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How can green industrial policy be used to support a low-carbon energy transition?

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Abstract

In light of the increasing evidence of the severe risks posed by human-induced climate change, there has been growing research on effective economic policies to mitigate against it. This dissertation focuses on the role of industrial policies, within the energy production sector, which aim to facilitate a transition towards 100% renewable energy production. Such policies have received relatively little analysis thus far, however, given the urgent need to move economies towards ecological sustainability, these policies should be explored as a potential tool for governments. To analyse these policies, a post-Keynesian stock-flow consistent (SFC) model is used in order to consider the many channels through which a green industrial policy mix could affect the real economy and the financial and government sectors. Furthermore, the model is able to adopt a forward-looking approach to energy capital investment, allowing firms to respond to future regulation in advance of it coming into effect.

Keywords: climate change; green industrial policy; stock-flow consistent modelling.

JEL classification: E12,E62,G18,Q43,Q58.

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1 Introduction

The recent Sixth Assessment report from the Intergovernmental Panel on Climate Change (IPCC) highlighted the need for economies to rapidly decarbonise in order to reduce the pace of global warming and mitigate against the damaging effects of climate change (IPCC 2021). The report states clearly that human activity is the driving force behind climate change, that human-induced climate change is already affecting weather and climate extremes globally and that limiting cumulative CO_2 emissions to net-zero will be necessary to reduce the pace of climate change.

This report is but the latest major publication in a growing scientific literature on the causes and impacts of human-induced climate change. Since the World Meteorological Organisation (WMO) voiced initial concerns around climate change in the 1970's, there have been several proposed policy approaches to control and/or mitigate against the effects of climate change. Despite growing evidence of the need for rapid decarbonisation, the focus of economists has been on a limited set of policy approaches. Much research has focused on market-based solutions where a social cost of carbon (SCC) is established and maintained by emission trading or a Pigouvian tax. This focus is a product of the application of neoclassical economic principles to climate change, whereby climate change is seen simply as a negative externality which can be properly priced through market-based solutions (Liu, Bauman, and Chuang 2019). Therefore, much economic modelling has concerned itself with assessing carbon taxes, or cap and trade systems, based on the optimal SCC rather than analysing the effects of alternative government policies such as fiscal subsidies and industrial policy. When such policies are acknowledged by mainstream economists they have often been disregarded due to the perceived risk of government failure (e.g.Helm (2010)).

Post-Keynesian economists have long argued against the primacy of market-based policies and advocated for more interventionist government policy (Arestis and Sawyer 1998; Harcourt and Kriesler 2015). It is argued that market-based approaches will ultimately be ineffective at achieving goals such as equality and full-employment and that such goals can only be achieved through government fiscal and industrial policies. Fontana and Sawyer (2013) apply post-Keynesian approaches to climate change and reaches the same conclusion, that government policies will likely be more successful than market-based approaches. Dafermos and Nikolaidi (2019) show that it is often an artefact of the questionable assumptions of orthodox climate models that government policies are ineffective and that post-Keynesian modelling techniques can be used to show their effectiveness.

The aim of this dissertation is not to discredit market-based approaches, but rather to explore alternative policies and their effectiveness. It will be argued that, in the face of the potential catastrophic damages that climate change can cause, it is the responsibility of policy makers to use any tools they can to avoid disaster. One such policy tool, which has received limited analysis in the climate economics literature, is green industrial policy. There is little agreement on how to define industrial policy; for the purposes of this dissertation, we use the definition of Tucker (2019) where industrial policy is defined as "any government policy that encourages resources to shift from one industry or sector into another, by changing input costs, output prices, or other regulatory treatment". Green industrial policy is, by extension, industrial policy where the resource shift is from "brown" sectors such as non-renewable energy production and fossil fuel extraction, towards "green" sectors such as renewable energy production. Therefore, green industrial policies include sector specific subsidies and taxation, along with targeted fiscal policy and regulation. Green industrial policies are now beginning to receive support, particularly from proponents of a Green New Deal (GND) approach to climate policy, with Pollin stating that the climate stabilisation project needs to focus "first and foremost, on industrial policies" (Pollin 2021). Furthermore, these policies are increasingly being incorporated in governments proposed green policy packages as evidenced in the UK where the government has set out its 10-point plan for a green industrial revolution (Johnson 2020) in which points 1-6 and 8 all reference either supporting green industries to grow or helping high emission industries to transition. Given the urgency of climate policy, along with growing interest amongst economists and policy makers in industrial policy, there are clear reasons to analyse the effects of green industrial policies for achieving climate goals and on the wider macroeconomy.

In assessing green industrial policy this dissertation will utilise the post-Keynesian stock-flow consistent (SFC) modelling approach pioneered by Godley and Lavoie (2007). It will be shown that the post-Keynesian approach allows consideration of macroeconomic effects which are crucial to understand the effects of industrial policy and that most orthodox modelling approaches lack the same considerations. In particular, the SFC approach is able to show the interconnected effects of different policies which allows for the effects of an industrial policy mix to be assessed.

Industrial policies can take many different forms, this dissertation will focus on the regulation of the energy sector in the form of a ban on the use of non-renewable energy and the use of fiscal levers, in the form of taxes and subsidies on the purchase of non-renewable and renewable energy capital respectively. The model will be used to assess these policies when implemented on their own and as part of a broader policy package. Banning non-renewable energy would likely be announced many years ahead of its implementation, therefore it is likely that firms would respond to the policy prior to it coming into effect. This necessitates a form of forward-looking structure which is not typical within SFC models. Therefore, a key innovation of this model will be the use of forward-looking behaviour in the energy sector, where firms' investment choices respond to future regulation when it is announced. Additionally, by using the SFC framework, the model is able to analyse the financial implications of environmental regulation policies.

This dissertation begins by reviewing the literature in Section 2, looking in turn at the modelling approaches to climate policy, their economic foundations and how industrial policy is modelled. Section 3 describes the structure of the model in detail. Section 4 shows the results of various simulations across several modelling scenarios. Finally, results are discussed, along with model limitations in Section 5, which is followed by a brief conclusion.

2 Literature Review

2.1 Modelling Approaches to Climate Policy

Until recently green industrial policy has received relatively limited analysis from economists. For Neoclassical economists industrial policy represents a distortion of markets by governments with industrial policy being difficult to design effectively in practice (Rodrik 2014). Greenhouse gas (GHC) emissions have typically been seen as a negative externality effect leading to a market failure in the energy sector where polluting energy sources are underpriced. The approach to dealing with such a market failure has typically been to advocate for so called "carbon-pricing" or a "social cost of carbon" (SCC) where, through a Pigouvian tax or cap and trade system, the price of carbon is increased to the appropriate level. Therefore a large body of research has focused on the estimation of the SCC.

The SCC has typically been estimated by using integrated assessment models (IAMs). IAMs adopt a form of cost-benefit analysis to derive their results. Damages from global warming impact future output, with mitigation policy included as an economic cost. Future welfare and damages are also subject to a discount rate [1], which is common practice in other cost-benefit models. This is indeed the approach taken by the well-known Dynamic Integrated Climate-Economy (DICE) model of W. Nordhaus and Sztorc (2013), with recent results of the DICE model advocating for a cost of carbon of $31 per tonne of CO^2. This cost of carbon leads to a predicted warming of 3-4^{o}C above pre-industrial levels by the end of the century, a level well above what has been proposed by the Paris agreement and the wider scientific community. However, other IAMs aside from DICE, and other studies applying DICE, do often estimate a significantly higher SCC. In a meta-analysis of the IAM literature, Wang et al. (2019) found SCC estimates in the range of -13.36 - 2386 $/tCO^2 with a mean value of 112.86 $/tCO^2. The authors find that these large fluctuations are due to the high sensitivity of these models to changes in the damage function and the intergenerational discount rate. Models may adopt more pessimistic damage functions in order to incorporate climate tipping points (Lemoine and Traeger 2014), or a lower discount rate as argued for by Stern (2013).

This sensitivity highlights a key methodological issue with the "policy optimisation" approach to climate change. It is generally acknowledged that there are high degrees of uncertainty in climate modelling i.e. W. Nordhaus (2018). However, the scale of climate uncertainties is larger than sometimes acknowledged, with Aldred (2012) stating that there is "scientific uncertainty about the future course of climate change, and, independently, uncertainty about the economic and social impacts of any forecast

[1] The discount rate represents the rate at which future welfare is discounted relative to current welfare. Typically, this is calculated based on the real return on investment which is estimated as a constant 4.25% over the period to 2100 (W. D. Nordhaus 2017). Using high discount rates such as this mean the optimal SCC, derived from IAMs, puts a far larger weight on current welfare than welfare in the distant future.

pattern of climate change". Furthermore, the physical effects of climate change occur through the dynamics of a multidimensional non-linear system with any climate policy interventions further compounding the existing uncertainties (Chenet, Ryan-Collins, and Van Lerven 2019). Therefore, analysis of climate change is done in the context of "fundamental" or "Keynesian" uncertainty where the future is unknown and unknowable and there is "no scientific basis on which to form any calculable probability whatever" (Keynes 1937). This implies that it is not truly possible to identify the SCC to any adequate degree of accuracy, a statement which is backed up by the very wide range of estimates presented within the IAM literature.

In light of these uncertainties, an alternative methodology to climate change policy, resting on the precautionary principle (Aldred 2012; Chenet, Ryan-Collins, and Van Lerven 2019) has been proposed. There are different interpretations of the precautionary principle from different economic schools (Aldred 2012) however for the purpose of this dissertation it is sufficient to describe the precautionary approach as one which seeks to minimise, as far as possible, the risk of irreversible and catastrophic damage to people and the environment. Within the context of climate change, this means assessing policies not on whether they represent the optimal trade-off between costs and benefits in the coming decades but instead on whether they serve to ensure human economic activity does not endanger planetary boundaries. Therefore, policies may be designed to ensure that GHC emissions are low enough to prevent planetary warming of 1.5^{o}C above pre-industrial levels.

A further methodological result of accounting for fundamental uncertainty is that there will always be unknown properties and parameters within economic models of climate effects. W. Nordhaus (2018) uses margins of error in parameter values to address this issue, however, this implicitly relies on a probabilistic approach to parameter estimation which is incompatible with fundamental uncertainty. Another approach, advocated for by Chenet, Ryan-Collins, and Van Lerven (2019), is to apply scenario analysis where a model is tested against a number of different possible climate change mitigation pathways. Recent climate models are increasingly adopting this approach with the NGFS (2021) presenting six climate mitigation scenarios which differ in the magnitude of transition and physical risks caused primarily by how (if at all) the transition to a low carbon economy is implemented. Similarly, the CCC (2020) present several scenarios in which they explore UK climate mitigation pathways where different policies have differing levels of effectiveness on, for example, social and behavioural change.

This sets the stage for analysing modelling approaches to industrial policy, which are generally analysed within the context of achieving climate related goals such as phasing out fossil fuel energy by a certain date. Such goals are often related to a country's commitments to climate agreements. Policies are analysed based on their effectiveness at achieving these goals and their impacts on socio-economic outcomes often within a variety of possible scenarios.

2.2 The Economic Foundations of Climate Models

The economic module of the majority of IAMs is based on Computable General Equilibrium (CGE) modelling techniques. Such models are based on neoclassical foundations, with households and firms maximising utility and profits respectively. Furthermore, CGE models have been applied on their own to assess a several climate policies including carbon taxes (Meng, Siriwardana, and McNeill 2013), green subsidies (Kalkuhl, Edenhofer, and Lessmann 2013) and feed-in-tariffs (Wei et al. 2019).

CGEs and by extension IAMs have faced a number of criticisms (Dafermos and Nikolaidi 2019). Typically, CGEs assume full employment, whereas modern economies are characterised by idle resources such that an increase in aggregate demand will increase output. For many IAMs and CGEs this is not the case which leads to green fiscal policies being seen purely as a cost due to any government spending effectively crowding out the private sector. Furthermore, within these models the financial system at most plays an intermediary role without endogenous money creation, such that climate policy can never be expansionary (Pollitt and Mercure 2018).

Overall, it is deemed that these models are likely to undervalue climate risks, due to not adequately accounting for uncertain effects mentioned previously. Simultaneously they tend to underestimate the positive effects that climate policies may have on the macroeconomy due to their economic assumptions. These models have therefore been criticised for failing to advocate for sufficient policies to tackle the climate emergency. Stern (2016) specifically criticises IAMs and advocates for more sophisticated modelling techniques, namely Dynamic Stochastic General Equilibrium (DSGE) models and Agent-Based Models (ABMs), to analyse climate policies.

DSGE models share many similarities with CGE models in that they are macroeconomic models based on micro-foundations of representative agents solving inter-temporal optimisation problems (Pesaran and Smith 2011). DSGE models however incorporate exogenous, stochastic shocks which result in fluctuations around a given equilibrium. For analysing climate policies, Golosov et al. (2014) build on W. Nordhaus and Sztorc (2013) by incorporating a DSGE economic module into an IAM to derive the optimal price of carbon while Ferrari and Nispi Landi (2021) use a DSGE approach to analyse the economic effects of a green quantitative easing programme. Although many of the critisisms of CGE models carry through to DSGE models it should be noted that many recent DSGE models do incorporate finance in a more sophisticated way, with the Ferrari and Nispi Landi (2021) model adopting the approach of Gertler and Karadi (2011) where banks raise funds from deposits and the interbank market. This approach to finance fails to account for endogenous money creation, however, other DSGE models such as that of Jakab and Kumhof (2018) do allow for this. The core structure of DSGE models is not so easily changed however, and all DSGE models will, to some degree, rely on representative agents with rational expectations solving an inter-temporal optimisation problem. Given the large degree of uncertainty around the effects of climate change and climate change mitigation policy it is highly unrealistic to assume that individuals are capable of forming such expectations. Furthermore, the representative agents in DSGE models make it highly difficult to create heterogeneity in the model between different agents/sectors which is a crucial component for analysing the effects of industrial policy.

Analysis of ABMs in any generality is challenging, as ABMs have been developed in many different ways across different schools of thought. The key feature of ABMs is dropping the assumption of a representative agent present in all models discussed thus far. However, the agents in ABMs can be anything from individuals to firms to classes. This allows agent based approaches to analyse the interactions between heterogeneous agents. Lamperti et al. (2019) develop a climate-based ABM, drawing on post-Keynesian tradition, to analyse the effects of climate change on financial instability. Lamperti et al. (2019) adopt an agent based financial sector with multiple heterogeneous banks, allowing for analysis of how individual bank failures could affect the system as a whole.

There are other post-Keynesian and heterodox models which adopt a stock-flow consistent (SFC) framework. SFC models follow the principle that within the model every financial asset must have a counterpart liability and therefore the financial and real spheres are integrated. It should be noted that ABMs and SFC models are not mutually exclusive, many ABMs may adopt an SFC framework and SFC models might introduce agents to analyse particular policies. Monasterolo and Raberto (2018) explore the impact of green subsidies on green investment in a SFC framework, concluding that green subsidies do have a positive effect on green investment. Monasterolo and Raberto (2018) use heterogeneous sectors and therefore their sectoral approach is close to that of an ABM.

The DEFINE model of Dafermos, Nikolaidi, and Galanis (2017) incorporates physical stocks and flows into the model itself and bridges the gap between post-Keynesian and ecological economics. This model has been used to explicitly assess the impacts of climate degradation on financial stability as in Dafermos, Nikolaidi, and Galanis (2018).

SFC models differ significantly from CGE and DSGE models by not relying on micro-foundations of representative agents. Decisions in SFC models are instead governed by behavioural equations which are usually derived from post-Keynesian principles. This leads to SFC modelling facing a number of criticisms related to the lack of micro-foundations, the “Lucas Critique” of agents who do not adapt their behaviour to policy changes and that SFC models are not clearly linked to economic theory (Burgess et al. 2016). As discussed already, the assumption of representative agents with rational expectations is at odds with much of the realities of how agents act in the face of climate change and therefore the lack of micro-foundations could be seen as a positive by allowing SFC models to better model these behaviours. The general lack of forward-looking agents in SFC models is very much linked to dropping the rational expectations assumption, that being said agents’ behaviour can be forward looking even in the presence of fundamental uncertainty and it is true that this is often not captured in the behavioural equations of SFC models. Usually this is an acceptable assumption, however in the face of certain policies, particularly where governments provide forward guidance, it is useful to include forward looking structures and this dissertation will explore how this could be achieved in practice. The limited link with mainstream economic theory is a product of SFCs being heterodox economic models developed by post-Keynesians, therefore they have a strong link with Keynesian/post-Keynesian ideas such as the principle of effective demand and endogenous money. These post-Keynesian principles have been shown to be highly relevant when analysing the effects of climate policy (Dafermos and Nikolaidi 2019).

The SFC framework, with post-Keynesian behavioural equations, includes the financial sector in the model, accounts for agents' fundamental uncertainty and can analyse knock-on effects of different policy mixes. Crucially, as shown in Dafermos, Nikolaidi, and Galanis (2018), these models allow for exploration of the potential effects of climate degradation on particular aspects of the economy (in this case the financial sector) rather than generalising climate change damages as a cost. Additionally, SFC models are highly compatible with agent based structures as in Lamperti et al. (2019) which allow a greater scope to consider how policies effect different agents and their interactions.

2.3 Modelling the Effects of Green Industrial Policy

Green industrial policy does not appear to have been analysed extensively in mainstream economic models. There have been some models which take an econometric approach to assessing environmental regulation, typically applied in China where such regulation is commonplace (Wenbo and Yan 2018; Zhang et al. 2020). However, such analysis falls far short of a comprehensive macroeconomic model of industrial policies which generally only seem to be analysed from a heterodox economic perspective.

Post-Keynesian scholars have typically taken a different approach to government policy than that of Neoclassicals. For post-Keynesians, governments can, and should, take a leading role in stabilising the economy with a particular focus on demand side policies aimed at achieving full employment (Kalecki 1943; Arestis and Sawyer 1998; Harcourt and Kriesler 2015). Acknowledgement of the effectiveness of demand side policy, along with generally envisioning a larger role for governments in the economy, has led to greater analysis of industrial policy from a post-Keynesian perspective. The growing focus of policy aimed at mitigating against the effects of climate change has led to further exploration of the role of industrial policy, with Pollin (2021) stating that the climate stabilisation project needs to focus "first and foremost, on industrial policies".

Several post-Keynesian models focusing on industrial policy have been developed in recent years. Nieto et al. (2020) develops a post-Keynesian model based around the MEDEAS IAM framework. MEDEAS is a demand-led IAM and does not necessitate equilibration, Nieto et al. (2020) expand upon MEDEAS with an energy extraction module and employment sub-module. The explicit consideration of energy leads to this being an "ecological" model, which is to say that the economy is modelled as being fundamentally dependent on the planet and climate. Furthermore, the employment sub-module allows for exploration of the positive effects that industrial policy can have on employment and macroeconomic goals. However, reliance on an IAM does lead to a fair number of exogenous variables in the economic module such as expected GDP growth. Furthermore, the model does not include a financial sector and financial flows. As models are analysing industrial policy it could be argued that an explicit consideration of finance is unnecessary, however the interconnectedness of the real and financial spheres should not be ignored in models (Lavoie 2011), as all policies can lead to feedback loops between the real and financial sectors of the economy. These limitations are explicitly acknowledged by Nieto et al. (2020) who highlights greater endogeneisation and incorporation of financial stocks and flows in an SFC framework as expected developments to their approach.

Monasterolo and Raberto (2019) apply the EIRIN SFC model to analyse the effect of a gradual phase-out of fossil fuel subsidies. Within their analysis the authors do consider scenarios where green capital investments are subsidised as fossil fuel subsidies are phased out. In their model, Monasterolo and Raberto (2018), disaggregate the non-financial sector (firms) into a number of different sub-sectors with differing levels of emissions. This disaggregation allows the authors to consider the effect of industrial policies which are applied to these different sectors. Godin et al. (2017) similarly use a heterogeneous firm sector, in this case to explore the effects of climate financial bubbles on an energy transition. This approach provides a good blueprint for how an SFC approach could be used to look at the effects of policies on different, interconnected, firm sectors. However, they fall short of analysing an industrial policy mix, with the focus mainly being on altering subsidies and taxes for different sectors.

The role of regulation in industrial policy packages has received little analysis in ecological models. However, with the need to transition away from carbon intensive industry becoming increasingly pressing, it is argued that more stringent and thus far unprecedented forms of regulation may be required. A key challenge for any model considering regulation is accurately measuring how a piece of regulation will affect firms and the economy as a whole. There are open questions as to how firms will respond to regulations and whether the regulation in reality could do more harm than good by causing irreparable damage to affected firms. A further challenge, particularly to the behavioural equations of SFC models, is when a policy includes forward guidance from the government, such as the UK government's planned ban of fossil fuel cars from 2035. A firm manufacturing petrol engines is likely to scale down production as 2035 approaches due to the engines having effectively no value beyond that time. Similarly, if the government was to announce a future ban of energy produced from fossil fuels it would be expected that firms would take some action prior to the ban coming into force, thus adopting a form of forward-looking behaviour.

2.4 Contribution

This dissertation aims to contribute to the growing literature of ecological macroeconomic models by developing a SFC model, loosely fitted to UK data, with a heterogeneous firm sector. The model will be used to analyse the effect of industrial policy on the transition from non-renewable to renewable energy production. The focus on green transition and industrial policy therefore makes this model novel among similar models in the literature. Furthermore the model will incorporate the effects of regulation in the form of a ban of the use of non-renewable energy capital. This form of regulation necessitates the introduction of forward looking decisions on the part of energy production firms. This is uncommon for SFC models with behavioural equations usually being based on the observed past. However, there are examples of forward-looking behaviour in SFC models such as in the model of Dunz, Naqvi, and Monasterolo (2021) and there is no fundamental reason why SFC behavioural equations cannot incorporate such behaviour. Finally, it is hypothesised that the efficacy of industrial policies will depend on an effective policy mix, rather than a single policy, so a scenario will be analysed where governments provide a fiscal support package to affected firms when planned regulation is announced.

3 Structure of the Model

The aim of this dissertation is to study how green industrial policy mixes affect the transition to renewable capital within the energy production sector along with the policy's effects on macroeconomic stability, profit rates and government debt. The model is designed following closely the approach of Dafermos, Nikolaidi, and Galanis (2015), with alterations made to focus on the energy production sector and industrial policy. Therefore, the economy is separated into six sectors:

1. *Production Firms.* Production firms produce both the single consumption good and all forms of capital by employing labour, their own physical capital and energy. They sell non-renewable and renewable capital to the energy production firms at a price determined by production costs and a mark up. In order to produce any output they must purchase energy from the energy production firms at a given price.

2. *Energy Production Firms.* Energy production firms produce energy, which is sold to production firms, using both renewable and non-renewable capital. Each period they choose how to split their investment between these capitals and then purchase the required capital from the production firms. It is within this sector that green industrial policy mixes are applied [2].

3. *Households.* Households are assumed to supply labour and split their wages between consumption and saving. For simplicity, households do not hold any government securities or firm equity and therefore all saving is in the form of bank deposits.

4. *Banks.* Banks hold the deposits of households and receive advances from the central bank while providing credit to non-financial firms. Banks are assumed to provide any loans demanded by increasing their advances as required. Banks discriminate between sectors by employing a different interest rate on production sector and energy sector loans. All interest rates are assumed to be determined by a spread above the interest rate on deposits. It is assumed that all bank profits are distributed to households.

5. *Government.* The Government receives tax income from households and non-financial firms while providing direct government spending to non-financial firms.

[2]The industrial policy in this model does not cause a resource shift between the different production sectors as it only affects the energy production sector. However, it is implicit in the model that industries within the energy production sector, such as non-renewable resource extraction, will have to disappear if there is a total transition to renewable energy production. The reason for not disaggregating the energy production sector in this model is that many non-renewable energy production firms also produce energy from renewable sources and hence can use their profits from non-renewable energy to invest in renewable energy capital, a process that would be challenging to capture if there were separate sectors for renewable and non-renewable energy production.

The government also implements subsidies and taxes on the purchase of renewable and non-renewable energy capital respectively. Government securities are sold to cover any required spending such that government spending is not constrained within the model as the central bank buys all securities.

6. *Central Bank*. The central bank takes a passive role in this model. It buys all securities issued by the government while providing advances needed by banks. Its only liability is High Powered Money which is transferred directly to the banking sector.

The model is described, at a high level in the following figures. Figure 1 shows the overall model structure and how different sectors interact with one another. For clarity, and in line with the SFC approach, the sectors in the model use double-entry accounting such that each financial asset has a counterpart liability. The balance sheet matrix, shown in figure 2, describes the various sectoral balances, again set to show the interaction between sectoral assets and liabilities. Finally figure 3 shows the transaction flow matrix in which all monetary flows are recorded as a payment for one sector and a receipt for another, therefore there are no "black holes" and the model is financially closed.

Figure 1. Model Diagram

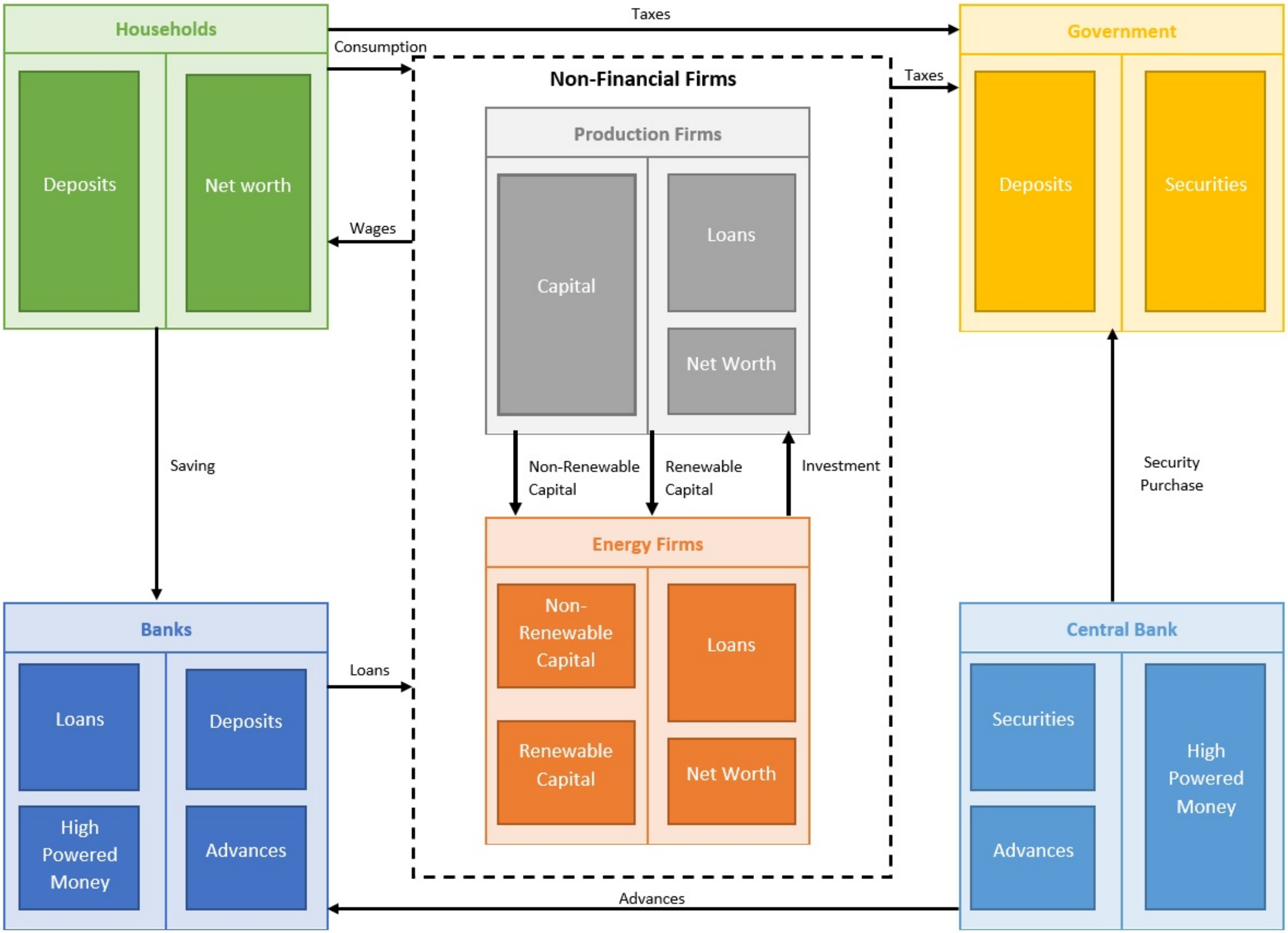


Figure 2. Balance Sheet Matrix

	Households	Production Firms	Energy Production Firms	Banks	Government	Central Bank	Total
Production firms' capital		$+ K_C$					$+ K_C$
Energy production firms' renewable capital			$+ K_R$				$+ K_R$
Energy production firms' non-renewable capital			$+ K_N$				$+ K_N$
Deposits	+D			-D			0
Production firms' loans		$-L_C$		$+L_C$			0
Energy production firms' renewable loans			$-L_R$	$+L_R$			0
Energy production firms' non-renewable loans			$-L_N$	$+L_N$			0
Government securities					-SEC	+SEC	0
Advances				-A		+A	
High Powered Money				+HPM		-HPM	
Total (net worth)	$+V_H$	$+V_C$	$+V_E$	0	-SEC	0	$+ K_C + K_R + K_N$

Figure 3. Transaction Flow Matrix

	Households	Production Firms		Energy Production Firms		Banks		Central Bank		Government	Total
		Current	Capital	Current	Capital	Current	Capital	Current	Capital		
Consumption	$-C$	$+C$									0
Production firms' investment		$+I_C$	$-I_C$								0
Energy Production firms' renewable investment		$+I_R$			$-p_{RS}i_R$						0
Energy Production firms' non-renewable investment		$+I_N$			$-p_{NT}i_N$						0
Wages	$+wN_C + wN_E$	$-wN_C$		$-wN_E$							0
Energy bill		$-p_E e_C$		$+p_E e_C$							0
Good production firms' profits	$+DP_C$	$-TP_C$	$+RP_C$								0
Energy production firms' profits	$+DP_E$			$-TP_E$	$+RP_E$						0
Banks profits	$+BP$					$-BP$					0
Central Bank Profits								$-CBP$		$+CBP$	0
Government production spending		$+G_C$								$-G_C$	0
Government energy spending				$+G_E$						$-G_E$	0
Household taxes	$-T_H$									$+T_H$	0
Production taxes		$-T_C$								$+T_C$	0
Renewable energy capital taxes				$-T_R$						$+T_R$	0
Non-renewable energy capital taxes				$-T_N$						$+T_N$	0
Energy Production taxes				$-T_E$						$+T_E$	0
Depreciation of production firm's capital		$-\delta_C K_{C-1}$	$+\delta_C K_{C-1}$								0
Depreciation of renewable energy capital				$-\delta_R K_{R-1}$	$+\delta_R K_{R-1}$						0
Depreciation of non-renewable energy capital				$-\delta_N K_{N-1}$	$+ \delta_N K_{N-1}$						0
Interest on deposits	$+int_D D_{-1}$					$-int_D D_{-1}$					0
Interest on production firms' loans		$-int_C L_{C-1}$				$+ int_C L_{C-1}$					0
Interest on energy production firms' renewable loans				$-int_R L_{R-1}$		$+ int_R L_{R-1}$					0
Interest on energy production firms' non-renewable loans				$-int_N L_{N-1}$		$+ int_N L_{N-1}$					0
Interest on government securities								$+int_S SEC_{-1}$		$-int_S SEC_{-1}$	0
Interest on Advances						$-int_A A_{-1}$		$+int_A A_{-1}$			0
Δdeposits	$-\Delta D$						$+\Delta D$				0
Δproduction firms' loans			$+\Delta L_C$				$-\Delta L_C$				0
Δenergy production firms' renewable loans					$+\Delta L_R$		$-\Delta L_R$				0
Δenergy production firms' non-renewable loans					$+\Delta L_N$		$-\Delta L_N$				0
Δgovernment securities									$-\Delta SEC$	$+\Delta SEC$	0
ΔAdvances							$+\Delta A$		$-\Delta A$		0
ΔHPM							$-\Delta HPM$		$+\Delta HPM$		0
Total	0	0	0	0	0	0	0	0	0	0	0

3.1 Firms

$$I = I_C + I_E \tag{1}$$
$$K = K_C + K_E \tag{2}$$

As there are two firm sectors, total investment is simply the sum of investment in conventional capital (I_C), which is used by production firms and investment in energy capital (I_E) used by energy production firms such that total investment is given by Eq. (1). Total capital stock is given by the sum of the respective capitals as in Eq. (2).

3.1.1 Production Firms

$$Y = C + I_C + I_E + G_C \tag{3}$$
$$PTP_C = Y - wN_C - int_C L_{C-1} - p_E e_C - \delta_C K_{C-1} \tag{4}$$
$$TP_C = (1 - t_C)PTP_C \tag{5}$$
$$E_C = \epsilon_C Y \tag{6}$$
$$RP_C = s_{FC} TP_{C-1} \tag{7}$$
$$DP_C = TP_C - RP_C \tag{8}$$
$$r_C = RP_C / K_C \tag{9}$$
$$lev_C = L_C / K_C \tag{10}$$
$$Y^* = v_C K_C \tag{11}$$
$$u_C = Y / Y^* \tag{12}$$
$$I_C = (1 - \phi)(\alpha_{0C} + \alpha_{1C} r_{C-1} + \alpha_{2C} u_{C-1})K_{C-1} + \delta_C K_{C-1} \tag{13}$$
$$\Delta L_C = I_C - RP_C - \delta_C K_{C-1} \tag{14}$$
$$\Delta K_C = I_C - \delta_C K_{C-1} \tag{15}$$
$$w = s_W \lambda_C \tag{16}$$
$$\lambda_C = \lambda_{C-1}(1 + g_{\lambda C}(1 - \phi)) \tag{17}$$
$$N_C = Y / \lambda_C \tag{18}$$
$$p_N = (1 + m)\left(\frac{w_{-1}}{\lambda_{C-1}} + p_{E-1}\epsilon_C\right) \tag{19}$$
$$p_R = (1 - \psi)(1 + m)\left(\frac{w_{-1}}{\lambda_{C-1}} + p_{E-1}\epsilon_C\right) \tag{20}$$

Eq. (3) shows that output produced by the production firm sector equals the sum of goods produced for consumption (C), production firm investment(I_C), the value of energy production capital sold to energy production firms ($p_{EK} I_E$) and government spending in the production sector G_C. Total pre-tax profits are given by Eq. (4); where

w is the wage rate, N_C is the number of workers employed in production firms, int_C is the interest rate on loans to production firms with L_C representing the outstanding loans. e_C is the amount of energy used by the production sector which is purchased from energy production firms at the energy price p_E. Finally δ_C is the rate of depreciation of conventional capital with the previous period stock being given by K_{C-1}. Sector profits are subject to a uniform percentage tax (t_C) such that total profits are determined by (5). The amount of energy demanded is given by Eq. (6) where ϵ_C is the energy intensity of production firms, which is assumed to be constant.

Eqs. (7) and (8) show how firms retain a part of their total profit and distribute the rest to households. The rate of retained profit and leverage ratio are given by Eqs. (9) and (10). Eq. (11) shows how full-capacity output (Q^*_C) is a function of capital stock and the full-capacity-to-output ratio (v_C). The rate of capacity utilisation (u_C) is given by Eq. (12).

Investment is determined through a traditional Kaleckian investment function (Eq. 13) where investment is a function of profit rate and utilisation rate with α_{0C},α_{1C} and α_{2C} being parameters. This approach to investment is well established in post-Keynesian models with a similar function being used the growth model of Kaldor (1957). Recent climate SFC models (Dafermos, Nikolaidi, and Galanis 2017) have also favoured this approach to investment. However, investment is assumed to decrease steadily over time as secular stagnation causes the rate of private investment to fall (Onaran 2016). This is captured by the term $(1 - \phi)$ where ϕ is a strictly increasing function of time, in this model ϕ follows a logistic function. Furthermore, firms invest to maintain capital stock hence the final term of the investment equations act to counteract capital depreciation. Firms' investment, retained profits and capital depreciation rates then determine the change in loans (ΔL_C) and capital stock (ΔK_G) through Eqs. (14) and (15).

The wage rate (which is assumed to be the same for all firms) is a proportion of the firm productivity, given by Eq. (16). Productivity is determined by Eq. (17) where $g_{\lambda C}$ is the initial productivity growth rate, productivity growth slows down over time at the same rate of investment again due to secular stagnation (Onaran 2016). The number of workers employed in the production sector is given by Eq. (18). Eqs. (19) and (20) determine the price charged by production firms for the non-renewable and renewable capital respectively sold to energy production firms. This approach to capital pricing is similar to that of (Gerst et al. 2013). The $(1-\psi)$ term is a decreasing term to represent how renewable capital becomes gradually less expensive over time, due to innovation, in this model this term is exogenous however it could be endogenised using Schumpeterian approaches as has been attempted in several of recent SFC models (Borsato et al. 2020; Caiani, Godin, and Lucarelli 2012).

3.1.2 Energy Production Firms

$$PTP_E = p_E E_C + G_E - wN_E - int_R L_{R-1} - int_N L_{N-1} - p_{RS}\delta_R K_{R-1} - p_{NT}\delta_N K_{N-1} \tag{21}$$

$$TP_E = (1 - t_E)PTP_E \tag{22}$$

$$RP_E = s_{FE}TP_{E-1} \tag{23}$$

$$DP_E = TP_E - RP_E \tag{24}$$

$$k_R = K_R/k_P \tag{25}$$

$$k_N = K_N/k_P \tag{26}$$

$$k_E = K_E/k_P \tag{27}$$

$$\mu = K_R/K_E \tag{28}$$

$$r_E = RP_E/K_E \tag{29}$$

$$lev_E = L_E/K_E \tag{30}$$

$$E_P = E_C(1 + \xi) \tag{31}$$

$$er = CF_R 8760 k_R \tag{32}$$

$$en = (e_P - er)(1 + \chi) \tag{33}$$

$$CF_N = en/8760k_N \tag{34}$$

$$CF_R = min(CF_{R1} + \upsilon, E_P/(8760k_R)) \tag{35}$$

$$CF_E = \theta CF_R + (1 - \theta)(CF_N) \tag{36}$$

$$\theta = er/e_P \tag{37}$$

$$EMIS = \omega en \tag{38}$$

$$i_E = (1 - \phi)(\alpha_{0E} + \alpha_{1E}r_{E-1} + \alpha_{2E}CF_{E-1})k_{E-1} + \delta_R K_{R-1} + \delta_N K_{N-1} \tag{39}$$

$$i_R = \beta i_E + ret_N K_{N-1} \tag{40}$$
$$i_N = (1-\beta) i_E \tag{41}$$
$$I_R = p_R i_R \tag{42}$$
$$I_N = p_N i_N \tag{43}$$
$$I_E = I_R + I_N \tag{44}$$
$$\beta = \beta_0 + \beta_1 (c_{N-1} - c_{R-1}) \tag{45}$$
$$\Delta K_R = i_R - \delta_R K_{R-1} \tag{46}$$
$$\Delta K_N = i_N - \delta_N K_{N-1} - ret_N K_{N-1} \tag{47}$$
$$K_E = K_R + K_N \tag{48}$$
$$p_{RS} = (1 - s_R) p_R \tag{49}$$
$$p_{NT} = (1 + t_N) p_N \tag{50}$$
$$c_R = \frac{p_{RS-1}(int_R + \delta_R)}{8760 CF_R} + \frac{w(1+\zeta)}{\lambda_E} \tag{51}$$
$$c_N = \frac{p_{NT-1}(int_N + \delta_N + ret_N)}{8760 CF_{N-1}} + \frac{w(1+\zeta)(1+\chi)}{\lambda_E} \tag{52}$$
$$\Delta L_R = p_{RS} I_R - \beta RP_E - p_{RS} \delta_R K_{R-1} \tag{53}$$
$$\Delta L_N = p_{NT} I_N - (1-\beta) RP_E - p_{NT} \delta_N K_{N-1} \tag{54}$$
$$L_E = L_R + L_N \tag{55}$$
$$\lambda_E = \lambda_{E-1}(1 + g_{\lambda_E}(1-\phi)) \tag{56}$$
$$N_E = E_P / \lambda_E \tag{57}$$
$$p_E = q[\theta c_R + (1-\theta) c_N] \tag{58}$$
$$\chi = \gamma_0 + \gamma_1 dep_{E-1} \tag{59}$$
$$dep_E = en/ENS \tag{60}$$
$$\Delta ENS = -en \tag{61}$$

Eq. (21) gives the total pre-tax profits of the energy production sector with p_E being the price of the conventional energy (E_C) sold to firms in the productive sector. Energy production firm costs include worker wages, the interest rate on green and brown loans and the depreciation of green and brown capital. Similarly to production firms, energy production firms are subject to a tax on profits (t_E) which is applied in Eq. (22). Eqs. (23) and (24) describe the retained and distributed profits of energy production firms.

Energy production firms hold both renewable and non-renewable capital stock. Eqs. (25)-(27) give the value of non-renewable, renewable and total energy capital stock in terms of kwH of energy production such that one unit of capital produces 1 kwH of energy. The term k_P in these three equations represents real value of 1 kwH of energy production and therefore allows for a transformation between the energy value of capital and the real value in USD, for simplicity k_P is assumed to be constant. Eq. (28) is used to calculate μ, the proportion of real capital which is renewable, the energy sector is considered to have fully transitioned once $\mu = 1$. Eqs. (29) and (30) give the rate of retained profit (r_E) and the leverage ratio (lev_E).

As energy production firms require energy for their own operations the energy produced (E_P), given by Eq. (31), is greater than the energy used by production firms E_C. Therefore, the proportion of energy required by energy production firms to produce energy for the productive sector (ξ), is strictly positive. It is assumed for simplicity that the excess energy needed is the same regardless of whether renewable or non-renewable energy is being produced.

When producing energy, firms initially use the renewable resource, which avoids cost associated with the extraction of the non-renewable resource. Therefore, Eq. (32) gives the maximum amount of energy which can be produced using the renewable resource, with CF_R representing the capacity factor of renewable capital and 8760 simply being the number of hours per year. CF_R is assumed to initially be lower than the non-renewable capacity factor (CF_N) due to the non-dispatchability of the related technology, this is backed up with real world estimates such as those in EIA (n.d.). Any energy demand not covered by the renewable resource must use the non-renewable resource. Eq. (33) gives the amount of non-renewable energy produced where χ represents the energy required to extract the non-renewable resource. Therefore as χ increases, the return of non-renewable energy investment is expected to fall, this mechanism causes renewable energy investment to naturally become more attractive over time without any policy intervention.

Eq. (34) gives the endogenously determined capacity factor of the non-renewable resource. CF_R is determined by Eq. (34) where CF_{R1} is the initial capacity factor of renewable energy and υ is the exogenous rate at which the renewable capacity factor increases due to technological progress in the renewable energy sector. It should be noted that there is an upper limit on CF_R at the point where all energy demand can be satisfied by the renewable resource and therefore excess energy is wasted. The capacity factor of the energy grid CF_E is given by Eq. (36) as a weighted average of CF_R and CF_N based on the respective proportion of energy production which is renewable/non-renewable. The proportion of energy produced using renewable sources (θ) is given by Eq. (37). Producing energy from the non-renewable resource leads to CO^2 being emitted. Emissions generated by non-renewable energy production are given by Eq. (38) where ω represents the carbon intensity of non-renewable energy production.

The nominal investment of energy production firms is determined by Eq. (39). As with production firms, energy production firms invest through a Kaleckian investment function while counteracting capital depreciation, where CF_E is used as a proxy for the utilisation rate of energy capital. Also, as with production firms, investment is assumed to fall over time due to secular stagnation, driven by the $(1-\phi)$ term. Nominal investment in renewable and non-renewable capital respectively is given by Eqs. (40) and (41). Renewable investment has the extra term $ret_N K_{N-1}$ which is part of the forward-looking investment structure to be described in section 3.6. The proportion of renewable investment β is determined by (45) and is assumed to be determined by the difference in the lagged levelised cost of capital along with other institutional, political and behavioural factors captured by β_0. The factors captured by β_0 can be highly significant, with Masini and Menichetti (2013) finding non-financial factors to be statistically significant drivers of renewable energy investment. Real investment levels are given by Eqs. (42), (43) and (44), these real investment values represent financial the flows which energy production firms use to buy capital from production firms. The change in nominal renewable and non-renewable capital stock is given by Eqs. (46) and (47) with total nominal energy capital stock being given by (48). Once again the $ret_N K_{N-1}$ term is a part of the forward looking investment term to be described later.

The price of renewable capital is subsidised by the government as in Eq. (49), while the price of non-renewable capital is subject to a tax in Eq. (50). Initially there is assumed to be no tax or subsidy with both s_R and t_N increasing to 0.25 within the "fiscal support package" scenarios. The lagged levelised costs of renewable and non-renewable capital respectively are given by Eqs. (51) and (52). For both equations the first term captures the cost of capital and the second term the cost of labour, which is higher for non-renewable energy production, due to the extraction cost χ. Renewable and non-renewable loans are then updated, based on these prices, according to Eqs. (53) and (54), with total energy loans given by Eq. (55).

Eqs. (56) represents the change in energy labour productivity which again grows slower over time due to secular stagnation. The number of workers employed in the energy production sector is given by Eq. (57). The price of energy is determined by a markup q on the costs of energy production as in Eq. (58).

Finally, the costs of non-renewable resource extraction (χ) is an increasing function of its depletion rate as in Eq. (59), as it is assumed that the cheapest non-renewable resource is extracted first. The depletion rate in a given period is simply given by the non-renewable resource use divided by the total stock of unextracted non-renewable resource (ENS) as in Eq. (60). Therefore, the change in unextracted non-renewable resource is simply given by Eq. (61).

3.2 Households

$$PTY_H = W + DP + BP + int_D D_{-1} \tag{62}$$

$$Y_H = (1 - t_H) PTY_H \tag{63}$$

$$W = wN \tag{64}$$

$$DP = DP_C + DP_E \tag{65}$$

$$C = c_1 Y_{H-1} + c_2 D_{-1} \tag{66}$$

$$\Delta D = Y_H - C \tag{67}$$

$$N = N_C + N_E \tag{68}$$

$$re = N / N_{LF} \tag{69}$$

The pre-tax disposable income of households is given by Eq. (62). Household income is equal to the sum of total wages W, total firm distributed profits DP, distributed bank profits BP_D and the interest on deposits. All household income streams are subject to a single percentage tax t_H which is applied in Eq. (63). The wages of households are given by the wage rate multiplied by the number of employed workers as in Eq. (64). Total distributed profits are given by Eq. (65). Households' consumption is a function of their income and deposits as in Eq. (66). In the model, households do not hold securities or bonds so the change in their deposits is simply their received income minus what they choose to consume, as shown in Eq. (66). The total number of workers employed is given by Eq. (68) with the employment rate given by Eq. (69) where N_{LF} is the total size of the workforce.

3.3 Commercial Banks

$$BP = int_C L_{C-1} + int_R L_{R-1} + int_N L_{N-1} - int_D D_{-1} - int_A A_{-1} \tag{70}$$

$$int_C = spr_C + int_D \tag{71}$$

$$int_R = spr_R + int_D \tag{72}$$

$$int_N = spr_N + int_D \tag{73}$$

$$\Delta A = \Delta D + \Delta HPM + \Delta L_C + \Delta L_R + \Delta L_N \tag{74}$$

Bank profits are equal to the interest payment on bank loans minus the interest paid by banks of deposits and advances as in Eq. (70). Interest on loans is determined by a spread on the interest rate of deposits as shown by Eqs. (71), (72) and (73). Finally commercial banks update their stock of advances based on their profits and the change in the stock of deposits and loans as shown in Eq. (74).

3.4 Government

$$Y_G = T - S_R - G - int_S SEC_{-1} \tag{75}$$
$$T = T_H + T_C + T_N + T_E \tag{76}$$
$$T_H = t_H PTY_Y \tag{77}$$
$$T_C = t_C PTP_C \tag{78}$$
$$T_E = t_E PTP_E \tag{79}$$
$$T_N = (p_N - p_{EK}) I_N \tag{80}$$
$$S_R = (p_{EK} - p_R) I_R \tag{81}$$
$$G = G_C + G_E \tag{82}$$
$$G_C = g_C Y_{-1} \tag{83}$$
$$G_E = g_E Y_{-1} \tag{84}$$
$$\Delta SEC = -Y_G \tag{85}$$

Government income is given by Eq. (75), as a sum of total tax income T minus spending on renewable subsidies S_R, direct government spending G and interest payments on government securities. Total tax and the calculation of respective taxes is given by Eqs (76)-(80). The subsidy is given by Eq. (81). Total government spending is given in Eq. (82), with the respective spending rates being given by Eqs. (83) and (84) which are determined by as a proportion of total output. Government energy spending is initially 1% of GDP with this level rising to 1.5% within the fiscal support package scenario. Governments face no constraints on their spending and are able to issue securities to cover any change in government income as in Eq. (85).

3.5 Central Bank

$$CBP = int_S SEC_{-1} + int_A A_{-1} \tag{86}$$
$$\Delta SEC_{RED} = \Delta HPM - \Delta A \tag{87}$$

Central banks are passive within this model, they provide advances to commercial banks and buy all government securities, therefore their only equation is the total profit equation which is given by the interest rates on these respective stocks as in Eq. (86). Eq. (87) is the redundant equation, which is used to check that the model is indeed stock-flow consistent by checking that is equal to the model determined security stock level in every period.

3.6 Forward Looking Investment Structure

Within this model energy production firms are able to make forward looking energy investment choices when they are made aware of the future ban on non-renewable energy capital. Without forward looking behaviour it is assumed that, when the ban comes into effect, firms non-renewable capital stock is wiped out and all must be immediately replaced by renewable capital. This is driven by the non-renewable retirement term ret_N which appears in Eqs. 40 and 47. ret_N takes a value between 0 and 1 and represents the proportion of non-renewable capital which is destroyed in Eq. 47 and then replaced by renewable capital in Eq. 40. Therefore, when firms are not forward looking, $ret_N = 0$ until the ban comes into effect and then $ret_N = 1$.

The forward looking variable ret_N is assumed to increase before the ban comes into effect. Firms are aware that once the ban comes into effect ret_N must equal 1, and therefore seek to gradually increase the rate at which they retire non-renewable capital before the ban, in order to avoid a sharp increase in investment when the ban occurs. This is achieved through updating ret_N according to a fitting function. This approach draws on the forward looking climate sentiments of banks within the model of Dunz, Naqvi, and Monasterolo (2021), however the approach in this model is more straightforward. For Dunz, Naqvi, and Monasterolo (2021) banks face uncertainty about future climate risks and hence combine their best guess of future outcomes with past trends to decide future interest rates. Firms in our model know for certain that the non-renewable ban will come into effect and therefore only need to fit their investment choices. The Bayesian learning approach of Dunz, Naqvi, and Monasterolo (2021) could be used for the situation where firms expect future constraints on non-renewable energy production, due to either government action or resource constraints, but do not know for certain when or what these constraints would be. This would also likely cause higher renewable investment than in the baseline model, however such analysis is left to future research and the focus of this model is on known future policies.

Therefore, the variable ret_N must be fitted according to a predefined fitting function between the policy announcement and the ban coming into effect. This function is assumed to take values between 0 and 1 and also to be increasing. For the simulations in this dissertation an arbitrary logistic function is used to capture the expectation that initially green investment picks up slowly and then gathers pace as it gets closer to the ban coming into effect.

4 Results

4.1 Model Calibration

The model has been calibrated using UK data, with several parameters being based off values from previous studies. Where parameter values could not be found they have been selected from a reasonable range. Furthermore, a number of parameters have been calibrated such that the model produces the baseline scenario outlined in the following subsection. This is broadly in line with recent SFC approaches such as that of Dafermos, Nikolaidi, and Galanis (2015). However, due to research limitations, there has not been any econometric calibration carried out for this model. Due to the lack of econometric calibration, along with the model being built from theory as opposed to from national accounting data, this model is a "theoretical" SFC model as opposed to the "empirical" models described by G. Zezza and F. Zezza (2019). Therefore, the model can be used to assess the potential effects of policy shocks, however it may not adequately represent the structure of any one economy which is an area where further research would be required.

4.2 Scenario Overview

4.2.1 Baseline Scenario

The baseline model is constructed at first such that it is in steady state, i.e. all stocks and flows are growing at a constant rate. This is a common approach in SFC modelling and, despite being a somewhat unrealistic assumption, is still argued to be useful for policy analysis (Caverzasi and Godin 2015). However, for the policy shocks that we aim to assess with this model a steady state approach is inappropriate for several reasons. Firstly, a steady state baseline implies a constant proportion of renewable energy capital whereas the predictions of the CCC (2020) and IPCC (2021) make it clear that even in the absence of policy there is expected to be a gradual transition towards renewable energy production. This natural transition is expected to be driven by factors such as a falling cost of renewable capital due to technological progress and increasing extraction costs of the non-renewable resource. Another factor, relevant to the simulations, is secular stagnation. There is now extensive empirical evidence, particularly in high-income countries, of a discontent between profit rates and private investment (Onaran 2016). This effect would be expected to lead to a declining rate of investment over time which is likely to affect the pace of a green energy transition.

To address these issues the baseline model is moved away from the steady state position. The natural transition is captured by properties of the model itself such as extraction costs increasing (χ) as resources are depleted. Furthermore, the price of renewable capital is assumed to steadily decrease to a fixed percentage of its initial price in order to account for technological progress in the production of renewable energy, driven by an increasing ψ value. Secular stagnation is also captured by assuming that investment growth slows over time, driven by an increasing ϕ value. Both ψ and ϕ are

Figure 4. Key features of the baseline scenario

Variable	2018 value	2040 value	Mean (2018 – 2040)
Economic growth (%)	3.00	2.09	2.80
Share of renewable energy in total energy (%)	34.20	57.04	43.20
Share of renewable capital in total energy investment (%)	34.84	64.14	47.10
Emissions ($MtCO_2e$)	472.72	551.32	534.47
Production firms profit rate (%)	2.63	2.59	2.62
Energy production firms profit rate (%)	1.45	1.41	1.44
Energy Production firms leverage ratio	0.05	0.05	0.03
Debt – GDP Ratio	0.94	0.99	0.95

exogenous variables following logistic functions. By accounting for these effects a baseline is reached where investment and output growth falls over time. Additionally, there is a natural transition towards renewable energy production, however, this transition is far slower than what would be required to achieve net zero emissions by targeted dates. These key features of the baseline scenario are shown in the Figure 4.

4.2.2 Policy Scenarios

The model is simulated across several policy scenarios representing different industrial policy approaches:

1. *Baseline Scenario.* As described above, baseline scenario without policy shocks.

2. *Non-renewable energy ban.* In 2030 a strict ban on non-renewable energy production comes into effect, energy production firms must replace all remaining non-renewable energy capital with renewable energy capital, therefore, regardless of any previous values, the retirement rate ret_N equals 1 in 2030.

3. *Non-renewable energy ban with fiscal support package.* The same ban on non-renewable energy production comes into effect in 2030 however between 2023 and 2030 the government subsidises the purchase of renewable energy capital while taxing the purchase of non-renewable energy capital. This is captured by an increase in the rate of tax on non-renewable capital purchase t_N, and the subsidy on renewable capital purchase s_R, from 0% to 25%. Additionally, the energy production sector is provided with a direct increase in government fiscal spending within the sector over this same period amounting to an increase in government energy spending g_E from 1% to 1.5% of output.

These scenarios are first run without the forward-looking investment function described in section 3.6. They are then all run again with the forward-looking investment function, where firms are assumed to be told in 2023 of the planned non-renewable energy ban coming into effect in 2030.

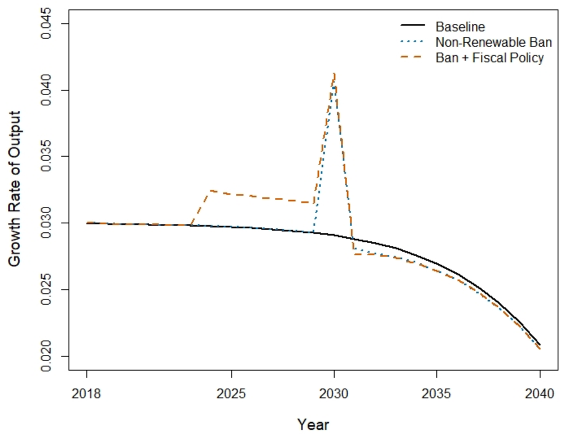
4.3 Simulation Results

4.3.1 Results without forward looking energy investment

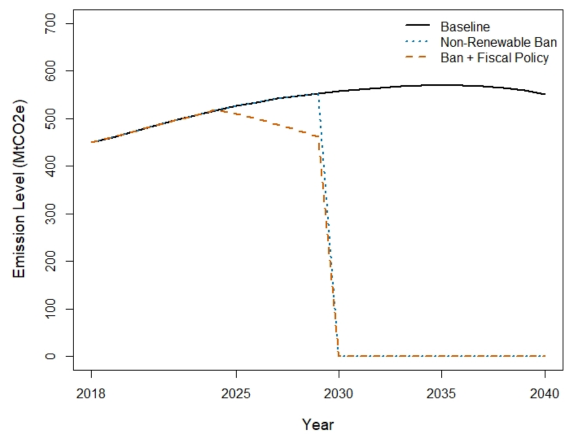
Simulations are initially run without forward looking investment within the energy production sector. Figure 5 shows the growth rate of output, yearly emission level, the Debt:GDP ratio, renewable investment level, non-renewable investment level, the leverage ratio of energy production firms, the share of renewable investment in total energy investment, the share of renewable energy in total energy production and the profit rates of production and energy production firms. These variables allow for assessment of the effects of the policy shocks on the macroeconomy, climate and firms.

When energy production firms are modelled without forward looking investment the implementation of a non-renewable energy production ban in 2030 leads to several sudden adjustments in the model. When the ban comes into effect energy production firms are forced to retire all their non-renewable capital and invest heavily in renewable capital increasing from \$4.8 billion in 2029 to \$ 95.8 billion in 2030 as shown in Figure 5d. This sharp investment rise leads to a spike in output growth (Figure 5a) along with a sharp increase in the leverage ratio of energy production firms (Figure 5f) which are

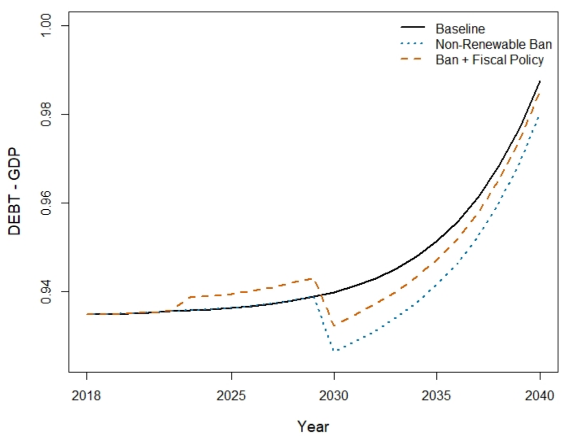
Figure 5. Effects of the implementation of a non-renewable energy ban without forward looking investment in the energy production sector.



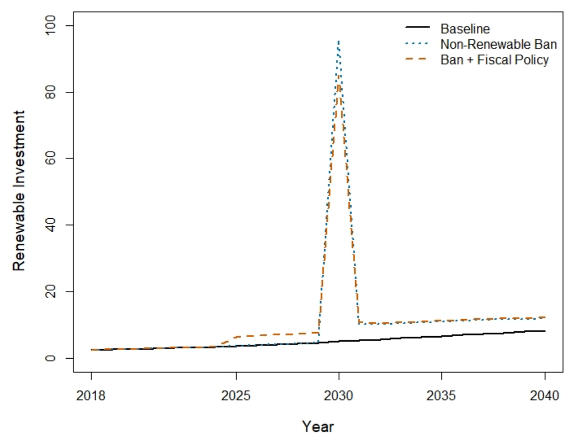
(a) Growth Rate of Output



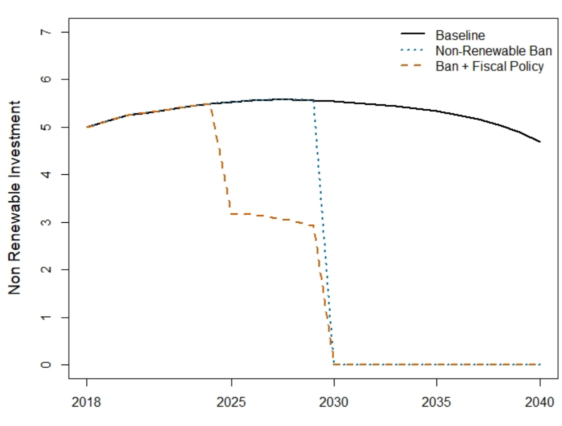
(b) Emission Level



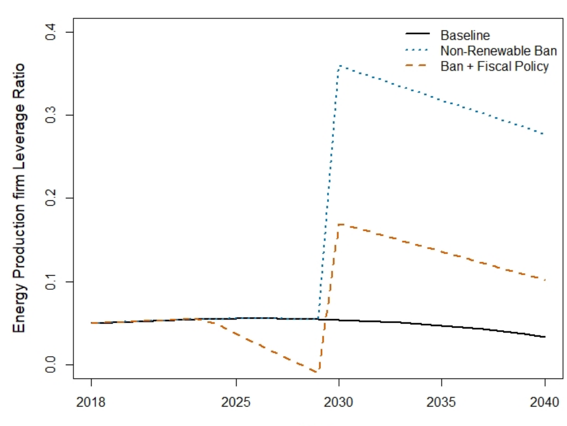
(c) Public DEBT - GDP Ratio



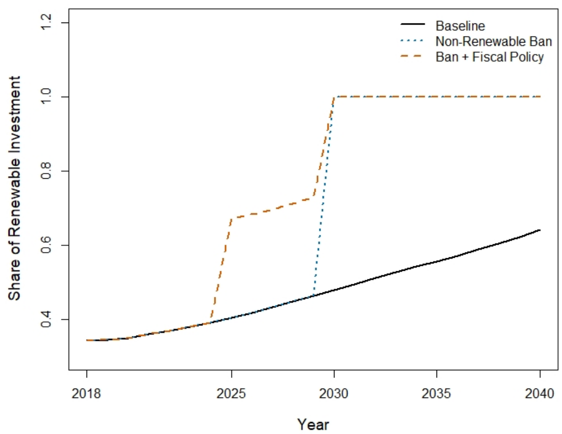
(d) Renewable Investment Level



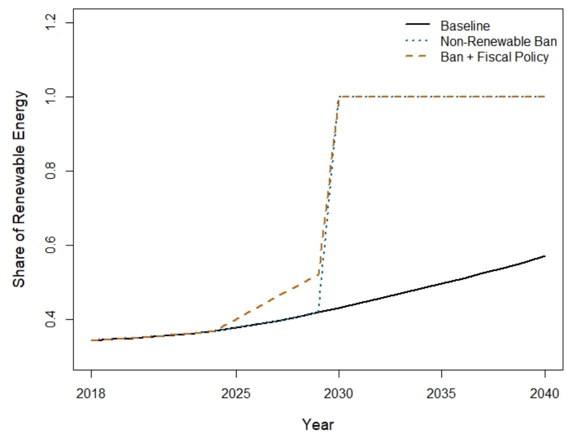
(e) Non-renewable Investment Level



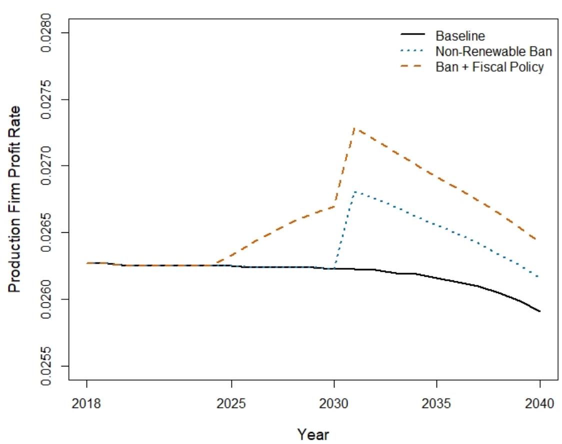
(f) Energy Firm Leverage Ratio



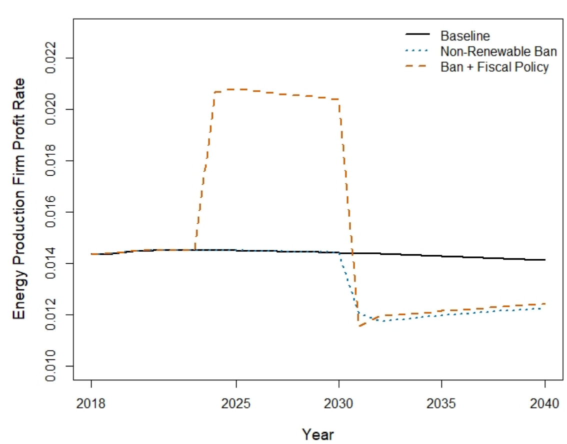
(g) Share of Renewable Investment



(h) Share of Renewable Energy



(i) Production Firm Profit Rate



(j) Energy Production Firm Profit Rate required to take out loans to cover their renewable investment. Finally, the profit rate of energy production firms fall while the profit rate of production firms rises (Figures 5i and 5j). This is driven by the levelised cost of renewable capital being lower than that of non-renewable capital. As energy firms capital becomes more renewable, the overall cost of energy production falls. Energy is priced on a fixed mark-up over costs, hence this causes a fall in the energy price which decreases the profits of energy production firms who sell the energy while increasing the profit rate of the production firms who are required to buy it.

The introduction of a fiscal stimulus between 2023-2030 slightly reduces the spike in renewable investment as energy production firms are incentivised, due to lower costs, to shift towards renewable investment earlier. This is driven by firms having greater profits for investment, due to direct government spending, as well as renewable/non-renewable capital purchase subsidies/taxes incentivising firms to invest a larger proportion of profit into renewable capital. The magnitude of this effect is therefore dependant on the scale of the fiscal policy itself. However, even under extreme scenarios (75% subsidy/tax and 10% of output spending in the energy sector), the spike is still large as energy firms over this period continue to invest heavily in non-renewable capital. Hence energy production firms are required to increase their level of loans significantly when the non-renewable ban comes into effect. The fiscal stimulus does serve to almost halve the maximum leverage of energy production firms during the transition as they use the extra profits from the fiscal stimulus to deleverage before 2030 and the subsidy to renewable capital purchase means they require less finance to purchase renewable capital in 2030. In these simulations, the fiscal stimulus does have a long run positive effect on output with output growth now being higher over the period while the government debt-GDP ratio (Figure 5c) remains lower than the baseline scenario, driven mainly by the higher output level.

These result should be viewed with some caution, however. There are several selected model parameters which can affect these results, including the depreciation rate of capitals (δ_C,δ_R,δ_N), respective firms investment response to profit rate and utilisation (α_{1C},α_{2C},α_{1E},α_{2E}), household propensity to consume out of income (c_1) and banks rate of retained profit (s_B). These parameters were set using best guess estimates and comparable values from related studies, therefore it is important to assess whether the above results are sensitive to changes in these values. Most of the results above stand even when these parameter values are significantly changed with the exception of the final result around the long run affect of the fiscal stimulus. It is found that whether the long run affect of this policy leads to higher output growth and a lower debt-GDP ratio is affected by parameter choices, particularly the responsiveness of conventional firm investment to profits (α_{1C}) and, to a lesser extent, household propensity to consume out of income (c_1). This is not unexpected as both these parameters serve to affect the size of the fiscal multiplier. A high α_{1C} and/or c_1 value results in the fiscal stimulus having the long run positive effect of output growth and the debt-GDP ratio seen above, however low values of either will lead to the opposite effect. As the effect is more pronounced for changes in α_{1C} we include sensitivity analysis for this parameter in Appendix A.

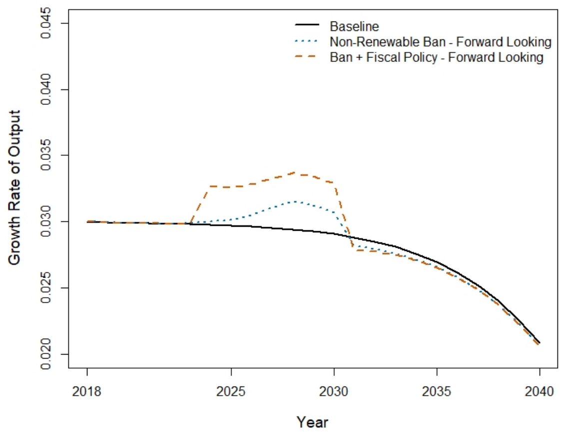
Overall, by design, the policy is successful in reducing the emission level (Figure 5b) in the energy production sector [3] which is required to be zero once the non-renewable ban is implemented, due to the removal of all non-renewable energy capital. However, these results do highlight several potential issues. This model has been constructed without credit rationing such that firms will be granted any level of loans they demand. In reality, firms will demand loans which banks may or may not choose to grant. Furthermore, banks may change their interest rates which are fixed in this model. Given that energy production firms increase their demand for loans so drastically it is likely that banks may not be prepared to grant all the loans they desire. This would lead to a lower renewable investment level than what would be needed to replace the now useless non-renewable capital which in turn would likely lead to energy supply problems which would then constrain production firms and affect overall output and macroeconomic stability. However, it has been assumed for these results that firms do not anticipate the future non-renewable capital ban, if instead the forward looking investment approach, described is section 3.6, is used then the results change significantly as shown in the following section.

4.3.2 Results with forward looking energy investment

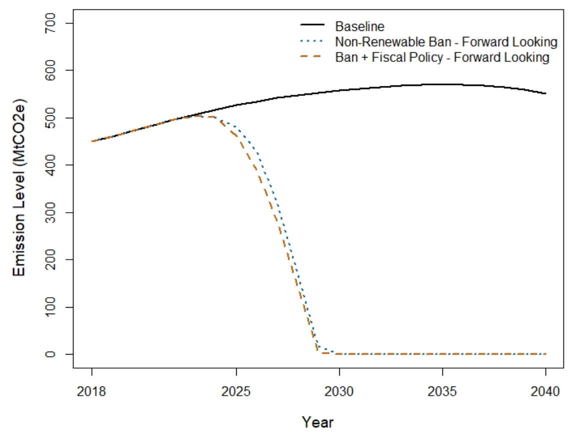
Figure 6 shows the results of the simulations with forward looking investment in the energy production sector.

[3]For clarity, emissions in this model are assumed to all be generated within the energy production sector and hence emissions from transport, household heating, farming and other sources are not accounted for. In reality, regulation of the energy production sector would not be expected to eliminate all emissions.

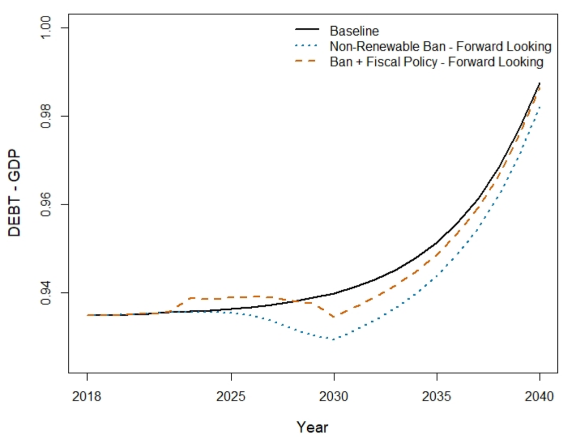
Figure 6. Effects of the implementation of a non-renewable energy ban with forward looking investment in the energy production sector.



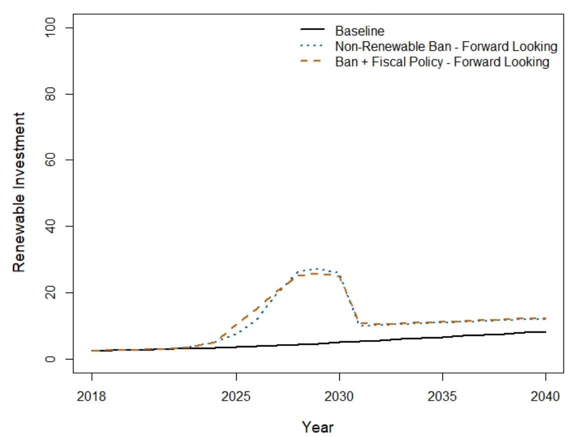
(a) Growth Rate of Output



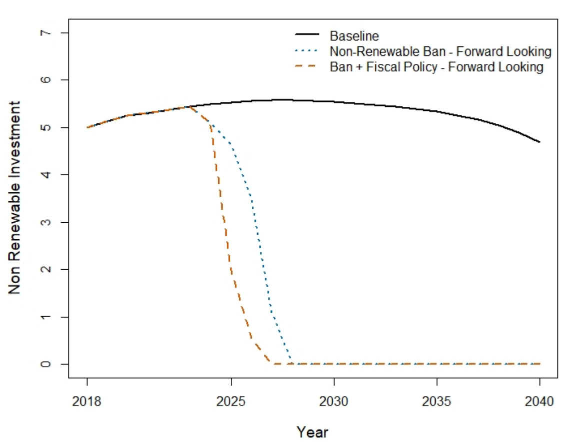
(b) Emission Level



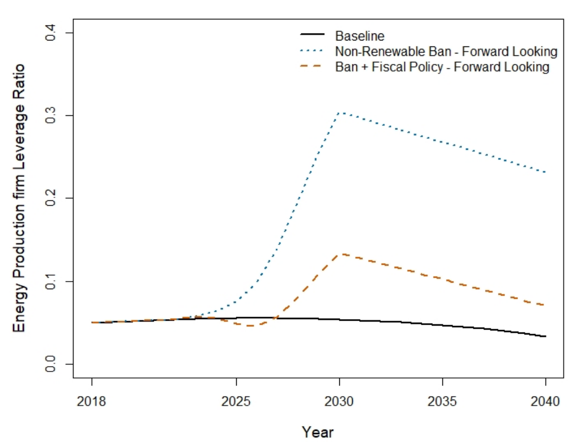
(c) Public DEBT - GDP Ratio



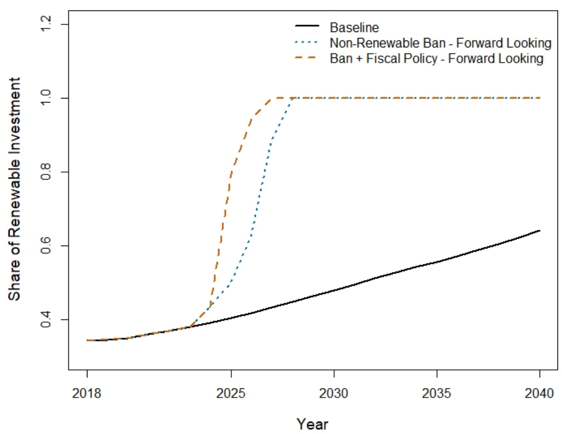
(d) Renewable Investment Level



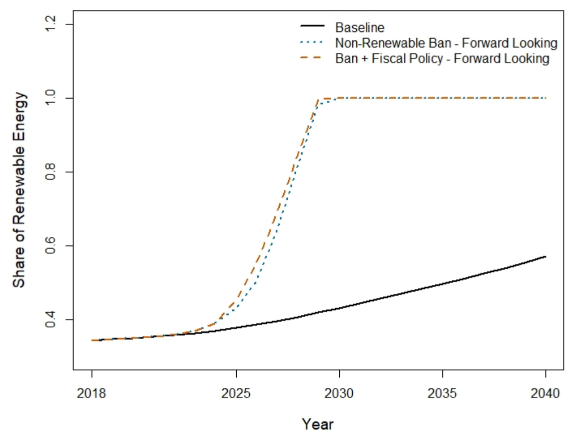
(e) Non-renewable Investment Level



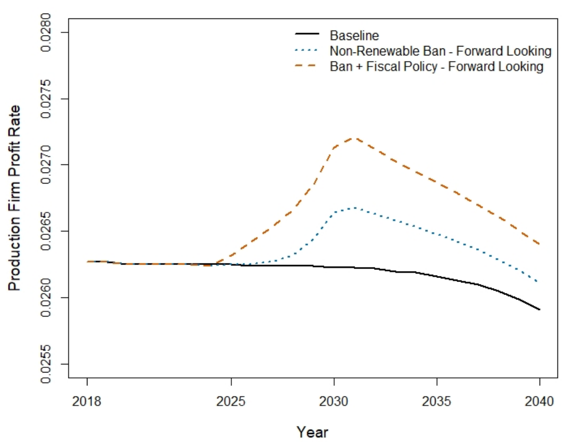
(f) Energy Firm Leverage Ratio



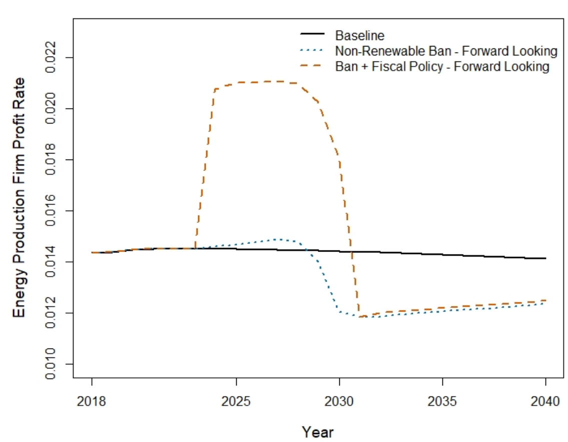
(g) Share of Renewable Investment



(h) Share of Renewable Energy



(i) Production Firm Profit Rate



(j) Energy Production Firm Profit Rate

The introduction of forward looking renewable investment causes significant differences in the simulation results. Most significant is the change in renewable investment levels which, under both policy regimes, begin to increase in 2023 as soon as regulation is announced and peak at the considerably lower level of around $27 billion (Figure 6d). This also results in a swifter energy transition with emissions levels falling sooner than in the previous simulations (Figure 6b).

The fiscal stimulus serves to lower emissions slightly faster than regulation alone, however the main impact is to energy firm profit rates (Figure 6i) and their leverage ratio (Figure 6f). During the fiscal stimulus period of 2023-2030 energy production firms profit rates are increased significantly, as in the non-forward looking case. Without forward-looking investment energy production firms used the extra profit to deleverage, however they now use it to directly fund renewable investment resulting in the smallest increase to energy firm leverage ratio of all scenarios. Finally, as in the previous results, the fiscal stimulus results in a lower Debt:GDP ratio than the baseline scenario (Figure 6c) . This is again dependent on parameter values however, as shown by the sensitivity analysis in Appendix A. Hence, proper empirical estimation of these parameters would be required to accurately assess how the policy would affect these variables.

5 Discussion

As a policy, banning the use of non-renewable energy at a certain point is perhaps the only way of ensuring a complete green energy transition, with the policy maker choosing the exact date at which energy emissions must cease. While effective for emission reduction, such a policy imposes a strong requirement on energy production firms which could cause negative knock on effects throughout the economy. In these simulations no form of regulation causes significant long-term issues for the macroeconomy, the growth rate of output is either above or only slightly below the baseline scenario, with stable firm profits and in all cases a positive effect on the governments' debt:GDP ratio. However, there are several limitations to this model which could affect this conclusion.

As mentioned already, there is no credit rationing by banks within this model with banks providing all demanded loans to firms. There is, however, empirical evidence that credit supply is likely to fluctuate. In particular, Lown and Morgan (2006) suggest that credit rationing occurs as a result of rising loan levels, such that when loan levels are higher banks are likely to tighten lending standards and issue fewer new loans. Such behaviour would undoubtedly impact the results presented above. In all cases energy production firms are required to increase their leverage ratio in order to cover the required renewable energy investment. Only in the case of forward-looking investment and a fiscal support package is the leverage ratio increase less extreme, and therefore less likely to be seriously impacted by credit rationing. It can be concluded that a non-renewable ban would require energy production firms to receive financial support during the transition period, with targeted fiscal policies being a promising approach. This model could be extended by explicitly incorporating credit rationing, as has been done by Dafermos, Nikolaidi, and Galanis (2018), with this being a promising area for future research with this modelling approach.

A key innovation of this SFC model is the incorporation of forward-looking investment decisions for energy production firms. While firms would be expected to alter their investment strategy when provided with forward guidance on regulation policies, it is not clear what form this would take. It has been assumed that energy production firms spread their energy investment across the years preceding the ban in order to fully replace existing non-renewable capital with renewable capital. This may be too optimistic an assumption as certain energy production firms may instead leave the industry or even seek to produce more non-renewable energy in order to use all non-renewable resource stock they have prior to the ban coming into effect. Therefore, there could be negative impacts such as higher emissions in the lead up to the ban or energy shortages after the ban comes into effect. The model, and forward looking structure, would have to be expanded to incorporate such effects. These considerations again highlight that a mix of policies may be required in addition to any regulation, as firms would likely need assistance to transition along with either incentives, or further regulation, to prevent higher emission levels prior to the ban coming into effect.

A further interesting result of the green energy transition is a fall in the profit rate of energy production firms due to the lower costs of renewable capital. A driving factor behind this result is the fixed mark-up adopted by energy production firms when pricing energy. Eichner (1973) presents an alternative approach where the mark-up is determined by the demand for and supply of investment funds to the firms. Therefore, price leading firms in oligopolistic industries will increase their mark-ups in order to increase cash-flow when they are expanding investment. Such an effect could have interesting implications for the model. Firstly, it could lead to energy firms funding more of their investment through profits as opposed to loans and therefore being less reliant on a fiscal stimulus, additionally if the higher mark-up persisted till after the non-renewable ban then it may cause a long run higher rate of profit for the energy production sector. Again, the incorporation of such an effect would be an interesting extension to the model.

While the analysis presented does provide some interesting results, its limitations should not be ignored. Many of these theoretical limitations have already been mentioned, such as a lack of credit rationing by banks and fixed mark up pricing by firms. Other assumptions include the lack of household investment in financial assets, the instantaneous conversion of investment into capital and the lack of transition effects from the elimination of sectors. Households only holding deposits as an asset reduces the scope for household investment behaviour causing more complicated, potentially destabilising, financial effects which would likely impact a green transition. The instantaneous conversion of investment flows to capital means energy production firms can rapidly transition from non-renewable to renewable energy production, however, energy capital typically takes a significant time to build which would cause this transition to be lagged and be slower than presented in the simulations above. The lack of transition effects is caused by not having a disaggregated energy production sector and therefore not accounting for certain sectors disappearing in a green energy transition, this could be remedied by disaggregating parts of the energy production sector in future models.

All models must balance specificity with tractability and while I believe the assumptions of this model do not compromise the core results there are certainly areas where the incorporation of different effects could be useful. Aside from theoretical extensions, the model could benefit greatly from added empirical validation. This empirical approach could take the form of estimating key variables such as investment's sensitivity to the rate of profit or it could employ the "bottom up" empirical SFC approach of G. Zezza and F. Zezza (2019) where the model is built from the national accounting data of a specific economy. This second approach, while requiring extensive data, would be highly beneficial for the analysis of industrial policy, as building a model from national accounting data would allow for greater granularity in analysing the impacts of policies on different sectors. This method would also align the model far closer to a single country's economy which would make it more useful for assessing possible industrial policy approaches, which are likely to have different effects depending upon the economy in which they are applied. A final possible extension would be the use of a more integrated climate module by employing the physical stocks and flows approach of Dafermos, Nikolaidi, and Galanis (2017). This would turn the model into an ecological macroeconomic model and allow it to better incorporate how climate change would affect the real economy.

6 Conclusion

Industrial policy, in the form of a ban to non-renewable energy production, appears to be an effective option for driving a green energy transition. The results of the simulations suggest that governments can use targeted fiscal policy in order to support firms through the transition, with the best results for both the climate and the economy being achieved in the regulation plus fiscal policy scenarios. This observation is similar to that of Dafermos and Nikolaidi (2019), who find a combined mix of fiscal policies to be more effective than any single policy analysed in isolation. Given the pressing issues highlighted by the IPCC (2021), the time for "moderate" policies is likely over. While the regulation in this dissertation is shown to have potentially destabilising effects, it is also shown that these can be mitigated through forward guidance and government fiscal support. Therefore, green industrial policies should be explored further and applied, as part of a broader set of policies, to achieve ecological sustainability.

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Appendix A: Sensitivity Analysis

Sensitivity analysis on the effects on output growth and the Public Debt-GDP ratio of changing the responsiveness of production firm investments to a change in profits (α_{1C}) is shown in Figure 7. The central case uses the value of α_{1C} that was used in the simulations (0.5). Case I represents low responsiveness to profit where α_{1C} is decreased to 0.25 whereas Case II represents high responsiveness where α_{1C} is increased to 1. In the table, Baseline refers to the baseline scenario with no policy, REG refers to regulation, FIS refers to the fiscal policy mix and FL refers to whether energy production firms adopt the described forward looking behaviour. A key observation from Figure 7 is that fiscal policy is effective in stimulating growth and reducing the Public Debt-GDP ratio when firms responsiveness to profit is high but that the policy has the opposite effect if it is low.

Figure 7. Sensitivity analysis of investments responsiveness to profit

	2030			2040		
	Case I	**Central Case**	**Case II**	**Case I**	**Central Case**	**Case II**
Growth rate of output (%)						
Baseline	2.909	2.908	2.905	2.098	2.086	2.061
REG	4.066	4.064	4.062	2.059	2.054	2.048
REG + FIS	4.104	4.123	4.162	2.053	2.056	2.068
REG + FL	3.059	3.069	3.088	2.067	2.060	2.050
REG +FIS +FL	3.257	3.288	3.349	2.058	2.060	2.069
Public Debt – GDP Ratio						
Baseline	0.939	0.940	0.940	0.986	0.988	0.989
REG	0.926	0.927	0.927	0.981	0.980	0.978
REG + FIS	0.933	0.932	0.931	0.989	0.985	0.977
REG + FL	0.930	0.929	0.929	0.983	0.982	0.980
REG +FIS +FL	0.935	0.935	0.933	0.990	0.986	0.978