Greta Thunberg effect and Business Cycle Dynamics: A DSGE model

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Greta Thunberg effect and Business Cycle Dynamics: A DSGE model*

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Abstract

The increasing concerns for the future effects of global warming have given rise to an unprecedented wave of environmental activism. This paper studies how this call for stronger climate actions could influence macroeconomic dynamics. We explore this topic, employing a Dynamic Stochastic General Equilibrium (DSGE) model extended to consider two classes of goods (i.e., Green and Dirty), variable green preferences, and a "Greta Thunberg" shock affecting consumers' sustainable attitudes. We find that: (i) environmental awareness plays a key role in reducing carbon emissions and green preferences; (ii) Greta Thunberg effect slows down aggregate output and investment; (iii) a green preference shock contributes to around 15 and 29 % of consumption, investment, and labor volatilities at the aggregate level.

JEL Classification System: *E32, Q51, Q54*

Keywords: *Carbon Emissions, Environmental Awareness, DSGE model, General Equilibrium, Global Warming, Green Consumer Behavior*

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1 Introduction

The adverse effects of a rapid increase in Greenhouse Gases (GHGs) concentration are one of the most critical concerns of policymakers worldwide. To avoid the dangerous consequence of climate change, the Paris Agreement established a global framework by limiting global warming to well below 2^oC and continuing efforts to limit it to 1.5^oC by 2050. Keeping the average global temperature below this critical threshold will require an ambitious emissions reduction effort from all agents. Therefore, world economies will need social and technological changes.

In this framework, households play a critical role, contributing to 72% of global greenhouse gas emissions (Hertwich and Peters, 2009; Duarte et al., 2015). They make pollution directly through cooking, heating, and transportation and indirectly through the consumption of goods produced by pollutant technologies. Several studies show that residential energy use accounts for almost 24% of GHG emissions in Europe. In the US, Bin and Dowlatabadi (2005) report that households' activities directly influence more than 40% of the total CO_2 (carbon dioxide) emissions. Baiocchi et al. (2010) show that households' consumption indirectly affects around 52% or 358 million tons of carbon dioxide emissions in the United Kingdom. These findings suggest that household behavior is a crucial component in climate policies since individuals can save immense amounts of carbon (the so-called "behavioral mitigation wedge") simply by changing their diet to avoid meat or forgoing air travel. In this connection, McKinsey and Company (2009) and Farber (2012) find that behavioral change contributes to removing between 4% and 8% of the overall emissions. Prevailing social norms, which shape individual decisions and are shaped by them, could respond to global environmental problems (Nyborg et al., 2016).

Recently, household environmental preferences has received substantial attention in the wake of climate change mitigation. Many researchers hold environmental knowledge, environmental awareness, environmental concern, skepticism towards environmental claims, environmental attitudes to be the main factors that may affect consumers' green purchasing behavior (Mostafa, 2009; Kim and Choi, 2005)[1]. From a micro-theoretical perspective, Conrad (2005), suggests that increasing environmental awareness negatively affects the utility of consuming a product for which a greener substitute is available. Polonsky et al. (2012) find a positive relationship between general and carbon-specific knowledge, attitude towards the environment, and general and carbon-specific behaviors. Joshi and Rahman (2015) demonstrate that the consumers' environmental concern and product functionality are two significant determinants of consumer green purchase behavior.

It is well-documented that public opinions about climate change are time-varying and related to economic conditions and weather anomalies. Elliot et al. (1995) demonstrate that changes influence environmental expenditures to support actual economic conditions. Kahn and Kotchen (2010) show a decrease in the probability that residents think global warming is happening when the state's unemployment rate increases. Reporting on survey data from

[1] Environmental knowledge can be defined as general knowledge of facts, concepts, and relationships concerning the natural environment and its major ecosystem. Environmental awareness defines knowing the impact of human behavior on the environment. Environmental concern is defined as a global attitude with indirect effects on behavior through behavioral intention (Kaufmann et al., 2012)

the Gallup organization, Jacobe (2012) finds a change in the respondents' behavior before and after the 2007 crisis. Before the crisis, a higher priority was given to the environment over the economy. Starting in 2009, Americans' priorities appear to have changed, with more respondents indicating that they believe economic growth should be given priority over the environment and by as much as an 18-point gap (Conroy and Emerson, 2014). Scruggs and Benegal (2012) find that public opinion about global warming is variable and driven by the business cycle and economic insecurity.

Several contributions aim to investigate environmental issues in a Dynamic Stochastic General Equilibrium (DSGE) context. Fischer and Springborn (2011) first have used a DSGE model to assess three different instruments (tax, cap, and intensity target) in reducing emissions. Heutel (2012) develops an E-DSGE model incorporating some aspects of Nordhaus's (2008) Dynamic Integrated Climate Economy model (DICE)[2] model, such as emissions abatement technology and the stock of pollution affecting the production process (i.e., damage function). Angelopoulos et al. (2013) investigate the implications of uncertainty for macroeconomic outcomes, environmental quality, and social welfare in both a second-and first- best framework. Annicchiarico and Di Dio (2015) is the first attempt that analyzes the economy's dynamic behavior under several environmental policy regimes in the presence of sticky prices à la Calvo (1983).

Although the analysis of the impact of supply shock on the environment is the main topic in the DSGE literature, some recent papers address this issue from another perspective, focusing on the economy's demand side.Chan (2019) explores the optimal environmental tax rate in an open economy with labor migration. The author demonstrates that the optimal environmental tax rate volatility and procyclicality are underestimated in the previous literature because a higher environmental tax rate could stimulate output, deter labor outflow, and attract labor inflow. Chan (2020) focuses on behavioral anomalies on the demand side of the economy, considering bounded rational households. The authors find that habit formation in consumption influences macroeconomics response to an environmental policy.

It should be emphasized that most of the existing literature on environmental policy analysis (e.g., Fischer and Springborn 2011; Heutel, 2012; Annicchiarico and Di Dio 2015) assumes a one-sector and one-good economy setting and thus does not take into account the impact of the macroeconomic shocks on households preferences between sustainable and polluting goods. Since consumers' behavioral changes are one of the key factors of sustainable economic development, neglecting households' preferences could result in a biased calculation of a specific shock impact and environmental policy.

In light of that, this paper investigates the underlying relation between environmental preferences, the real economy, and carbon emissions and the corresponding macroeconomic consequences in a New Keynesian (NK)–DSGE model augmented with time-varying environmental concern. To this purpose, we introduce a "low-carbon" sector in the standard NK

[2]It is a model of the class of integrated assessment models. That is, comprehensive models that include climate as well as science and economic aspects. See Nordhaus (2013) and the Nordhaus home page at Yale Department of Economics (http://www.econ.yale.edu/~nordhaus/homepage/homepage.htm). For a criticism of these class of models, see Ackerman et al. (2009).

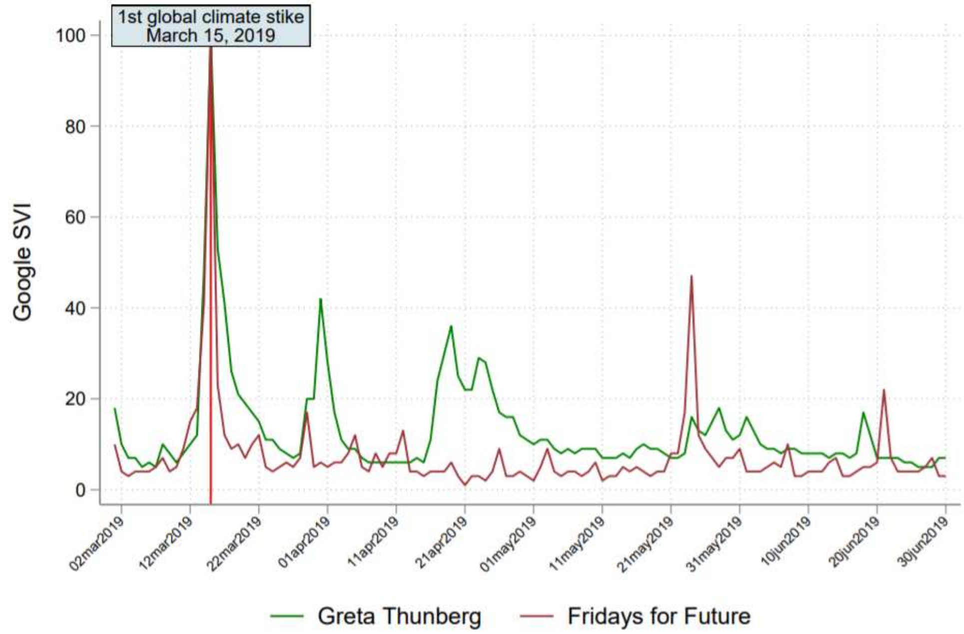

Figure 1: Google search index on Greta Thunberg. Note: This figure shows the daily global Google Trends Search Value Index (SVI) for the topic "Greta Thunberg" from March1, 2019, through June 30, 2019. The index varies from 0 to 100 and represents search interest relative to the highest point on the chart

setting and simulate a positive green preference shock. This paper features several elements of novelty with respect to the existing literature on environmental issues in this research field.

First, as far as we know, no paper has investigated the role of environmental concern in a general equilibrium framework. As a matter of fact, a two-sector model describes the economy with two classes of goods (i.e., "sustainable" and "pollutant") produced respectively by firms operating in the "low-carbon" and "high-carbon" sector. This model allows environmentally-friendly behavior, which consists of purchasing and consuming products and services that are benign toward the environment; for instance, we refer to fast-moving consumer goods, such as sustainable non-durable products.

The second one, to the best of our knowledge, no other study examines the impact of an environmental preference shock on macroeconomic dynamics. This shock represents an event affecting public opinion about environmental issues and makes consumers more sensitive to environmental problems. Fig. 1 displays the daily global Search Value Index (SVI) from Google Trends for Greta Thunberg, the initiator and inspiring leader of the "Fridays For Future" movement. The consideration to the climate activist spikes around March 14, 2019, and remains at relatively high levels up to March 20, 2019. In this connection, many studies point out that (Baiardi and Morana, 2021, among others) Greta Thunberg's environmental activism and the "*Fridays for future*" movement generated a sizable upward shift in EU environmental attitudes in 2019. Ramelli et al. (2021) find that the strike's unanticipated success caused a decrease in the stock prices of carbon-intensive firms. The authors find that the negative pricing of carbon intensity is influenced by higher public attention to climate activism. Furthermore, after the first Global Climate Strike (March 20, 2019), financial analysts downgraded their longer-term earnings forecasts on carbon-intensive firms.

Analyzing behavioral changes in rational expectation framework allow to address the following research questions: *(i) what are the implications of an environmental preference shock for the economy? (ii)To what extent does environmental awareness influence the macroeconomic effects of a technology shock?* The answers to these questions can be summarized as follows. First, this study demonstrates that environmental awareness plays a key role in reducing emissions and green preferences interact significantly with the sectoral business cycle. In particular, a green preference shock shifts the demand from polluting to sustainable goods and induces factor reallocations in favor of the green sector. However, a green preference shock does not imply the procyclicality of sustainable consumption: a Greta Thunberg effect slow-down aggregate output and investment. Since sectoral reallocation is not driven by changes in firms' productivity or household income availability, aggregate output's final impact is sub-optimal. Moreover, although the green preference shock's importance is scant at the aggregate level, it constitutes the second source of fluctuation in many key variables. At aggregate level contributes to around 15 and 29 % of consumption, investment, and labor volatilities. At the sectoral level, a green preference shock plays a significant role in driving output fluctuations.

Second, a pollutant TFP shock leads to sustainable consumption procyclicality documented in US data only if households are environmentally aware. As a consequence, this technology shock affects households' priorities, increasing sustainable consumption and actions. This kind of shock reduces households' economic insecurity, allowing them to focus on issues related to climate change. Behavioral change in households consumption attitudes increases demand for sustainable goods more than the polluting ones. Their choices impact the productive sector, stimulating production in the low-carbon sector. Finally, due to revisiting priorities, the negative effects on carbon emissions are smoothed.

The remainder of the paper is organized as follows. Section 2 describes the two-sector New Keynesian model. Section 3 discusses the parametrization and steady-state properties of the model. Section 4 provides a model fit analysis. Section 5 shows results in terms of impulse response analysis and variance decomposition. Section 6 concludes and discusses the future research agenda.

2 Empirical Evidence on Green Attitude

This section explores and discusses the main empirical evidence related to U.S. public opinion about climate change and global warming. Measuring environmental concerns is inherently difficult. It is related to perceptions, socioeconomic conditions, behavioral biases, and social peer influence. As this is almost impossible to quantify directly, there exists no agreed measure of concern in the literature. In order to define the main empirical evidence on opinions about environmental issues, this study considers four widely cited U.S. environmental concern measures in the literature (e.g., Scruggs and Benegal, 2012). In this connection, to measure environmental concerns about environmental issues, we refer to public opinion polling on climate change from the Gallup Organization. The four concerns measures are proportion of

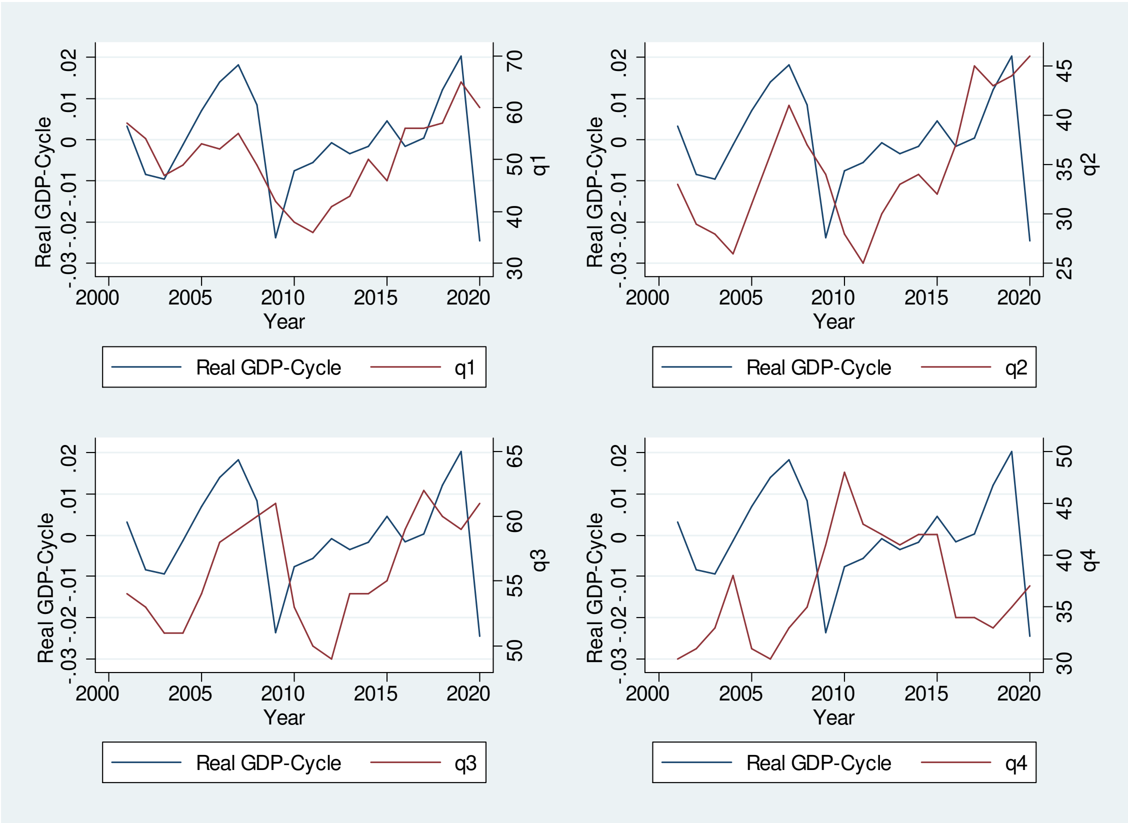

Figure 2: Environmental Concern and U.S. Business Cycle. Note The blue solid lines show the HP- filtered real annual GDP in the four panels.The red solid lines define the environmental concern indexes. Q1: % prioritize the environment over economic growth; Q2: % worried about global warming;Q3:% consider climate change already begun;Q4: % think global warming news are exaggerated.

survey respondents that: *prioritize the environment over economic growth (Q1);are worried about global warming (Q2); consider climate change already begun(Q3); think global warming news are exaggerated (Q4).*

Figure 1 shows Gallup Organization poll trends on public support for the selected environmental issues and the cyclical component for real annual GDP in 2001-2021. Figure 1a displays the percentage of American adults who prioritize the environment over economic growth. Public priorities for environmental issues are strictly related to short-term economic conditions. More precisely, we can observe three different changes in environmental concern. First, before the recent financial crisis, starting from 2003, environmental concerns grew among respondents. In March 2007, 55% of respondents prioritized the environment over economic growth. However, between 2008 and 2013, as the economy struggled to emerge from the recession, more Americans prioritized the economy over the environment, with a brief exception in May 2010 after the Gulf of Mexico oil spill (Gallup, 2019). In the last decade, interest in environmental issues has grown. Other Gallup survey questions on environmental issues manifest similar trends over time. Figure 1b illustrates the percentage of adults saying that they worried greatly about climate change. The percentage of people reporting that they worried about warming " a great deal " peaked at the top of the economic

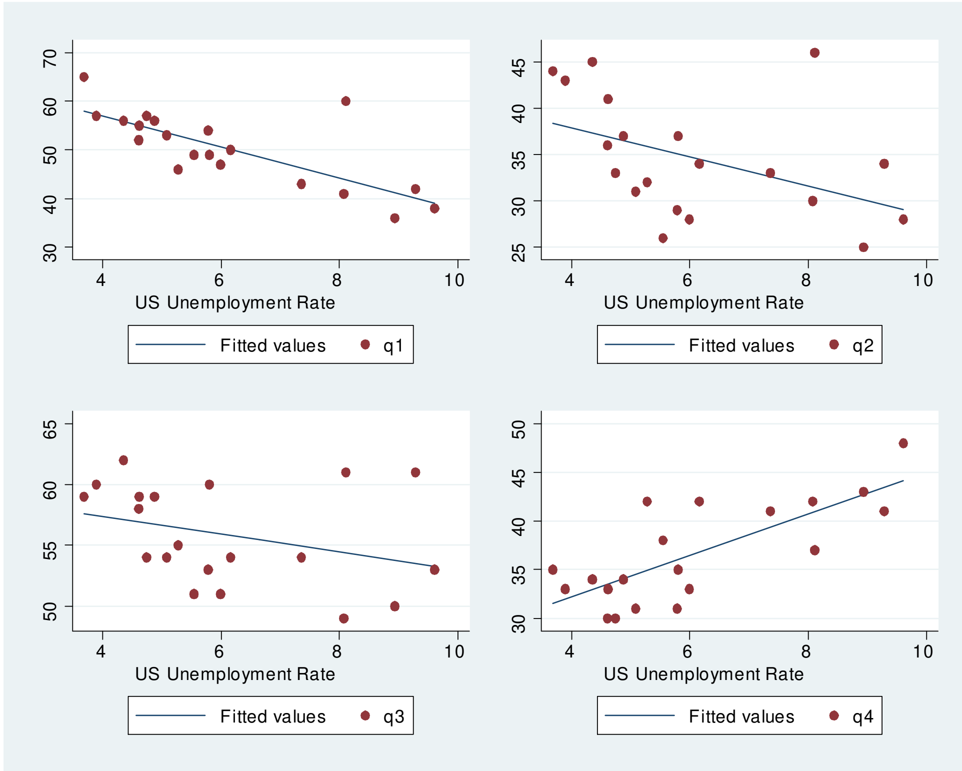

Figure 3: Scatter plot of environmental concerns and U.S. unemployment rate.

cycle (i.e., in 2001, 2008, and 2019). At the beginning of ’00s, the percentage of adults saying that they worried a great deal about warming was around 30%. Concern for environmental issues declined sharply during the recent financial crisis of 2007. Before the financial crisis, public concern rose to 40% and then declined considerably: to 33% March 2009, to 28% in March 2010, and to 25% in March 2011. Figure 1d shows the percentage of respondents agreeing that media generally exaggerate the seriousness of global warming. During economic slow-down phases, respondents increase their skepticism for media news about environmental issues. Specifically, during the recent financial crisis, their skepticism increased from 35% to 41% in 2009 and 48% in 2010. Agreement with the scientific consensus that warming effects are already begun shows a similar pattern (Figure 1c). It rose steadily between 2004 and 2008 to 61%. However, in March 2009, only 53% agreed that the effects of warming were already being felt.

There exist two main explanations for fluctuating public attitudes about climate change. First, they have adjusted their views about the climate in light of the economic crisis. A second explanation is related to short-term weather patterns. Many studies point out that people believe that global warming occurs if they think that recent local temperatures are higher than normal (Li et al., 2011; Krosnick et al., 2006; Egan and Mullin, 2010).

Figure 2 shows scatterplots capturing the relationship between environmental concern indexes and annual U.S. unemployment rate from the *Bureau of Labor Statistics*. Unemployment is a more appropriate measure of economic conditions because it directly affects the well-being and happiness of the overwhelming majority of households and it is estimated

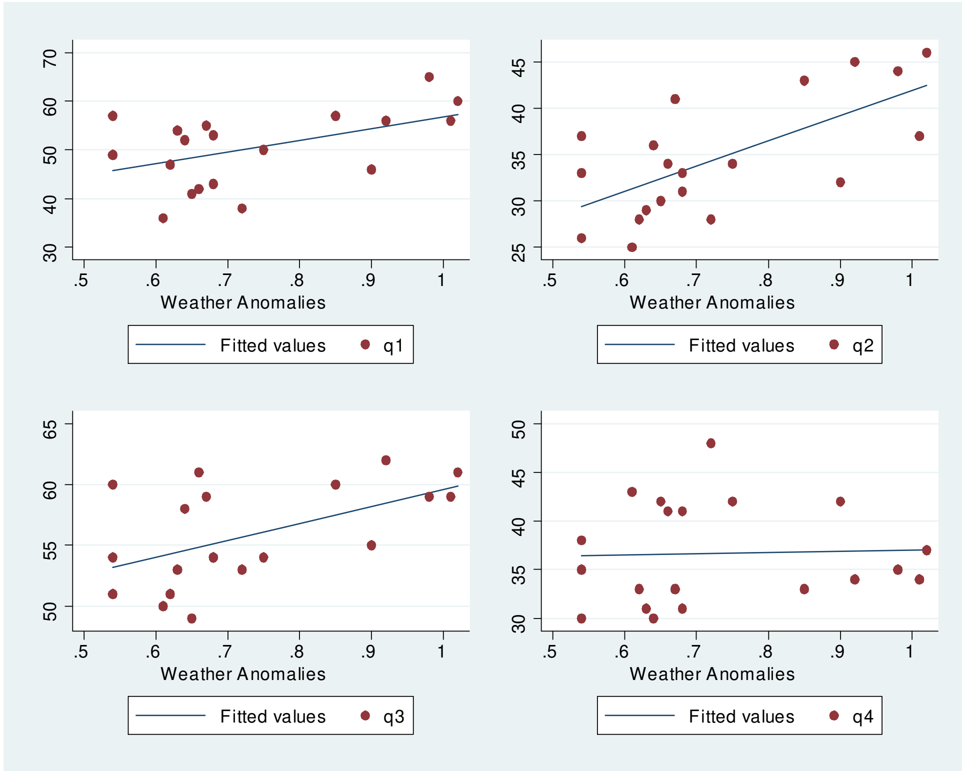

Figure 4: Scatter plot of environmental concerns and weather anomalies.

directly via very large population surveys. First, there exists a clear negative correlation between the percentage of respondents favoring the environment over the economic growth and the US unemployment rate ($\rho = -0.76, p-value = 0.001$). Still, there is a similarly strong negative correlation between the unemployment rate and the percentage of respondents worried about global warming ($\rho = -0.44, p-value = 0.05$). Less significant is the correlation with the scientific consensus that global warming already begins ($\rho = -0.33, p-value = 0.15$). On the contrary, data show a positive correlation between the national unemployment rate and skepticism for media news about environmental issues ($\rho = 0.75, p-value = 0.001$).

To explore the effect of temperature on attitudes about climate change, we focus on more recent anomalies in national local weather. We use data from *NASA's Goddard Institute land-ocean temperature index* (NASA, 2011). Figure 3 shows scatterplots capturing the relationship between environmental concern indexes and the weather anomalies. First, it is possible to identify and positive and significant relationship between prioritizing the environment and weather anomalies ($\rho = 0.50, p-value = 0.05$). The same positive relationship is displayed for consensus ($\rho = 0.54, p-value = 0.01$) and concern ($\rho = 0.67, p-value = 0.001$) for global warming . However, skepticism for news media and weather anomalies do not appear to show a significant relationship. In light of that, this paper seeks to introduce time-varying public perceptions on environmental issues in the household's choices in a DSGE framework.

3 The Model

This section presents a two-sector New Keynesian (NK) model augmented to capture behavioral changes of households and their potential contribution towards sustainable consumption. The model presents the following types of agents: households, two intermediate goods producers, and two final goods producers operating in each economic sector. Moreover, we introduce the standard monetary policy rule set by the Central Bank to complete the model.

More in detail, the model features a continuum of identical and infinitely-lived households with a measure of unity. They derive utilities from leisure and two types of consumer goods: sustainable (green) and polluting (dirty) goods. Households supply labor and capital to the intermediate producers and hold a government bond.

There are two intermediate production sectors: low-carbon and high-carbon sectors. Both sectors produce similar intermediate goods, but they differ in the production process. The low-carbon (green) firms combine productive inputs through sustainable processes for the environment. The high-carbon sector (dirty) features a pollutant production process and emits significant carbon emissions to the atmosphere.

The intermediate goods producers supply their output to final goods producers who differentiate and repackage them for household consumption. Final goods producers in both sectors are characterized by monopolistic competition and price stickiness in the form of quadratic adjustment costs à la Rotemberg.

This paper features several elements of novelty with respect to the existing literature on DSGE model with environment applications. Specifically, we assume that utility derived from consumption goods is strictly related to knowledge and awareness about climate change. In addition, we investigate the role and significance of an environmental preference shock, which represents a novelty in general equilibrium literature.

3.1 Households

The representative infinitely lived household derives utility from consumption C_t and disutility from hours worked in the dirty sector ($L_{D,t}$) and in the green one ($L_{G,t}$). The utility function assume the following functional form:

$$U_t(C_t, L_{D,t}, L_{G,t}) = \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\gamma}}{1-\gamma} - \theta_D \frac{L_{D,t}^{1+\psi_D}}{1+\psi_D} - \theta_G \frac{L_{G,t}^{1+\psi_G}}{1+\psi_G} \right), \qquad q > 0,\ \theta_j > 0, \psi_j > 0 \tag{1}$$

where $\mathbb{E}_t$ is the expectation operator, $\beta \in (0,1)$ is the subjective discount factor, γ denotes risk aversion parameter, θ_G and θ_D capture disutility from green and dirty labor, ψ_D and ψ_G are the inverse of *Frish elasticity* parameters. Households consumption basket C_t is described by a constant elasticity of substitution (CES) aggregate consumption bundle defined over the two consumption goods $C_{G,t}$ and $C_{D,t}$:

$$C_t = \left[(\gamma_t^c)^{1/\sigma_c} C_{G,t}^{\frac{\sigma_c - 1}{\varepsilon}} + (1-\gamma_t^c)^{1/\sigma_c} C_{D,t}^{\frac{\sigma_c - 1}{\sigma_c}} \right]^{\frac{\sigma_c}{\sigma_c - 1}}, \quad \gamma_t^c \in (0,1) \tag{2}$$

where σ_c is the constant elasticity of substitution parameter between the two sectors. Here, the definition of *"Green consumption"* is related to environmentally responsible consumption where consumers consider the environmental impact of purchasing, using, and disposing of various products or using various green services (e.g., sustainable and organic goods). "*Dirty consumption*" refers to high-carbon intensity consumption; for example, goods that feature a high carbon footprint; γ_t^c is the key parameters in our model, measures household environmental preferences. In order to capture the empirical evidence discussed in the previous section, this study considers time-varying environmental preferences. We use it as a proxy for environmental awareness: when γ_t^c is high, consumers are environmentally concerns and derive higher utility levels from low-carbon emission goods.

Minimizing total consumption expenditure $P_t C_t = P_{G,t} C_{G,t} + P_{D,t} C_{D,t}$ subject to the consumption bundle (Eq.2) yields the demands function for green ($C_{G,t}$) and dirty consumption ($C_{D,t}$):

$$C_{G,t} = \gamma_t^c \left(\frac{P_{G,t}}{P_t} \right)^{-\sigma_c} C_t, \tag{3}$$

$$C_{D,t} = (1 - \gamma_t^c) \left(\frac{P_{D,t}}{P_t} \right)^{-\sigma_c} C_t, \tag{4}$$

where $P_{G,t}$ is the price of sustainable consumption goods and $P_{D,t}$ is the price of pollutant good. The total aggregate consumption price is given by:

$$P_t = \left[\gamma_t^c P_{G,t}^{1-\sigma_c} + (1 - \gamma_t^c) P_{D,t}^{1-\sigma_c} \right]^{\frac{1}{1-\sigma_c}}, \tag{5}$$

Furthermore, physical capital accumulates according to the following laws of motion:

$$K_{G,t} = (1 - \delta_G) K_{G,t-1} + \varepsilon_t^{inv} I_{G,t}, \tag{6}$$

$$K_{D,t} = (1 - \delta_D) K_{D,t-1} + \varepsilon_t^{inv} I_{D,t}, \tag{7}$$

where δ_G and δ_D are the depreciation rate of green and dirty capital, respectively; $I_{j,t}$ is household sectoral investment, and $K_{j,t}$ is the sectoral capital stock; ε_t^{inv} denotes an AR(1) shock process to the marginal efficiency of investment (MEI):

$$\log(\varepsilon_t^{inv}) = \rho_{inv} \log(\varepsilon_{t-1}^{inv}) + (1 - \rho_{inv}) \log(\varepsilon_{ss}^{inv}) + \epsilon_t^{inv}, \tag{8}$$

where $0 < \rho_{inv} < 1$ is the first-order autoregressive persistence parameter and ϵ_t^{inv} denotes the *i.i.d* $\mathrm{N}(0, \sigma_{inv})$ random shock to the marginal efficiency of investments.

Moreover, investment decisions are subject to convex capital adjustment costs $\Gamma_{k,j}(K_{j,t}, I_{j,t})$ of the type:

$$\Gamma_{k,j}(K_{j,t}, I_{j,t}) = \frac{\gamma_j^K}{2} \left(\frac{I_{j,t}}{K_{j,t}} - \delta_j \right)^2, \gamma_j^K > 0, \tag{9}$$

where γ_j^K governs the scale of the adjustment cost.

Households consume and invest in both sectors and have access to a one-period risk free bond B_t, sold at a price R_t^{-1} and paying one unit of currency in the following period. Households receive dividends $D_{j,t}$ from the ownership of domestic intermediate good-producing firms (green and dirty), and payments for factors they supply to these firms: rental rate of capital ($R_{j,t}$) and wages ($W_{j,t}$). Households intertemporal budget constraint read as:

$$C_t + \frac{P_{G,t}}{P_t} I_{G,t} + \frac{P_{D,t}}{P_t} I_{D,t} + \frac{B_t}{P_t} + \frac{P_{G,t}}{P_t}\Gamma_{k,G}(K_{G,t}, I_{G,t}) + \frac{P_{D,t}}{P_t}\Gamma_{k,D}(K_{D,t}, I_{D,t}) =$$

$$= \frac{R_{t-1}B_{t-1}}{P_t} + \frac{P_{G,t}}{P_t} W_{G,t}L_{G,t} + \frac{P_{D,t}}{P_t} W_{D,t}L_{D,t} + \frac{P_{G,t}}{P_t} R_{G,t}K_{G,t} \frac{P_{D,t}}{P_t} R_{D,t}K_{D,t} + \frac{P_{G,t}}{P_t} D_{G,t} + \frac{P_{D,t}}{P_t} D_{D,t}, \tag{10}$$

The representative household choose the sequences $\{C_t, B_t, L_{G,t}, L_{D,t}, I_{G,t}, I_{D,t}, K_{G,t}, K_{D,t}\}_{t=0}^{\infty}$ to maximize (1), subject to (10), (6) and (7). The first order conditions with respect to consumption, government bond, green labor, dirty labor, green investments, dirty investments, green capital and dirty capital, are the following:

$$C_t^{-\gamma} - \lambda_t = 0, \tag{11}$$

$$\frac{1}{R_t} = \beta \mathbb{E}_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\Pi_t} \right), \tag{12}$$

$$\frac{P_{G,t}}{P_t} W_{G,t} \lambda_t = \theta_G L_{G,t}^{\psi_G}, \tag{13}$$

$$\frac{P_{D,t}}{P_t} W_{D,t} \lambda_t = \theta_D L_{D,t}^{\psi_D}, \tag{14}$$

$$\varepsilon_t^{inv} Q_{G,t} = \gamma_G^K \left(\frac{I_{G,t}}{K_{G,t}} - \delta_G \right) + 1, \tag{15}$$

$$\varepsilon_t^{inv} Q_{D,t} = \gamma_D^K \left(\frac{I_{D,t+1}}{K_{D,t+1}} - \delta_D \right) + 1, \tag{16}$$

$$\begin{aligned} Q_{G,t} &= \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} \frac{P_{G,t+1}}{P_{t+1}} \left[R_{G,t+1} + \gamma_G^K \left(\frac{I_{G,t+1}}{K_{G,t+1}} - \delta_G \right) \frac{I_{G,t+1}}{K_{G,t+1}} - \frac{\gamma_G^K}{2} \left(\frac{I_{G,t+1}}{K_{G,t+1}} - \delta_G \right)^2 \right] + \\ &\quad + \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} Q_{G,t} (1 - \delta_G), \end{aligned} \tag{17}$$

$$\begin{aligned} Q_{D,t} &= \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} \frac{P_{D,t+1}}{P_{t+1}} \left[R_{D,t+1} + \gamma_D^K \left(\frac{I_{D,t+1}}{K_{D,t+1}} - \delta_D \right) \frac{I_{D,t+1}}{K_{D,t+1}} - \frac{\gamma_D^K}{2} \left(\frac{I_{D,t+1}}{K_{D,t+1}} - \delta_D \right)^2 \right] + \\ &\quad + \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} Q_{D,t} (1 - \delta_D), \end{aligned} \tag{18}$$

where λ_t denotes the Lagrangian multiplier associated to the flow budget constraint and measures the marginal utility of consumption according to Eq. 11; $Q_{j,t}$ measures the relative marginal value of installed capital with respect to consumption (i.e. the Tobin's q). $\Pi_t = (P_t/P_{t-1})$ measures inflation in the final-good sector. Eq. (12) represents Euler equation and combined to Eq. (11) define the intertemporal decision of households. Eqs.(13) and (14) optimize the labor supply in the green and dirty sector, respectively. Eqs. (17) and (18) are optimality conditions for green and dirty investments. Eqs. (17) and (18) defines the price of green and dirty capital.

3.1.1 Modeling Households Green Preferences

We start the discussion about model properties, modeling environmental behavioral changes among households in a DSGE framework. Since papers dealing with behavioral components in DSGE models had been in short supply up to now, there is no well-established way in the literature to model a shock and behavior like this. Here, we present the simplest option considering time-varying weights in the CES consumption index (Eq. 2). In order to model the behavioral part, we start from the empirical pieces of evidence discussed in section one and previous studies in this field (Frederiks et al. 2014, among others).

First, public preferences amongst economy and environment are time-varying. Short-term economic conditions and weather anomalies drive environmental preferences. Consequently, shocks affecting the business cycle and carbon emissions dynamics should account for the formalization of green preferences. Moreover, pro-environmental consumption behaviors are strictly related to knowledge about environmental issues, as documented in numerous studies in this research field (Conrad, 2004; Polonsky et al.,2012; Joshi and Rahman, 2015). Before considering action, households need to reach a certain level of knowledge and awareness about climate change, energy, and the environment (Niamir et al. 2020). Therefore, we assume that bounded rational individuals make consumption decisions related to global warming and climate change knowledge. According to Scruggs and Benegal (2012), this study assumes that weather anomalies directly affect households' perceptions of environmental issues. An increase in extreme weather events such as heatwaves, droughts, cyclones, blizzards, and rainstorms activate consciousness about the seriousness and immediacy of climate change. Since human emissions of carbon dioxide (in particular, deviations from their pre-industrial level) are a primary driver of climate change, we model environmental concerns as follow:

$$\phi_t^{ec} = \left(\frac{E_t}{E_{ss}}\right)^{\phi e}, \tag{19}$$

where the term in the parentheses defines the deviation of carbon emissions (E_t) from its steady-state value (E_{ss}). This kind of formalization is an adaptation of pollution perception defined in Schumacher and Zou (2008) and Ott and Soretz (2018). Green attitude is captured by the parameter ϕ_e which indicates that individuals perceive their influence on climate change only partially. In other words, consumers do not realize the full impact of their economic activity on the resulting pollution level. More precisely, ϕ_e represent the *intention* parameter and capture the *knowledge-action gap.* It is clear that what people say and what they do are sometimes very different things. A piece of knowledge about environmental issues does not translate fully into sustainable consumption actions. Many people report that they are concerned about climate change and understand the importance of saving energy, yet this concern does not reliably translate into taking ongoing, practical steps to reduce household energy consumption (Frederiks et al., 2014). If a household reaches a certain level of intention, it is going to decide or act.

Second, concern for climate change has risen over time, but neither linearly nor homogeneously. In the light of recent events and the potential effect of leadership cues on public polarization on environmental issues, we are inclined to associate these changes with Donald Trump's denial campaigns and Greta Thunberg's environmental activism, which have impacted climate change attitudes worldwide over the last three years (Baiardi and Morana, 2021). The sizable upward shift in EU environmental attitudes in 2019 possibly reflects a public response to Greta Thunberg's environmental activism and the "*Fridays for future movement.*" Greta Thunberg's protest, which started in September 2018, rapidly became a worldwide phenomenon and involved about 4 million people across 169 countries by September 2019. This interpretation appears to be consistent with the robust evidence on the political leader-follower linkage about climate change perceptions for the U.S. (Bruelle et al., 2012; Dunlap, 2014).

Furthermore, to complete green preferences formalization, we consider a shock affecting public opinion about environmental issues and makes consumers more sensitive to environmental problems. We can think of such a shock as a change in consumer preferences following a policy intervention, for example, development at the national level of information and awareness-raising policies about the environmental issues; or a natural disaster that increases concern about environmental issues; or a change in consumer sentiment, e.g., following a *Greta Thunberg* speech, as discussed in section one.

Moreover, a large body of research shows that people persist in displaying seemingly irrational yet predictable tendencies to retain the status quo, stick to default settings or defer decision-making entirely (inertia), especially as the amount or complexity of information increases (Samuelson et al., 1988; Kahneman et al., 1991). To account for these empirical facts, we model green preferences as an autoregressive process influenced by habit persistence, environmental concern (ϕ_t^c), and a Greta Thunberg shock (ε_t^{gt}), as follows:

$$\frac{\gamma_t^c}{\gamma_{ss}^c} = \left[\left(\frac{\gamma_{t-1}^c}{\gamma_{ss}^c} \right)^{\rho_c} \left(\frac{\phi_t^{ec}}{\phi_{ss}^{ec}} \right)^{1-\rho_c} \right] \exp(\epsilon_t^{gt}), \tag{20}$$

where $0 < \rho_c < 1$ denotes the behavioral persistence parameter, and ϵ_t^{gt} denotes the $i.i.d$ $\mathrm{N}(0, \sigma_{gt})$ random shock to the environmental preferences.

To gain intuition into the workings of the model, it is useful to evaluate how time-variyng environmental preferences affect equilibrium dynamics. According to Eq. 20, household awareness translates into specific environmental actions if the intention parameter (ϕ_e) is greater than zero after an economic shock. In this scenario, environmental awareness households assess the typical economic utility; however, they combine and harmonize the behavioral and economic parts of the decision-making process. In this model, consumers may deviate from the optimal economic choice if the behavioral part outweighs it, e.g., the level of knowledge and intention raise high enough to reconsider the economic trade-offs. Thus, households are characterized by a multi-step decision-making process. After a shock hitting the economy, households maximize their utility function. Then, they evaluate the environmental impact of such shock and adjust their preference for sustainable and polluting goods. In this story, the economic impact of a specific shock plays a significant role. In addition, we consider that households could change their preferences after an exogenous preference shock.

3.2 Production

The economy presents two sectors: "*Green*" and "*Dirty*". In each sector, intermediate firms produce final output using two different technologies. Firms in the low-carbon sector employ sustainable production processes using mainly renewable resources, emitting a low quantity of carbon dioxide into the atmosphere. In contrast, firms in the pollutant sector employ pollutant technology (e.g., fossil fuel) and produce a high amount of carbon emissions(Carbon-Intensive firms)[3].

3.2.1 Carbon-Intensive Intermediate Firms

The intermediate carbon-intensive firms firms produces a dirty output employing high-carbon inputs according to the following technology:

$$Y_{D,t} = \varepsilon_t^a A_D K_{D,t}^{\alpha_D} L_{D,t}^{(1-\alpha_D)},\ \alpha_D \in (0,1) \tag{21}$$

where α_D is the share of dirty capital in the production process; A_D is the specific technology available in the pollutant sector, and it control the scale of the symmetric total factor productivity shock (ε_t^a) that follows a first-order autoregressive process with an IID-Normal error term:

$$\log\left(\varepsilon_t^a\right) = \rho_a \log\left(\varepsilon_{t-1}^a\right) + (1-\rho_a)\varepsilon_{ss}^a + \epsilon_t^a, \tag{22}$$

where $0 < \rho_a < 1$ is the first-order autoregressive persistence parameter and ϵ_t^{gt} denotes the $i.i.d$ N$(0, \sigma_a)$ random shock to the total factor productivity.

Production activity in the dirty sector is pollutant. Emissions at dirty firm level, E_t , are assumed to be proportional to dirty output:

$$E_t = \xi Y_{D,t} \tag{23}$$

where ξ determines the emission intensity. The aim of the dirty representative firms is to choose capital and labor in order to maximize profits ($\Pi_{D,t}$) given as:

$$\max_{K_{D,t},L_{D,t}} \Pi_{D,t} = \frac{P_{D,t}}{P_t}\left[Y_{D,t} - R_{D,t}K_{D,t} - W_{D,t}L_{D,t}\right], \tag{24}$$

The first order conditions for capital, labor are given respectively as:

$$r_{D,t} = R_{D,t}\frac{P_t}{P_{D,t}} = \Psi_{D,t}\alpha_d\varepsilon_t^a K_{D,t}^{\alpha_d-1}L_{D,t}^{1-\alpha_d}, \tag{25}$$

$$w_{D,t} = W_{D,t}\frac{P_t}{P_{D,t}} = \Psi_{D,t}(1-\alpha_d)\varepsilon_t^a K_{D,t}^{\alpha_d}L_{D,t}^{-\alpha_d}, \tag{26}$$

[3] As in Apostolakis (1990), we consider the complementarity between capital and energy. We assume that green capital is complementary to renewable energy and dirty capital is complementary to fossil fuel energy.

where equations (25) and (26) are the demands for capital and labor, and $\Psi_{D,t}$ is the marginal cost component of additional units of labor and capital required to produce an extra unit of output. $\Psi_{D,t}$ is also the Lagrangian multiplier of the profit maximization problem.

3.2.2 Green Intermediate Firms

The intermediate green firms produces a sustainable good combining labor and low-carbon capital according to the following technology:

$$Y_{G,t} = \varepsilon_t^a A_G K_{G,t}^{\alpha_G} L_{G,t}^{(1-\alpha_G)}, \ \alpha_G \in (0,1), \tag{27}$$

where α_G is the share of dirty capital in the production process; A_G is the specific technology available in the pollutant sector, and it control the scale of the symmetric total factor productivity shock (ε_t^a) that follows a first-order autoregressive process with an IID-Normal error term as specified in Eq. (22). The aim of green firms is to choose capital and labor in order to maximize profits ($\Pi_{j,t}$) given as:

$$\max_{K_{G,t},L_{G,t}} \Pi_{G,t} = \frac{P_{G,t}}{P_t} Y_{G,t} - \frac{P_{G,t}}{P_t} K_{G,t} - \frac{P_{G,t}}{P_t} W_{G,t} L_{G,t}, \tag{28}$$

The first-order conditions for capital and labor are given respectively as:

$$r_{G,t} = R_{G,t} \frac{P_t}{P_{G,t}} = \Psi_{G,t} \alpha_G \varepsilon_t^a K_{G,t}^{\alpha_G - 1} L_{G,t}^{1-\alpha G}, \tag{29}$$

$$w_{G,t} = W_{G,t} \frac{P_t}{P_{G,t}} = \Psi_{G,t} (1-\alpha_G) \varepsilon_t^a K_{G,t}^{\alpha_G} L_{G,t}^{-\alpha_G}. \tag{30}$$

where $\Psi_{G,t}$ is the marginal cost component of additional units of labor and capital required to produce an extra unit of output. $\Psi_{G,t}$ is also the Lagrange multiplier of the profit maximization problem.

3.2.3 Final Good Producers

Final good producers act in a noncompetitive setting, firms can choose their price, taking the production price index $P_{j,t}$. We assume a sticky price specification based on Rotemberg (1982) quadratic adjustment cost in both sectors of the economy.

$$\Gamma_{P_G,t}(P_{G,t} Y_{G,t}) = \frac{\gamma_G^P}{2} \left(\frac{P_{G,t}}{P_{G,t-1}} - 1 \right)^2 P_{G,t} Y_{G,t}, \tag{31}$$

$$\Gamma_{P_D,t}(P_{D,t} Y_{D,t}) = \frac{\gamma_D^P}{2} \left(\frac{P_{D,t}}{P_{D,t-1}} - 1 \right)^2 P_{D,t} Y_{D,t}, \tag{32}$$

The Rotemberg model assumes that a monopolistic firm faces a quadratic cost in adjusting its nominal prices that can be measured in terms of the final goods with γ_j^P being the price stickiness parameter which accounts for the negative effects of price changes on the customer-firm relation[4]. Formally, the firm sets the price $P_{j,t}$ by maximizing the present discounted

[4] Rotemberg price adjustment cost parameter is stricly related to Calvo (1983) parameter. Specifically, $\gamma_j^P = \frac{\upsilon_j(\sigma-1)}{(1-\upsilon_j)(1-\beta\upsilon_j)}$. Where υ_j defines the Calvo's propability parameter.

value of profits subject to demand constraint $Y^i_{j,t} = \left(\frac{P^i_{j,t}}{P_{j,t}}\right)^{-\sigma} Y_{j,t}$. At the optimum we obtain the Rotemberg version of non-linear New Keynesian Phillips Curve (NKPC) for the green sector:

$$(1-\sigma) + \sigma\Psi_{G,t}\frac{P_t}{P_{G,t}} = \gamma^P_G\left(\Pi_{G,t}-1\right)\Pi_{G,t} - \beta\mathbb{E}_t\frac{\lambda_{t+1}}{\lambda_t}\left[\gamma^P_G\left(\Pi_{G,t+1}-1\right)\left(\Pi_{G,t+1}\right)^2\frac{Y_{G,t+1}}{Y_{G,t}}\frac{1}{\Pi_{t+1}}\right], \tag{33}$$

The price adjustment rule satisfies the following first order condition for the pollutant producers given as:

$$(1-\sigma) + \sigma\Psi_{D,t}\frac{P_t}{P_{D,t}} = \gamma^P_D\left(\Pi_{D,t}-1\right)\Pi_{D,t} - \beta\mathbb{E}_t\frac{\lambda_{t+1}}{\lambda_t}\left[\gamma^P_D\left(\Pi_{D,t+1}-1\right)\left(\Pi_{D,t+1}\right)^2\frac{Y_{D,t+1}}{Y_{D,t}}\frac{1}{\Pi_{t+1}}\right], \tag{34}$$

where σ_j is price elasticity of demand.

The following equations respectively allow to identify the sectoral price levels and the inflation rate for the consumption price index:

$$\Pi_t = \frac{P_t}{P_{t-1}}, \tag{35}$$

$$\Pi_{G,t} = \frac{P_{G,t}}{P_{G,t-1}}, \tag{36}$$

$$\Pi_{D,t} = \frac{P_{D,t}}{P_{D,t-1}}, \tag{37}$$

where P_t is defined by equation (5).

3.3 Monetary Policy

The monetary authority manages the short-term nominal interest rate R_t in accordance to the following simple interest-rate rule:

$$\frac{R_t}{R_{ss}} = \left(\frac{R_{t-1}}{R_{ss}}\right)^{\iota_r}\left[\left(\frac{\Pi_t}{\Pi_{ss}}\right)^{\iota_\pi}\left(\frac{Y_t}{Y_{ss}}\right)^{\iota_y}\right]^{(1-\iota_r)}\exp(\epsilon^r_t), \tag{38}$$

where Y_t is the aggregate output and R_{ss}, Π_{ss}, and Y_{ss} denote the deterministic steady-state of the nominal interest rate inflation rate and aggregate output; ι_r is the monetary policy inertia parameter; ι_π is the coefficient on inflation in the feedback rule and ι_y is the coefficient on output and ϵ^r_t denotes the $i.i.d$ $N(0,\sigma_r)$ random shock to the monetary policy.

3.4 Aggregation and Equilibrium

This study explores the economy in a decentralized contest. The stochastic behavior of the model is driven by five exogenous disturbances: total factor productivity (ε^a_t), investment-specific technology (ε^{inv}_t), *Greta Thunberg* (ε^c_t) , public spending (ε^g_t) and monetary policy

(ε_t^r) shocks. The decentralize competitive equilibrium for a given shock processes, initial green and dirty capital stock, initial environmental quality and green preferences is a list of sequences $\{C_t, C_{G,t}, C_{D,t}, B_t, L_{G,t}, L_{D,t}, I_{G,t}, I_{D,t}, K_{G,t+1}, K_{D,t+1}\}_{t=0}^{\infty}$ for the households, and input prices $\{W_{G,t}, W_{D,t}, R_{G,t}, R_{D,t}, P_{G,t}, P_{D,t}\}_{t=0}^{\infty}$ such that : (i) the household maximizes its utility function subject to its budget constraint and its environmental awareness; (ii) the intermediate and final goods firms maximize their profits; (iii) carbon emissions and sectoral capital follow their law of motion; (iv) all markets clear. Market clearing condition is given by:

$$Y_t = C_t + I_t + \varepsilon_t^g + \frac{P_{G,t}}{P_t}\Gamma_{k,G}(K_{G,t}, I_{G,t}) + \frac{P_{D,t}}{P_t}\Gamma_{k,D}(K_{D,t}, I_{D,t}) + \Gamma_{P_G,t}(P_{G,t}Y_{G,t}) + \Gamma_{P_D,t}(P_{D,t}Y_{D,t}), \tag{39}$$

where Y_t, C_t, I_t and ε_t^g are the aggregate output, consumption, investment and public spending shock process:

$$P_tY_t = P_{G,t}Y_{G,t} + P_{D,t}Y_{D,t}, \tag{40}$$

$$P_tI_t = P_{G,t}I_{G,t} + P_{D,t}I_{D,t}, \tag{41}$$

$$\log(\varepsilon_t^g) = \rho_g \log(\varepsilon_{t-1}^g) + (1-\rho_g)\log(\varepsilon_{ss}^g) + \epsilon_t^g, \tag{42}$$

where $0 < \rho_g < 1$ is the first-order autoregressive persistence parameter and ϵ_t^g denotes the $i.i.d$ $\mathrm{N}(0, \sigma_g)$ random shock to the public spending.

Total consumption and total price are given by Eqs. (2) and (5), total labor is equal to:

$$L_t = L_{G,t} + L_{D,t}, \tag{43}$$

The emission stock is accumulated according to the following equation:

$$M_t = (1-\delta_m)M_{t-1} + E_t$$

where $\delta_m \in (0,1)$ is the emissions natural decay and E_t is the current period carbon emissions.

4 Parametrization

In order to parametrize the model, we combine calibration and estimation methods. The model is calibrated for the US economy, and the GHG considered is carbon dioxide, the main gas leading to global warming. Table1 lists the parameter values fixed in the *Bayesian* estimation.

The parameters of the utility function are calibrated as follows. We set the discount factor β equal to 0.99 that implying a steady-state nominal interest rate equal to 1.01; risk aversion parameter γ is fixed to 2, as in most dynamic stochastic general equilibrium studies (see, e.g., Chang and Kim, 2007); the inverse of Frish elasticities (ψ_j) are equal to 1. Labor disutilities are calibrated endogenously. As in Acemoglu et al. (2012) we assume a substitution elasticity parameter σ_c equal to 1.5. To calibrate the initial weight of green preferences in the CES function, we refer to the *Nielsen Company* study. Their analysis defines sustainable consumption by combining sustainability into free-from, clean, simple, sustainable, and organic labels. In 2018, the sales of sustainable products in the U.S. amounted to approximately 128.5 billion U.S. dollars, make up 22% of total store sales[5].

Structural parameters characterizing the dirty economy are calibrated as in the standard macroeconomic literature. Share of capital (α_D) and its depreciation rate (δ_D) are equal to 0.33 and 0.025, respectively; as in Annicchiarico and Diluiso (2019); adjustment cost of capital (γ_I) is set equal to 3 a the Rotemberg adjustment cost (γ_D^P) is fixed to 28.

The parameters describing the monetary policy rule are based on a standard Taylor rule: the central bank reaction on inflation and the output gap equal 1.5 and 0.125. The coefficient determining the persistence of the policy rule on the lagged interest rate is set at 0.70.Turning to the environmental sector, we set the carbon emissions intensity (ξ) and the natural decay of carbon emission (δ_m) as in Heutel (2012) and equal to 0.45 and 0.0012, respectively.

Structural parameters in the green sector, shock process parameters, and standard deviations are estimated with Bayesian estimation techniques using four key macroeconomic quarterly U.S. time series as observable variables: the quarterly log difference of real GDP, real consumption, real investment, and inflation to reduce them. The model is estimated over the sample period from 1990:1 to 2016:4. A full description of the data used and the estimation technique is given in the appendix. We summarize the prior and the posterior distributions of these parameters in Table. All the distribution functions follow the convention in the literature.

Parameters	Values	Descriptions
γ	2.00	Coefficient of risk aversion
β	0.99	Discount Factor
ε	1.50	Elasticity substitution between goods
$\overline{\gamma}$	0.22	Initial green preferences
δ_D	0.025	Depreciation rate - Dirty Sector
α_D	0.33	Capital share - Dirty Sector
σ	6.00	Elasticity of Substitution within Each Sector
ψ_D	1.00	Inverse of Clean Frish Elasticity
θ_D	5.34	Labor Disutility Dirty Sector
θ_G	1.91	Labor Disutility Green Sector
γ_D^I	3.00	Investment adjustment costs
γ_D^P	28.00	Rotemberg Adjustment cost
ι_π	1.50	Interest rate rule parameter
ι_y	0.13	Output rule parameter
ι_r	0.50	Monetary Policy Persistence
ξ_D	0.38	Emission per unit of dirty output
δ_m	0.0012	Emissions Decay rate

Table 1- Calibrated parameters

Following Smets and Wouters (2007), we set the prior on the share of capital in the

[5]Source: Nielsen Product Insider, powered by Label Insight, Week ending 10/20/2018. Cited in "Was 2018 the Year of the Sustainable Consumer?" https://www.nielsen.com/us/en/insights/news/2018/was-2018-the-year-of-the-influential-sustainable-consumer.html

production function as a normal distribution with a mean of 0.30 and a standard error of 0.05. The depreciation rate for the green capital is assumed to follow a gamma distribution with a mean of 0.025 and 0.01 as standard deviation. The prior adjustment cost parameter for investment has a Normal distribution with a mean of 5 and a standard error of 1.5, as in Christiano, Motto, and Rostagno (2013). To define the Rotemberg Adjustment cost in the green sector, we assume that Calvo probabilities is to be around 0.5 and follows a beta distribution with a standard error of 0.1. As in standard Bayesian literature, the standard errors of the shocks are assumed to follow an inverse-gamma distribution with a mean of 0.010 and a standard deviation equal to 0.2. The persistence of the five AR(1) processes is beta distributed with a mean of 0.7 and a standard deviation of 0.2.

The prior distribution of parameters plays an important role in estimating the intention parameter. Since this is the first attempt to estimate this parameter in a DSGE framework, we refer to the extant literature on Bayesian estimation to define an adequate prior distribution. Specifically, when the parameter is between 0 and 1, either uniform or Beta distribution can be set as the prior distribution. For the knowledge-action gap parameter, we define a beta distribution with a mean of 0.30 and a standard deviation equal to 0.10.

Table 2 gives the mode, the mean, and standard deviations of the posterior distribution of the parameters obtained by the Metropolis-Hastings algorithm. The productivity, government spending, and investment processes are estimated to be the most persistent with an AR(1) coefficient of 0.89, 0.92, and 0.91, respectively. The mean of the standard error of the shock to the productivity process is 0.014. The standard deviation for the investment and public spending shock is estimated to 0.0031 and 0.197, respectively. In contrast, both the persistence and the standard deviation of the monetary policy shock are relatively low (0.43 and 0.0017, respectively).

Parameters	**Prior Distribution**	**Prior**		**Post.**		
		Mean	**SD**	**Mode**		**SD**
α_G	Normal	0.300	0.05	0.280	0.236	0.328
δ_D	Gamma	0.025	0.01	0.024	0.016	0.030
γ_G^I	Normal	3.000	1.50	3.091	2.789	3.371
υ_G	Beta	0.500	0.10	0.631	0.549	0.714
ϕ_e	Beta	0.500	0.10	0.628	0.507	0.750
ρ_c	Beta	0.700	0.10	0.855	0.798	0.927
ρ_a	Beta	0.700	0.10	0.899	0.883	0.916
ρ_i	Beta	0.700	0.10	0.914	0.894	0.931
ρ_g	Beta	0.700	0.10	0.925	0.903	0.951
σ_a	Inverse Gamma	0.010	0.10	0.014	0.012	0.018
σ_i	Inverse Gamma	0.010	0.10	0.003	0.002	0.003
σ_g	Inverse Gamma	0.010	0.10	0.019	0.017	0.022
σ_{gt}	Inverse Gamma	0.010	0.10	0.004	0.002	0.005
σ_r	Inverse Gamma	0.010	0.10	0.001	0.001	0.002

Table 2- Estimation results for model parameters

Capital share in the green production function is estimated to be around 0.29. It implies that the green sector is less capital intensive than the pollutant one, as common practice. The posterior mean of capital depreciation rate is 0.0246, somewhat smaller than the depreciation rate in the pollutant sector. The Bayesian estimation shows that green capital adjustment costs are higher than the pollutant one, and around 3.10. The mean of the degree of price indexation (0.63) is estimated to be less than the pollutant sector and implying a Rotemberg adjustment cost equal to 22.

Turning to the estimates of the main behavioral parameters, it turns out that the mean of the posterior distribution is typically relatively close to the mean of the prior assumptions. However, the intention parameter is much higher than the prior mean (0.30), and it is estimated to be around 0.60. Persistence and the standard deviation of the green preference shock are relatively low (0.7 and 0.004, respectively). In contrast, green preferences show a high habit parameter (0.85).

Table 3 reports the deterministic steady-state values for the key variables in accord with the discussed calibration and estimation. At the initial state, households invest and consume more in the dirty sector than in the clean sector. The capital depreciation rate plays a crucial role in choosing the sector to invest in, making the green investment less profitable. As a result, the clean sector size is smaller than the dirty, in line with the US economy's current stylized facts. The above economic conditions imply the reasonable requirement that the green sector is backward relative to the dirty sector. As Acemoglu et al. (2012), $A_D > A_G$ imposes the reasonable condition that initially the gree sector is sufficiently backward relative to the dirty (fossil fuel) sector.

Variable	Description	Model
C/Y	Consumption-Output ratio	0.60
I/Y	Investment-Output ratio	0.18
C_C/Y	Green Consumption-Output ratio	0.15
C_D/Y	Dirty Consumption-Output ratio	0.45
I_C/Y	Green Investment-Output ratio	0.04
I_D/Y	Dirty Investment-Output ratio	0.14
C_C/C	Green Consumption Share	0.25
C_D/C	Dirty Consumption Share	0.75
E/Y	Emissions Intensity	0.30
A_G	Steady-State value of total factor productivity green	0.78
A_D	Steady-State value of total factor productivity dirty	1.40

Table 3- Steady-State Properties

5 Results

In this section, we analyze the dynamic properties of the model to explore the importance of a green preference shock and environmental concern in DSGE modeling. We first look at variance decomposition for a conditional and unconditional variance to evaluate the importance of a green preference shock in driving the business cycle. Following, we investigate the equilibrium response of a Green Preference exogenous shock in the economy. Moreover, we focus on the environmental concerns impact on the economy and environment variables after selected macroeconomic shocks under two alternative environmental attitudes. Simulation results for the competitive economy have been obtained by using a 'pure' perturbation method which amounts to a second-order Taylor approximation of the model around its deterministic steady state.

5.1 Variance Decomposition

This section analyzes the contribution of a green preference shock in selected variables volatility. Table 5 display the unconditional posterior variance decomposition. The short-run variation of aggregate and sectoral output, consumption, and investments are mainly driven by shock to productivity. Monetary policy shock plays a slightly small role, explaining a portion of the 0.20-5.45 % of the short-term variation. On the opposite, public spending shock explains a much higher variation in the short term, affecting about 20 % of aggregate consumption and labor and dirty consumption volatility. Also, environmental preferences are mainly driven by a productivity shock (58%) and less by a green preference shock (25%).

Variable	Description	ϵ_t^{gt}	ϵ_t^{a}	ϵ_t^{m}	ϵ_t^{g}	ϵ_t^{i}
Y	Output	4.20	84.51	2.57	5.29	3.44
C	Consumption	25.12	44.81	3.91	20.63	5.53
I	Investment	16.41	60.54	4.51	11.04	7.51
N	Labor	28.95	35.24	5.45	22.44	7.92
Y_G	Green Output	19.90	60.20	2.92	10.27	6.71
C_G	Green Consumption	5.71	90.76	0.40	0.97	2.15
I_G	Green Investment	7.77	85.10	0.82	0.92	5.39
N_G	Green Labor	31.92	26.55	5.63	25.69	10.22
Y_D	Dirty Output	16.02	66.80	3.44	7.59	6.15
C_D	Dirty Consumption	11.49	71.55	1.84	12.54	2.58
I_D	Dirty Investment	8.72	82.09	0.20	7.98	1.01
N_D	Dirty Labor	3.62	89.00	1.11	5.36	0.90
E	Emissions	12.53	71.70	3.17	7.13	5.47
γ^c	Green Preferences	24.01	58.03	2.69	8.59	6.68

Table 5- Posterior variance decomposition- Unconditional Variance

Although the sectoral technology shock is the primary source of variability, a Green Preference shock constitutes the second source of fluctuation in many key variables. At aggregate level contributes to around 15 and 29 % of consumption, investment, and labor volatilities. At the sectoral level, a green preference shock plays a significant role in driving output fluctuations.

5.2 Impulse Response Analysis

The purpose of this section is twofold. First, we focus on the role of a green preferences shock on the economy and emissions dynamics. To this end, we analyze household behavior to an exogenous shock affecting their environmental preferences. Following, we investigate how green preferences respond to macroeconomic stimuli. Hence, we explore how households' preferences respond to a technology shock (representing the main source of business cycle volatility) under two alternative environmental attitudes. The simulations have been obtained using numerical analysis and perturbation methods to simulate the economy and compute the equilibrium conditions outside the steady-state. We solve the model using a second-order Taylor approximation around its steady state[6]. All results are reported as percentage deviations from the initial steady state over a 40-quarter period.

5.2.1 Greta Thunberg Shock

Assessing the effects of a demand shock turns out to be interesting (and innovative) since the demand side may affect the supply of green versus dirty goods. Therefore, we simulate a preference shock in the clean sector to quantify environmental preference shocks' economic and environmental impacts.

First, this kind of shock temporarily increases environmental preferences. Since consumers are affected by consumption habits, this shock does not fully translate into household behavioral changes at the shock impact. However, consumers gradually change their eco-friendly behavior, reaching a peak after five quarters. If households become more sensitive to environmental issues, they shift the demand from polluting consumption goods towards sustainable goods. Households value the current utility from green goods relatively more than the future utility and vice versa for the dirty consumption. An environmental preference shock stimulates the supply of sustainable products, and green firms increase their demand for production inputs. Hence, this shock induces factor reallocations between the two sectors. In detail, demands for labor hours and investment shift from the green sectors to the dirty ones. Changes in consumption preferences trigger a slow-down in the pollutant sector production.

Turning to the aggregate variables, we note that a green preference shock increases aggregate consumption and labor at the impact. On the contrary, a Greta Thunberg shock slow-down aggregate output and investment. Since sectoral reallocation is not driven by changes in firms' productivity or households resources, the final impact on aggregate output is sub-optimal. Hence, green preference shock does not imply procyclical behavior with environmental preferences, as documented in the data in section 1. However, an environmental preference shock positively impacts climate change mitigation, reducing carbon emissions concentration in the atmosphere.

5.2.2 Technology Shock

This section presents the impulse response functions of the key macroeconomic variables after a TFP shock. Since an advance in an economy's productivity level could simultaneously lead to higher output and air pollutant emission, households are attracted by the higher output level; however, they are deterred by the polluted environment. To understand the trade-off between these two forces, we analyze how time-varying environmental concerns may affect the standard equilibrium dynamic after a technology shock. Second, we investigate if a productivity shock could lead to the procyclicality of environmental preferences, as documented in the U.S data. To this end, we test two models: an NK model without behavioral changes (environmentally unaware households) and a model with environmentally aware households. In the first case, the model is a standard two-sector New Keynesian model and the intention parameter (ϕ_m) is equal to zero . In the other case, households revise their priorities between

[6] See Judd (1998) and Schmitt-Grohé and Uribe (2004). The model has been solved in Dynare. For details, see http://www.cepremap.cnrs.fr/dynare/ and Adjemian et al.(2011).

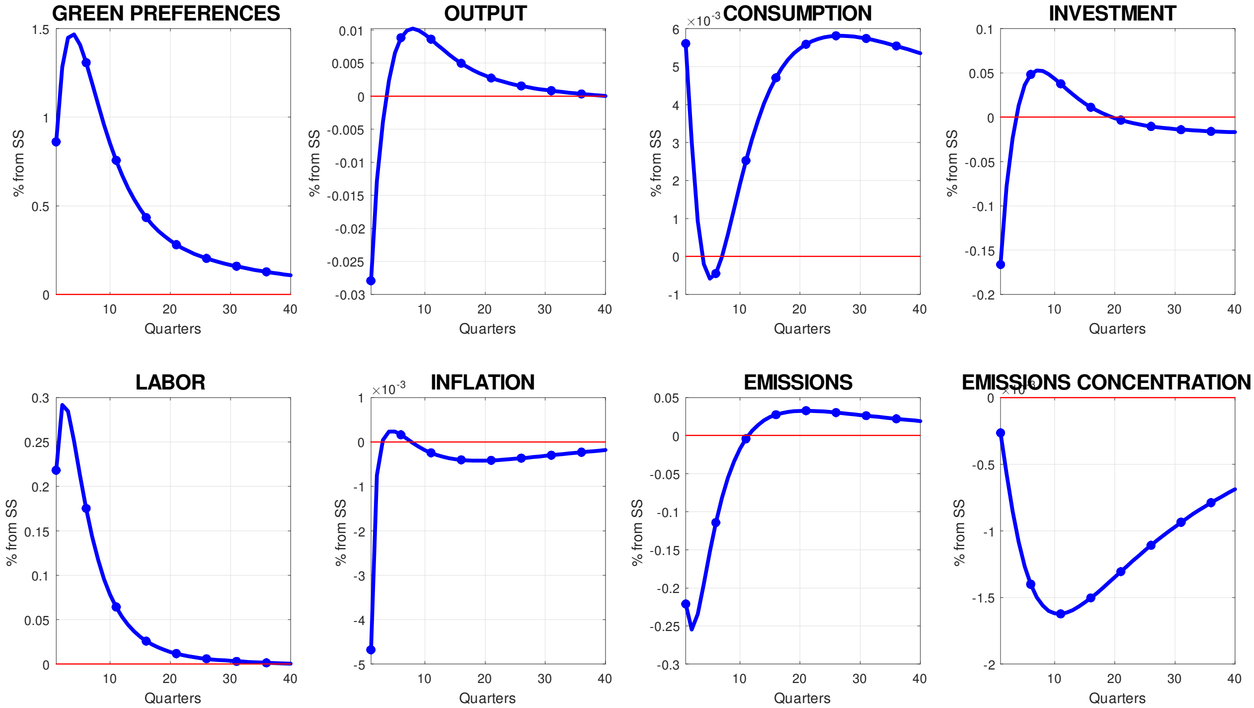

Figure 5: Impulse Response Functions to a 1% Greta Thunberg shock- Aggregate Variables

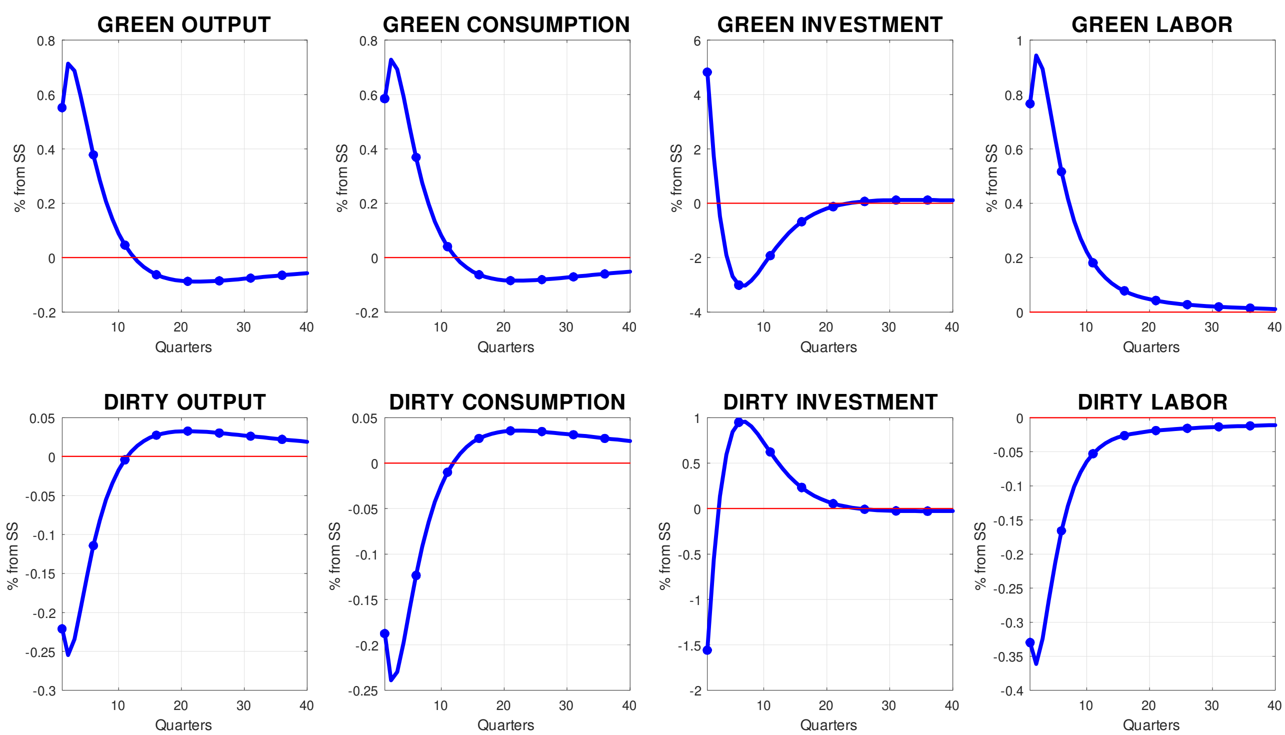

Figure 6: Impulse Response Functions to a 1% Greta Thunberg shock-Sectoral Variables

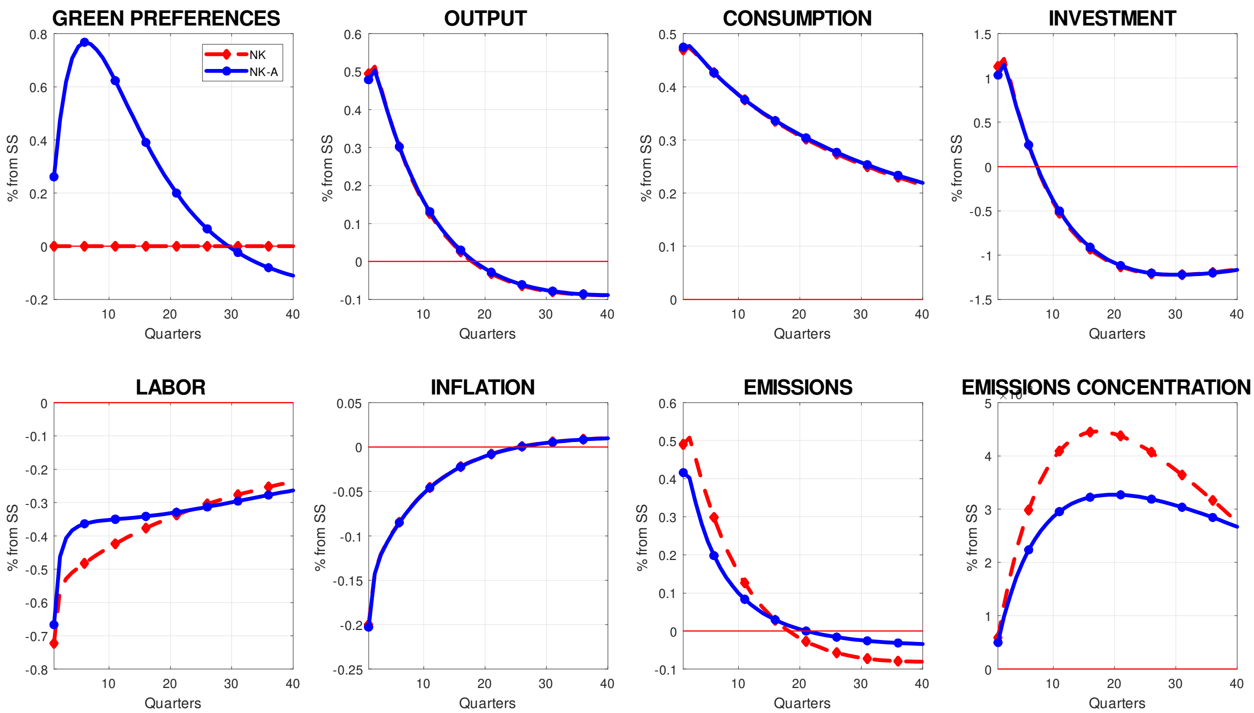

Figure 7: Impulse Response Functions to a 1% Technology Shock-Aggregate Variables

economy and environment after a macroeconomic shock, and the intention parameter is positive ($\phi_m = 0.60$). Fig. 5 and 6 display the economy's response to a one percent increase in productivity under two different environmental attitudes: unaware (i.e., standard NK model) and aware (NK-A).

As expected, output, consumption, and investment rise immediately following a positive technology innovation and then follow hump-shaped responses. Since the beneficial effects of a positive innovation on productivity are temporary, households will find it optimal to build up the capital stock during the early phases of the adjustment process when productivity is higher. As a consequence, consumption show hump-shaped dynamics. Hours and inflation fall immediately at shock impact. Both the sticky prices and the investment adjustment costs contribute to hours decline. However, the productivity improvement induces a corresponding increase in emissions since we assume a proportional relationship between dirty output and emissions. Although environmental concern does not significantly change shock response at the aggregate level, our setting provides significant changes at the sectoral level compared to the standard NK formulation. First, a positive technology shock increases eco-friendly consumption through the income effect. Second, the higher emission increases affect households' opinions about environmental issues, revising their priority among the environment and economy.

As a result, at the shock impact, environmental preferences rise. Households do not change their habits immediately but gradually change consumption behavior, adopting more eco-friendly consumption actions in the first five quarters. In the two-sector NK baseline model (dotted line), after the TFP shock, households do not revise their preferences. Afterward, households do not change their habits, increasing both consumptions likewise. The two-

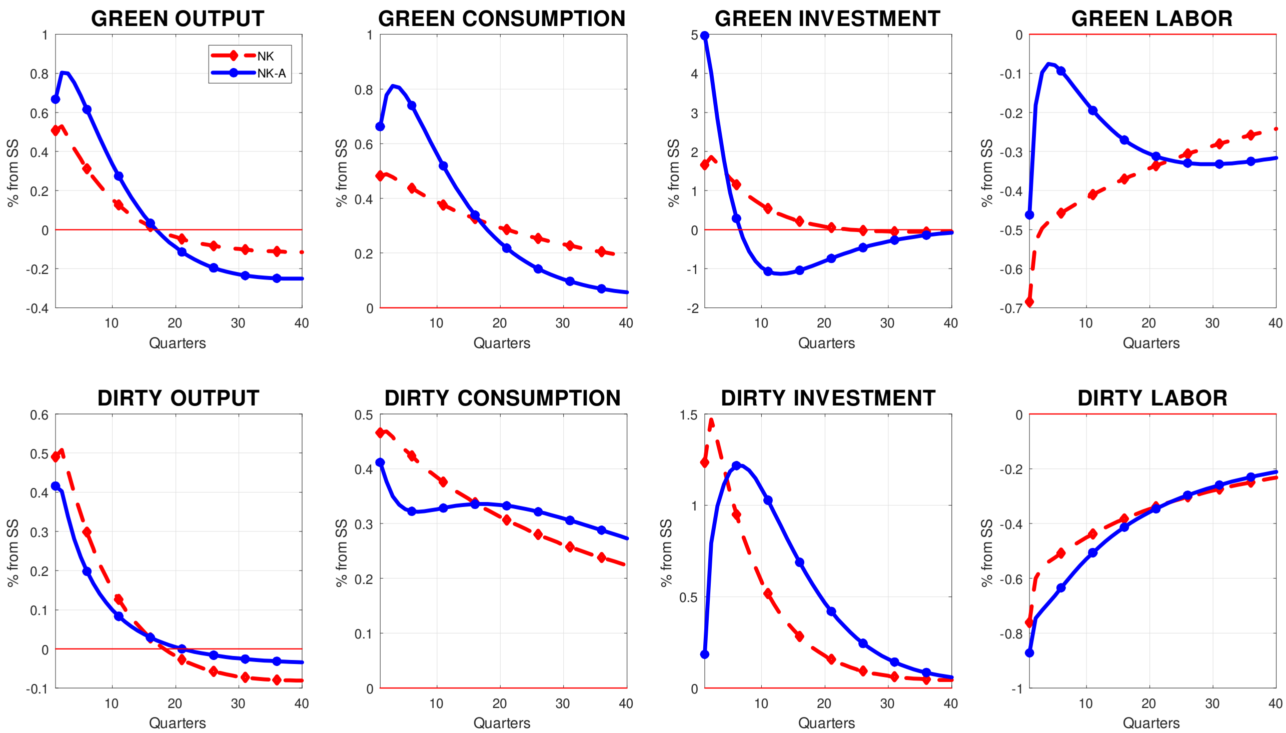

Figure 8: Impulse Response Functions to a 1% Technology Shock-Sectoral Variables

sector NK model with environmental awareness (solid line) captures the empirical evidence related to public opinion about global warming. Specifically, during positive economic phases, households change their priorities, increasing sustainable consumption and actions. This kind of shock reduces households' economic insecurity, allowing them to focus on issues related to climate change. Behavioral change in households consumption attitudes increases demand for sustainable goods more than the polluting ones. Their choices impact the productive sector, stimulating production in the low-carbon sector.

As a result, output in the green sector rises more than the baseline model and the pollutant sector. Moreover, changes in demand composition affect input allocation between sectors. First, agents prefer to postpone investment in the pollutant sector to devote more resources to the green sector. This mechanism favors green labor demand. Finally, due to revisiting priorities, the negative effects on carbon emissions are smoothed. Even if neglected in standard DSGE literature, behavioral changes significantly affect sectoral dynamics after a productivity shock.

6 Conclusions

This study investigates environmental awareness's effects on green preferences, economic dynamics, and environmental quality. To this purpose, we have developed a parsimonious DSGE model to stress the households' attitudes in a context where it is established that carbon emissions will rely on changing human behavior.

This study demonstrates that environmental awareness plays a key role in reducing emissions and green preferences interact significantly with the sectoral business cycle. In particular, a green preference shock shifts the demand from polluting to sustainable goods and induces factor reallocations in favor of the green sector. However, a green preference shock does not imply the procyclicality of sustainable consumption: a Greta Thunberg effect slowdown aggregate output and investment. Since sectoral reallocation is not driven by changes in firms' productivity or household income availability, aggregate output's final impact is sub-optimal. Moreover, although the green preference shock's importance is scant at the aggregate level, it constitutes the second source of fluctuation in many key variables. At aggregate level contributes to around 15 and 29 % of consumption, investment, and labor volatilities. At the sectoral level, a green preference shock plays a significant role in driving output fluctuations.

Furthermore, a pollutant TFP shock leads to sustainable consumption procyclicality documented in US data only if households are environmentally aware. As a consequence, this technology shock affects households' priorities, increasing sustainable consumption and actions. This kind of shock reduces households' economic insecurity, allowing them to focus on issues related to climate change. Behavioral change in households consumption attitudes increases demand for sustainable goods more than the polluting ones. Their choices impact the productive sector, stimulating production in the low-carbon sector. Finally, due to revisiting priorities, the negative effects on carbon emissions are smoothed.

In this regard, several discussions may arise. First, promoting the development at the national level of information and awareness-raising policies about the environmental issues targeting households could be ineffective in the long run if the social-economic structure is not capable of internalizing them. Second, educated consumers could play a positive role to incentivize a low-carbon lifestyle. Human capital progress through improvement in education access will help to produce more aware consumers. Hence, improved social policies and increased investment in education could indirectly influence the clean sector choices and make awareness-raising policies more effective.

In light of that, this study lays the foundation to investigate other interesting aspects of consumption habits or heterogeneous preferences. As for the former, changing human behavior toward more responsible attitudes is not taken for granted, but inertia cannot be overlooked. The latter should be taken into account that the sensitiveness and awareness toward a "greener" world are not for everyone. "Brown" preferences, or some form of myopia, do play a role in this story. The next chapter examines how sustainable consumption and behavioral changes affect the environmental policy ranking to deepen this research topic.

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