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THE IMPACT OF THE REAL INTEREST RATE ON GREEN INVESTMENT: EVIDENCE FROM THE UNITED STATES

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Abstract. Monetary policy has an impact on CO_2 emissions which is not entirely understood in the literature. Whereas there is a consensus that the impact is indirect through investments, the literature does not investigate the impact of monetary policy on (green) investments. Additionally, we argue in this paper that monetary policy can have a different impact on 'green' investments and 'brown' investments. This paper focuses, therefore, on the impact of monetary policy on investments. In particular, this paper empirically investigates whether the real interest rate has a different effect on green investment, compared to general investment, using quarterly data from the United States between 2004 and 2020. The results from the autoregressive distributed lag model show that the real interest rate is negatively related to the ratio of green investment relative to total investment. This result emphasizes the importance of the green investment effect channel and suggests that monetary policy has an unintentional role in climate policy which should be considered by policy makers.

Keywords: green investment, brown investment, interest rate, monetary policy, climate policy, USA.

JEL Classification: O330, Q550, Q580, E520.

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1. Introduction

Governments set environmental policies to curb emissions in an attempt to combat global warming and its impact on life and nature (Stern, 2008). Macroeconomic policies, on the other hand, emphasize macroeconomic stability, but indirectly affect emissions. By setting the nominal interest rate, the Central Bank can create temporary changes in the real interest rate (RIR), which impacts decisions regarding consumption, savings, and investment. Those decisions affect energy consumption, investment in green technologies, and subsequently CO_2 emissions. In light of the growing world population and economic growth, investment in green technologies, such as renewable energy, is particularly important to curb emissions. However, research on the effect of the RIR on green investment (GI) is limited despite the policy relevance of it. Understanding this effect enables Central Banks to design policies that promote both economic stability and a greener economy.

After China, the United States is the largest emitter of CO_2 emissions, accounting for almost 15% of it in 2018 – China is responsible for 31% of total CO_2 emissions (The World Bank, 2022). Moreover, between 2004 and 2020, renewable energy investment merely accounted for about 1% of total investment in the U.S., and in 2021, only 12% of its primary energy consumption came from renewable energy (U.S. Energy Information Administration, 2022). For those reasons, understanding how the United States can promote green investment is of particular interest.

In this paper, we investigate the direct impact of monetary policy on (green) investment. We argue that green investment is more sensitive to changes in the interest rate then other types of investment, such that monetary policy can impact the relative amount of green investment vis-à-vis other types of investment. Di Luccio (2023) argues that renewable energy projects are more affected by an increase in interest rates because of the higher upfront investments required. However, to the best of our knowledge, no paper has showed this empirically.

We contribute to explaining a puzzle in the related literature analyzing the effect of monetary policy on emissions. Isiksal et al. (2019), Qingquan et al. (2020) and Chishti et al. (2021) find a negative relationship between the RIR and CO_2 emissions. Qingquan et al. (2020) explain this result by arguing that a lower interest rate increases consumption and discourages savings, thereby increasing energy consumption and subsequently CO_2 emissions. In contrast, Muhafidin (2020), Pradeep (2022) and Shobande (2022) find a positive relationship between the RIR and CO_2 emissions. In this case, the argumentation is that a lower interest rate increases investment in carbon-efficient technologies, which leads to a reduction in CO_2 emissions (Pradeep, 2022). However, Pradeep (2022) does not analyze empirically whether this is indeed the channel through which an increase in the interest rate leads to an increase in CO_2 emissions. Our paper argues that the real interest rate affects green investment differently from other types of investments, particularly from brown (i.e. high-carbon) investments.

The contradicting results in the literature suggest that there are different channels through which the RIR affects CO_2 emissions. On the one hand, the interest rate influences CO_2 emissions through its effect on total output, suggesting a negative relationship between the RIR and total CO_2 emissions. On the other hand, the interest rate influences investment decisions in brown and green (i.e. low-carbon) technologies in different ways. The latter, is the approach we follow. More specifically, we hypothesize that since green investment is generally associated with a high initial cost and returns that materialize later in the future (Arena et al., 2018), it is more sensitive to changes in the interest rate than other types of investments. As such, the real interest rate has a negative impact on green investment, which could explain the positive impact of the real interest rate on CO_2 emissions found in the literature (Muhafidin, 2020; Pradeep, 2022; Shobande, 2022).

From a theoretical perspective, green investment is expected to be more sensitive to changes in the interest rate than brown investment (Eyraud et al., 2013; Monasterolo & Raberto, 2018; Glemarec & Connelly, 2011). However, there is not yet – to the best of our knowledge – empirical evidence for this statement. Eyraud et al. (2013) show that the real interest rate has a negative impact on green investment, but does not provide empirical evidence for the hypothesis that green investment is more sensitive to the real interest rate than other types of investments. The current research contributes to the existing literature on monetary policy and green investment by examining empirically the extent to which the interest rate has a different effect on green investment than on brown investment, using data from the United States. More specifically, we analyze the effect of the RIR on the ratio of green investment relative to total investment. To this end, we use the Autoregressive Distributed Lag (ARDL) model with quarterly time series data between 2004-Q1 and 2020-Q2. Our results provide a better understanding of the effect that the interest rate can have on CO_2 emissions through investment in green technologies.

The remainder of this paper is structured as follows. Section 2 covers the previous literature on this topic, which will result in the theoretical framework, as outlined in Section 3. Section 4 covers the data and methodology used in the empirical analysis. The results of this analysis are presented in Section 5. Section 6 provides a robustness analysis. The final Section concludes the paper with a discussion of the limitations, policy recommendations and suggestions for future research.

2. Literature review

CO_2 emissions tend to move along with economic activity (Annicchiarico & Di Dio, 2017; Chan, 2020; Isiksal et al., 2019). Therefore, *ceteris paribus*, an expansionary monetary policy, aimed at stimulating the economy, is expected to have the side-effect of increasing CO_2 emissions. In line with this, Qingquan et al. (2020) argue that monetary policy influences CO_2 emissions through two channels, namely through consumers and through producers. The authors state that a decrease in the RIR – which they use as a proxy for expansionary monetary policy – increases lending power of both consumers and producers and discourages savings. This allows producers to invest in new capacity and thus to produce more. Simultaneously, it allows consumers to consume more. Consequently, energy consumption and thus CO_2 emissions increase. This suggests, from a theoretical perspective, a negative relationship between the RIR and the absolute level of CO_2 emissions. Similarly, Chan (2020) argues that, in order to stabilize carbon emission cycles, the RIR should increase whenever the emission level is above the target emission level. Aguila and Wullweber (2024) point out that higher interest rates slows down the transition to a greener economy. Contractionary monetary policy as such can ameliorate environmental quality (Chishti et al., 2021). The empirical findings from Qingquan et al. (2020) support this hypothesis; that is, they find a significant positive long-term relationship between expansionary monetary policy (proxied by a decrease in the RIR) and CO_2 emissions based on a dataset of 14 Asian economies.[1] In this same line, Isiksal et al. (2019) show, for Turkey, that the RIR negatively affects CO_2 emissions; and Chishti et al. (2021) find that expansionary monetary policy deteriorates environmental quality in the BRICS economies.[2]

On the contrary, Muhafidin (2020) finds that the interest rate has a significant positive effect on CO_2 emissions in Indonesia, using an ARDL bound testing approach. In line with this, Pradeep (2022) applies dynamic ARDL simulations with annual data from 1971 to 2014 and finds that the interest rate is positively related with CO_2 emissions in India in both the short- and long-run. According to Pradeep (2022), this positive relationship can be explained by the negative impact that the interest rate has on investment in durable goods – such as electrical machines and automobiles – and the subsequent effect on emission levels. However, the author does not discuss whether the interest rate has a similar effect on carbon intensive investments, which would again lead to a negative effect on emissions. Moreover, he does not show empirically whether the result is indeed caused by a change in green investment. Similarly, Shobande (2022) finds a positive relationship between the real interest rate and CO_2 emissions in the East African Community,[3] but also does not empirically analyze the intermediate effect on green investment.

[1] Bangladesh, China, India, Sri Lanka, Israel, Turkey, Malaysia, Japan, Indonesia, Thailand, the Philippines, Iran, Korea, and Pakistan.

[2] Brazil, Russia, India, China, and South Africa.

[3] Kenya, Uganda, Tanzania, Burundi, Rwanda, and South Sudan.

Thus, previous research indicates that there are two opposing channels that determine the effect of the RIR on CO_2 emissions. The first channel posits that, through an increase in total output, a decrease in the RIR increases CO_2 emissions, because of the pro-cyclical nature of CO_2 emissions. From now on, we will refer to this effect as the *output channel*. The second channel is concerned with the incentive in favour of green investment that is associated with a decrease in the RIR. We call this effect the *green investment channel*. Figure 1 provides a representation of these two channels, which gives a framework for understanding how the interest rate affects emissions, both in the short- and long-run.

In reality, the green investment channel is more difficult to observe than the output channel for several reasons. First, it takes some time before an investment in a green technology actually results in CO_2 reduction and this effect is spread out over a longer period of time, because it is not the level of investment in one particular period that matters for CO_2 emissions, but rather the accumulation of green investment over time. Next to this, whereas the output channel affects total emissions, the green investment channel influences relative emissions (i.e. CO_2 emissions relative to total output), because investment in renewable energy and energy efficiency reduce the amount of CO_2 emissions for the same level of energy consumption. If we look at the absolute amount of CO_2 emissions, this effect can easily be overshadowed if the total amount of energy consumption increases at the same time. Moreover, a profound theoretical framework and empirical analysis of the green investment channel is missing in the existing literature. Our research contributes, therefore, to the understanding of the green investment channel, as represented by the grey outlined part of Figure 1.

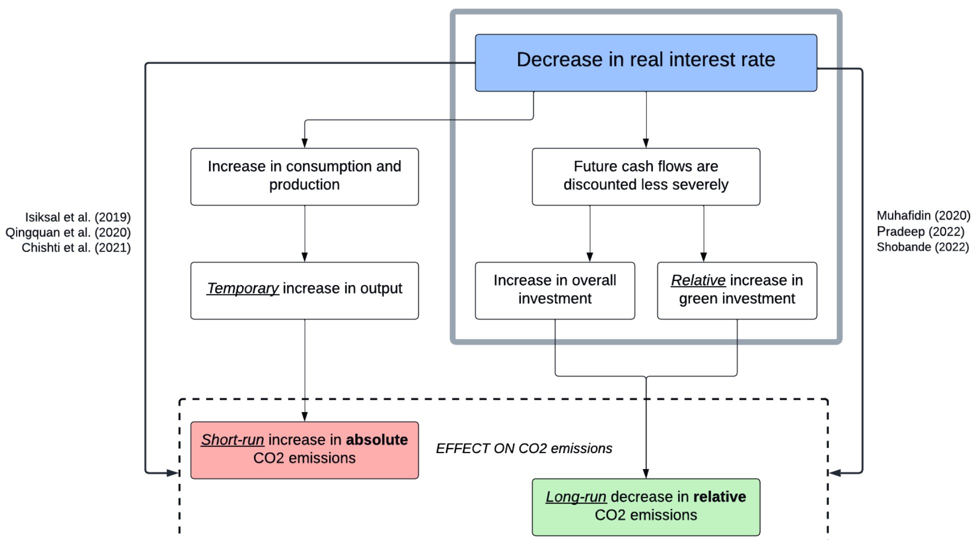

Figure 1. Representation of the effect of the RIR on CO_2 emissions through the output channel and the green investment channel. The focus of the current study is represented by the grey outlined part of the figure

Eyraud et al. (2013) investigate empirically which factors influence green investment, which they define as "investment necessary to reduce greenhouse gas and air pollutant emissions, without significantly reducing the production and consumption of non-energy goods"

(p. 853). Using a dataset of 35 advanced and emerging countries between 2004 and 2010, the authors apply a fixed-effects approach to test the effect of GDP per capita, population, human capital, fossil-fuel prices, production costs of green capital goods, profit, public policies to support GI, and the interest rate on green investment. The authors argue that high interest rates tend to reduce investment, and GI in particular, because "the bulk of the cost of producing renewable energy is upfront, and because their capital intensity is generally high compared to traditional technologies" (p. 858). Therefore, the authors expect the interest rate to be negatively related to GI. The empirical results support this hypothesis: the long-term RIR has a negative and significant effect on GI with a lag of one year. However, the authors do not analyze empirically whether the effect that the RIR has on GI is indeed different from its effect on other types of investment.

The results from Eyraud et al. (2013) suggest that lower interest rates benefit the environment by promoting green investment. However, as emphasized by Altaghlibi et al. (2022), in order to reduce climate change, it is crucial that the cost of capital for green investment is lower than the cost of capital for brown investment. As argued by Monasterolo & Raberto (2018), firms' decision to invest in green or brown capital depends on which of the two has the highest expected net present value (NPV). In general, brown capital is associated with a lower initial cost compared to green capital, but requires more raw material per unit of output (Monasterolo & Raberto, 2018). In line with this, Tran et al. (2020) state that "It is hard to see the benefits of green investment in a short time" (p. 66) and Arena et al. (2018) argue that the returns from environmental innovation tend to materialize over a longer period of time, compared to general innovation. Similarly, Eyraud et al. (2013) argue that – from a theoretical point of view – investment in renewable energy should be particularly sensitive to the interest rate, because the majority of the cost associated with it is upfront. Moreover, Glemarec and Connelly (2011) state that "a key financial barrier for a number of low-emission, climate-resilient investments [...] is the need for substantial upfront investment. Hence, climate investment is particularly sensitive to interest rates" (p. 94–95). According to Cox et al. (2013), "with efficient capital markets, discount rates should converge with interest rates" (p. 4). In other words, GI becomes more attractive relative to brown investment when future cash flows are discounted at a lower rate, suggesting that a lower interest rate promotes green investment more than brown investment (Monasterolo & Raberto, 2018).

Other papers which have investigated the determinants of green investment (Azhgaliyeva et al., 2018, 2023; Bento et al., 2020; Barabanov et al., 2021) have conducted a cross-country analysis. Azhgaliyeva et al. (2018) analyzed the impact of fiscal and financial policies on private investment in renewable energy and found a positive impact from feed-in tariffs and loans. Bento et al. (2020) controlled for auctions on renewable capacity and found a positive effect of tenders. Additionally, the authors did not find that the long-term interest rate affects the renewable capacity. Barabanov et al. (2021) use a dataset on 763 firms across 40 countries to analyze the determinants of corporate green investments and find that the size of a firm matters, that is, larger firms tend to have more green investments. Azhgaliyeva et al. (2023) found that government renewable energy policies are effective to stimulate private investment. Finally, other papers have analyzed specific policies to stimulate green investment, such as "window guidance" in China (Dikau & Volz, 2023), fiscal policies and environmental stringency in the G7 economies (Bashir et al., 2023); while Bartocci et al. (2024) have built a theoretical model to analyze green fiscal and nonstandard monetary policy in the euro area.

3. Theoretical framework

This Section develops a theoretical framework for the relationship between the RIR and green investment. We assume a company which intends to make an investment and can choose between a brown investment, such as an expansion of the production capacity, or a green investment, such as installing solar panels. The company has two options to finance this investment. The first option is to take on a loan to finance the initial investment and use the returns from the investment to repay the principal and interest payments of the loan. The second option is to use the company's own excess cash to finance the investment, which is associated with the opportunity cost of interest payments from another investment. Since companies generally do not want to be exposed to interest rate risk, we can assume that many firms will take on a fixed interest rate loan or hedge the interest rate risk, such that the best approximation of the interest rate over the lifetime of the investment is the current interest rate. Furthermore, future interest payments are devalued by inflation. For those reasons, all future cash flows need to be discounted by the long-term real interest rate, r.

The company will assess the profitability of both projects, based upon the net present value (NPV) of the project, which is obtained by summing up all discounted future cash flows and subtracting the initial investment cost. First, the firm will determine whether or not to invest at all. The firm will choose to invest if at least one of the projects is profitable, i.e. if the condition expressed in Equation (1) is satisfied.

$$\max\left(\sum_{t=1}^{\infty}\frac{CF_t^{GI}}{(1+r)^t}-I^{GI},\sum_{t=1}^{\infty}\frac{CF_t^{BI}}{(1+r)^t}-I^{BI}\right)>0, \tag{1}$$

where CF_t^{GI} and CF_t^{BI} represent the real returns in year t of the green and brown investment respectively, and I^{GI} and I^{BI} represent the initial investment of the green and brown investment respectively, which are all strictly positive. If the condition in Equation (1) is satisfied, the firm will determine which project to invest in. The firm will invest in the green project if its NPV is larger than that of the brown alternative – i.e. if the condition expressed in Equation (2) is satisfied – and in the brown investment otherwise.

$$\sum_{t=1}^{\infty}\frac{CF_t^{GI}}{(1+r)^t}-I^{GI}>\sum_{t=1}^{\infty}\frac{CF_t^{BI}}{(1+r)^t}-I^{BI}. \tag{2}$$

Following the previous literature which suggest that green investment is generally associated with a high initial cost (Eyraud et al., 2013; Glemarec & Connelly, 2011; Monasterolo & Raberto, 2018), we assume that $I^{GI}>I^{BI}$. For simplicity, we assume that both investments have the form of a constant growth perpetuity, i.e. the stream of cash flows continues indefinitely, such that we can rewrite:

$$\frac{CF_1^{GI}}{r-g^{GI}}-I^{GI}>\frac{CF_1^{BI}}{r-g^{BI}}-I^{BI}, \tag{3}$$

where g^{GI} and g^{BI} represent the growth rates of the green and brown investment respectively. Writing the NPV in this form requires the assumption that $r > g$ (Olsson, 2005), because otherwise the value of the sum of future cash flows would become negative. Since the literature posits that green investment is generally associated with returns that materialize later in the future (Arena et al., 2018), while brown capital requires more raw material per unit of output (Monasterolo & Raberto, 2018), it is logical to assume that the growth rate of the brown investment is only a fraction, 0 < α< 1, of the growth rate of the green investment, where the latter is strictly positive, i.e.: $g^{BI} = \alpha \times g^{GI} > 0$. For reasons of comparability, we assume that the cash flows in year 1 are the same for both the green and brown investment, i.e.: $CF_1^{GI} = CF_1^{BI} = CF_1$. Under these assumptions, Equation (3) can be rewritten as:

$$\frac{CF_1}{r - g^{GI}} - I^{GI} > \frac{CF_1}{r - \alpha \times g^{GI}} - I^{BI}. \tag{4}$$

Equation (4) can be rewritten in terms of the difference between the green and brown investment:

$$diff = \frac{CF_1}{r - g^{GI}} - \frac{CF_1}{r - \alpha \times g^{GI}} - I^{GI} + I^{BI}. \tag{5}$$

Taking the partial derivative with respect to r gives:

$$\frac{\partial diff}{\partial r} = -\frac{CF_1}{\left(r - g^{GI}\right)^2} + \frac{CF_1}{\left(r - \alpha \times g^{GI}\right)^2}. \tag{6}$$

Since α < 1, the second term is smaller than the first term, meaning that:

$$\frac{\partial diff}{\partial r} < 0. \tag{7}$$

Equation (7) shows that the difference between the NPV of the green and brown investment is decreasing in r. Thus, our theoretical framework shows that for higher interest rates, green investment becomes less attractive compared to brown investment. We test this hypothesis in the empirical model.

4. Data and methodology

We use quarterly data from the United States between 2004 Q1 and 2020 Q2. Following Eyraud et al. (2013), green investment is measured by the investment in renewable energy capacity in billions of U.S. dollars. We retrieve this data from the Bloomberg New Energy Finance (BNEF) website, which includes all money invested in energy generation from solar, geothermal, biomass and waste-to-energy, wave and tidal, wind (only projects of more than 1MW), hydropower (only projects between 1MW and 50MW), and biofuel (only projects with a capacity of at least one million litres per year). For small-scale projects, such as rooftop solar, Bloomberg uses annual installation data, provided by industry associations and governments, to estimate investment levels (Frankfurt School-UNEP Centre/BNEF, 2020). Since the main focus of this research is to analyze whether the interest rate has a different effect on green investment than on brown investment, renewable energy investment is divided by gross private domestic investment (GPDI), for which quarterly data in millions of U.S. dollars is provided by the U.S. Bureau of Economic Analysis. We divide this data by 1000 in order to convert it to the same unit of measurement as the renewable energy investment (billions of U.S. dollars). The resulting ratio provides a measure of green investment relative to total investment. Figure A1 in Appendix A shows this GI ratio over time from 2004 to 2020.

The main independent variable for this research is the real interest rate. Because investment decisions are generally based on medium- to long-term plans (Eyraud et al., 2013), we consider the long-term RIR. The Federal Reserve Bank of Cleveland provides monthly data on the 10-year real interest rate. We convert this data to quarterly data by taking the average of each three months. A plot of the long-term RIR over time can be found in Appendix A, Figure A2. Figure 2 shows the scatter plots of GI against the RIR (on the left) and GPDI against RIR (on the right). Both plots show a negative relationship, but the slope of the relationship between the RIR and GI is steeper than that of the relationship between the RIR and GPDI, which suggests that the real interest rate indeed has a stronger effect on green investment than on general investment. This can also be observed from the negative relationship in the scatter plot of the GI ratio against the RIR, presented in Figure A9 in Appendix B.

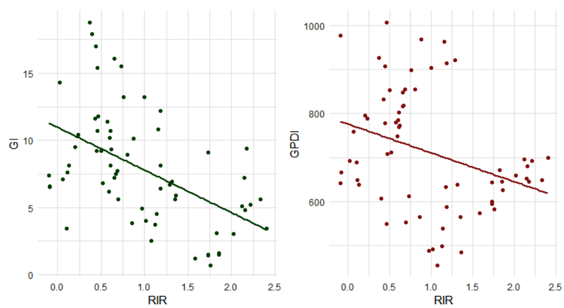

Figure 2. Scatter plot of GI against RIR (left) and GPDI against RIR (right)

To prevent omitted variable bias in the model, we control for other variables that might affect the ratio of green investment. We follow Eyraud et al. (2013) and control for GDP per capita, population, fuel prices and public policies to support green investment. Following Eyraud et al. (2013), crude oil prices are used as a measure for fossil-fuel prices. To this end, we use the producer price index of crude petroleum, which is provided by the U.S. Bureau of Labor Statistics. Data on GDP per capita and population is provided by the U.S. Bureau of Economic Analysis. We also control for corporate profit and non-financial leverage to take into account firm-specific determinants at a country level (Barabanov et al., 2021). Finally, we control for carbon dioxide emissions to take into account the aggregate effect of firms on their green investment decisions. For all of these control variables, a plot over time can be found in Appendix A (Figures A3 to A8).

Eyraud et al. (2013) find that the feed-in-tariff (FIT) is one of the most important instruments for promoting renewable energy investment. However, in the United States, the FIT is not widely used. More common public policies to promote renewable investment in the United States are: rebates for purchasing renewable generation equipment, renewable portfolio standards, net metering, and the investment tax credit (ITC) and production tax credit (PTC) (U.S. Energy Information Administration, 2013). According to Ajadi et al. (2020), renewable energy investment in the United States is particularly influenced by the schedule of expiry of the PTC and ITC. In line with this, Barradale (2010) argues that the pattern of repeated expiration and renewal of the PTC had created large fluctuations in wind energy investment in the United States. The PTC is more similar to the FIT compared to the ITC, in the sense that the former two policies are performance-based incentives whereas the latter is an investment-based inventive (U.S. Energy Information Administration, 2013). For those reasons, the empirical analysis controls for the PTC using a dummy variable that is equal to 1 for each period in which the PTC is scheduled to expire. In addition, the analysis uses another dummy variable to control for the financial crisis (2007 Q4 – 2009 Q2) and the COVID-19 crisis (2020 Q1). An overview of all variable definitions and sources can be found in Table 1.

Table 1. Overview of variable definitions and sources

Abbreviation	Definition	Source
GI_ratio	Investment in renewable technologies divided by Gross private domestic investment	Bloomberg (2022) U.S. Bureau of Economic analysis (2022b)
RIR	10-Year Real interest rate	Federal Reserve Bank of Cleveland (2022)
fuel_price	Price of crude petroleum	U.S. Bureau of Labour Statistics (2022)
GDPPC	GDP per capita	U.S. Bureau of Economic analysis (2022a)
population	Total population	U.S. Bureau of Economic analysis (2022c)
leverage	Nonfinancial Leveral Subindex	Federal Reserve Bank of Chicago (2024)
Profit	Corporate profit	U.S. Bureau of Economic Analysis (2024)
CO_2	Fossil fuels carbon dioxide emissions	U.S. Energy Information Administration (EIA) (2024)
Crisis	Dummy for financial- and COVID-19 crisis	Federal Reserve Economic Data (2022)
PTC expiry	Dummy for PTC expiry	Sherlock (2017)

Table 2 provides some basic summary statistics of the continuous variables. This table shows that for all of the variables there are 66 observations, so there are no missing values. Furthermore, the skewness of all of the continuous variables lies within the acceptable range of between –1 and +1. Therefore, it is not necessary to take the logarithm of any of the variables. Table 3 provides the frequencies of the dummy variables.

Table 2. Summary statistics

	N	mean	sd	min	max	skewness
GI_ratio	66	0.01	0.01	0.00	0.03	0.84
RIR	66	0.97	0.69	–0.10	2.41	0.46
fuel_price	66	191.65	70.37	46.00	384.30	0.38
GDPPC	66	52796.11	6606.55	41358.00	65501.00	0.32
population	66	314164.05	11877.66	292875.00	331841.00	–0.15
leverage	66	–0.01	1.36	–1.51	2.72	0.87
profit	66	1900.69	369.45	1068.90	2517.70	–0.27
CO2	66	1370.36	112.44	971	1587	–0.41

Table 3. Frequency table

	N	0	1
PTC_expiry	66	54	12
crisis	66	58	8

First, all of the continuous variables are tested for stationarity. According to the Augmented Dickey-Fuller (ADF) test, GI_ratio and fuel_price are I(1), RIR, GDPPC, profit and CO2 are I(2) and leverage and population are I(3). However, the Augmented Dickey-Fuller test does not take into account any potential structural breaks in the data and as a result, the power of this test is low in the presence of a break (Nunes et al., 1997). The Zivot and Andrews unit root test – on the other hand – allows for a sudden change in the level and/or the slope of the time-series. This potential point break is determined endogenously (Nunes et al., 1997). The main analysis will rely on the results of the Zivot and Andrews test. The results from this test are presented in Table 4. For none of the potential point breaks there is a clear economic argument.[4] Therefore, the breaks are not incorporated in the main analysis.

Table 4. Results from the Zivot and Andrews unit root test

Variable	Order of integration	Potential point break
GI_ratio	I(1)	2011-Q3
RIR	I(1)	2012-Q3
fuel_price	I(1)	2008-Q2
GDPPC	I(2)	2009-Q1
population	I(2)	2010-Q4
Leverage	I(2)	2009 Q3
Profit	I(2)	2008 Q4
CO_2	I(0)	2009 Q1

The autocorrelation function (ACF) plot shows that the GI ratio has a moving average component of order 1 and partial autocorrelation function (PACF) plot shows that it also has an autoregressive component of order 1. Both plots can be found in Figure A10 of Appendix C. Considering the multivariate nature of the analysis and the autoregressive component of the dependent variable, the most suitable estimation model is the Autoregressive Distributed Lag (ARDL) model. The ARDL model is an OLS-based model, which allows the dependent variable to be explained by its own lags and the levels and lags of the independent variables. A major advantage of the ARDL model is that it is known to produce relatively robust and reliable results on small samples, compared to other estimation techniques (Latif et al., 2015; Narayan, 2004). This is particularly favourable because the sample size of the current study is quite small. We applied an optimization algorithm in R to find the best ARDL order specification.[5] The results indicate that the optimal model includes the first lag of GI_ratio, RIR, fuel_price and population. However, in order to prevent over-fitting of the model, we only considered the lags of the dependent variable and the main independent variable.

5. Results

Table 5 provides the results from the ARDL model. Model (1) represents the baseline specification in which the first difference of the GI ratio is explained by its own lag, the first difference of the RIR and a time trend. As expected from the theory, the change in the RIR

[4] Moreover, the results remain largely unaffected if any of these structural breaks is incorporated in the analysis (see Appendix E).

[5] This algorithm was executed in R software using the auto ardl function from the ARDL package.

has a negative effect on the change in the GI ratio. This effect is statistically significant at the 5% level. The coefficient of the change in the RIR indicates that an increase in the change in the RIR by 1 percentage point is associated with an average decrease in the change in the GI ratio of –0.007, *ceteris paribus*. In the second model, the lag of the RIR is added. The lag itself has no significant impact on the change in the GI ratio and adding it to the model does not alter the coefficient or standard error of the first difference of RIR, even though the significance level increases slightly. Furthermore, the adjusted R-squared becomes worse from including the lagged independent variable. From a theoretical point of view it

Table 5. Determinants of green investment relative to total investment

	Dependent variable:					
	d(GI_ratio, 1)					
	(1)	(2)	(3)	(4)	(5)	(6)
L(GI_ratio, 1)	−0.723*** (0.118)	−0.746*** (0.124)	−0.711*** (0.122)	−0.744*** (0.118)	−0.758*** (0.121)	−0.730*** (0.128)
d(RIR, 1)	−0.007** (0.003)	−0.007** (0.003)	−0.007** (0.003)	−0.007** (0.003)	−0.008** (0.003)	−0.007** (0.003)
L(RIR,1)		–0.001 (0.001)				
d(fuel_price, 2)			−0.00001 (0.00001)	−0.00000 (0.00001)	−0.00000 (0.00001)	−0.00000 (0.00001)
d(GDPPC, 2)			0.00000 (0.00000)	0.00000 (0.00000)	0.00000 (0.00000)	0.00000 (0.00000)
d(population, 2)				0.00001** (0.00000)	0.00001** (0.00000)	0.00001** (0.00000)
d(leverage, 2)						0.0001 (0.0001)
d(profit, 2)						0.0001 (0.0001)
CO_2						–0.00001 (0.00001)
PTC_expiry					0.001 (0.001)	0.001 (0.001)
crisis					–0.001 (0.002)	–0.001 (0.002)
trend	0.0001** (0.00003)	0.0001 (0.00004)	0.0001** (0.00003)	0.0002*** (0.0001)	0.0002*** (0.0001)	0.0002** (0.0001)
Constant	0.005*** (0.001)	0.007** (0.003)	0.005*** (0.001)	–0.010 (0.006)	–0.010 (0.006)	–0.002 (0.013)
Observations	65	65	64	64	64	64
R^2	0.395	0.400	0.409	0.466	0.473	0.497
Adjusted R^2	0.366	0.360	0.358	0.410	0.397	0.391
Residual Std. Error	0.004 (df = 61)	0.004 (df = 60)	0.004 (df = 58)	0.004 (df = 57)	0.004 (df = 55)	0.004 (df = 52)

Notes: *p < 0.1; **p < 0.05; ***p < 0.01. Results from the ARDL model using time-series data from the United States between 2004 and 2020.

makes sense that the lag of the RIR does not impact the GI ratio, because – as discussed in the theoretical framework – investors are expected to consider the current interest rate in their investment decisions. For those reasons, the lagged RIR is left out of all subsequent models.

The third model adds the second difference of the fossil fuel price and the second difference of GDP per capita. Both control variables do not have a significant impact on the change in the GI ratio and the coefficient of the change in the RIR still remains unchanged. A possible explanation for this insignificant effect of fossil fuel price and GDP per capita – which is contradicting with the results of Eyraud et al. (2013) – might be that in this analysis the second difference of these variables is taken (instead of the level). Model (4) adds the second difference of population, which has a positive and significant effect on the change in the GI ratio. This positive effect of population can be explained by the increasing energy demand that is associated with an increasing population, which requires investment in alternative energy sources, such as renewable energy (Eyraud et al., 2013). The R-squared and adjusted R-squared indicate that this model is substantially better in explaining the variation in the change in the GI ratio than any of the preceding models.

Model (5) adds the dummy for PTC expiry and the dummy for the financial- and COVID-19 crisis. Surprisingly, neither of the dummy variables has a significant impact on the change in the GI ratio. A possible explanation for the insignificant effect of the PTC is that this policy is not available for all types of renewable energy, which makes the effect that the policy has on total renewable energy investment unnoticeable. Regarding the crisis, a possible explanation is that during economic downturns, not only investment in green technology, but also overall investment decreases, which does not necessarily change the ratio. The inclusion of the dummy variables slightly increases the magnitude of the coefficient of the change in the RIR, but the significance level stays the same compared to the previous model. Finally, the insignificant results of this coefficients could also be a result of omitted variables. Therefore, our final model also adds firm-specific variables (leverage and profit) and CO_2 emissions. The results are presented as model (6). The addition of these variables does not change our main results. In all of the specifications, the effect of the change in the RIR on the change in the GI ratio is negative and statistically significant at the 5% or 1% level. The sign and magnitude of the coefficient remain relatively stable, regardless of the control variables. Taking into account the adjusted R-squared and the economic reasoning, the preferred specification is Model (4). In this model, the independent variables together explain about 53.2% of the variation in the change in the GI ratio. Since all of the independent variables in this model have a Variance Inflation Factor (VIF) score well below the boundary of 5 (see Figure A11 in Appendix D), there are no issues of multicollinearity in the model. Furthermore, a BreuschPagan test is performed to check for heteroskedasticity of the error term. The p-value of 0.524 indicates that there is not sufficient evidence to reject the null hypothesis that the error variances are equal. In other words, there are no issues of heteroskedasticity in the model.

6. Robustness analysis

The results of the Augmented Dickey-Fuller test requires taking higher order differences of some of the variables compared to the results of the Zivot and Andrews Unit Root test. More specifically, according to the ADF test, RIR is I(2) instead of I(1) and fuel price and population are I(3) instead of I(2). Taking higher order differences has some disadvantages. First of all, more data points get lost, because it is not possible to take the difference of the first observation. Since the dataset is already relatively small, losing observations comes at the cost of lower reliability of the results. Next to this, higher order differenced variables become very difficult to interpret, and therefore the results become less valuable in terms of economic significance. Nevertheless, it is important to check whether the results remain stable if these higher order differences are taken. The results of this robustness analysis are presented in Table 6.

Table 6. Robustness analysis

	Dependent variable:				
	d(GI_ratio)				
	(1)	(2)	(3)	(4)	(5)
L(GI_ratio, 1)	−0.751*** (0.131)	−0.757*** (0.137)	−0.761*** (0.135)	−0.819*** (0.136)	−0.832*** (0.139)
d(RIR, 2)	−0.003 (0.002)	−0.003 (0.002)	−0.003 (0.002)	−0.004* (0.002)	−0.004* (0.002)
L(RIR, 1)		–0.002 (0.001)			
d(fuel_price, 3)			0.00001 (0.00001)	0.00001 (0.00001)	0.00001 (0.00001)
d(GDPPC, 2)			0.00000 (0.00000)	–0.00000 (0.00000)	–0.00000 (0.00000)
d(population, 3)				0.00001* (0.00000)	0.00001* (0.00000)
PTC_expiry					0.001 (0.001)
Crisis					–0.001 (0.002)
Trend	0.0001** (0.00004)	0.0001* (0.00004)	0.0001** (0.00004)	0.0002*** (0.0001)	0.0002*** (0.0001)
Constant	0.005*** (0.001)	0.006* (0.003)	0.005*** (0.002)	–0.010 (0.008)	–0.009 (0.008)
Observations	64	64	63	63	63
R^2	0.359	0.359	0.375	0.413	0.419
Adjusted R^2	0.326	0.315	0.320	0.350	0.333
Residual Std. Error	0.005 (df = 60)	0.005 (df = 59)	0.005 (df = 57)	0.004 (df = 56)	0.005 (df = 54)

Notes: *p < 0.1; **p < 0.05; ***p < 0.01. Results from the ARDL model using time-series data from the United States between 2004 and 2020.

The first model is again the baseline specification, which includes only the lagged dependent variable, the second difference in the RIR and a time trend. This time, the effect of the RIR becomes insignificant, but the sign of the coefficient remains consistently negative. In the second model the lagged independent variable is added again. In line with the main results, this variable has no significant effect on the change in the GI ratio and its inclusion does not alter the coefficient and standard error of the second difference in the RIR. Model (3) again adds the second difference of GDP per capita and this time the third difference of fossil fuel price. Again these variables do not have a significant effect and the effect of second difference of the RIR remains unchanged. In the fourth model, the third difference of population is added. In line with the main results, this variable has a positive effect on the change in the GI ratio, which is statistically significant at the 10% level. As a result of the inclusion of this variable, the second difference of the RIR also becomes statistically significant again. This time at the 10% level. Moreover, the R-squared and adjusted R-squared improve substantially. Finally, in Model (5), the dummy variables for PTC expiry and crisis are added again. Similar to the main results, these variables do not have a significant effect on the change in the GI ratio, the other coefficients remain largely unchanged, and the R-squared barely improves, leading to a decline in the adjusted R-squared.

Overall, the results of the robustness analysis are very similar to the main results. Again Model (4) is the preferred specification for the same reasons as before. This model suggests that an increase in the second difference of the RIR by 1 percentage point leads to decrease in the change in the GI ratio by 0.004. This effect is statistically significant at the 10% level. The R-squared indicates that the model explains about 41.3% of the variation in the change in the GI ratio.

7. Conclusions

The contradicting results from previous research indicate that the relationship between the real interest rate and CO_2 emissions is affected by two opposing channels. Through the *output channel*, an increase in the RIR decreases CO_2 emissions by discouraging consumption and consequently energy consumption. Through the *green investment channel* – on the other hand – an increase in the RIR increases CO_2 emissions by disincentivizing overall investment, and green investment in particular. Our paper has focused on the latter channel. More specifically, it analyzed whether the RIR had an effect on the ratio of green investment relative to total investment in the United States between 2004 and 2020.

The results of the Autoregressive Distributed Lag model support the hypothesis that the RIR has a negative effect on the ratio of green investment. This result confirms the existence of the *green investment channel* in the United States. Assuming that green investment contributes to a decrease in CO_2 emissions, then our finding suggests that the relationship between the RIR and CO_2 emissions is more complex than indicated by previous research on this topic. The results from this study are in correspondence to the finding that the RIR has a negative impact on green investment, but it adds the insight that green investment is more sensitive to the interest rate than other types of investment. Furthermore, our research provides a profound explanation for the positive relation between the RIR and CO_2 emissions found in previous literature. At the same time, it does not contradict the negative relationship between the RIR and CO_2, because this relationship depends on the circumstances which makes one of the two channels dominant. A limitation of our research is the relatively short time period and the focus on the grey area of Figure 1, that is, we do not address the link with emissions. For future research, further investigation of the interplay between the green investment channel and the output channel is needed. This includes analyzing the short- and long-run dynamics and investigating under which circumstances one channel outweighs the other. Moreover, one avenue would be to investigate whether the real interest rate has a different effect on absolute emissions than on relative emissions, as the former is mainly influenced by the output channel whereas the latter is mainly influenced by the green investment channel. This would require analyzing the dynamics within Figure 1.

Despite these shortcomings, the results have important implications for monetary policy and climate policy. First of all, our research shows that the two policies should become more integrated. It also emphasizes that monetary policy makers should not only consider the economic consequences of their policies, but also how this affects environmental performance. In time of climate change, and its pernicious consequence to biodiversity, various aspects of animal and human lives and economic losses, a better understanding of how different policies affect the environment is urgently needed.

Author contributions

AVDE conceived the study and was responsible for the design and development of the data analysis. AVDE, JS and MS were responsible for data collection. AVDE and JS conducted the empirical analysis. AVDE and JS were responsible for data interpretation. AVDE wrote the first draft of the article. JS and MC contributed to the rewriting of the draft and further data analysis.

Disclosure statement

The authors declare that they have no relevant or material financial interests that relate to the research described in this paper.

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APPENDIX

Appendix A. Plots of continuous variables over time

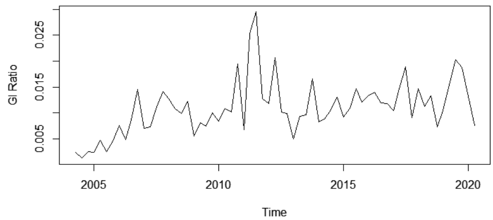

Figure A1. Green investment as a fraction of total investment over time. Data retrieved from Bloomberg (2022) and U.S. Bureau of Economic analysis (2022b)

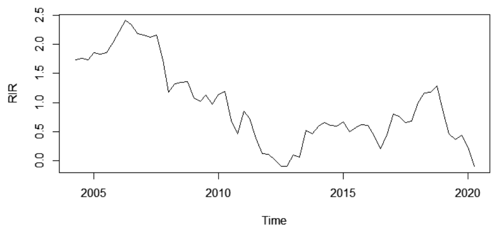

Figure A2. Long-term real interest rate over time. Data retrieved from Federal Reserve Bank of Cleveland (2022)

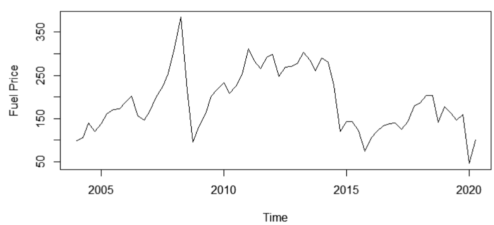

Figure A3. Price of crude oil over time. Data retrieved from U.S. Bureau of Labour Statistics (2022)

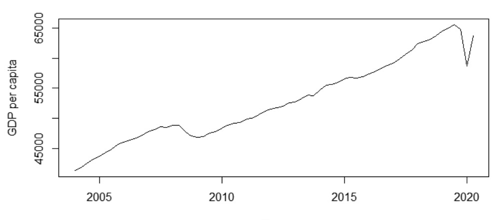

Figure A4. GDP per capita over time. Data retrieved from U.S. Bureau of Economic analysis (2022a)

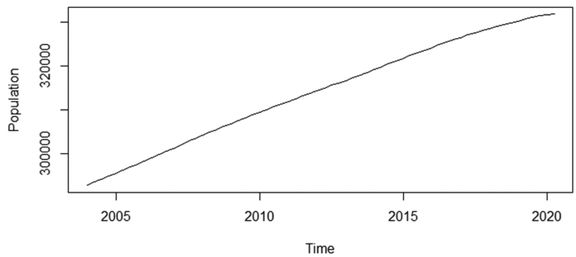

Figure A5. Population over time. Data retrieved from U.S. Bureau of Economic analysis (2022c)

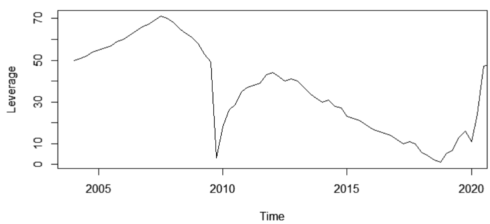

Figure A6. Leverage over time. Data retrieved from Federal Reserve Bank of Chicago (2024)

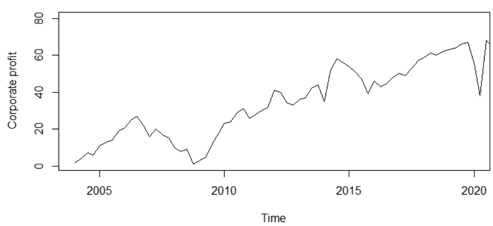

Figure A7. Corporate profit over time. Data retrieved from U.S. Bureau of Economic Analysis (2024)

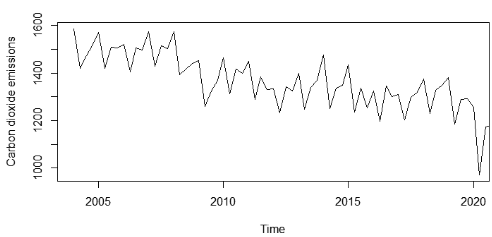

Figure A8. Total fossil fuels carbon dioxide emissions. Data retrieved from U.S. Energy Information Administration (EIA) (2024)

Appendix B. Scatter plot of GI ratio against RIR

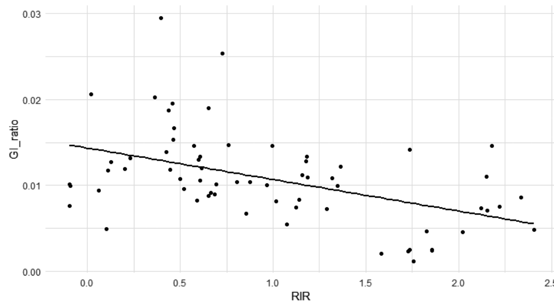

Figure A9. Scatter plot of the GI ratio against the real interest rate

Appendix C. ACF and PACF plots

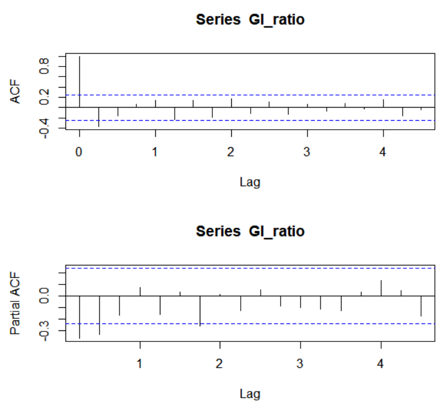

Figure A10. ACF and PACF plot of first difference of GI ratio

Appendix D. VIF values

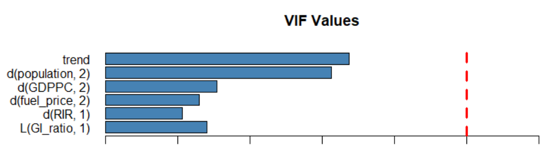

Figure A11. VIF scores of independent variables in model 4

Appendix E. Testing the effect of structural breaks

Table A1 presents the results from including the structural breaks – as suggested by the Zivot and Andrews test – in the regression analysis. Model (1) represents the preferred specification from the main analysis.

In the subsequent models, for each of the continuous variables a dummy is added which is equal to 0 before the structural break corresponding to that variable and 1 afterwards. Besides the break-point for the real interest rate, none of the dummy variables has a significant effect on the change in the GI ratio. Moreover, the results remain largely unaffected by including the structural breaks. Even though the break-point of the RIR (i.e. 2012 Q3) does have a significant effect on the change in the GI ratio, there is no reason to include it in the main analysis, because there is no clear economic reason for this structural break. Nevertheless, even if it would have been included, this would not have led to substantially different results.

Table A1. Testing effect of structural breaks

	Dependent variable:				
	d(GI_ratio, 1)				
	(1)	(2)	(3)	(4)	(5)
L(GI_ratio, 1)	−0.744*** (0.118)	−0.760*** (0.120)	−0.841*** (0.119)	−0.746*** (0.121)	−0.738*** (0.118)
d(RIR, 1)	−0.007*** (0.003)	−0.008*** (0.003)	−0.006** (0.003)	−0.008*** (0.003)	−0.007** (0.003)
d(fuel_price, 2)	0.00000 (0.00001)	0.00000 (0.00001)	0.00001 (0.00001)	0.00000 (0.00001)	0.00000 (0.00001)
d(GDPPC, 2)	0.00000 (0.00000)	–0.00000 (0.00000)	0.00000 (0.00000)	–0.00000 (0.00000)	0.00000 (0.00000)
d(population, 2)	0.00001** (0.00000)	0.00001** (0.00000)	0.00001*** (0.00000)	0.00001* (0.00000)	0.00001** (0.00000)
Trend	0.0002*** (0.0001)	0.0001 (0.0001)	0.0004*** (0.0001)	0.0002*** (0.0001)	0.0002*** (0.0001)
break_GI_ratio		0.002 (0.002)			
break_RIR			–0.006** (0.002)		
break_GDPPC				–0.0004 (0.003)	
break_ population					0.003 (0.003)
Constant	–0.010 (0.006)	–0.008 (0.006)	–0.016** (0.006)	–0.009 (0.007)	–0.012* (0.007)
Observations	64	64	64	64	64
R^2	0.466	0.474	0.520	0.466	0.475
Adjusted R^2	0.410	0.408	0.460	0.399	0.409
Residual Std. Error	0.004 (df = 57)	0.004 (df = 56)	0.004 (df = 56)	0.004 (df = 56)	0.004 (df = 56)

Notes: *p < 0.1; **p < 0.05; ***p < 0.01. Results from the ARDL model using time-series data from the United States between 2004 and 2020.