influencing economic success. In line with the political economy perspective, strong state institutions and capable public administration have become the cornerstones of Rwanda's transformation (World Bank, 2020). Rwanda's strong economic growth has been driven by strategic government-directed resource allocation, particularly in sectors such as energy, which has supported its position as a leading recipient of official development assistance (Marijnen and van der Lijn, 2012). The government of Rwanda replaced municipalities with new territorial entities and reformed their functions, strengthening the influence of the ruling political party, the Rwandan Patriotic Front (RPF) at all administrative levels, down to villages. Government officials are bound by a detailed personal performance contract ("imihigo") with the President of the Republic, Paul Kagame, reflecting the government's strategic objectives. This top-down system has been an effective tool of performance management (World Bank, 2020), suggesting there is little scope for interest groups to exert political pressure, along the lines suggested by Becker (1983).

Political stability is one of six Worldwide Governance Indicators (WGIs) used by the World Bank to describe broad patterns in perceptions of the quality of governance across countries and over time (Kaufman et al., 2010). The quality of governance is crucial to the effectiveness of institutions, and to the creation of an attractive business environment for inward investment, particularly in the energy sector (Sumanjeet, 2015). Under the leadership of the RPF, Rwanda has come to be regarded as one of the most politically stable and safest countries in Sub-Saharan Africa and as a success story by the international donor community (Marijnen and van der Lijn, 2012). Other WGI indicators – control of corruption, government effectiveness, rule of law, and regulatory quality – show that Rwanda ranks highly both in Africa and globally, and this stability has helped FDI grow from $119 million in 2010 to $384.46 million in 2019 (Mukeshimana et al., 2021).

Another aspect of the quality of institutions in Rwanda is the strong legal and policy framework that promotes gender equality, although challenges remain. In developing countries, women do the bulk of household work, which includes gathering and collecting wood fuel, and cooking (Adom and Nsabimana, 2022). Women also work longer hours in a day than their male counterparts (Biran and Mace, 2004). The longer hours devoted to gathering and collecting biomass imposes a higher opportunity cost on women, which inhibits them from engaging in other economic ventures (Adom and Nsabimana, 2022). One of the inputs in our ToC, the provision of off-grid subsidies, can assist women to become more economically active. Off-grid solar energy gives women more flexible schedules, reduces fuel collection time, enables work outside the home, and increases nighttime safety.

Table 1

Overview of variables and data sources.

Variable	Description	Data Source	URL
Access to electricity	Percentage of the population with access to electricity.	World Bank Open Data	link
Renewable energy consumption	Share of renewables in total final energy consumption.	World Bank Open Data	link
Total GHG emissions	Total greenhouse gas emissions in kilotons of CO_2 equivalent, excluding emissions relating to Land Use, Land-Use Change, and Forestry (LULUCF).	World Bank/EDGAR (European Commission)	link
GDP growth	Annual growth rate of GDP at market prices.	World Bank Open Data	link
Population growth	Annual growth rate for the population.	World Bank Open Data	link
Cooling Degree Days (CDD)	Number of days when cooling is required due to temperature (measured in degrees Celsius).	Climate Change Knowledge Portal, World Bank (ESG Dataset)	link

Rwanda's commitment to renewable energy is reflected in its robust policy frameworks designed to address its energy deficit and promote sustainable development. The policies that comprise the National Electrification Strategy (NES) focus on increasing access to electricity through both on-grid and off-grid solutions, emphasizing the role of private sector participation (Koo et al., 2018). Rwanda's Ministry of Infrastructure in collaboration with the Ministry of Environment and Natural Resources also created a Biomass Energy Strategy (BEST) in 2009 to address the unsustainable use of biomass by promoting alternative fuels such as liquefied petroleum gas (LPG), biogas, and improved cookstoves (Republic of Rwanda, 2015a).

Despite these policy efforts, several challenges impede the full realization of Rwanda's renewable energy goals. Financial barriers are among the most critical obstacles. The high initial costs associated with renewable energy technologies deter investment, particularly from private entities (Rolffs et al., 2015). Infrastructure limitations also pose significant challenges. The lack of adequate transmission and distribution networks in remote areas makes grid expansion costly and, in some cases, impractical (Mandelli et al., 2016). Socio-cultural factors further complicate the adoption of renewable energy technologies. Traditional cooking practices and resistance to change hinder the uptake of improved cookstoves and alternative fuels (Puzzolo et al., 2016).

Studies assessing the impact of Rwanda's renewable energy policies indicate mixed results. There has been a marked increase in electricity access and a gradual shift towards renewable energy sources (Blimpo and Cosgrove-Davies, 2019). Based on the RISE framework, Rwanda scores favourably in terms of its policy environment and the institutional capacity for renewable energy (World Bank, 2020). Comparative studies suggest that countries with robust financial mechanisms are more likely to achieve greater success in renewable energy adoption (Long et al., 2024). A study of 143 countries found that increasing access to affordable financing could greatly increase solar panel adoption in equatorial developing nations (Ondraczek et al., 2015).

Independent Power Producers (IPPs) are a cornerstone of the country's energy strategy to achieve its ambitious electrification targets and diversify the energy mix. The government provides subsidies and tax exemptions on equipment for IPPs and off-grid solutions to reduce upfront costs and business risks (Republic of Rwanda, 2015b). The socio-economic effects of Rwanda's Electricity Access Roll-Out Program (EARP) are investigated by Lenz et al. (2017), who use a theory of change approach to identify channels through which a connection to the national grid impacts household income, health, and education. Using a difference-in-differences (DiD) design based on connected households in treatment communities compared to matched non-connected households in control communities, they find weak evidence for socio-economic improvements.

The impact of renewable energy policies on decarbonizing the energy mix in 100 developing countries is assessed by Galeazzi et al. (2024), who find that they largely fail to deliver on their goals, based on an analysis of data from the World Bank's RISE indicators. Most relevant for Rwanda from the findings is the importance they assign to policies that encourage private sector participation by addressing what they call counterparty risk, through schemes such as government guarantees for the price of electricity, to encourage private investment. Rwanda has several government schemes that reduce counterparty risk, such as the provision of access roads and other infrastructure to facilitate IPP projects and allowing forward payment for transmission connections to be recouped through PPAs Republic of Rwanda (2015a).

4. Data and methodology

4.1. Data

The empirical analysis draws on a balanced panel dataset covering 42 African countries from 2000 to 2020.[2] Data are sourced from the World Bank.[3] The study focuses on three primary outcome variables: the percentage of the population with access to electricity, the share of renewable energy in total energy consumption, and total GHG emissions measured in kilotons of CO_2 equivalent. The predictor variables used to construct the synthetic controls are GDP growth, population growth, Cooling Degree Days (CDD) to capture climate-driven variation in energy demand, and lagged values of each outcome variable. These predictors ensure that the synthetic controls closely replicate Rwanda's pre-treatment trends and account for unobserved heterogeneity. Table 1 gives a detailed overview of the data.

4.2. Descriptive statistics

Our final panel dataset used for this analysis covers 42 African countries over the period from 2000 to 2020, resulting in a total of 882 country–year observations for the 21 year period. Table 2 presents the descriptive statistics for the main dependent and independent variables used in the synthetic control models. The variables include our three outcome indicators, access to electricity, renewable energy consumption, and GHG emissions, as well as the key predictors used for the SCMs, namely GDP growth, population growth and cooling degree days (CDDs), a measure used to quantify the demand for energy needed to cool buildings.

Access to electricity, measured as the percentage of the population with electrical power, is a fundamental indicator of a nation's development and the well-being of its citizens. This metric holds particular importance for Rwanda in the context of its ambitious goal to dramatically increase the proportion of its citizens with access to electricity and thereby transform their lives by enabling education, healthcare, and economic activities. Comparing Rwanda's electrification rate before

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[2] The World Bank data sources are shown in Table 1. Due to limitations in data coverage, not all African countries are included (see Table A.5).

[3] Greenhouse gas data are sourced by the World Bank from the European Commission's Emissions Database for Global Atmospheric Research (EDGAR), available at https://edgar.jrc.ec.europa.eu/.

Table 2
Descriptive statistics.

Variable	Mean	Std. Err.	95% Conf. Low	95% Conf. High	N
Access to electricity (% of households)	36,96	0,87	35,26	38,67	882
Renewable energy consumption (% of total)	65,57	0,93	63,75	67,39	882
Total GHG emissions (kt CO_2 eq.)	43577,36	2889,37	37906,50	49248,21	882
GDP growth (annual, in %)	3,97	0,24	3,50	4,43	882
Population growth (annual, in %)	2,51	0,03	2,44	2,57	882
Cooling Degree Days (CDD) (in degrees Celsius)	4371,81	58,96	4256,10	4487,53	882

Note: The dataset spans 21 years from 2000 to 2020 and includes 42 African countries.

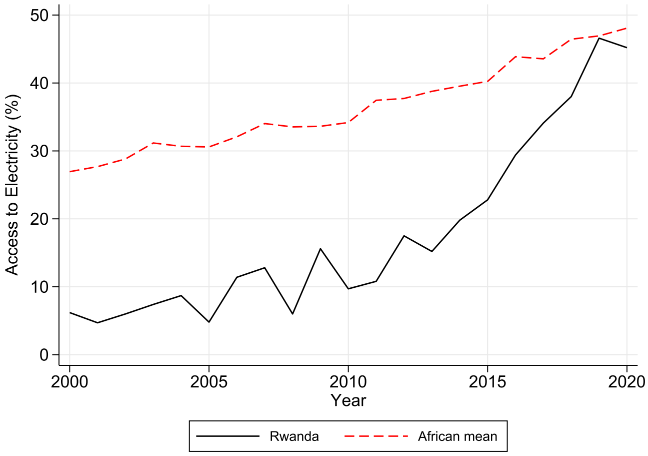

Fig. 2. Access to electricity (percent of population).

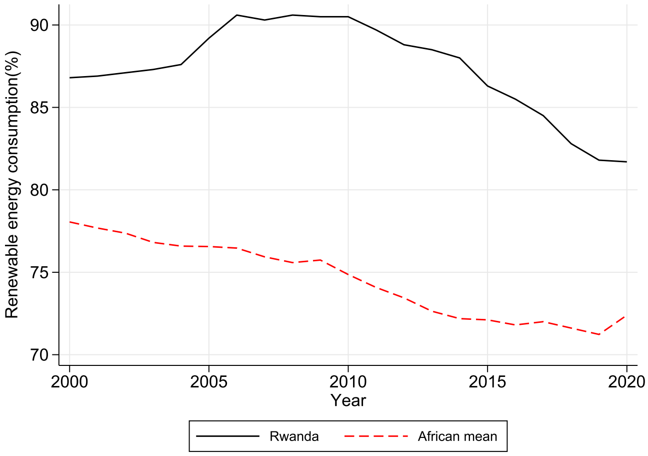

Fig. 3. Percentage of renewable energy consumption.

and after the implementation of the NES, and against a synthetic control composed of similar countries without such a strategy, allows us to isolate the effects of the NES. This approach provides valuable insights into how effective the policy has been in advancing Rwanda toward its goal of universal electricity access.

Fig. 2 highlights the differences between Rwanda and other African countries in their access to electricity. We can see a significant increase in access to electricity after 2010 in several countries. However, when we compare Rwanda with the population-weighted mean of all African countries, we can see a substantially stronger increase in Rwanda after 2015, with access increasing from about 23% in 2015 to almost 50% in 2020.

The percentage of renewable energy consumption in Fig. 3, as reported by the World Bank, is a key metric for gauging a country's progress toward sustainable energy use. Rwanda has long relied on renewable energy, with its share exceeding 80% in the 2000s — above the African mean. We can also see a downward trend in Rwanda, starting in 2010, that is also visible in the African mean. The NES aims to expand electricity access nationwide, emphasizing renewable sources like solar, hydro, and biomass. This focus is crucial for reducing greenhouse gas emissions, decreasing reliance on imported fossil fuels, and promoting long-term economic resilience.

However, using this variable has its drawbacks. The World Bank's renewable energy data, sourced from the International Energy Agency (IEA), may not fully capture informal or small-scale renewable activities in rural Rwanda, such as community solar projects or unrecorded biomass use. Additionally, data gaps and delays can make it hard to get a complete, up-to-date picture of renewable energy consumption. Despite these limitations, we use renewable energy consumption as our second dependent variable. This allows us to assess the impact of the NES on promoting renewable energy use, while interpreting the results cautiously.

Total greenhouse gas emissions, as reported by the World Bank and measured in kilotons of CO_2 equivalent,[4] is a vital measure of a country's environmental footprint and role in global climate dynamics. Lowering GHG emissions is a central aim of Rwanda's NES, which aims to expand access to electricity largely through renewable energy sources, thereby reducing dependence on fossil fuels. GHG emissions is a key variable in our analysis as it indicates the environmental effectiveness of the NES. We therefore use total GHG emissions as our third dependent variable.

As highlighted in Fig. 4, Rwanda has fairly low GHG emissions compared to other African countries, in part driven by the relatively smaller size of its economy.

4.3. Analytical framework and the synthetic control method design

Our empirical approach is motivated by the need to evaluate the causal effect of Rwanda's 2016 National Electrification Strategy (NES) on key economic and environmental outcomes. The NES represents a major public policy intervention aimed at overcoming energy market failures, addressing underinvestment in rural electrification, and accelerating the structural transformation of the economy. From an economic perspective, expanded access to electricity involves infrastructure investment to enhance productivity (Dinkelman, 2011), enabling the adoption of complementary technologies, and reducing time and health costs associated with traditional energy sources. At the same time, changes in the energy mix and increased electricity use

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[4] This is a unit of measurement used to express the amount of greenhouse gases (GHGs) emitted or avoided, standardized to the equivalent amount of carbon dioxide (CO_2) in terms of its global warming potential (GWP). It allows for the aggregation of different GHGs, like methane (CH_4) or nitrous oxide (N_2O), into a single unit based on their relative impact on climate change compared to CO_2.

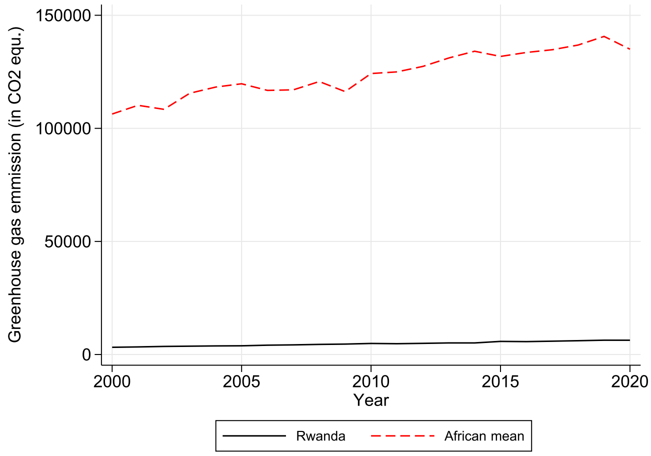

Fig. 4. Total greenhouse gas emissions.

have direct implications for environmental externalities, particularly greenhouse gas (GHG) emissions.

The NES is modelled as a policy intervention that occurs in 2016. We treat Rwanda as the only treated unit and assume that the reform takes full effect from this year onward. Accordingly, the years 2000–2015 are defined as the pre-intervention period, and the post-2016 years (2016–2020) are used to estimate treatment effects. This specification allows us to construct a counterfactual trajectory for Rwanda by comparing observed outcomes post-2016 with those of a weighted combination of control countries that did not implement a comparable electrification strategy during the same period. The assumption is that any deviation between Rwanda and its synthetic control after 2016 reflects the effect of the NES.

Our empirical framework is grounded in the potential outcomes approach to causal inference, where we seek to estimate the counterfactual path of Rwanda's energy and environmental indicators in the absence of the NES. However, due to the non-random and nationwide nature of the policy intervention, traditional econometric identification strategies (e.g., difference-in-differences) are limited. We therefore apply the Synthetic Control Method (SCM), which constructs a data-driven synthetic counterfactual by optimally weighting a combination of similar countries that did not implement a comparable electrification reform during the same period. The SCM allows us to isolate the effect of the NES on access to electricity, renewable energy consumption, and GHG emissions, under the assumption that the synthetic control reproduces the trajectory Rwanda would have followed in the absence of the policy.

Our approach captures both direct impacts (e.g., infrastructure investments that boost access) and indirect effects (e.g., shifts in the energy mix and industrialization pathways). The outcomes we analyse are therefore not only energy metrics but proxies for structural economic transformation and environmental sustainability, aligned with Rwanda's long-term development goals.

This study integrates a ToC framework with the Synthetic Control Method (SCM) to assess the causal impact of Rwanda's 2016 NES on electricity access, renewable energy consumption, and greenhouse gas emissions. The ToC framework, grounded in institutional and political economy theory, maps the causal pathways through which NES inputs – such as public investment, regulatory reform, and donor-private sector engagement – translate into measurable outcomes. It also accounts for trade-offs between access, affordability, and sustainability, offering a nuanced understanding of how policy mechanisms interact with structural and institutional dynamics. Developed by Abadie and Gardeazabal (2003) and further refined by Abadie et al. (2010), the SCM complements this framework by constructing a counterfactual scenario using a weighted combination of control countries that did not implement similar electrification reforms. This method is particularly well-suited for evaluating large-scale policy interventions where randomized experiments are infeasible. It allows for robust causal inference by comparing Rwanda's post-intervention outcomes with those of a synthetic control that closely mirrors its pre-intervention trajectory.

Recent studies such as Ribeiro and Jamasb (2025) emphasize the value of using the SCM and other causal inference models to evaluate regulatory interventions in the electricity sector. These methods are particularly well-suited for small-n case studies, such as national electrification strategies, where randomized control trials are infeasible. The SCM enables the construction of a counterfactual scenario by synthesizing a weighted combination of control units that did not implement similar reforms. This approach has been successfully applied to assess the impact of innovation-stimuli regulations in Great Britain and Italy, providing robust causal inference and addressing challenges related to limited comparison units.

In our SCM design, Rwanda is treated as the intervention unit, with the NES considered to have taken effect in 2016. The donor pool comprises 41 African countries that did not implement comparable electrification strategies during the same period. The SCM procedure involves three key steps: first, pre-treatment matching is conducted to construct a synthetic Rwanda using optimal weights from the donor pool; second, post-treatment comparisons are made to estimate the causal effect of the NES; and third, robustness checks – including leave-one-out tests, placebo tests, and covariate balance diagnostics – are performed to validate the findings. Following best practices outlined by Gilchrist et al. (2023), we implement in-space placebo tests and assess root mean squared errors. The average treatment effect on the treated (ATT) is computed as the difference between Rwanda's actual outcomes and those of the synthetic control. Weights are optimized to minimize the discrepancy in predictor variables during the pre-treatment period, subject to non-negativity and unit sum constraints.

Mathematically, the synthetic control $\hat{Y}_0^1$ for treated unit $J = 1$ is defined as:

$$\hat{Y}_0^1 = \sum_{j=2}^{J} w_j Y_j \tag{1}$$

where Y_j represents the outcome variable for control unit j, and w_j are the weights assigned to each control unit such that $\sum_{j=2}^{J} w_j = 1$ and $w_j \geq 0$ for all j. The weights are chosen to minimize the discrepancy between the treated unit and the synthetic control in terms of pre-intervention characteristics.

One of the core advantages of the SCM is its ability to address identification challenges in observational policy settings. Unlike traditional econometric models that rely on strong functional form assumptions or parallel trend conditions, the SCM constructs a data-driven counterfactual by optimally weighting control units to closely reproduce the treated unit's pre-intervention outcomes. This framework allows for a transparent and credible comparison between actual and synthetic outcomes post-intervention. The credibility of causal inference in the SCM rests primarily on the quality of the pre-treatment match.

The methodology encompasses the following steps:

1. Selection of Predictor Variables: these are growth in GDP per capita, renewable energy consumption, population growth and a temperature-related measure of energy demand (cooling degree days). These predictors are used to match the treated units with suitable control units.
2. Construction of the Synthetic Control: for each treated country, a synthetic counterpart is constructed using a weighted combination of control countries that did not implement similar renewable energy policies during the study period. The weights $w_{(j)}$ are optimized to minimize the difference between the treated unit and the synthetic control in the pre-intervention period. This is formalized as:

$$\frac{min}{w} \sum_{k=1}^{K} \left(X_{1,kj} - \sum_{j=2}^{J} w_j X_{j,k} \right)^2 \tag{2}$$

Table 3
Predictor variables used in synthetic control models.

Predictor Variable	Description and Justification
GDP growth (annual %)	Proxy for macroeconomic development and investment capacity
Population growth (annual %)	Controls for demographic pressure on energy infrastructure
Cooling Degree Days (CDD)	Captures climate-driven variation in energy demand
Lagged dependent variables	Ensures pre-treatment trend matching and accounts for unobserved heterogeneity

Table 4
Donor composition and weights in synthetic control models.

Outcome Variable	Countries with Non-Zero Weights (Weight)
Access to electricity	Liberia (43.6%), Sierra Leone (33.2%), Lesotho (18.8%), Ghana (3.2%), Sudan (1.2%)
Renewable energy consumption	Central African Rep. (37.9%), Nigeria (25.5%), Burundi (19.2%), Zimbabwe (6.4%), Madagascar (6.0%), Zambia (3.0%), Gabon (1.7%), Togo (0.3%)
GHG emissions	Burundi (41.1%), Lesotho (35.6%), Cabo Verde (10.6%), Equatorial Guinea (9.4%), Uganda (2.5%), Botswana (0.8%), Kenya (0.1%)

Note: Weights are derived from the SCM optimization process to best match Rwanda's pre-treatment characteristics.

where $X_{j,k}$ represents the value of predictor k for control unit j, and K is the number of predictors.

3. Estimation of Treatment Effects: the impact of the policy is estimated by comparing the post-intervention outcomes of the treated unit with those of the synthetic control. The average treatment effect on the treated (ATT) at time T is calculated as:

$$\text{ATT} = Y_1(T) - \hat{Y}_0^1(T) \tag{3}$$

where $Y_1(T)$ is the observed outcome for the treated unit at time T, and $\hat{Y}_0^1(T)$ is the estimated outcome from the synthetic control.

4. Inference and Validation: to ensure the robustness of the results, placebo tests and sensitivity analyses are conducted. Placebo tests involve applying the SCM to control units as if they were treated, to verify that the estimated effects for these units are negligible. Additionally, the method's assumptions – such as the existence of a convex hull and the absence of spillover effects – are critically evaluated to validate the causal interpretations.

When applying the SCM to evaluate interventions like Rwanda's National Electrification Strategy, it is essential to include lags of the dependent variable as predictors. Incorporating these lags captures the temporal dynamics of the data, ensuring that the synthetic control closely mirrors the historical trajectory of the treated unit before the intervention. This practice enhances the pre-intervention fit, accounts for unobserved factors, and strengthens the robustness of the causal inference. As Abadie et al. (2010) emphasize, including lagged outcome variables is crucial for constructing a credible synthetic control that approximates the characteristics of the treated unit. Similarly, Ben-Michael et al. (2021) advocate the use of lagged dependent variables to improve the accuracy and reliability of SCM estimates.

Our identification strategy assumes that donor countries did not experience similar electrification reforms in 2016 and during the post-2016 period. This assumption is crucial for isolating the effect of the NES, as the presence of similar policies in donor countries could introduce a bias due to spillover effects. As highlighted in Fig. 16 in the Appendix, we can see no strong increase in access to electricity after 2016 in the donor pool countries for the Renewable Energy Consumption SCM, suggesting that no similar policies, or at least no similarly effective policies, were introduced after 2016 in these countries. In the SCM for Greenhouse Gas (GHG) Emissions, we can observe two countries that show an increase in access to electricity, namely Kenya and Uganda. While Kenya has a very small weight in the donor pool (0.1%) and would not significantly influence our treatment effect, Uganda could probably influence our results. However, our leave-one-out test, reported in Fig. 12, suggests that Uganda does not affect our overall result.

4.4. Model selection and donor composition

To evaluate the causal impact of Rwanda's 2016 National Electrification Strategy (NES), we apply the SCM using three separate models, each corresponding to a key outcome: access to electricity, renewable energy consumption, and greenhouse gas (GHG) emissions. The donor pool consists of 41 African countries that did not implement similar national electrification reforms during the study period. For each outcome, a synthetic control is constructed as a weighted combination of the donor countries that best replicates Rwanda's pre-intervention trends.

The selection of predictor variables is critical to ensure that the synthetic control resembles Rwanda not only in terms of the outcome variables' past trajectories but also in relevant economic and structural characteristics. Table 3 summarizes the variables used in our SCM specification. Annual GDP growth and population growth are included as macroeconomic fundamentals that influence both energy demand and infrastructure expansion. Cooling Degree Days (CDD) serve as a climate-based predictor, capturing latent variation in electricity demand driven by temperature-related cooling needs.[5] In line with recommendations by Abadie et al. (2010) and Ben-Michael et al. (2021), we also include lagged values of the dependent variable to closely match pre-treatment trends and account for unobserved time-invariant factors.

The combination of these predictors allows the SCM to isolate the policy effect of the NES from other unrelated structural or climatic influences that may have affected Rwanda's energy and environmental outcomes. Table 4 provides an overview of the donor countries that received non-zero weights in each synthetic control model. Full weight distributions and covariate balance diagnostics are presented in Appendix.

While the weights for each donor country are derived through the SCM optimization algorithm to best match Rwanda's pre-treatment characteristics, it is important to note that many of the countries with significant weights, such as Liberia, Sierra Leone, Lesotho, and Burundi, share key structural similarities with Rwanda. These include small-to-medium population size, low-to-lower-middle income status, relatively low baseline electrification rates, and limited industrial energy demand, which make them plausible comparators in the context of energy transitions. Many also face similar geographic and infrastructural constraints,

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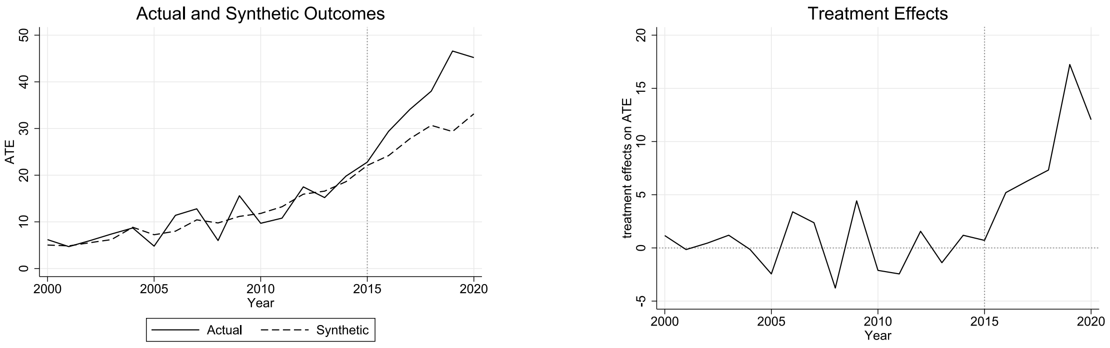
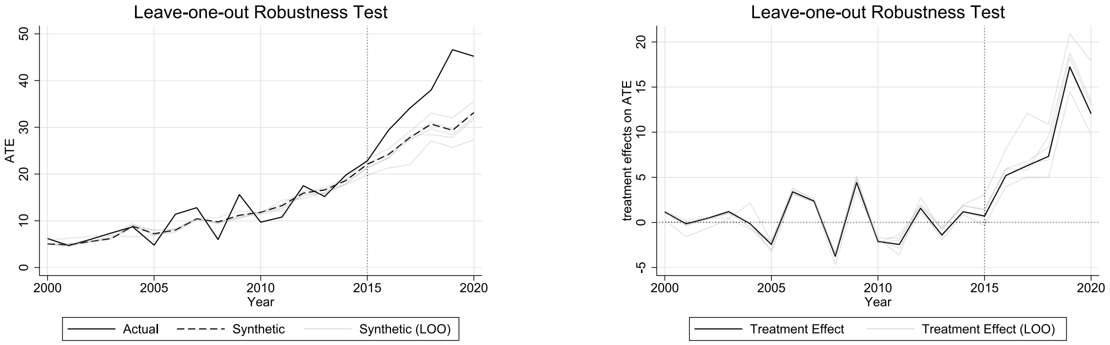
[5] Cooling degree days measure how much a day's average temperature is above a specific baseline, and can be used to estimate the energy needed to cool a building. For example, if the highest temperature during a day was 32 °C and the lowest temperature was 19 °C, then the mean temperature for that day was (32+19)/2 = 25.5 °C. If the baseline temperature is 18 °C, as the mean is above the baseline the cooling degree days are 25.5 - 18 = 7.5 °C.



(a) Predicted ATE (b) Treatment effect

Fig. 5. The impact of the NES (2016) on access to electricity (ATE).



(a) Predicted ATE (b) Treatment effect

Fig. 6. Leave-one-out test: Access to electricity (ATE).

such as dispersed rural populations and reliance on biomass or off-grid systems. Thus, while the statistical fit justifies their inclusion quantitatively, the synthetic control also makes sense economically and socially as a group of peer countries with comparable energy access challenges and development profiles.

5. Results

In this section, we present the findings from our three distinct Synthetic Control Method (SCM) analyses, each corresponding to one of the primary outcome variables: access to electricity, renewable energy consumption, and greenhouse gas emissions.

5.1. The impact of the NES (2016) on access to electricity

The NES emphasized the acceleration of economic growth, which requires reliable and widespread access to electricity for industries, businesses, and households. Our results depicted in Fig. 5(a) demonstrate a clear evaluation of the impact of the intervention on access to electricity as a percentage of the population. Pre-intervention trends show a strong alignment between the treated unit and its synthetic control, validating the robustness of the synthetic control model in replicating baseline trends. After the reform, a notable divergence emerges, indicating a significant effect of the intervention on electricity access. The upward trajectory for the treated unit, relative to the flatter or declining trend in the synthetic control, suggests a positive policy impact.

The synthetic control model demonstrates a reliable fit in the pre-treatment period, reflected by an RMSE of 2.19 and an R-squared value of 0.81. We control for GDP growth, population growth, and cooling degree days, so that our synthetic control has similar GDP growth, population growth, and climate-related energy demand. The close match in covariate values between the treated unit and the synthetic control during this period supports the effectiveness of the synthetic control setup. The treatment effect (Fig. 5(b)) indicates that the access to electricity in 2019 was about 17 percentage points higher than in the synthetic control where no NES was implemented and 12 percentage points higher in 2020.[6] The average treatment effect is 9.6 percentage points and therefore economically highly significant.

We perform a Leave-One-Out (LOO) test to evaluate the robustness of the Synthetic Control Method (SCM). This involves recalculating the synthetic control by systematically excluding one donor unit at a time. This ensures that the results are not overly influenced by any single donor unit. Fig. 6 highlights the results these robustness checks. The synthetic control group outcome (Fig. 6(a)) does not change much, when leaving one donor out, as indicated by the grey lines. As a result, the treatment effect is still very significant, no matter which of the donor countries we leave out of our model (Fig. 6(b)).

As an additional robustness check, we compare the observed treatment effect to placebo effects estimated for countries where no National Electrification Strategy (NES) was implemented. This allows us to verify that the treatment effect is specific to the treated unit. To do this, we

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[6] While our findings suggest a significant impact of the NES on electricity access, we acknowledge that the attribution of these effects should be interpreted with caution. Pre-existing trends and structural drivers – such as prior investment programs, regional policy initiatives, or donor-funded electrification projects – may have also contributed to observed changes. Although the Synthetic Control Method mitigates some of these concerns by closely matching pre-intervention trajectories, we emphasize that unobserved time-varying factors may still influence post-treatment effects.

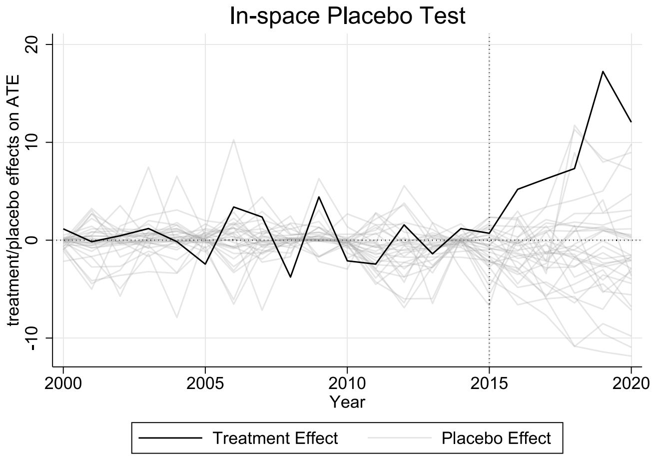


Fig. 7. Placebo test: Access to electricity (ATE).

create counterfactual scenarios by applying the treatment to countries that did not experience such a reform. If the placebo units show no significant changes while the treated unit exhibits a pronounced effect, it provides stronger evidence that the treatment is responsible for the observed outcome. As highlighted in Fig. 7 the in-space placebo test indicates that the treatment effect is not mirrored in any of the placebo tests, where treatment is applied to a different country. This strengthens the argument that the observed treatment effect is not due to random chance but can be attributed to the intervention.

The observed success in increasing electricity access directly demonstrates the effectiveness of the causal pathways envisioned by our ToC, which maps how inputs like public investment, institutional reform, and donor-private sector engagement activates mechanisms such as infrastructure rollout, private sector participation, and regulatory enforcement to produce this measurable outcome.

5.2. The impact of the NES (2016) on renewable energy consumption

The NES aimed to boost renewable energy projects, particularly in rural electrification and the supply of industrial power. Shifts from traditional biomass to modern renewables such as biogas or solar would also contribute to this growth. However, if non-renewable solutions (e.g., diesel generators for short-term needs) were also adopted, their contribution might dilute the overall share of renewables.

Fig. 8 shows the results from the synthetic control analysis for Renewable Energy Consumption. Again, we control for GDP growth, population growth, and cooling degree days, meaning our synthetic control has a similar GDP growth, population growth, and climatic environment. Our model has an R-squared of 0.48 and the RMSE is 0.78. Rwanda experienced a notable decrease in renewable energy consumption as a percentage of total energy use compared to its synthetic counterpart following the implementation of the NES in 2016. Before the policy intervention, the alignment between Rwanda and its synthetic control demonstrates a strong pre-intervention fit, indicating that the synthetic model effectively captures the pre-treatment trend in renewable energy consumption.

However, post-2016, the observed decline in Rwanda's renewable energy consumption relative to the synthetic control suggests that the NES may have inadvertently prioritized other energy sources or faced challenges in sustaining renewable energy's share in the overall mix. This result highlights the complexities of energy transitions, where increased electrification – often a primary goal – may not always align with maintaining or expanding the renewable energy share, especially in contexts with competing energy needs and resource limitations. These findings call for a deeper evaluation of the NES's implementation to ensure that electrification goals align with broader renewable energy adoption strategies.

The synthetic control model achieves a good pre-treatment fit for renewable energy consumption, but in the years following the NES implementation (2016–2020) the actual renewable energy consumption consistently falls short of the synthetic control's projections, with a treatment effect of about −4 percentage points in 2020. This indicates that the NES led to a decrease in the share of renewables in total energy consumption by that amount.

This suggests that contrary to the NES's objectives, renewable energy consumption did not increase as anticipated. However, we caution against interpreting this decline as a policy failure. Rwanda has historically relied heavily on biomass – classified as renewable – for household energy. As the NES expanded electricity access through both grid and off-grid solutions, part of this transition likely involved replacing traditional biomass with electricity derived from mixed sources, including fossil fuels. This shift can temporarily reduce the renewable share, even if it improves health, productivity, and energy reliability. Thus, the decline in renewable energy share may reflect a structural transition away from biomass rather than reduced commitment to sustainability. While more granular data on biomass use would be ideal, we interpret this pattern as a plausible consequence of Rwanda's energy transition strategy in a low-income, electrifying context. Fig. 9 presents the results of the leave-one-out robustness checks. The synthetic control group's outcome remains largely unchanged when individual donors are excluded, as shown by the grey lines in Fig. 9(a). Consequently, the treatment effect remains highly significant regardless of which donor country is omitted from the model (Fig. 9(b)).

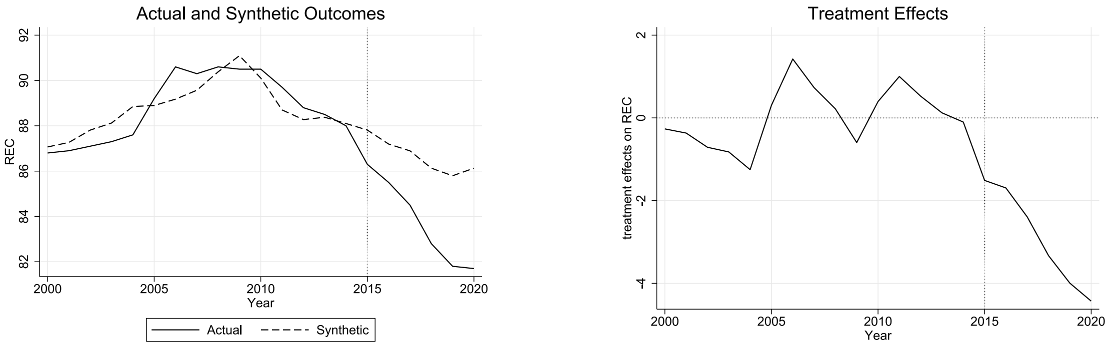
When restricting the placebo tests to only units that show a similar MSPE as in our model, we can see some heterogeneity in the results. The initial findings point toward a decrease in renewable energy consumption post-NES, and there is only one placebo unit that leads to a similar, slightly stronger treatment effect (Fig. 10). Therefore, we have to be careful not to over-interpret our result, as almost all treatment effects show a very different post-treatment trajectory.

The decrease in the share of renewable energy consumption highlights one of the critical trade-offs explicitly integrated into our ToC framework: the challenge of balancing rapid electrification with maintaining or expanding the share of renewable energy. The findings suggest that while electricity access was prioritized, the shift might have inadvertently reduced the relative contribution of traditional renewable sources. This reveals the “sustainability paradox” identified by the study, where accelerated access coincided with a decline in renewable energy share. Conflicting logics found in institutional theory (e.g., market efficiency versus social equity) can also help interpret this outcome. The urgent need for widespread access might have led to energy solutions that were quicker or more cost-effective to deploy, even if they were not exclusively renewable, temporarily reducing the overall renewable share as traditional biomass use decreased.

5.3. The impact of the NES (2016) on total Greenhouse Gas (GHG) emissions

The idea behind the NES was to promote economic growth through industrialization and infrastructure development. Industrial sectors such as manufacturing, transport, and construction typically lead to increased GHG emissions due to higher energy consumption, fossil fuel use, and production processes. As the NES promoted large-scale infrastructure projects (e.g., the building of roads to energy plants), the associated construction activities potentially lead to higher emissions from cement production, machinery use, and transport. Even though the NES give a strong priority to renewable energy sources, the impact on GHG emissions is not clear a priori.

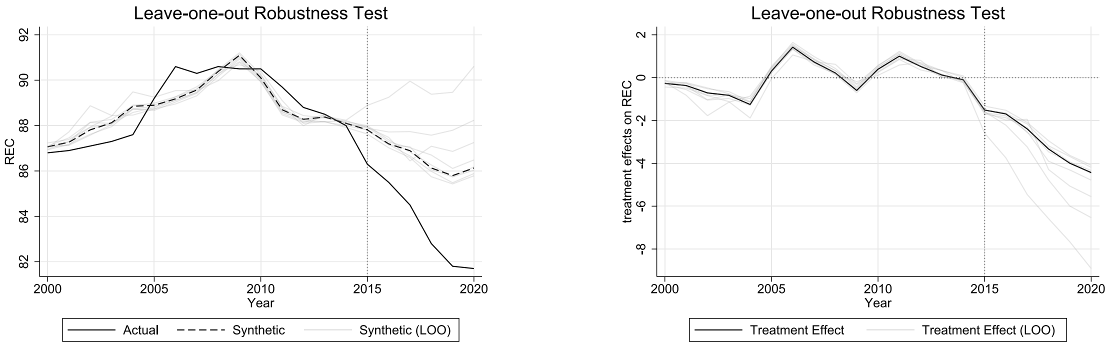
Fig. 11 analyses the impact of the NES on total greenhouse gas (GHG) emissions and thus its environmental implications. Our SCM model exhibits an R-squared of 0.852 and a RMSE of 246.1. We observe



(a) Predicted REC

(b) Treatment effect

Fig. 8. The impact of the NES (2016) on Renewable Energy Consumption (REC).



(a) Predicted REC

(b) Treatment effect

Fig. 9. Leave-one-out test: Renewable Energy Consumption (REC).

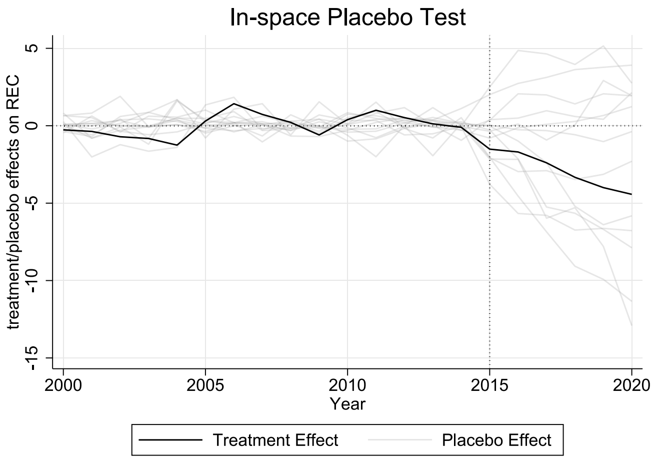


Fig. 10. Placebo test: Renewable Energy Consumption (REC).

a strong pre-intervention alignment between Rwanda and its synthetic control, validating the model's effectiveness in capturing the historical trend. In the post-treatment period there is a noticeable increase in GHG emissions compared to the synthetic control. Rwanda's GHG emissions exceed those of the synthetic Rwanda by about 1070 kilotons of CO_2 equivalent in 2020 and is contrary to the NES's general environmental objectives. The increase is likely due to the intended acceleration of industrialization as part of the NES, which typically leads to higher GHG emissions due to increased energy demand and industrial activity.

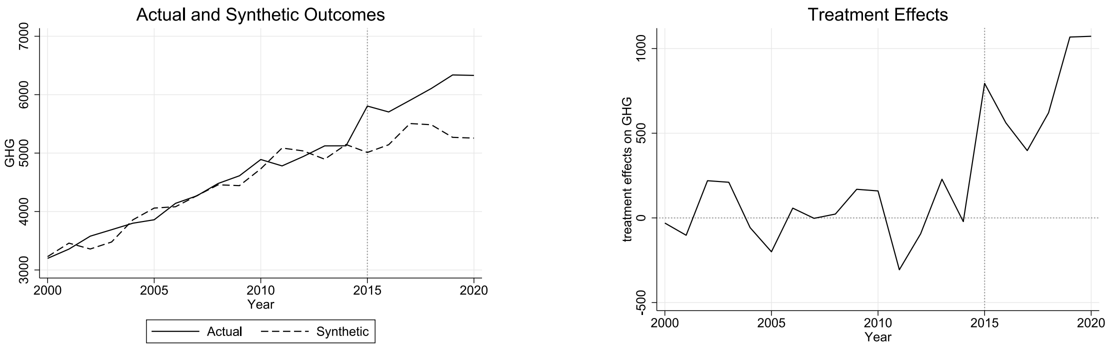
The leave-one-out robustness test shows very stable results (Fig. 12), indicating that the choice of the donor countries is not driving our results. As highlighted in Fig. 12(b), the treatment effect stays positive, and above 500 kilotons of CO_2 equivalent, no matter which of the single donor countries we leave-out.

The in-space placebo test (Fig. 13) complicates our interpretation. It suggests that the increase may be due to random fluctuations rather than the NES. There are several other countries in the sample that have higher treatment effects, even without the NES in place. This implies that our treatment effect could be random.

In essence, there appears to be a rise in GHG emissions following the NES implementation. Possible explanations might include concurrent economic growth in emissions-intensive sectors and/or delays in rolling out renewable energy projects.

To address concerns that aggregate GHG emissions may reflect non-energy-related sources, we implement a two-step approach to isolate the variation in emissions attributable to electricity use. First, we estimate a linear regression of GHG emissions on electricity consumption, GDP growth, population growth, and cooling degree days, and then use the predicted values from this model as a proxy for energy-related emissions. This enables us to isolate the variation in GHG emissions associated with electricity expansion. Second, to account for potential nonlinearity in this relationship, we apply a Box–Cox transformation and re-estimate the model using the transformed outcome. We then apply the Synthetic Control Method to the resulting predicted series. Results from both specifications, linear and Box–Cox, are presented in Fig. 14. While the magnitude of the effects vary, both approaches consistently show that GHG emissions attributable to energy use increased following the NES, reinforcing the evidence of an emissions-access trade-off.

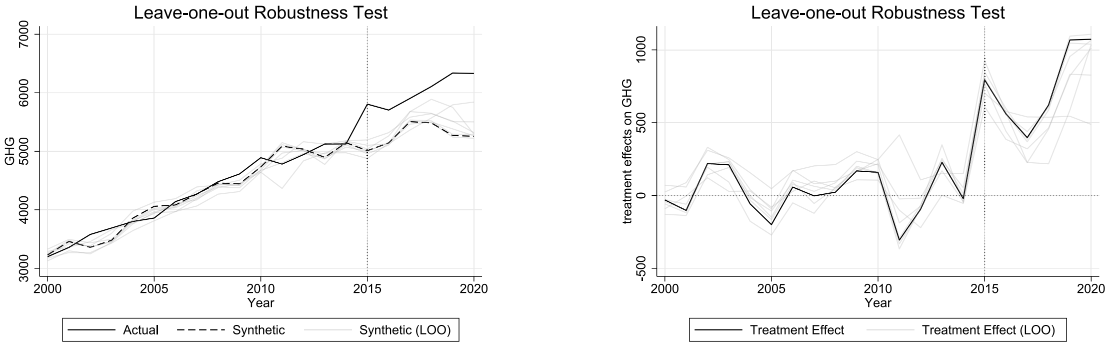
The increase in total GHG emissions directly illustrates another complex trade-off identified by our ToC: the balance between expanding electricity access and mitigating adverse environmental impacts.



(a) Predicted GHG

(b) Treatment effect

Fig. 11. The impact of the NES (2016) on Greenhouse Gas (GHG) Emissions.



(a) Predicted GHG

(b) Treatment effect

Fig. 12. Robustness checks: Greenhouse Gas (GHG) Emissions.

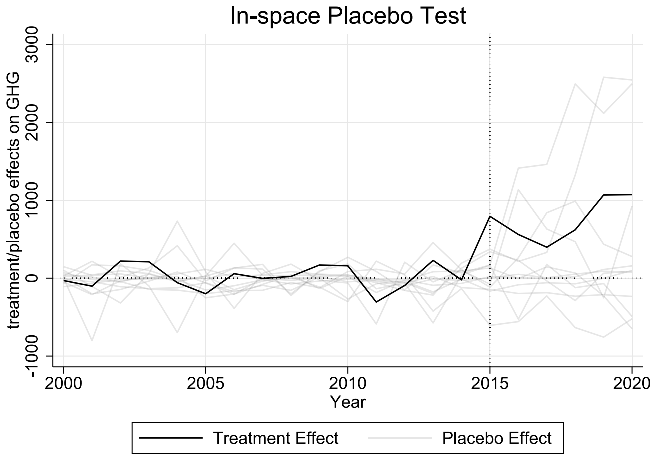


Fig. 13. Placebo test: Greenhouse Gas (GHG) Emissions.

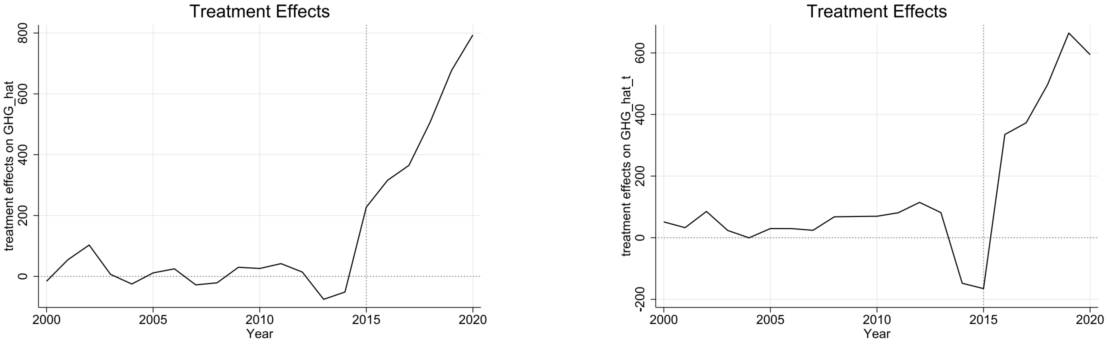
Rwanda's focus on rapid economic growth and structural transformation (driven by its strong governance and strategic planning) might have, in practice, led to increased energy demand and associated emissions from industrial and construction activities, even as renewable energy sources were promoted. This highlights how the pursuit of ambitious development goals, interpreted through the lens of political economy and institutional logic, can lead to complex and sometimes conflicting outcomes regarding environmental sustainability.

5.4. Robustness check to account for possible interdependence between electrification outcomes

Although we estimate separate SCMs to isolate the primary effect of the NES on each electrification outcome (access to electricity, renewable energy consumption, and GHG emissions) these outcomes could be interdependent. As a robustness check we therefore include, for each electrification outcome, lagged values of the other two outcomes among the predictor variables, ensuring that the synthetic control reproduces Rwanda's joint pre-policy dynamics across electricity access, renewable energy consumption, and GHG emissions. This approach allows each model to capture outcome-specific effects while preserving consistency across the broader energy transition framework. Fig. 15 highlight that our main results do not change when we include these lagged variables.

6. Conclusion and discussion

This study provides a rigorous evaluation of Rwanda's 2016 National Electrification Strategy (NES), employing the Synthetic Control Method (SCM) to isolate its impact on electricity access, renewable energy consumption, and greenhouse gas (GHG) emissions. Our findings



(a) Linear model

(b) Box-Cox

Fig. 14. The impact of the NES (2016) on Greenhouse Gas (GHG) Emissions.

demonstrate that the NES significantly reshaped Rwanda's energy landscape, yielding three key outcomes. First, the strategy led to a substantial increase in electricity access, with an estimated 17-percentage point rise relative to the synthetic control. This aligns with the NES's core objective of achieving universal electrification and supports broader socio-economic development goals, such as greater consumption and labour force participation (Adom and Nsabimana, 2022; Acheampong et al., 2021). Second, the expansion of access was accompanied by a decline in the share of renewable energy consumption, suggesting that the rapid scale-up of electricity supply may have inadvertently reduced the relative contribution of traditional renewable sources (Brunet et al., 2021). Third, we observe a notable increase in GHG emissions following the NES's implementation, likely driven by industrial and infrastructure development; an outcome consistent with broader concerns about the environmental trade-offs of energy transitions in developing country contexts (Galeazzi et al., 2024; Tello, 2025).

These findings are particularly important because they reveal that Rwanda stands out among African countries for its success in expanding electrification, but that this achievement came at the cost of environmental sustainability. As a regional leader in electrification progress, Rwanda's experience provides important lessons for other Sub-Saharan African countries navigating the complex trade-offs between energy access, renewable integration, and climate resilience (Bisaga et al., 2021; Blimpo and Cosgrove-Davies, 2019). Our theoretical framework – drawing on the theory of change (The Center for Theory of Change, 2025), political economy (Andreas et al., 2022; Mcloughlin, 2014), and institutional theory (DiMaggio and Powell, 1983; Scott, 1987) – helps to explain the interplay between electrification, renewable energy, and emissions, and informs a set of actionable policy recommendations.

First, integrated energy planning is essential to balance access with sustainability. Policymakers should prioritize low-carbon grid expansion and incentivize hybrid systems that combine centralized and decentralized renewable energy sources (Bhattacharyya and Palit, 2016; Mandelli et al., 2014). To increase the financial capacity for renewable energy development, the government of Rwanda should continue leveraging international donor funding mechanisms, such as the Climate Investing Funds (CIF), a multilateral donor fund that channels aid through the World Bank and the African Development Bank. CIF currently supports private-sector off-grid energy solutions to expand renewable energy access in rural areas, including standalone solar photovoltaic mini-grids (CIF, 2025).

Second, while the NES benefited from strong institutional leadership (Chemouni and Dye, 2020), the environmental trade-offs suggest that coordination between energy, environment, and infrastructure ministries must be strengthened to ensure policy coherence (Greenwood et al., 2011).

Third, although off-grid solar systems have played a critical role in expanding rural access (Grimm et al., 2017; Bisaga et al., 2021), their contribution to total energy consumption remains limited. Scaling up support for decentralized renewables through targeted subsidies, concessional financing, and technical assistance is vital (Rolffs et al., 2015).

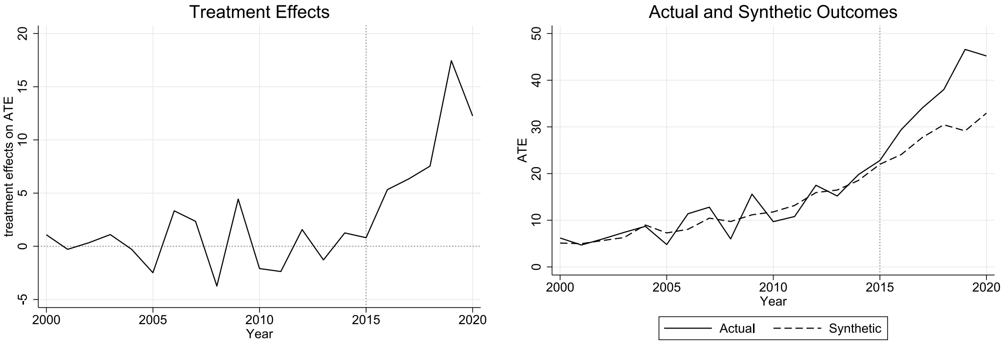
Fourth, while the government of Rwanda has provided guidelines for energy efficiency (Rwanda Utilities Regulatory Authority, 2013) it could further its efforts to promote greater consumer awareness of the benefits of renewable energy, especially since a large proportion of the population still rely on traditional biomass, and as households are the dominant consumers of electricity (51%) the bulk of which demand is primarily used for lighting (Republic of Rwanda, 2015a).

Fifth, the government of Rwanda should strengthen its initiatives to address the affordability gap for households, thereby promoting the adoption of clean energy technologies. This could be achieved by supporting low-income households to purchase individual solar systems through the provision of soft loans, or through measures similar to the subsidies previously provided for biogas digesters (Republic of Rwanda, 2011). Biogas digesters convert organic waste into biogas, providing a cleaner cooking fuel than firewood or charcoal. They also ease pressure on forests, preserve land arability, and cut greenhouse gas emissions to help address climate change (Biran and Mace, 2004; Puzzolo et al., 2016).

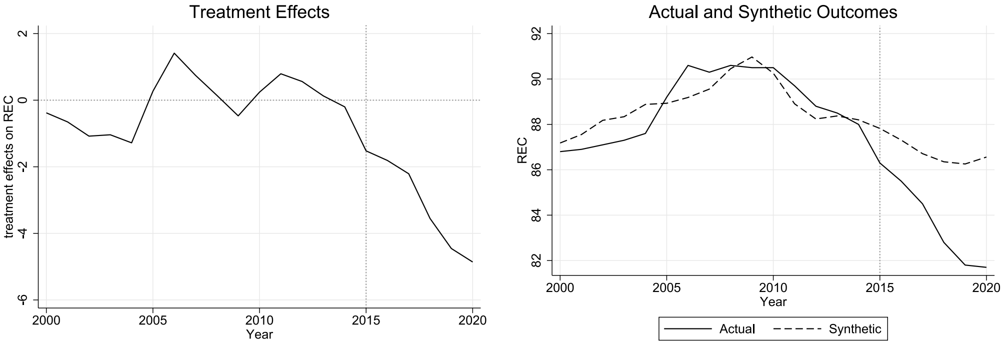
Despite its contributions, this study has some limitations that also suggest directions for future research. First, while the SCM offers a robust framework for causal inference (Abadie et al., 2010; Gilchrist et al., 2023), its validity depends on the quality of the pre-treatment match and the absence of confounding time-varying shocks. Although we achieve a strong pre-intervention fit, unobserved factors – such as concurrent political reforms or donor-driven infrastructure investments – may have influenced outcomes independently of the NES. Future research could address this by employing mixed-methods approaches that combine quantitative evaluation with qualitative fieldwork to uncover underlying mechanisms (Dye, 2020b; Blimpo and Cosgrove-Davies, 2019).

Second, our reliance on national-level data limits the granularity of our analysis. Aggregate indicators may obscure sectoral and spatial variations, making it difficult to assess regional disparities or sector-specific dynamics. Future studies should leverage geospatial data, household surveys, and sectoral emissions inventories to provide an in-depth understanding of electrification impacts (Candelise et al., 2021; Koo et al., 2018).

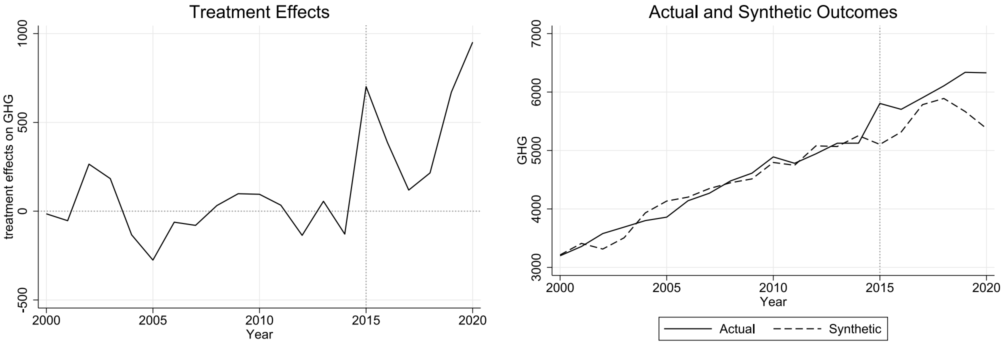
Third, our use of separate SCMs to isolate the primary effect of the NES on each electrification outcome ignores the possibility that these outcomes could be interdependent. We therefore include, for each electrification outcome, lagged values of the other two outcomes among the predictor variables, as a robustness check, and find that our main results are unaffected.



(a) Access to Electricity including lagged values of REC and GHG Emissions

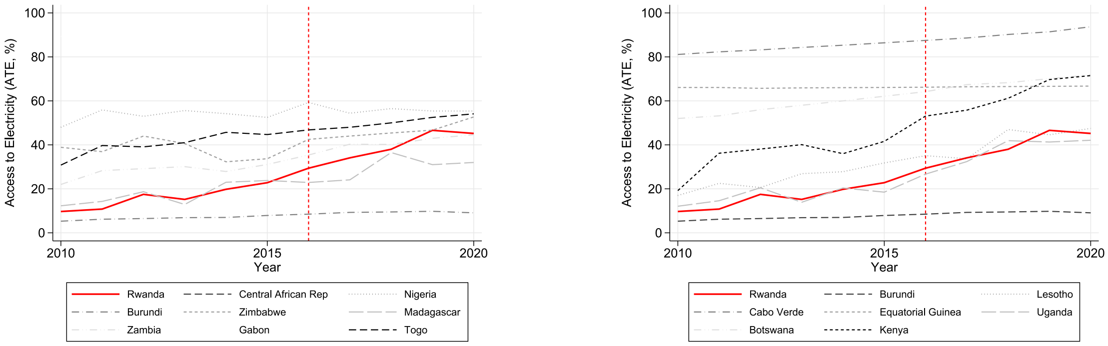


(b) Renewable Energy Consumption including lagged values of ATE and GHG Emissions



(c) Greenhouse Gas Emissions including lagged values of ATE and REC

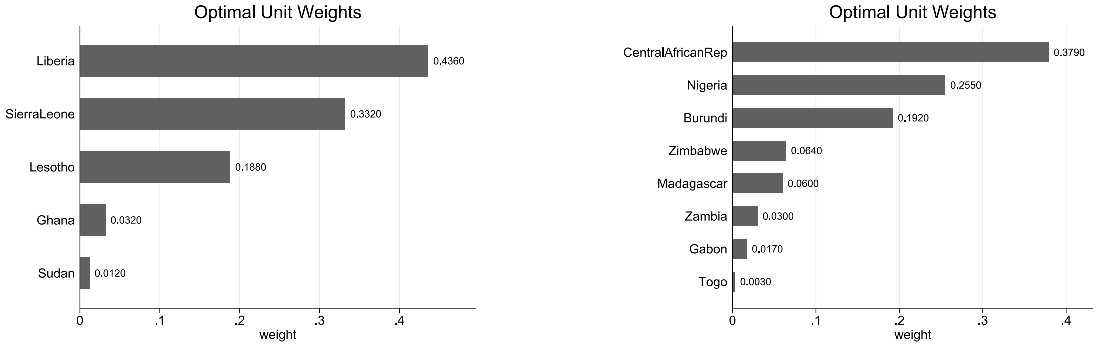
Fig. 15. Robustness checks - including lagged values for Electrification Outcomes (Access to Electricity (ATE), Renewable Energy Consumption (REC) and Greenhouse Gas (GHG) Emissions).



(a) REC model: Rwanda vs Donor Pool

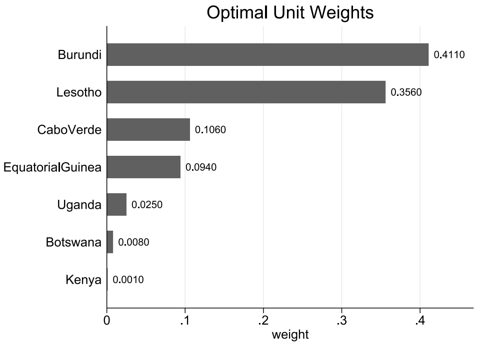
(b) GHG Emissions model: Rwanda vs Donor Pool

Fig. 16. Access to electricity in donor pool countries.



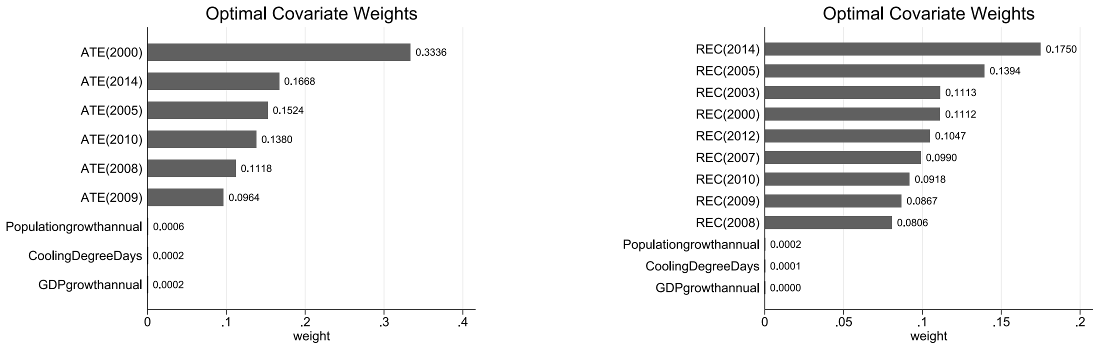
(a) Access to Electricity

(b) Renewable Energy Consumption



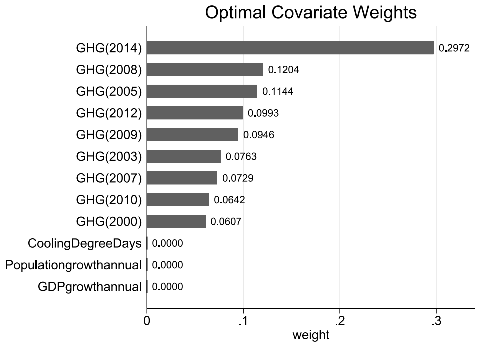
(c) Greenhouse Gas Emissions

Fig. 17. Weights of the Synthetic Control Group.



(a) Access to Electricity

(b) Renewable Energy Consumption



(c) Greenhouse Gas Emissions

Fig. 18. Weights of the Covariates.

Table A.5
List of African countries included in the analysis.

List of Countries
Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Congo, Djibouti, Equatorial Guinea, Eritrea, Gabon, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe

Fourth, the SCM identifies average treatment effects but does not capture distributional impacts across population groups or the long-term sustainability of electrification gains. Future research should explore heterogeneity in outcomes, such as differences in access between urban and rural households or across income and gender groups, using disaggregated and longitudinal data (Alam et al., 2018; Byaro et al., 2024). Additionally, there is a need to examine the durability of off-grid systems, the financial viability of mini-grids, and the resilience of national grids to climate and economic shocks (Mandelli et al., 2016; Ondraczek et al., 2015).

Finally, future work should continue to refine and apply theoretical frameworks that integrate energy transitions with institutional and political economy dynamics. Comparative studies across countries with varying governance structures and regulatory environments could help identify enabling conditions for successful electrification (Power and Kirshner, 2019; Chang and Berdiev, 2011). Interdisciplinary research linking energy access to wider development outcomes, such as education, health, and climate adaptation, would further inform inclusive and sustainable policy design (Banerjee et al., 2021; Messerli et al., 2019).

To conclude, while Rwanda's NES has made commendable strides in expanding electricity access, it also underscores the complex trade-offs between development and sustainability. By integrating robust evaluation methods with a multi-theoretical lens, this study not only contributes to the empirical literature but also offers actionable insights for policymakers. As countries across Sub-Saharan Africa pursue similar electrification goals, Rwanda's experience offers both inspiration and caution, highlighting the need for strategies that are not only ambitious but also environmentally and socially sustainable.

CRediT authorship contribution statement

Filippo di Pietro: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Kevin Campbell:** Conceptualization, Writing – Review & Editing. **Michael Christl:** Validation, Software, Methodology, Investigation, Data curation. **Frederick Kibon Changwony:** Supervision, Conceptualization, Writing.

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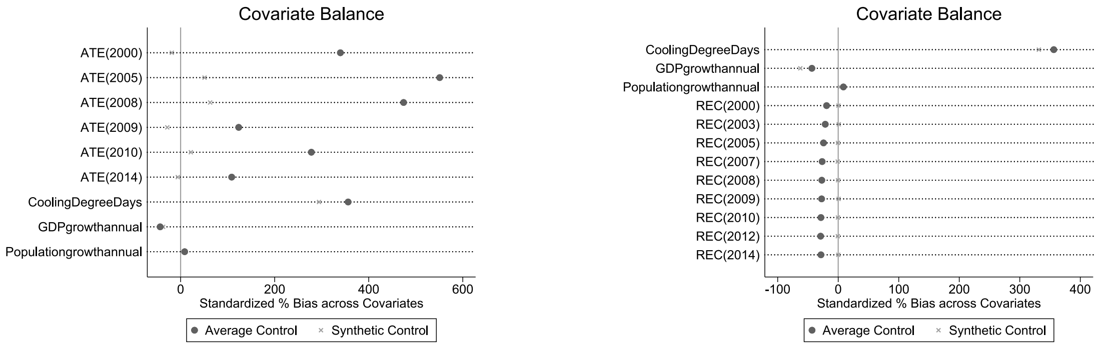
Appendix A

See Figs. 17–19.

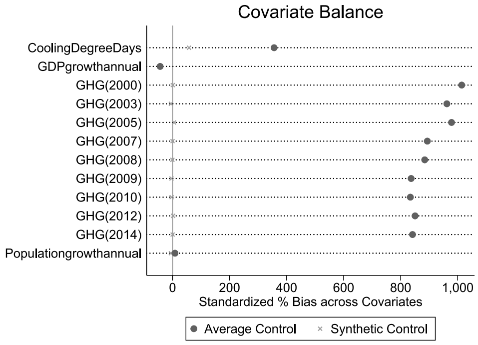
Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2026.109196.



(a) Access to Electricity

(b) Renewable Energy Consumption



(c) Greenhouse Gas Emissions

Fig. 19. Covariates balance.

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