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Financing the Green Transition: The Role of Green Bonds in Renewable Electricity Expansion

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Abstract

This study examines the interplay between monetary policy and the deployment of renewable electricity in Europe, addressing gaps in the existing literature. Against the backdrop of escalating greenhouse gas emissions, the paper examines the impact of monetary policy on the development of green energy infrastructure. By examining various determinants influencing the deployment of renewable electricity, the study identifies a novel area, the relationship between monetary policy and the evolving energy landscape characterised by increased private sector involvement and a shift from consumers to 'prosumers'. Using a pan-European approach from 2008 to 2022, the research poses two key questions: (1) Are interest rate movements associated with variations in renewable electricity deployment across different forms of renewable electricity generation? (2) Does the level of private sector involvement contribute to heterogeneity in the impact of monetary policy? The study uses rigorous panel analysis to unravel these dynamics, providing insight into the critical factors shaping the future trajectory of green energy in Europe. This research contributes to understanding the nuanced drivers of renewable electricity deployment and informs policymakers, researchers, and stakeholders working towards a sustainable energy transition.

Keywords: renewable electricity deployment, renewable electricity, European energy landscape, green bonds, panel cointegration

JEL Classification: E22, E52, Q20

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1 Introduction

The growing awareness of societies that greenhouse gas (GHG) emissions associated with human activities reinforce the greenhouse effect and contribute to climate change has shifted the focus of communities and decision makers to the use of green energy and renewable electricity. This is intended to diminish human carbon footprint in the environment. The Intergovernmental Panel on Climate Change (IPCC) of the United Nations suggests that only prompt actions and deep reductions in GHG emissions can limit global warming to "well below 2°C" (Clarke et al., 2022), as compared to the preindustrial era. To achieve the goal, the IPCC proposes a substantial reduction in fossil fuel consumption, expansion of production from zero- and low-carbon energy sources, and increased use of electricity and alternative energy carriers.

According to the International Energy Agency (IEA, 2023), global energy-related GHG emissions from energy combustion and industrial processes reached a new high of 41.3 Gt CO_2-eq in 2022, of which carbon dioxide represented 89% of total GHG emissions. The sectoral decomposition of global CO_2 emissions reveals that power sector is the primary source, followed by industry, transport and buildings. The largest contributors to energy sector GHG emissions are coal, oil and natural gas, which are responsible for 44%, 34% and 22% of energy sector CO_2 emissions, respectively (IEA, 2023). Despite this state of affairs, the IEA scenarios of global energy flows in 2060 and 2070 predict very significant changes in sources of primary supply of energy. Depending on the scenario and the predicted future global energy use the sources of primary supply may be different, however, two general patterns emerge. First, it is assumed that the power plants and heat sector will almost double their share in the process of energy supply, at the expense of the refinery industry. Moreover, it is assumed that renewable electricity sources, including wind, solar, bioenergy and others, will replace coal, natural gas, and oil to a large extent (IEA, 2023).

The aforementioned changes predicted by the IEA point to very accelerated changes in the renewable electricity sector in the next decades and call for an in-depth analysis of the process underpinning the green electricity deployment. In recent years, a rapidly growing body of literature has emerged to identify the factors that determine investment in renewable electricity and green energy in general. The potential determinants of renewable electricity deployment considered in the hitherto published papers are numerous and can be grouped into different categories.

First, the economic drivers of the investment in renewable electricity (or energy) are studied, including income, fossil fuel prices, electricity prices, local financial sector development, capital accumulation or flows, and size of the industrial sector. In one of the very first articles on this subject Chang et al. (2009) find that energy prices are positively correlated with renewable electricity development, however, this dependency is observed only for OECD member countries that exhibit high economic growth, whereas low economic growth countries seem to be unresponsive to energy prices. Using panel data over the period 1994 to 2003 and for 18 emerging countries Sadorsky (2009a) concludes that an increase in GDP should lead to higher renewable consumption. Brunnschweiler (2010) study the role of the local financial sector in the development of renewable electricity showing that countries with underdeveloped financial sectors do not provide an efficient channel of financing to renewable electricity producers. Romano and Scandurra (2011) investigate impact of nuclear power generation, GDP, technological efficiency, and CO_2 emissions on the share of renewable electricity deployment, demonstrating different estimates for low and high carbon economies. Using a panel of Central American countries from 1980 to 2010 Apergis and Payne (2014) find long-run relationship with structural breaks between renewable electricity consumption, GDP, CO_2 emissions, coal prices and oil prices. Similarly, Kehrel and Sick (2015) argue that oil prices drive the diffusion of renewable energy technologies. Using panel data of 30 countries over the period 2000 to 2013 Kim and Park (2016) conjecture that well-developed financial markets promote growth of the renewable electricity sector and lead to CO_2 emissions reduction. Lin and Omoju (2017) highlight that oil prices and financial development have a significant impact on renewable electricity generated without hydropower, while FDI, Kyoto protocol, capital accumulation, and resource rents do not affect renewable electricity generation. Cohen et al. (2021) show that European respondents show interest in community renewable energy deployments.

Next, environmental-orientated issues are investigated, including GHG emissions and resource depletion, which are intended to highlight environmental concerns of societies and increased awareness of limited resources. Sadorsky (2009b) finds that GDP and CO_2 emissions seem to positively determine renewable energy consumption in the G7 countries in the long-run, while the results for oil price impact are mixed. Contrary to the aforementioned study, the results of research for European countries conducted by Marques et al. (2010) point to CO_2 emissions and GDP negatively influencing the deployment of renewable energy. Using panel dateset of 122 countries over the period 1980 to 2010 Zhao et al. (2013) observe a significant role of CO_2 emissions, income, and renewable electricity policies, such as tax policy, investment incentives, and feed-in tariffs. Applying a hierarchical model on a large dataset of countries over four decades Bayulgen and Ladewig (2017) claim that economies characterised by political constraints suffer less from status-quo players who aim to slow the progress of clean energy reforms. In the study for 9 Mediterranean countries over the period 1980 to 2012 Belaïd and Zrelli (2019)) find a long-run relationship between renewable and nonrenewable electricity consumption, CO_2 emissions and GDP. They also affirm that renewable electricity has a positive effect on the environment. Sun and Yao (2023) investigate energy use and mineral resource depletion in China. They point to a positive correlation between CO_2 emissions, resource depletion, and energy use and highlight the need to invest in renewable energy sources.

Furthermore, country-specific power market characteristics are considered, such as electricity consumption, electricity security, local fossil fuel production and fossil fuel rents. Using a panel of five largest European countries over the period 2000 to 2010

Nicolini and Tavoni (2017) show that renewable energy subsidies, such as feed-in tariffs and green certificates, have been effective in promoting green energy capacity. The role of oil, gas and coal rents on renewable energy consumption in the United States and China has been investigated by Korkmaz (2022), who finds a long-run relationship for the United States, but not for China. Overland et al. (2022) observe that renewable energy resources are more evenly distributed than fossil fuel reserves, which can support the energy transition and lead to more decentralised global energy production.

Moreover, knowledge-related issues associated with technological innovation are studied in the literature. Lee and Howard (2021) focus on technical efficiency and innovation associated with renewable electricity generation. They argue that cost innovation plays a considerable role in renewable expansion. In turn, using Chinese data from 2005 to 2017 Zheng et al. (2021) conclude that technological innovation in renewable energy, represented by patent stock, promoted renewable power generation in China. The meta-analysis of Del Río and Kiefer (2022) indicates that feed-in tariffs are the major factor promoting innovation within the renewable electricity sector.

Another area of research is the impact of support policies and regulatory drivers (e.g. implementation of the Kyoto protocol or feed-in tariffs) that has been extensively investigated in numerous papers. Using a panel data set of 119 developing countries for 1980-2006 Brunnschweiler (2010) argues that the adoption of the Kyoto Protocol positively affects the development of renewable energy. Considering regulatory policies, fiscal incentives and public investments for developed countries from 2004 to 2011 Romano et al. (2017) find that not all policies support renewable energy investments and there are significant differences in their effectiveness. McGowan (2020) describes the process of policy learing and curtailment of renewable electricity support policies, based on feed-in tariffs, in Germany and the United Kingdom, which in turn can create constraints for increased growth of renewable electricity. Using panel data for EU countries from 2000 to 2015 Mac Domhnaill and Ryan (2020) claim that taxes on retail electricity prices that are supposed to fund the green transition are effective in promoting renewable electricity. Implementation of the Kyoto protocol and CO_2 emissions have been found to be significant for the energy transition by Przychodzen and Przychodzen (2020). Contrary to the aforementioned results, Dogan et al. (2023) find that environmental taxes and energy taxes have a negative impact on renewable energy deployments in EU countries.

The next problem is significance of such political factors as institutional quality, government ideology or the EU membership. Using a panel data set for 108 developing countries from 1980 to 2010 Pfeiffer and Mulder (2013) claim that implementation of economic and regulatory instruments as well as stable, democratic regimes accelerate the diffusion of non-hydro renewable energy technologies for electricity, whereas support policy programmes, increasing electricity consumption and high fossil fuel production seem to weaken the diffusion. Schaffer and Bernauer (2014) find that EU membership and a structure of the political system are significant factors that promote the deployment of renewable energy. In contrast to the findings of Pfeiffer and Mulder (2013), Schaffer and Bernauer (2014) argue that high shares of fossil (and nuclear) energy seem to strengthen the diffusion of renewable energy technologies. Abban and Hasan (2021) explore government orientation and nature of government systems as drivers of renewable energy investments. They claim that the left- and central-orientated governments promote renewable energy investments to a larger extent than the right-orientated ruling parties. Using a panel data set for 45 sub-Saharan Africa countries from 1960 to 2017 Acheampong et al. (2021) find that institutions are likely to respond to carbon emissions, however, there is no causality between carbon emissions and green energy. Saba and Biyase (2022) claim that institutional quality, corruption control, and the rule of law are important drivers of the development of renewable electricity. Similarly, Rahman and Sultana (2022) argue that institutional effectiveness and corruption control significantly affect renewable energy consumption. Finally, the importance of the demographic situation is verified by considering population size, human capital, poverty, and other demographic characteristics. Aguirre and Ibikunle (2014) find population growth to be a non-significant determinant of renewable energy deployment. Using data for over 180 US cities Kunkel et al. (2022) one can observe that population, education, and poverty are correlated with renewable energy development. The size of the population is found to be a significant driver of the demand for green energy in the provinces of China by by Feng et al. (2023).

As is clearly visible from the survey presented above, the literature on the factors that can impact the deployment of renewable electricity has become very voluminous. Numerous potential drivers are coupled with different statistical frameworks and definitions of renewable electricity (or energy) deployment, which in turn can be in absolute level, per capita level, or share, for electricity supply, consumption or capacity. As a result, there is little to no consensus within the literature on the clear identification of determinants affecting the deployment of renewable electricity. However, some factors are usually confirmed to be significant drivers, even though with different (positive or negative) estimated impacts. Bourcet (2020) in his comprehensive survey of the literature on the deployment of renewable energy (or energy) concluded that (i) most studies find that support policies have a statistically significant and positive impact (ii) population size acts as a stimulant, (iii) income effect may be positive or negative, depending on the time span and countries considered, (iv) similarly, influence of GHG emissions may be positive or negative, and (v) local financial sector development and institutional quality should have a positive impact.

Although the process for determining the deployment of renewable electricity has been studied extensively in the literature, there is one more potential mechanism, which has not yet received the appropriate attention. That is, the potential interlinkages between monetary and energy policy. The stable growth of renewable electricity deployment in recent years may be largely attributed to technologies that are used willingly by households and private companies. Solar photovoltaics, bioenergy, and offshore/onshore wind turbines are increasing their share in the green energy sector. This is coupled with an increased share of private sector investments and a gradual change in the role of households, which traditionally were considered to be consumers, to the new role of both consumers and producers. This phenomenon has been highlighted, and even the term "prosumers" has been coined. The shift from state-owned hydro power stations to private sector investment in solar photovoltaics, offshore/onshore wind and bioenergy is a primary reason, which necessitates to address a new question. Does monetary policy foster the development of renewable electricity deployments?

The literature on dependencies between monetary policy and green electricity deployments is scarce, however, the notable exception is the paper of Hashmi et al. (2022), who have studied the impact of real interest rates, gross domestic product per capita and crude oil prices on renewable electricity consumption in the US. Using data from the United States and a long time span, they conclude that the real interest rate negatively influences renewable electricity consumption in the United States, while the other variables exert a positive effect. However, this significant result cannot be considered as a general one, due to the following reasons. First of all, it is based on a purely one country analysis (US). Secondly, the sample span starts in 1960, well before the technology changes related to solar photovoltaics and other renewable electricity subsectors. Finally, the renewable electricity sector in this time span is dominated by hydroelectric power stations, which are usually owned directly or indirectly by the state.

In this paper, we address primarily two problems which seem to be crucial for renewable electricity deployment in the context of interdependencies with monetary policy. Firstly, are renewable electricity deployments in different forms of renewable electricity generation caused by interest rates movements? Secondly, do the various shares of the private sector's involvement in different forms of renewable electricity generation induce heterogeneity within the impact of monetary policy? To this end, we use a panel of European countries, covering a period from 2008 to 2022. The use of European countries helps to reduce country-specific results, whereas the time span is strongly associated with rapidly increasing key electricity system mitigation options, including solar photovoltaics, wind power and bio-generation.

Parallel to the investigation of dependencies between monetary policy and renewable electricity deployments, we examine the role of specific capital market solutions which were created to promote and enhance renewable electricity dissemination. To this end, we explain the investment destinations of green bonds within the renewable electricity sector and estimate the impact of green bond issuance on each renewable electricity subsector.

The remainder of this paper proceeds as follows. In Section 2 we present spatiotemporal dissemination of renewable electricity in Europe, divided into solar photovoltaics, offshore/onshore wind, hydro and bioenergy. In Section 3 we introduce green bond issuance in Europe and its utilisation. In Section 4 we refer to the underpinnings of potential dependency between renewable electricity investment and monetary policy. The main empirical results are presented in Section 5. We conclude and present the policy implications in Section 6. Data sources are presented in the Appendix A.

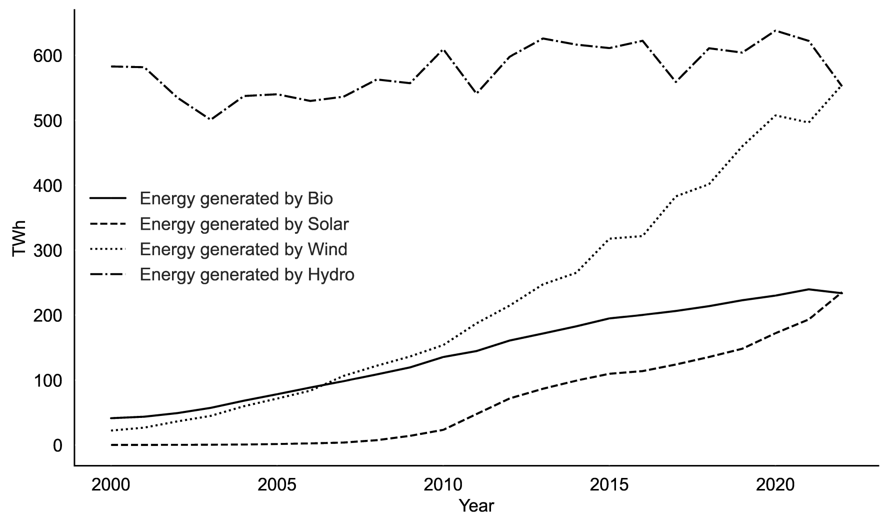
2 Renewable electricity deployment in Europe

The European Union (EU) and other European nations lead the global effort to combat climate change and shift towards a more sustainable and resilient energy infrastructure. In recent years, the necessity to decrease greenhouse gas emissions and minimise dependence on finite fossil fuels has driven Europe into a dynamic and transformative phase. Several pioneering projects have emerged as leaders in renewable electricity, making a substantial contribution to a diverse energy mix and a decrease in carbon dioxide emissions. At the heart of this progress is the ambitious implementation of green energy sources, including wind, solar, hydro, and bioenergy. Figure 1 shows the electricity generated from renewable sources by technology, alongside total electricity consumption in leading European countries between 2000 and 2022. Over this period, renewable electricity production rose from around 646 terawatt hours to more than 1,576 terawatt hours-an increase of over 200%. The evolution is credited to improvements in renewable technology, along with the enforcement of various policies to facilitate the growth of renewable electricity sources. The most significant increases were observed in wind and solar sources, which have become increasingly prevalent in the energy mix since 2010. The bioenergy generated grew steadily in the sample, whereas the hydro energy remains stable over time.
The cross-sectional analysis applied in the empirical investigation covers all of Europe apart from Belarus, Ukraine and Russia. The analytical framework only includes countries in the sample if their annual energy production from a particular source exceeded the 1 terawatt-hour (TWh) threshold in 2022, according to strict criteria. This criterion serves to narrow the sample size, focusing on countries with significant energy generation from the stated source. This enhances the robustness and relevance of the empirical findings within the European context.

2.1 Solar

In recent years, Europe has experienced a considerable increase in investment and implementation of solar energy projects. One of the notable initiatives is the Solarpark Meuro located in Germany, which exemplifies the significant investments in photovoltaic technology. The Solarpark Meuro, currently under construction, is planned to have a capacity of approximately 166 megawatts, and stands as evidence of Germany's strategic utilisation of its solar potential.
The 130 million dollars Tagus Solar Power Plant is under construction in Spain.

Figure 1: Electricity generated from renewable electricity sources by technology



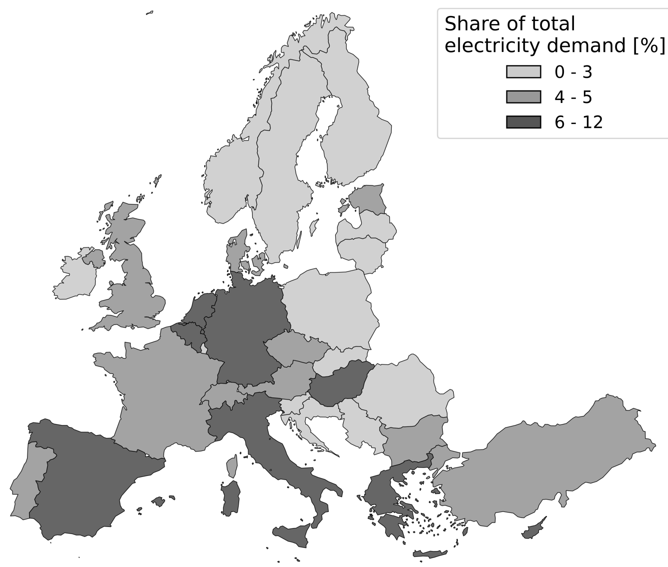
Notes: Countries included: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkiye, United Kingdom.

The project aims to meet the electricity needs of the region, powering 95,850 homes and avoiding the annual emission of 43,250 tonnes of CO_2.
Another successful project example is the Troia Solar PV Park, a ground-mounted 121.5 MW solar photovoltaic power project located in Apulia, Italy, which is currently operational. It has proven to be effective in compensating for 80,000 tonnes of carbon dioxide emissions annually. The Figure 2 illustrates the proportion of the contribution of solar energy to the electricity demand in various European nations. In particular, a concentration of solar energy infrastructure is observed in the southern regions compared to its northern counterparts. This spatial variation is inherently correlated with solar irradiance, as southern latitudes receive greater sunlight intensity. The cartographic representation provides a visual testament to the geographical alignment of solar investments with optimal sun exposure, underscoring the influence of climatic factors on the strategic placement of renewable electricity projects.

2.2 Wind

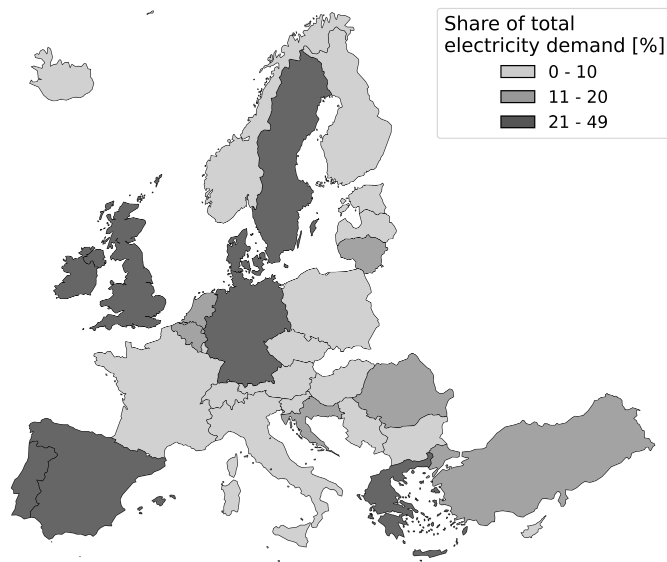
Wind power is emerging as a crucial component of Europe's sustainable electricity mix, driven by technological advancements in turbine design and supportive policy frameworks. The EU has positioned itself as a global leader in wind power deployment, with a strong focus on both onshore and offshore projects.

Figure 2: Spatial distribution of solar share of total electricity demand in 2021



The onshore sector has benefited from considerable investment, aimed at expanding and upgrading existing wind farms, as well as constructing new installations. Government support mechanisms, including feed-in tariffs, auctions, and renewable electricity targets outlined in the EU's Clean Energy Package, have significantly incentivised private and public investments in onshore wind projects.
Meanwhile, offshore wind investments have gained notable traction, fuelled by the extensive wind resources located in European waters. Pioneering efforts, such as Hornsea Wind Farm in the United Kingdom and the Borssele Wind Farm in the Netherlands, demonstrate the significant scope and aspiration of offshore wind investments in Europe.
In addition, cross-border joint initiatives and projects have become more important, promoting collaboration among European countries in the quest to maximise wind energy production. The North Seas Energy Cooperation aims to improve the development of offshore wind power in neighbouring countries, encouraging the efficient use of resources and infrastructure. The Figure 3 illustrates the proportion of the contribution of wind energy to the electricity demand in various European nations. A clear pattern emerges, indicating a strong correlation between wind energy production and specific geographic, economic and topographic factors. Regions with high wind velocities exhibit significantly higher electricity generation from wind sources, highlighting the direct impact of wind resources on the spatial distribution of wind power installations. Moreover, a significant correlation seems to exist between economic resources and governments' willingness to support wind energy production.

Figure 3: Spatial distribution of wind share of total electricity demand in 2021



Countries with a higher wind energy production generally have more advanced economic structures. The proximity to maritime expanses further facilitates the development of offshore wind farms, making it a critical factor. The map presented provides valuable preliminary information on the relationship between wind resources, economic development, and geographical characteristics that impact the potential for sustainable energy in the region.

2.3 Hydro

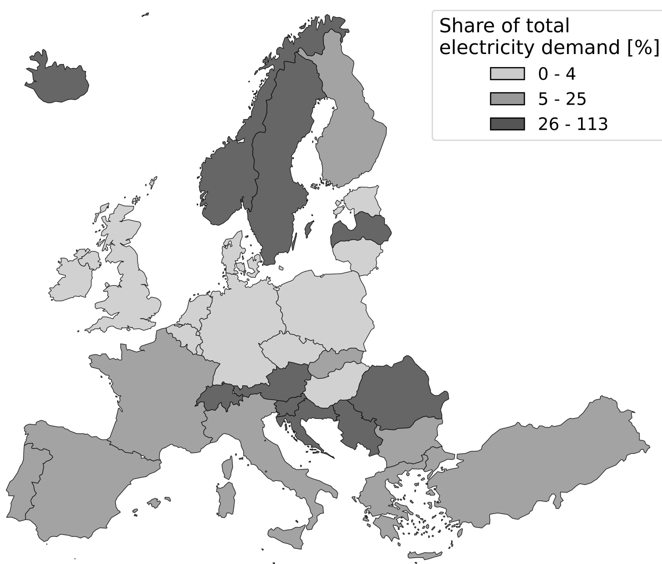
Investments in hydroelectric power generation in Europe in recent years have showcased a complex landscape influenced by advances in technology, environmental concerns, and the need for sustainable energy solutions. As a mature and established source of renewable electricity, hydropower has garnered focused investments to upgrade existing infrastructure and establish new projects.

In the context of modernisation, a significant proportion of investments have been focused on increasing the effectiveness and capability of ageing hydroelectric facilities. This typically entails updating turbines, generators and control systems to conform with contemporary technological standards. Incorporating sophisticated monitoring and control technologies has been essential in optimising the performance of current hydroelectric plants. It has been indicated by Quaranta et al. (2021) that about half of hydroelectric plants require modernisation.

In addition, investments have been allocated to the advancement of new hydroelectric

ventures, ranging from large- to small-scale installations. Large-scale projects, which often involve the construction of dams and reservoirs, have the potential to generate significant amounts of electricity and improve grid stability. Notable examples include continued investment in the expansion of current hydroelectric facilities in the Pyrenees (Rodriguez, 2012). However, ecological considerations have substantially hindered new constructions of hydroelectric plants, as advised in Collier et al. (2004) work on hydroelectric power.
In recent times, there has been a growing interest in small-scale hydropower projects, also known as run-of-river installations. In particular, in areas where sustainability is a crucial consideration, these projects have gained momentum because they avoid the need for significant landscape changes. By capitalising on the natural flow of rivers and streams, such schemes align well with modern environmental and social sustainability goals. It is necessary to exercise caution in the operation of small hydroelectric plants, as certain methods may have adverse environmental effects (Kuriqi et al., 2021).
Incentivising investments in hydroelectric power, initiatives such as European Green Deal reflect the commitment of the European Union to clean energy and decarbonisation. Financial instruments, such as subsidies, grants and project financing, have enabled the implementation of various hydropower projects across the continent. The Figure 4 illustrates the proportion of the contribution of hydro energy

Figure 4: Spatial distribution of hydro share of total electricity demand in 2021



Notes: A share above 100% indicates that the country (in this case, Norway) produces more hydroelectric energy than it consumes, resulting in net exports.

to the electricity demand in various European nations. The map clearly illustrates the correlation between high precipitation areas and hydroelectric production, especially where rivers and mountainous terrain converge. This concurrence corresponds to the inherent dependence of hydroelectric power production on the availability of water resources. A notable concentration of impressive hydropower figures is apparent in northern European countries. This is due to the abundance of rivers and elevated terrain that supports a robust hydroelectric infrastructure. Similarly, other European nations display comparable hydropower figures, reflecting the combined effort of the continent to adopt diverse portfolios of sustainable energy solutions.

2.4 Bio

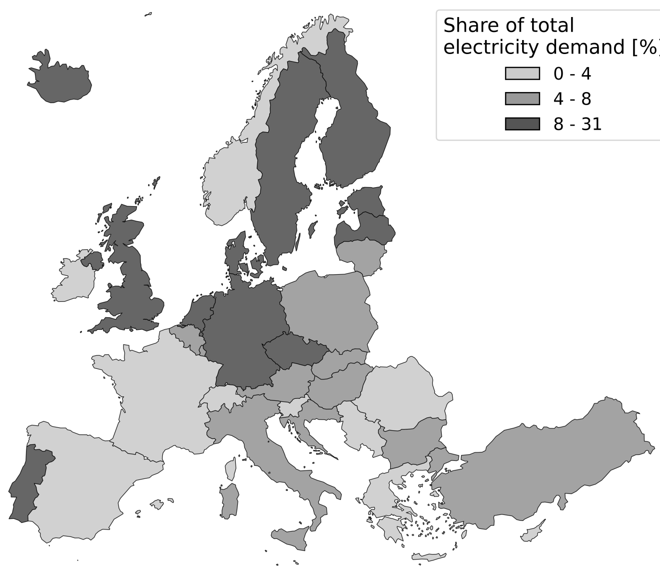
In recent years, investments in bioenergy, geothermal energy and biomass for energy production have become an integral part of the multifaceted framework of the European renewable electricity sector. This strategic diversification underlines a deliberate commitment to utilise a spectrum of sustainable sources, addressing environmental concerns and strengthening energy security across the continent. In this paper, bioenergy, geothermal, and biomass sources are aggregated into a single category termed bio, which represents the smallest share within the renewable electricity portfolio. Despite their relatively modest share, investments in bioenergy, geothermal and biomass play an important role in contributing to Europe's sustainable energy goals and embody a nuanced and diverse approach to the renewable electricity transition.

Bioenergy, originating from organic materials, has undergone significant investment in technologies, including anaerobic digestion, biogas production, and combustion of organic waste. Numerous European countries have established policy frameworks, such as feed-in tariffs (Banja et al., 2019) and subsidies, to promote the use of organic residues and energy crops for the production of bioenergy. These investments not only contribute to the achievement of renewable electricity targets, but also address waste management challenges through the repurposing of organic materials for energy generation.

Geothermal energy investments are gaining momentum, driven by the inherent sustainability and reliability of this renewable source. Countries located along the boundaries of the tectonic plate, such as Iceland and Italy, are leading the way in geothermal development. Enhanced geothermal systems (EGS) and deep drilling technologies have extended the geographical reach for geothermal investments, creating opportunities for increased capacity and wider deployment throughout Europe.

Biomass, which comprises organic matter including wood, agricultural residues and crops specifically grown for energy use, remains an attractive investment option for both traditional and innovative applications (De Wit and Faaij, 2010). Biomass power stations, sometimes utilising advanced technologies like Combined Heat and Power (CHP), have expanded significantly. They provide a contribution to both electricity generation and heating. In addition, investments in advanced bioenergy technologies, such as second- and third-generation biofuels, aim to solve worries about land use change and competition with food crops for resources. The Figure 5 illustrates the

Figure 5: Spatial distribution of bio share of total electricity demand in 2021



proportion of biomass, geothermal and bioenergy contribution to electricity demand in various European countries. The map values are likely to be explained by soil quality, indicating the impact of productive land and biomass accessibility on the deployment of biomass-based energy generation. Furthermore, nations located within the limits of the tectonic plates, as evidenced by the presence of geothermal resources, display higher values on the map, emphasising the importance of geological attributes in geothermal energy production.

3 Green bonds issuance within the Europe

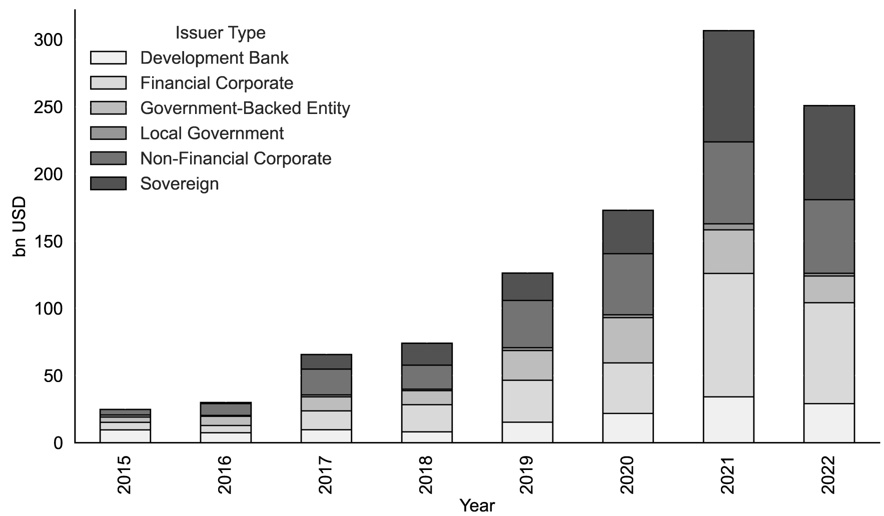
In recent times, the pressing need to address climate change has led to a change in thinking within financial markets, with investors placing greater emphasis on the environmental impact of their investments. The European Investment Bank (EIB) pioneered the issuance of green bonds to direct financial investments towards environmentally sustainable projects. This instrument has supported funding for renewable energy, energy efficiency, and climate adaptation, helping advance broader environmental goals.

Green bonds are debt securities that are created specifically to finance environmentally beneficial projects. The first green bond was introduced in 2007, when multilateral institutions such as the European Investment Bank (EIB) and the World Bank issued AAA-rated bonds. Since 2014, the market has gained notable momentum and each subsequent year has consistently ended with new record-breaking all-time highs. Several informative works provide detailed information on green bonds. Gianfrate and Peri (2019) suggests that green bonds may play a crucial role in sustainable economic practices. Bhutta et al. (2022) conducted a thorough review of the literature on this topic. Furthermore, Flammer (2021) highlights the growth of the green bond market and the benefits they offer to businesses, investors and the ecosystem. The literature on green bonds is inadequate, particularly in relation to the empirical investigation of their influence on renewable electricity.
Green bonds display crucial characteristics including:

1. Purposeful Issuance – being released for environmental or social purposes, as explicitly outlined in the bond's issuance prospectus.
2. Strict Utilisation of Proceeds – Funds raised through green bonds must solely finance projects that comply with specific environmental criteria. These criteria are often defined by an independent third-party certification body.
3. Transparency in Proceeds Utilisation – Green bonds are required to maintain transparent reporting of the allocation and use of funds. This information is usually disclosed in the bond's prospectus and reiterated in annual reports to ensure transparency and accountability in the allocation of funds.

Green bonds are divided according to the purpose of their use: (i) energy (34% of total green bonds in Europe), (ii) transport (18%), (iii) water (7%), (iv) buildings (27%), (v) land use and marine resources (4%), (vi) industry (0%), (vii) waste (4%), (viii) information and communication technology (0%). Green bonds are issued worldwide, with Europe being the main issuer, responsible for an average of 46% of issuance between 2014 and 2022. Beginning in 2021, the Asia-Pacific region began to account for a significant portion, representing 25% of the issuance that year. The Figure 6 illustrates the overall trend in green bond issuance, revealing a clear upward trajectory, demonstrating a growing commitment to sustainable finance. The aggregate sum issued underwent significant growth, rising from $17.90 billion in 2014 to an impressive $294.20 billion in 2021. The sharp increase observed since 2017 highlights the growing acceptance and implementation of green bonds as a feasible financial tool in different industries.
However, the decrease in green bond issuance in 2022, triggered by geopolitical uncertainties and an energy crisis, amplifies the vulnerability of green bonds to external conditions and emphasises the need for resilience in the face of worldwide uncertainties. As green bonds become more prominent, their response to geopolitical and economic challenges highlights the evolving nature of sustainable finance and the continued efforts needed to strengthen the resilience of green investments.
The rise in private sector participation in recent years is notable, accounting for more

Figure 6: Green bond issuance in Europe by issuer



Data source: Climate Bonds.

than half of total issuance. This suggests a marked change in corporate and investor attitudes towards environmental sustainability. This trend marks a shift away from traditional financial practices and reflects a shared acknowledgement of the need to incorporate environmental considerations into financial decision making.

Green bonds provide multiple benefits to both investors and issuers. By financing environmental well-being projects, investors can maintain a balance between risk-adjusted financial returns and positive environmental outcomes. Furthermore, green bonds assist investors in meeting Environmental, Social, and Governance (ESG) requirements (Tsang et al., 2023) and align with entities committed to robust ESG principles. The enhanced transparency offered by green bonds enhances risk assessment for investors whilst ensuring conformity to precise criteria for environmental or social objectives.

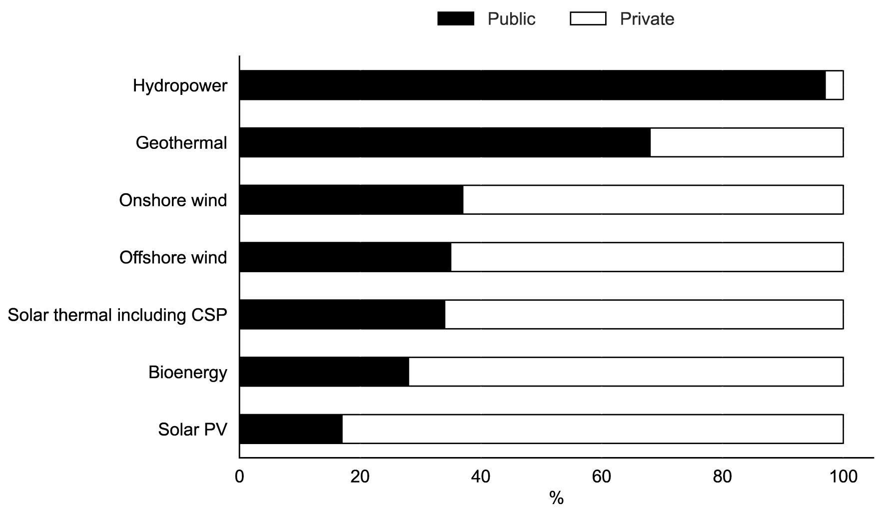
Nevertheless, it is crucial to take into account the disadvantages associated with green bonds. The recentness and small size of the green bond market could result in inferior liquidity, making it challenging to sell these bonds when required. The lack of a standardised approach for green bonds could result in confusion and jeopardise the attainment of the stated environmental advantages. Moreover, the restricted means of implementing and upholding the integrity of green bonds could prove to be testing for investors seeking rectification in cases where issuers become non-compliant with their promises to be environmentally responsible. The issue of green bonds incurs upfront and ongoing expenses, such as certification, reporting, and verification costs, which add to financial considerations.

Public policy has a key influence on the mobilisation and redirection of private capital, a critical factor in the promotion of green investment. This requires the implementation of coherent climate policies and the creation of robust frameworks that encourage and facilitate sustainable investment practices. Achieving this transformative change requires strategic alignment between government policies, regulatory frameworks and market incentives. Governments have a central role to play in creating an environment in which sustainable investment is not only encouraged but also financially incentivised, with the ultimate goal of creating a financial ecosystem in which green bonds become a mainstream investment choice, reflecting a collective commitment to a low carbon and environmentally responsible future.

4 Monetary policy and green energy deployment

The transition from a fossil fuel-based economy to one based on renewable and sustainable energy sources also brings structural changes to the energy sector. As illustrated in Figure 7, renewable energy technologies are largely developed and deployed by the private sector. In 2020, approximately 83% of the global investments in solar photovoltaics and more than 60% in offshore and onshore wind came from private financing. Private actors are also the main investors in bioenergy and solar thermal technologies. In contrast, many state-owned enterprises are more exposed to existing fossil fuel subsidies and regulatory frameworks that favour conventional energy sources, see Sovacool (2017), Koplow (2018), Taylor et al. (2020) and Ritchie (2025). These include preferential tax treatment and pricing mechanisms that lower the cost of fossil fuel production and consumption, factors that can slow the pace of the energy transition if not addressed through policy reform. The increased role of private companies, communities and households in the transition to renewable energy requires investigating whether a part of monetary policy related to interest rate movements affects investments in renewable energy capacity. This can be substantiated by the results of micro-based analyses, which exploit individuals' drivers in the decision-making process. For example, Brudermann et al. (2013) find that the repayment period seems to be crucial for individuals' decisions on investment in photovoltaics. Similarly, a survey-based study by Fleiß et al. (2017) suggests that financial beliefs are a cornerstone in the promotion of photovoltaics diffusion by increasing private investment in citizen participation initiatives in photovoltaics. Moreover, it should be noted that renewable energy technologies are capital intensive, compared to fossil fuel technologies, and a significant part of their life-cycle cost is incurred at the beginning of the investment, see Egli et al. (2018). As a result, it is likely that the high cost of capital can hinder renewable energy deployment. A similar finding, based on investments in renewable energy in India, has been suggested by Shrimali et al. (2013). State-owned companies' investments in renewable energy, including large hydroelectric facilities, may be more resilient to interest rate changes. This should happen when governments are willing to achieve the goal proposed by the IPCC and

Figure 7: Share of public/private investments by renewable energy technology, 2020



Notes: CSP = concentrated solar power; PV = photovoltaic.sim
Data source: IRENA and CPI (2023).

foster energy policies that support the deployment of renewable energy. The variation in public/private investment in renewable energy points to a possible heterogeneity of the impact of interest rates. Therefore, it is stressed that solar/wind/bio/hydro power should be modelled individually.

Another argument in favour of the potential heterogeneous influence of interest rates on renewable energy investment has been given by Schmidt et al. (2019), who studied the impact of interest rates on the levelized cost of electricity for photovoltaics and wind power in Germany. They found that interest rates exert a different impact with respect to each renewable energy technology. Therefore, increasing interest rates can potentially affect each sustainable electricity technology deployment in a different way.

Contrary to the arguments and findings mentioned above, Shah et al. (2018) suggest that monetary policy shocks do not have a significant effect on renewable energy investment. However, it should be noted that this result is based on a historical sample covering the period 1960-2015, and the renewable energy investments are modelled jointly, including hydro power. Similar conclusions are stated by Deleidi et al. (2020), who have also found that the concept of crowding-in/out mechanism is inapplicable to studies of the renewable energy sector.

5 Empirical results

Although there is no consensus within the literature on the determinants of renewable electricity investment, it seems that financial and economic drivers combined with climatic factors play a crucial role in the spatiotemporal dissemination of renewable electricity technologies in energy infrastructure.
First, we assume that it is not economic growth on its own pushing renewable electricity investments, as predicted by the standard accelerator theory, but the propitious economic and financial framework embodied in specifically designed mechanisms, which are created to promote sustainable electricity capacity and to fill the associated outstanding investment gap. The IPCC of the UN and the Climate Policy Initiative (CPI) name this framework as climate finance. Attracting investors to divert capital towards the renewable electricity sector requires specific capital market solutions that address the needs of institutional investors, and green bonds seem to play a crucial role in the process. Therefore, with regard to the relationship between renewable electricity deployment and its determinants, we assume that green bond issuance, as described in chapter 3, may promote the former.
Furthermore, we expect that factors driving relative profitability should be of crucial importance. This is in line with the Keynesian theory of investment, which predicts the marginal efficiency of capital and the interest rate to be of utmost importance. Moreover, as suggested by micro-based analyses mentioned in chapter 4, the financial factors seem to be significant for individuals' investment decisions. Therefore, we assume that renewable electricity deployments may be driven by interest rates, which represent the cost of capital and total installed cost of given renewable electricity technology. Another factor considered that seems to affect relative profitability is fossil fuels prices, as already suggested in a number of papers. Finally, as stressed in chapter 2, it seems that the climatic factors should be important for the decision-making process for the deployment of renewable electricity.
Overall, the model we formulate is as follows:

$$reg_{it} = f(gb_{it}, LTN_{it}, cost_{it}, fossil_{it}, METEO_{it}) \tag{1}$$

where REG is the share of renewable electricity generation for given technology (solar, wind, bio, hydro) to the overall electricity demand, GB denotes green bonds issuance, LTN is 10-year treasury bond yield, $COST$ stands for total installed cost of selected technology, $FOSSIL$ is country-specific index of prices for imported fossil fuels, $METEO$ denotes meteorological variable or geographical factor, like temperature (solar irradiance approximation), wind velocity, soil texture class (indicator for biomass generation) or precipitation. All variables expressed in small letters are in natural logarithms.
The panel dataset comprises annual data from 2008 to 2022 and includes European countries generating at least 1 TWh of renewable electricity per year for the respective technology. The base sample consists of 15 countries that have issued green

bonds: Austria, Belgium, Denmark, Finland, France, Germany, Italy, Lithuania, the Netherlands, Norway, Poland, Spain, Sweden, Switzerland, and the United Kingdom. To ensure consistency and relevance of the data, countries that did not meet the 1 TWh production threshold for a given technology were excluded from the estimations related to that specific source. Accordingly, Switzerland was excluded from the analysis of wind energy. In the case of solar energy, Finland, Lithuania, and Norway were omitted. For hydroelectricity, Belgium, Denmark, Lithuania, and the Netherlands were removed from the sample. Similarly, Lithuania and Norway were excluded from the bioenergy equation. These adjustments were made to improve the robustness of the estimations by removing countries with missing, incomplete, or statistically non-informative data related to specific renewable technologies. The data are derived from Our World in Data, Eurostat, Climate Bonds, International Energy Agency (IEA), International Renewable Energy Agency (IRENA) and Google Earth Engine. See the detailed data sources and the definitions of the variables in Table A1 in the A.

The results of the inference on the order of integration for processes that generate panel data are presented in Table 1. The first generation and second generation panel unit root tests proposed by Im et al. (2003) and Pesaran (2007) are used, both assuming individual roots in the alternative, as opposed to the LLC test derived by Levin et al. (2002). The tests indicate that the dependent variable for all renewable electricity technologies is generated by process integrated of order one, apart from hydropower generation share, which exhibits mean-reverting property. Moreover, green bond issuance, price index of imported fossil fuels, and cost of technology (apart from bio-power) are indicated to be generated by process integrated of order one, whereas interest rate and climatic factors are generated by stationary processes.

According to the results of Kao (1999) and Pedroni (1999) panel cointegration tests presented in Table 2, there is a long-run steady-state between variables in Equation (1) for wind, solar and bio power. This means that the non-stationary behaviour of the renewable electricity generation share can be well explained by stochastic trends pushing green bonds issuance, the total cost of technology, and fossil fuel prices, supplemented by stationary movements of interest rates and climatic factors. Hence, it can be concluded that there is a long-run relationship between REG and its determinants for wind, solar and bio-energy, as formulated in Equation (1). Since the share of hydro power generation seems to be generated by a stationary process, there is no need to verify whether the cointegration property holds.

In order to investigate the impact of green bond issuance, interest rates, cost of technology, fossil fuel prices, and the climatic factor on renewable electricity generation, as described in Equation (1), the Fully Modified Ordinary Least Squares (FMOLS) method, considered in the context of nonstationary panel data by Phillips and Moon (1999), is applied for wind, solar and bio power. It should be noted that the time span of our sample covers a relatively short period of time, which precludes application of multivariate statistical frameworks, like panel vector autoregression or

Table 1: Panel unit root tests

	IPS	CIPS
wind	-0.69***	-1.82***
solar	-0.80***	-2.19***
hydro	-5.31	-2.91
bio	-1.08***	-2.28**
gb	11.94***	-0.98***
LTN	-2.97	-4.69
fossil	-0.10***	-0.94***
cost_wind	8.02***	NA
cost_solar	6.29***	NA
cost_hydro	2.93***	NA
cost_bio	-9.63	NA
METEO_WIND	-22.59	-4.91
METEO_SOLAR	-17.97	-4.18
METEO_HYDRO	-7.7	-4.46
METEO_BIO	-75.07	NA

Notes: ***, ** and * indicate significance at 1%, 5% and 10% levels respectively. Variables denoted in lowercase letters are expressed in logarithmic form, whereas uppercase variables are presented in levels.

Table 2: Cointegration tests

	Kao	Pedroni
wind	-2.519***	-2.168**
solar	-3.46***	-2.126**
hydro	-	-
bio	-2.055**	-4.274***

Notes: ***, ** and * indicate significance at 1%, 5***, ** and * indicate significance at 1%, 5% and 10% levels respectively.

global vector autoregression. Moreover, the FMOLS estimator with nonparametric corrections for serial correlation and endogeneity bias seems to be superior in such a short sample, as compared to alternative univariate approaches like panel autoregression or dynamic ordinary least squares, which use lags (and leads for the latter) to correct for mentioned above biases. Since the process generating the share of renewable electricity is stationary, the standard ordinary least squares method is applied for hydropower.

The estimation results reported in Table 3 show that green bond issuance, interest rates, technology cost, fossil fuel prices, and climatic factors are the crucial drivers of the share of renewable electricity generation in European countries. From the results observed, it can be stated that green bond issuance, fossil fuel prices and climatic factors have a positive effect on renewable electricity generation, except for the indicator $METEO$ for bio-energy, which is statistically insignificant. However, it should be stressed that bio power is a relatively small remainder category which consists of several different subcategories, including biomass, geothermal energy and bioenergy. Regarding interest rates and technology cost, the estimation results confirm that they negatively affect REG. The results of Pesaran (2021) CD test reported in Table 4 indicate a lack of cross-sectional error dependence.

Table 3: Estimates of cointegrating vectors

Variables	WIND	SOLAR	BIO	HYDRO
gb	0.203***	0.166***	0.052***	
LTN	-0.122***	-0.594***	-0.042**	
cost	-0.267***	-0.806***	-0.067*	
fossil	0.249***	0.577***	0.110***	
METEO	0.340***	0.237***	-0.391	0.942***

Notes: This table reports the results of the FMOLS estimation for Equation (1). ***, ** and * indicate significance at 1%, 5% and 10% levels respectively.

Table 4: Cross-section dependence test

	Pesaran CD	
wind	-0.094	(0.925)
solar	1.056	(0.291)
hydro	-1.463	(0.143)
bio	1.388	(0.165)

Notes: P-values are reported in parentheses.

As can be seen from the estimation results in Table 3, although the general pattern for all renewable electricity technologies is consistent, there is a significant difference in the impact of drivers, with respect to each technology. In particular, a notable difference occurs for interest rates, for which the highest impact is observed in the case of the solar power sector. Considering that this sector of power generation is characterised by the highest share of private capital engagement and the main part of the life-cycle cost of investment for solar photovoltaics and solar thermal facilities is incurred at the beginning, a strong impact of interest rates is expected for this sector. The regression results show that decreasing the interest rate by 1pp boosts *REG* for solar power by up to 60%, while wind power and bio power receive 13% and 4%, respectively. However, it should be noted that our sample covers the period, which is generally characterised by low interest rates and a high pace of growth for renewable electricity technologies deployments. Therefore, to exclude sample-specific results for these estimates, further research with longer time spans may be necessary.

Furthermore, the results show that the solar power sector is more susceptible to changes in the cost of technology as well as fossil fuel prices. Again, this seems to be induced by the high share of private capital involvement, including households and communities, and is in line with the findings of microbased studies, which outline financial beliefs and financial factors as crucial for investors' decisions. The estimation results in Table 3 show that an increase in technology cost 10% reduces the share of solar power generation by 12%, wind power by 3%, and bio power by about 0.7%. Similarly, fossil fuel import prices also exert a significant influence on the dissemination of renewable electricity, since a 10% increase in fossil fuel prices leads to a 7.5%, 2.8% and 1.2% increase in *REG* for solar, wind and bio power, respectively. Moreover, the issuance of green bonds appears to play an important role in the case of wind power generation, as an increase 10% in the issuance of green bonds leads to an increase in wind power and solar power generation of about 2% and 1.7%, respectively. It should be highlighted that these figures correspond to green bond investment destinations, as described in Section 3.

Finally, the climatic factors like temperature, wind velocity and precipitation also play a significant role in explaining the renewable electricity deployment. However, their limited variance within the time domain suggests that these factors primarily explain the spatial pattern of renewable electricity dissemination, unless century-long time scales are considered.

6 Conclusions and policy implications

A low-carbon energy transition requires substantial changes in energy systems and increased use of electricity from renewable sources. To this end, significant investments are needed in renewable electricity (and energy) technologies. However, as stressed by international agencies, the pace of investments needed to achieve the climate goal proposed by the UN' IPCC should be vastly increased. The IEA (2023) postulates that investments in the sector at least quadruple. Therefore, investigating the drivers of the deployment of renewable electricity is of crucial importance for possible mitigation of climate change and the successful energy transformation of global economies.

In this paper, we examine the monetary drivers, economic and financial factors, as well as meteorological and geographical determinants of the deployment of renewable electricity. We have found that interest rates negatively affect green electricity

dissemination for wind, solar and bio-power, but significant differences in interest rates impact exist. According to our results, the solar power sector is the most susceptible to interest rate changes, which seems to be caused by the highest share of private sector involvement and the high upfront cost of investment. Wind and bio-power deployments are moderately influenced by interest rates, whereas the hydro power sector seems to be immune to this factor, which seems to be due to a negligible share of private sector involvement.
Furthermore, we have found that the issue of green bonds is of crucial importance for renewable electricity deployments, especially for wind power and solar power generation. This finding reflects the fact that investments in renewable electricity technologies are highly capital-intensive. Therefore, special capital market solutions are necessary to divert capital flows towards this investment destination and to create favourable and substantial financial framework.
Next, we have confirmed that variables defining relative profitability, namely total installed cost of given technology and fossil fuel prices, are important factors driving turbulent behaviour of renewable electricity deployments for wind, solar and bio-power. Moreover, the higher the share of private engagement, the higher the elasticities toward both financial variables.
Finally, our results replicate an obvious dependency of renewable electricity deployment on meteorological and geographical factors. However, these factors appear to be the primary responsible for the spatial dissemination of sustainable electricity technologies.
The aforementioned results let us formulate several policy implications. First, to boost renewable electricity capacity and to gather a pace other than the one attained by total electricity demand, it is a necessary condition that national and supranational institutions provide substantial channels of green investment financing. Our results show that green bond issuance is a proper mechanism in this case. Furthermore, interest rate policy was found to be a significant factor that provides an important channel through which renewable electricity deployments can be stimulated. This is especially valid in the case of solar power and offshore/onshore wind turbines. Finally, it is important to cancel governments support for fossil infrastructure, which decreases fossil fuels prices, and to redirect this flow towards green counterparts.

Disclaimer

The views expressed are solely those of the authors and do not necessarily reflect the position of the institutions with which the authors are affiliated.

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A Data sources

Table A1: Variable definitions and data sources

Variables	Definitions	Units	Source
SOLAR	Electricity generation from solar	TWH	Our World in Data
HYDRO	Electricity generation from hydro	TWH	Our World in Data
WIND	Electricity generation from wind	TWH	Our World in Data
BIO	Electricity generation from bioenergy, biomass and geothermal	TWH	Our World in Data
EL_DEMAND	Final consumption of electricity	TWH	Eurostat
GB	Green bonds	billion euro	Climate Bonds
LTN	Long-term interest rates (maturity of around 10 years)	percentages per annum.	Eurostat
FOSSIL	Weighted index of prices for imported fossil fuels.	euro/100kg	Eurostat and IEA
COST_WIND	Total installed cost of wind	EUR/kW	IRENA
COST_SOLAR	Total installed cost of solar	EUR/kW	IRENA
COST_HYDRO	Total installed cost of hydro	EUR/kW	IRENA
COST_BIO	Total installed cost of bio	EUR/kW	IRENA
METEO_WIND	10m v-component of wind	m/s	Google Earth Engine
METEO_SOLAR	Average air temperature at 2m height	C	Google Earth Engine
METEO_HYDRO	Total precipitation	m	Google Earth Engine
METEO_BIO	Oil Texture Class (USDA System)	b0	Google Earth Engine