Energy Economics 138 (2024) 107844

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Trilemma or Trinity? The nexus of economic growth, circular economy and net zero

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ARTICLE INFO

JEL classification:
O44
Q43
Q52
Q55
Q58

Keywords:
Net zero
Growth
Circular economy
Pollution
Capital
Recycling

ABSTRACT

How can economies achieve economic growth without causing negative environmental externalities? There are two aspects to the long-standing debate on 'sustainable growth'. A first-best solution is for economies to replace fossil fuels with renewable energy sources, mitigating carbon emissions. A second-best solution is to also adopt efficient waste management, recycling residual waste and pollutants (including hard-to-abate carbon) from production (circular economy). We establish a simple growth model that integrates three fundamental pillars of economics: (i) the net zero carbon target in environmental economics (ii) the circular economy, dealing with waste management in resource economics, and (iii) sustainable growth, in growth economics. We argue that growth, circularity and net zero emissions present a trinity of solutions to the sustainable growth problem, showing that the circular economy is a necessary condition for achieving net zero. We show that an economy with 'active' environmental policy achieves net zero faster than one with 'passive' policy, and also eliminates carbon emissions.

1. Introduction

How can economies achieve economic growth without causing negative environmental externalities? This critical question has occupied the minds of researchers and policymakers alike over the past few decades, leading to debates around 'sustainable growth' - broadly defined as economic growth in the present that does not reduce the prosperity of future generations (Le Kama, 2001; Beltratti et al., 1994).

There are two aspects to sustainable growth: the first relates to the overwhelming dependence of economies on fossil fuels for the production of output and their growth- for example, over 80% of global primary energy consumption today is still met by fossil fuels (IEA, 2022). The economic theory of exhaustible resources states that fossil fuels (e.g., oil, gas, coal) are a non-renewable, depletable resource; e.g., extracting a barrel of oil from the ground today leaves less resource for future generations. The theory proposes an optimal dynamic extraction path which takes this intertemporal characteristic into account (Hotelling, 1931).

In practice, however, the depletion of fossil fuels and notion of supply-driven 'peak oil' has to date been disproven, as theory does not account for the role of technological innovation. Namely, fossil fuel producers/firms use sophisticated technologies to discover and extract deeper and more difficult deposits of fossil fuels (e.g. the 'shale oil and gas revolution' in the US) and are likely to continue to do so, for as long as incentives to extract and produce fossil fuels profitably exist. This contradicts the hypothesis on 'peak oil supply' or claims that "the oil will run out".

The second aspect of sustainable growth is particularly relevant in a climate-constrained world: negative environmental externalities. Conventionally, these refer to the pollution of the natural environment resulting from economic growth -e.g. air, water and soil - and 'sustainable growth' is growth with minimised (ideally eliminated) pollution (e.g. through reducing waste, and recycling). Specifically, carbon emissions from fossil fuels and associated supply chains have severe consequences for the climate. More than a century of burning carbon-emitting fossil fuels, as well as unequal and unsustainable energy and land use, has led to global warming of 1.1 °C above pre-industrial levels (IPCC, 2023).

In response, there has been an acceleration of ambitions on climate action, with 140 countries (covering 90% of global GDP) adopting or considering targets to achieve net zero carbon dioxide ($C0_2$) emissions by mid-century (CAT, 2022). This is driven by evidence from the Intergovernmental Panel on Climate Change (IPCC, 2018) stating that limiting global warming to 1.5 degrees Celsius to avoid dangerous

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https://doi.org/10.1016/j.eneco.2024.107844
Received 1 October 2023; Received in revised form 2 August 2024; Accepted 16 August 2024
Available online 22 August 2024

climate change would require 'global net human-caused emissions of $C0_2$ to fall by about 45% from 2010 levels by 2030, reaching "net zero" around 2050'. These statements are in line with the goal of the Paris Agreement (UNFCCC, 2016). Achieving net zero entails reducing emissions from economic activity to as close to zero as possible, and balancing any residual emissions (e.g. from hard-to-abate sectors) through carbon removal, resulting in a net-neutral impact on the climate. Given the above, growth based on fossil fuels is not sustainable (IPCC, 2023).

The challenge therefore is to achieve sustainable growth that does not rely on depleting carbon-emitting exhaustible natural resources with serious negative environmental externalities. Two potential solutions present themselves. As a first-best solution economies can replace fossil fuels by developing renewable (zero-carbon) energy sources such as solar and wind energy for electricity production, and its derivatives such as renewable hydrogen[1] and renewable ammonia[2] for hard-to-abate sectors. Secondly, economies can adopt methods, such as recycling, to convert waste and pollutants from the production of economic output including carbon and reintroduce them into the production process in a circular loop (e.g. through Carbon Capture, Storage and Use or CCUS).[3] In resource economics, the latter approach is referred to as "circular economy".

The research question posed at the beginning of this paper can thus be rephrased to: is sustainable economic growth achievable in a net zero, circular economy?

In this paper, we establish a simple neoclassical growth model that integrates three fundamental pillars of economics: (i) the net zero carbon target, which addresses the challenges of environmental economics, (ii) the circular economy, which deals with waste management in resource economics, and (iii) sustainable growth, a research topic in growth economics. Our model provides a representation of the dynamics between these three pillars, offering policymakers a framework or tool of analysis, in terms of balancing trade-offs and priorities, and a set of possible outcomes.

Our model explores two scenarios: (i) passive policy of carbon abatement and recycling, where the government sets fixed targets for the rate of carbon capture and recycling, and (ii) active policy, where the government mandates that emissions reduction (through increasing the stock of renewable resources), recycling, and CCUS of residual hard-to-abate carbon, must increase over time at a certain rate.

Our growth model presents three important findings. First, to ensure a smooth transition from non-renewable to renewable growth paths, it is essential that the production technology allows for substitution between these two types of resources. Technically, this requires the production function to have an elasticity of substitution between non-renewable and renewable resources exceeding unity. The higher the value of this elasticity, the greater the growth potential from non-renewable to renewable substitution. Second, net zero carbon emissions cannot be achieved solely with the substitution of non-renewable with renewable resources. We show that it is essential to have efficient waste management, and technologies and environmental policies that prioritise waste recycling. This can be achieved through circular economy. This might include technologies such as carbon removal, but they are yet to be proven at scale and would require robust regulatory frameworks to ensure that they do not preempt 'mitigation' as the first-best solution. Third, an economy following an active environmental policy (e.g. with targets for recycling, pollution abatement, or investment) will achieve the net zero carbon target faster than one with a passive government policy (e.g. a singular economy-wide net zero emissions target). Governments may rely on either market, or regulation-based approaches while designing environmental policies.

The next section reviews the literature on the nexus between net zero, circular economy and sustainable growth. Section 3 develops the model and main findings, and Section 4 contains discussion and policy implications. Section 5 concludes.

2. Literature review

We review the literature related to three fundamental pillars of economics: (i) the net zero carbon target, which addresses the challenges of environmental economics, (ii) the circular economy, which deals with waste management in resource economics, and (iii) sustainable growth, a research topic in growth economics. We begin by briefly describing the key scholarship in the pillars. We focus on studies which have tried to address the nexus between these three pillars. We then describe an illustrative example of how an integrative framework would apply to the energy sector.

2.1. Overview

The net zero target has its origins in climate science. For any global temperature objective, there is a finite budget of carbon dioxide that is allowed into the atmosphere, alongside other GHGs (Fankhauser et al., 2022). Beyond this budget, any further release must be balanced by removal into sinks – that is, aggregate emissions are "net zero". For the Paris Agreement objective of a temperature rise of 1.5–2 °C above pre-industrial levels, the remaining carbon budget has been estimated at 250 Gigatonnes of CO_2 ($GtC0_2$) (Lamboll et al., 2023), and will shrink with each year that emissions reduction targets are missed. Net zero has been incorporated into environmental economics as a boundary condition for assessing the impact of negative environmental externalities from economic activity (Fankhauser et al., 2022).

The scholarship on circular economy (CE) shares its origins between several major schools of thought. These include: the functional service economy (or the performance economy) (Stahel, 2016); the 'cradle to cradle' design philosophy (McDonough and Braungart, 2002); biomimicry; the industrial ecology (Lifset and Graedel, 2002); 'natural capitalism' (Hawken et al., 1999); and the blue economy systems approach (Pauli, 2010; EMF, 2020). An application of CE to entire economic or industrial sectors involves the development of a cyclic system that aims to eliminate waste by turning goods that are at the end of their life cycle into resources for new ones, and by maximising the utilisation capacity of goods (e.g. by means of product-sharing, or the product-as-a-service) (Stahel, 2016; Ferasso et al., 2020). Closing material loops in industrial ecosystems can create a continual use of resources; this can, in theory, be achieved through long-lasting design, proactive maintenance, recycling, repairing, refurbishment, and manufacturing (Geissdoerfer et al., 2018; Ferasso et al., 2020). For instance, as around 25% of global energy use is estimated to serve the production of major materials, the more efficient use of these presents a significant opportunity for emissions reduction (Hertwich et al., 2019).

The traditional resource consumption model is linear: resources are extracted from natural systems to make products, and disposed once they have served their purpose, without the full value of their component materials being realised (Popplewell et al., 2019). A circular economy aims to move away from this, by designing out waste, maximising value, improving maintenance and returning materials into the cycle at the end of their lives (Popplewell et al., 2019). A transition to a circular economy aims to decouple growth from resource consumption, providing a strategy to achieve both economic and environmental goals (Popplewell et al., 2019).

There is little to no theoretical or empirical literature that directly addresses the interaction between these three concepts across the three pillars of economics discussed above. Most macro-level studies are

[1] Produced through electrolysers.

[2] Produced from renewable hydrogen using a synthesis process.

[3] CCUS involves the sequestration ('capture') of carbon emissions from source, their storage and use in the production of materials. For example 'composites' which can be used in building construction. In this way, carbon emissions are transformed into non-emitting, embodied carbon.

qualitative and do not go beyond a discussion of how the interaction between sustainable growth and circular economy has evolved over time. There are some sector-level studies which provide a closer illustration of these interactions.

Ajayi and Pollitt (2022) looks at the future growth of productivity under net zero climate change policies in the UK. It argues that while green growth and a green industrial revolution are popular concepts, they are difficult to pin down theoretically and measure empirically. Advanced economies that minimise environmental impact will struggle to grow under conventional measures of GDP (even for sectors such as electricity, in which demand is expected to grow); adjustments to GDP measurement might make a difference, but it is difficult to imagine that the difference will be large. It concludes that fundamentally, if net zero requires higher physical inputs and reduces physical output, it will be challenging to raise measured productivity.

Mastini et al. (2021) critically analyses two 'master narratives' on climate change mitigation that represent a break with traditional market-based environmental policy: the Green New Deal (GND) and degrowth. The latest articulation of the GND posits the importance of public investments for financing the energy transition, of industrial policies to lead the decarbonisation of the economy, of the socialisation of the energy sector to allow longer investment horizons, and of the expansion of the welfare state to provide social protection to citizens in the context of heightened environmental vulnerability and any economic contraction. It argues that all of these proposals are coherent with the degrowth narrative; further, that a GND should not depend on GDP growth for its financing, but rather should mobilise financial resources through the reallocation of public expenditures, the increase of marginal taxation on the top income brackets, and the public issuance of sovereign money.

Wang et al. (2023) investigates the effects of a circular economy in the generation and recycling of solid municipal waste, globalisation, linear economic growth and renewable energy consumption, on CO_2 emissions growth from 1990 to 2020 for seven major CO_2-emitting countries. It argues that top emitters should consider the treatment of municipal waste as a solution towards sustainable development, and lean towards developing sustainable and scientific waste management practices.

Noda and Kano (2021) analyse whether it is possible to simultaneously achieve continued economic growth and a zero net emission of pollution (in the sense of a zero residual amount of pollution created minus pollution abated) within the context of a growth model with endogenous fluctuations. It assumes that societies implement the 'kindergarten rule' of pollution abatement such that pollution is cleaned up as it is created, and refer to the proportion of pollution abatement expenditure in gross domestic product (GDP) for achieving zero net emission of pollution flow as the 'kindergarten rule level of abatement'. The model leads to the appearance of a no-innovation growth phase (called the Solow regime, 1974) and innovation-led growth phase (called the Romer regime, 1990) in the presence of pollution abatement. In the Solow regime, the economy experiences higher growth in consumption and a faster decrease in the kindergarten rule level of abatement, while the economy experiences lower growth in consumption and a slower decrease in the kindergarten rule level of abatement in the Romer regime.

Sectoral studies focus on net zero growth and circular economy approaches (in part or in whole) in the agriculture sector (Sarker et al., 2023), the built environment (Passer et al., 2020), the transport sector (Neves et al., 2018), and electrofuels i.e. which store low-carbon energy vectors such as hydrogen (Rusmanis et al., 2023).[4]

[4] There is also a stream of literature that is geographically focused and heavily context-specific — we do not include this literature given the theoretical scope of this paper, but relevant examples of this literature include Khalid and Jalil (2019) and Khalid et al. (2021) which find evidence of interfuel substitution between renewables and non renewables in the energy sector.

The literature is inconclusive on the relationship between sustainable growth, environmental policies and the abatement of pollution or waste. Regulation is seen as necessary to enforce environmental policies, but the conditions under which it may lead to sustainable economic growth are unclear. We seek to explore and address this gap through our model.

2.2. An example of a circular economy: Hydrogen

The energy sector, which faces unique challenges in getting to net zero, provides an example of how the growth-net zero-circular economy nexus might operate. The dominant approach to achieve net zero emissions has been to replace fossil fuels with renewables for electricity generation, as well as to improve the efficiency of energy use. Electricity production comprises the largest single source of CO_2 emissions, this strategy has led to significant gains in emissions reduction.

There are however, challenges: although governments are moving towards the renewable-based electrification of entire economic sectors as a next step (i.e. decarbonisation by 'electrons'), direct electrification may not be possible for technical and/or economic reasons, in 'hard-to-abate' industrial sectors outside of electricity generation (Sen et al., 2021). The above approach also does not account for the globalisation of trade (e.g. supply chains), and spatial dissociation between places of extraction, production, and consumption. International trade enables the costs of decarbonisation to be shifted outside national borders, creating negative externalities elsewhere.

The circular economy approach offers a potential solution to the above-mentioned challenges as it enables localised production and consumption, as well as waste recycling, by 'closing loops'.

An example is the renewable hydrogen sector. There are three routes to producing low-carbon or renewable hydrogen:

(i) Renewables-to-hydrogen can be achieved by utilising renewable electricity to split water (H_20) through electrolysis to produce hydrogen. The conversion losses in this route could be high, and under certain conditions it would make sense to utilise renewable energy directly, and 'green' hydrogen and 'green' ammonia only for hard-to-abate industrial processes, or for long-term seasonal storage (Cesaro et al., 2022).

(ii) Synthesising the renewable or green hydrogen into 'green' ammonia which can be used to balance seasonal electricity demand on the grid (through storage) or as a fuel (e.g. green ammonia in shipping), as well as in the conventional market for fertilisers (which currently uses fossil gas to produce ammonia).[5]

(iii) Waste-to-hydrogen can be achieved through producing biomethane (also known as biogas) with Carbon Capture and Storage (CCS) to capture the carbon - or Carbon Capture, Use and Storage (CCUS) which utilises sequestered carbon in the production cycle, as CCS only involves storage of carbon (e.g. geological) rather than utilisation of the carbon as an input. This would requires CCUS technology to be deployed at scale (which is not yet the case).

As observed from the review of literature, a primary condition for a circular economy is the substitutability of inputs. As 'energy' or 'electricity' are both homogeneous commodities that can be produced from fossil fuels and renewables alike, we can assume high levels of substitutability between non-renewable and renewable inputs. For instance, we can assume that renewable electricity and all its derivatives, including renewable (green) hydrogen and ammonia produced using renewable electricity, can substitute for coal, oil or natural gas-based energy production.

A secondary condition for circular economy is the minimisation of pollution from waste. Essentially, all three options above satisfy this criteria. However, option (iii) entails the possibility of some carbon

[5] Some countries like Japan are exploring the burning of green ammonia in turbines for power plants (See Rich and Hida, 2023).

as 'waste' that can only be recycled if appropriate technologies are deployed at scale. The latter may require substantial investments in scaling up, whereas options 1 and 2 are based on technologies that are arguably at higher readiness levels.[6] Evidence shows that analysts have consistently and systematically overestimated the future costs of key green energy technologies — including solar, wind, green hydrogen and electric storage (Way et al., 2022). This is because they fail to fully consider 'learning effects', also known as 'experience curves', which describe a well-known pattern in which cost declines are associated with increasing cumulative production, as each element of the production value chain accrues more 'experience'. (Way et al., 2022) develop a new, empirically-grounded forecasting method for incorporating this effect into estimates of renewable energy deployment costs and rates, applying it to historical data for solar, wind, batteries, and electrolysers used to produce hydrogen from electricity. This shows that clean energy costs will very likely continue to fall and the more widely used these technologies become, the faster this will occur.

3. A growth model of a net zero carbon circular economy

In this section, we lay out a simple Solow growth model of a Net Zero Carbon Circular Economy. For the sake of simplicity and avoiding distractions, the intertemporal choice of consumption and saving is suppressed by resorting to a simple Solow consumption-saving rule. We focus only on the production and technology side of the economy. Time (t) is discrete and starting from zero. We consider an aggregative scenario where the economy-wide production takes place with the aid of two reproducible inputs namely non-renewable (K_t^N) and renewable capital (K_t^R) and labour which is inelastically supplied. After normalising labour the per capita production of final goods is written in a standard CES production function as follows:

$$Y_t = Z_t \left[(1-\omega) K_t^{N\frac{\sigma-1}{\sigma}} + \omega K_t^{R\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

where Z_t is the total factor productivity (TFP) which is specified as

$$Z_t = \frac{A}{1 + \alpha P_t + \beta P_t^2} \tag{2}$$

with A is a positive constant. The stock of pollutants (P_t) adversely affects current TFP. This adverse effect can occur either by excessive temperature in the environment as in DICE model or adverse health effect on productivity (Golosov et al., 2014). As P_t approaches zero, the TFP reaches the upper bound A. We assume all pollutants emit carbon, contributing to global warming. In reality, there are other pollutants — such as plastics, which pollute the earth's water and soil. As this paper focuses on carbon emissions, and the net zero carbon emissions target, we abstract from these complications here.

A fraction (ν) of final output (Y_t) goes to a stock of waste (W_t) because some waste is inevitable during the production process. In other words,

$$W_t = \nu Y_t \tag{3}$$

Let a fraction θ of the waste be recycled and converted to renewable capital (K_{t+1}^R) at the end of date t. Renewable capital is also created through direct investments such as into solar and wind power generation, and hydroelectricity. The law of motion of renewable is therefore:

$$K_{t+1}^R = (1-\delta_R) K_t^R + \theta W_t + \rho Y_t \tag{4}$$

where δ_R is a fractional rate of depreciation of renewable capital, θ is the rate of recycling of waste to generate renewable which is a policy instrument. We assume a constant Solow saving rule which means that the rate of investment in renewable (ρ) is exogenous.[7]

The nonrenewable capital is extracted from fixed exhaustible resources. Let $\overline{K}^{EX}$ be the total stock of exhaustible resources. Investment in nonrenewable (I_t^N) entails extracting exhaustible resources (say crude oil). The rate of extraction (ς) is based on the principle of Hotelling's rule and it is a policy instrument.[8] Let I_t^N rise at the rate of the real interest rate. In other words,

$$I_t^N = (1+\varsigma) I_{t-1}^N \tag{5}$$

The time path of nonrenewable is thus:

$$K_{t+1}^N = \overline{K}^{EX} - I_t^N \tag{6}$$

In other words, as the amount of investment in nonrenewables increases, it draws down the fixed exhaustible resource.

The dynamics of pollution is given by

$$P_{t+1} = (1-\delta_p) P_t + (1-\theta) W_t \tag{7}$$

where δ_p is the natural pollution depletion rate. The second term, $(1-\theta)W_t$ on the right hand side of (7) is the hard-to-abate pollutants which goes to the landfill. Ideally, we want θ to reach unity someday which means all waste is recycled. Until this happens the stock of pollutants will be on a rising trend.

3.1. Net zero carbon and pollution abatement

A net zero carbon target means that net emissions must reach zero. In order to attain net zero carbon emissions, after emissions have been mitigated (reduced) to the extent possible, any residual carbon emissions (e.g. from hard-to-abate sectors) must be offset through carbon removal (e.g. carbon capture, utilisation and storage). In our stylised model, the net emission (NETCO2) is given by:

$$NETCO2_t = (1-\theta) W_t - \delta_p^* P_t \tag{8}$$

The first term, $(1-\theta)W_t$ is the waste output which cannot be abated and adds to the pollution pool. The second term, $\delta_p^* P_t$ is the extent of carbon capture which is policy determined. In principle, δ_p^* must exceed δ_p to ensure that the net zero carbon target is achieved and does not conflict with the long run growth.

Imposing the steady state net zero target, $NETCO2_t = 0$ and use of (3), gives rise to the following equation for the pollution intensity:

$$\frac{P_t}{Y_t} = \frac{(1-\theta)\nu}{\delta_p^*} \tag{9}$$

The immediate implication is that net zero carbon does not necessarily reduce or eliminate the stock level of pollution from the environment. Even if the policy authority removes the flow of carbon to the environment by setting $\delta_p^* = 1$, the residual pollution from hard to abate waste is still $(1-\theta)\nu$. Unless the recycling is done to the fullest extent (setting $\theta = 1$), the pollution cannot be entirely eliminated from the environment. This makes the circular economy a necessary condition for pollution abatement. We have the following proposition

Proposition 1. *Net zero carbon does not eliminate persistent stock pollution unless it is aided by efficient waste management.*

[6] For example, green ammonia already has a globally accessible market (e.g. in the fertiliser sector) which therefore requires an expansion in investment to rapidly increase their deployment. (See Rich and Hida, 2023).

[7] The rate of investment in renewable can also be influenced by policy. For example, the UK government uses Contracts-for-Difference auctions to procure renewable projects (e.g. wind) through auctions in which the private sector bids. However, participation in this bid is a private initiative not necessarily manadated by policy.

[8] One can assume that the government administers all the oil fields and allows it to be extracted at a rate (ς) governed by Hotelling's lemma.

3.2. Long-run growth

Long run growth or a balanced growth path is defined as a scenario where the final output (Y_t) and the stock of renewable (K_t^R) grow at the same rate while the stock of nonrenewable (K_t^N) vanishes dictated by policy. We assume that in the long run, the stock of pollution reaches zero through a package of active policies and due to disappearance of fossil fuel intensive resources which we do not explicitly model. We have the following key result.

Proposition 2. *If $\sigma > 1$, when K_t^N goes to zero, we get (1) as a limiting form:*

$$Y_t = A[\omega^{\frac{\sigma}{\sigma-1}}]K_t^R \tag{10}$$

and the balanced pollution free growth rate is given by:

$$G = 1 - \delta_R + (\nu\theta + \rho)A\omega^{\frac{\sigma}{\sigma-1}} \tag{11}$$

Proof. Use (1) to verify that

$$Y_t/K_t^R = Z_t \left[(1-\omega)(K_t^N/K_t^R)^{\frac{\sigma-1}{\sigma}} + \omega\right]^{\frac{\sigma}{\sigma-1}} \tag{12}$$

The first term in the square bracket in (12) approaches zero if and only $\sigma > 1$. Since P_t in (7) approaches the steady state zero, it means (12) approaches (10). Next rewrite (4) as

$$K_{t+1}^R/K_t^R = (1-\delta_R) + \theta\nu(Y_t/K_t^R) + \rho(Y_t/K_t^R)$$

which proves (11). □

A few observations are in order. First, the long run growth rate, (11) is rising in ω which means growth is higher in an economy with a greater renewable bias in the technology. Second, the long run growth rate is rising in σ. In other words, the greater the substitutability between nonrenewable and renewable capital, the higher the long run growth rate. Third, the long run growth rate is higher if recycling rate θ and investment rate ρ are higher. Fourth, the long run growth rate in a circular economy (with $\nu > 0$) is higher than in a linear economy with $\nu = 0$. The last two features of the long run growth highlight the importance of a circular economy for growth potential.

So far we have described the properties of long run (balanced) growth path. We next turn our attention to the short run (or transitional) growth properties of our model circular economy model. Using (1) we can write the short run growth equation as follows:

$$\frac{Y_{t+1}}{Y_t} = \left(\frac{Z_{t+1}}{Z_t}\right)\left[\frac{(1-\omega)\left(\frac{K_{t+1}^N}{K_{t+1}^R}\right)^{\frac{\sigma-1}{\sigma}} + \omega}{(1-\omega)\left(\frac{K_t^N}{K_t^R}\right)^{\frac{\sigma-1}{\sigma}} + \omega}\right]^{\frac{\sigma}{\sigma-1}}\left(\frac{K_{t+1}^R}{K_t^R}\right) \tag{13}$$

Over time as the economy traverses along the short run path, as the stock of pollutants (P_t) approaches the steady state, the first term ($\frac{Z_{t+1}}{Z_t}$) which is the TFP ratio approaches unity. As long as $\sigma > 1$, the second term also approaches unity as the ratio of nonrenewable to renewable resources decreases, and the second square bracket term approaches unity. The economy converges to the balanced growth path where output and renewable grow at the same rate. The time to convergence depends on the intensity of policy to eliminate nonrenewable which is summarised by the parameter (ς) in (5).

3.3. Illustrative simulation

We have four policy targets, namely (i) net zero carbon, (ii) efficient waste management, (iii) sustainable renewable growth, (iv) time to convergence. We have four policy instruments, namely (a) pollution removal (δ_p), (b) rate of recycling (θ), (c) rate of extraction of

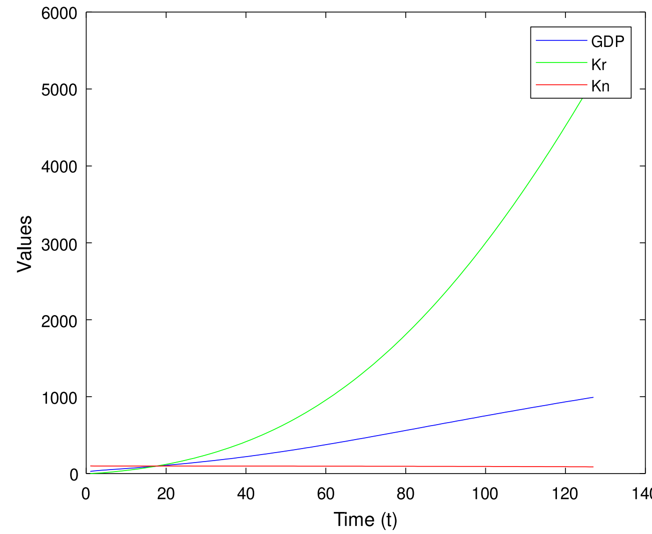

Fig. 1. Simulation of the GDP, Renewable, Nonrenewable

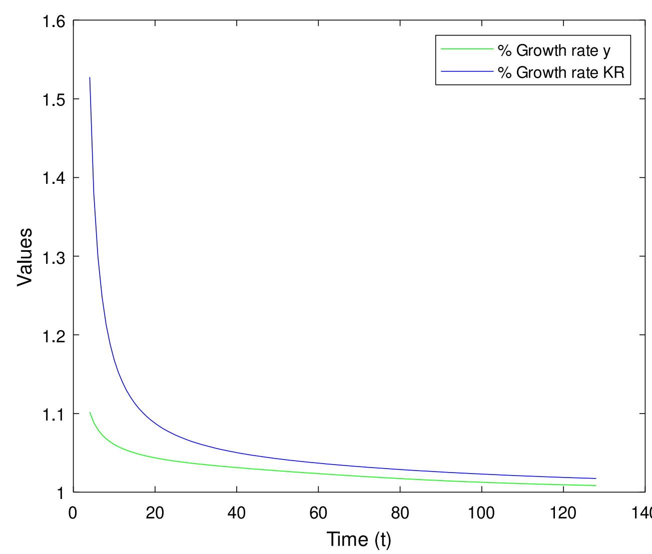

Fig. 2. Simulation of the Growth rate output and renewable

non-renewable (ς) and, (d) the elasticity of substitution between nonrenewable and renewable (σ). We report the results of a few simulation experiments regarding the effects of tinkering with these instruments on our targets. The time unit is a quarter. Given that 2050 is the target year for net zero, we set $T = 128$ as our time span although that does not necessarily mean that the economy converges to long run growth path in year 2050.

For illustration, we set the structural parameters at the following levels. $A = 1, \alpha = 0.01,\ \beta = 0.02, \omega = 0.5,\ \nu = 0.05,\ \rho = 0.1, \delta_R = 0.001$. The four policy instruments are set at the baseline levels, $\zeta = 1.02$, $\delta_p^* = 0.9$, $\theta = 0.9$, $\sigma = 2$. Starting from initial conditions where $K_R = K_N = P = 1$, we trace out the time paths of the economy. The stock of exhaustible resources $\overline{K}^{EX}$ is fixed at 10. Figs. 1 through 4 plot the time paths of GDP, renewable and nonrenewable. Over time the economy grows and approaches the balanced growth path. Nonrenewable resources decline in use both in level and in proportion to renewables.

Figs. 5 and 6 plot the carbon intensity and the carbon level in the economy. Although carbon intensity falls, curiously the absolute level of carbon does not fall. For reduction in carbon level, more proactive policy intervention is necessary, which we discuss later.

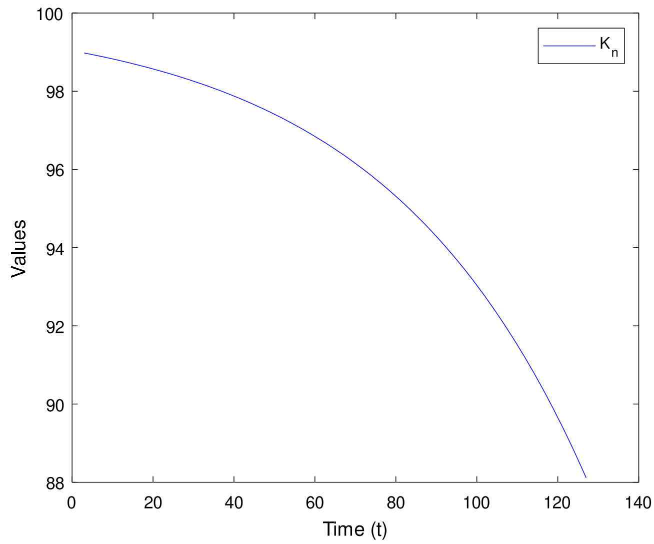

Fig. 3. Stock of nonrenewable

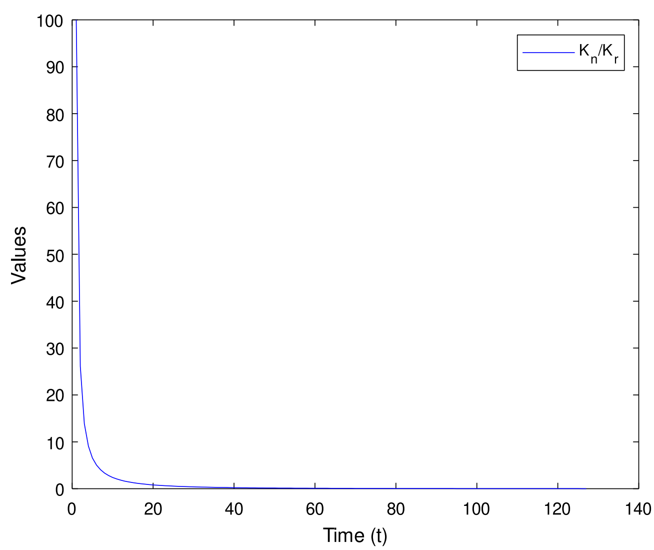

Fig. 4. Ratio of nonrenewable to renewable

Table 1
Sensitivity of time to convergence to elasticity of substitution between N and R.

σ	2.0	2.5	3.0	3.5
T	61	49	43	39

How fast does the economy converge to the long run growth path? Our sensitivity analysis suggests that the most crucial parameter that determines the time to convergence is the elasticity of substitution (σ) between nonrenewable and renewable. Table 1 reports the time to convergence for various values of σ. The higher the elasticity of substitution between renewable and nonrenewable, the faster the time to convergence. For $\sigma = 3.5$, the economy converges to a renewable and net zero growth path in about ten years.

Table 2 reports the sensitivity of the long run growth rate of GDP with respect to θ. Greater recycling has a notably positive growth effect. The sensitivity of growth to recycling highlights the importance of circular economy in influencing growth. Table 3 reports the sensitivity

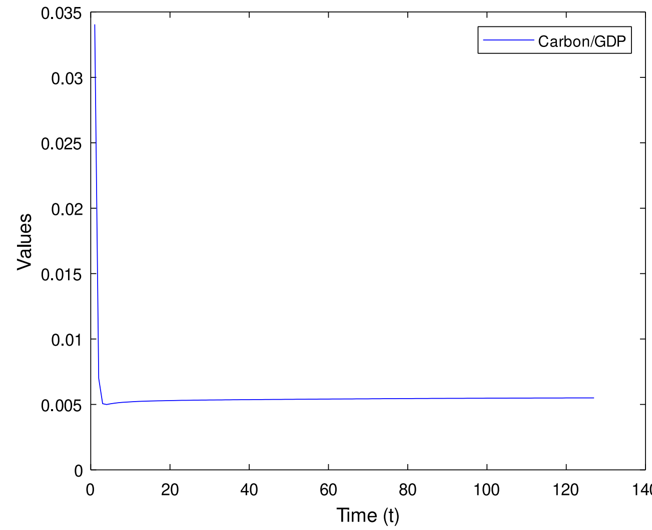

Fig. 5. Carbon Intensity

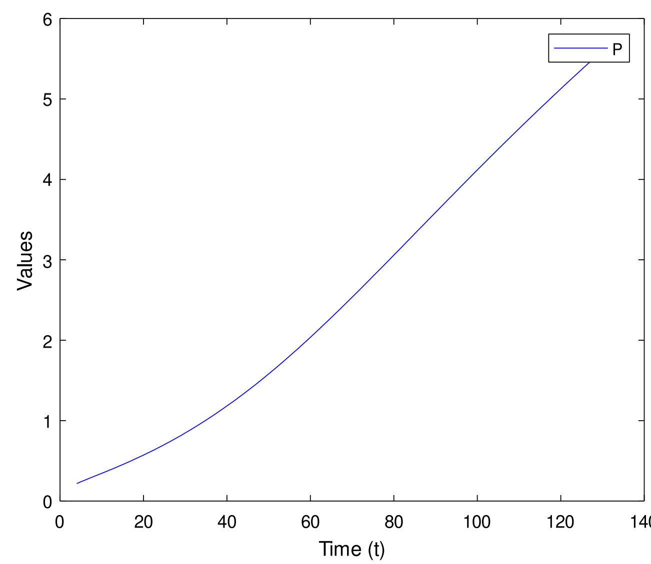

Fig. 6. Carbon

Table 2
Sensitivity of growth rate to recycling of waste.

θ	0.3	0.5	0.7	0.9
Long run growth rate	1.52%	1.77%	2.03%	2.28%

Table 3
Sensitivity of growth rate to the renewable-nonrenewable substitution.

σ	2	2.5	3.0	3.5
Long run growth rate	2.28%	2.89%	3.26%	3.35%

of growth to increase in the elasticity of substitution between nonrenewable and renewable. The greater degree of substitution boosts the long run growth rate.

3.4. Towards a more proactive pollution abatement and waste management policy

As above, we discussed the effects of environmental policy when the government sets some policy instruments with a target to attain pollution free sustainable growth. The policy implication is that waste

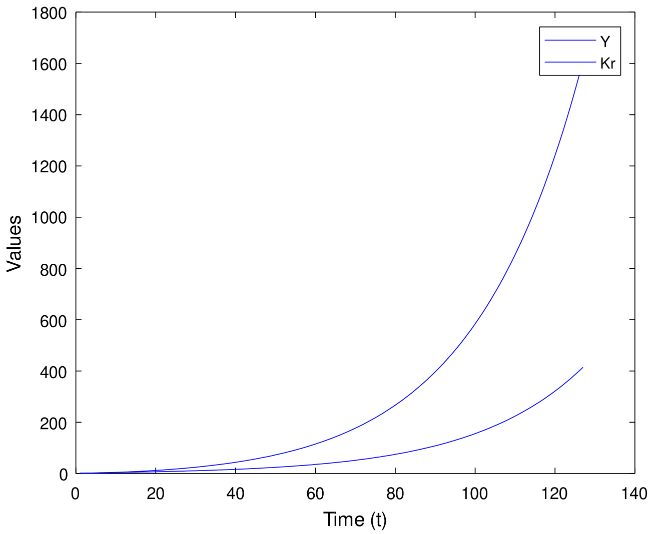

Fig. 7. Simulation of the GDP, Renewable

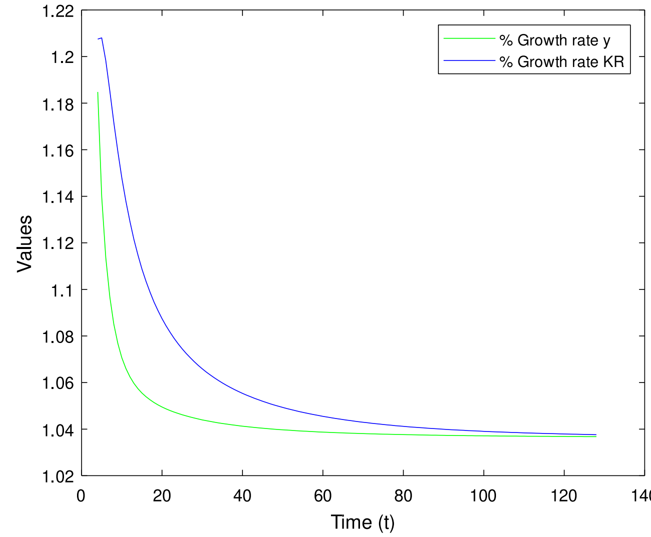

Fig. 8. Simulation of the Growth rate output and renewable

management in a circular economy environment is crucial to attain these goals. One undesirable feature of the policy environment is that although the net zero carbon target is achieved with a decline in pollution intensity, the level of pollution (carbon) does not decrease as seen in Fig. 6. To lower the carbon level in the economy, more proactive environmental policy is needed where the government takes direct control by mandating a time path of pollution removal and recycling. We give here an example of such proactive policy environment. The government lays out a path for θ_t and δ_{pt} as follows:

$$\delta_{pt} = 1 - \frac{1}{\lambda_1^t} \tag{14}$$

and

$$\theta_t = 1 - \frac{1}{\lambda_2^t} \tag{15}$$

where $\lambda_1 > 1$ and $\lambda_2 > 1$. Given these two time paths, it is guaranteed that δ_{pt} and θ_t asymptotically approach unity. The higher the sizes of λ_1 and λ_2, the greater the proactiveness of the authority to adhere to zero as well as net zero carbon.

This is the first best environment because the long run growth rate (11) is maximised when θ_t approaches unity. For illustration, fix the parameters λ_1 and λ_2 at 2.0. Given the same values for the other baseline parameters, the long run growth rate settles at 3.65%. The time paths of the economy are plotted in Figs. 7 through 10. The economy smoothly lands in the long run carbon free growth path. What is noteworthy is that the stock of carbon (Fig. 10) also declines to zero very quickly in this environment.

4. Discussion and policy implications

Our model provides a representation of the dynamics between net zero carbon, sustainable growth and circular economy, offering policymakers a framework of analysis with which to design policy that can balance trade-offs and priorities, and map a set of possible outcomes. It presented two environmental policy scenarios: (i) passive policy, and (ii) active policy. Our results suggest that net zero emissions can be achieved faster with sustainable growth in a circular economy framework, with policy intervention in four areas: policies increasing the elasticity of substitution between non-renewable and renewable capital; policies increasing the rate of recycling; policies promoting pollution removal (including of hard-to-abate carbon emissions); and, policies disincentivising investments into nonrenewables.

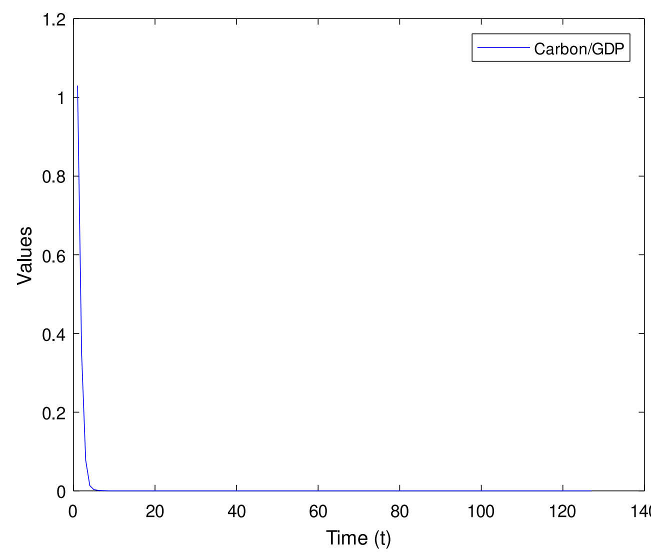

Fig. 9. Carbon Intensity

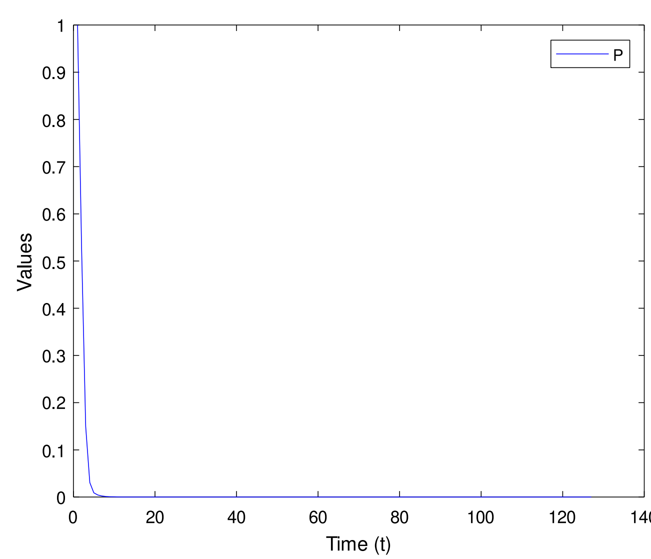

Fig. 10. Carbon

We consider the first and fourth above as interchangeable objectives; a higher elasticity of substitution might reflect lower investment in nonrenewables, and vice versa. Governments face choices in the types of instruments they may adopt to achieve their policy objectives: in neoclassical economics, a distinction is made between market-based approaches and regulation (Swaney, 1992). In theory, both approaches should lead to an efficient outcome. In practice, regulatory approaches assume that a policymaker has access to perfect information to set policies that result in optimal outcomes, whereas this is not always the case; the costs of compliance to regulatory interventions can also be high. Market-based approaches utilise economic incentives to enable market participants to reveal their preferences and enable information availability; further, in addition to reducing compliance costs and promoting technical innovation, market-based policies may be less easily manipulated by narrow interests (Swaney, 1992).

In our model, a passive policy scenario may be one that reflects a market-based approach, in which the government's role is limited to creating enabling conditions for markets to function efficiently and deliver least-cost outcomes. For instance, in order to promote pollution removal, governments may introduce tradeable pollution permits-i.e. by setting an industry limit for pollution, and then allowing firms in the industry to determine how much they are willing to pay to pollute. An illustration of such an approach is the European Union's Emissions Trading System (ETS). 0ver time, the government could reduce allocations of permits in order to raise their price and incentivise more firms to switch away from non-renewable inputs.

An active policy scenario, such as the one we describe in our model, could involve government introducing measures on top which limit investments in polluting sectors of the economy, and progressively tightening these limits, often working to a set timeline. For example, the UK's Climate Change Act of 2008 has set 'carbon budgets' every 5 years, which progressively become smaller as the country gets closer to its 2050 net zero target, with the aim of incentivising economic agents to ramp up mitigation and abatement activity. A carbon tax is another example of a regulatory approach, although there are many issues to be considered in its incidence, design, and utilisation of revenues (Timilsina, 2022). For instance, the literature shows that there may be a trade-off between efficiency and equity in the case of imposing an economy-wide carbon tax, as the regressivity of the tax would imply that the lowest-income households which spend a proportionally larger share of household income on goods and services are impacted the hardest. This might be offset by recycling revenues back to poor households, but the literature suggests that this could have a regressive impact on economic growth (Timilsina, 2022).

The *markets versus command* dichotomy has however, been challenged (Jeanrenaud, 1997; Swaney, 1992). Environmental policy is made in a context of both market failure and government failure; on the one hand, leaving environmental protection to the free market, relying on notions of corporate social responsibility and altruistic consumer and shareholder preferences, will not deliver optimal results (Hepburn, 2010). On the other hand, completely socialising the delivery of environmental protection is likely to fail because nation states rarely have the depth and quality of information required to instruct all the relevant agents to make appropriate decisions (Hepburn, 2010). Thus, as for many areas of policy, appropriate models of environmental intervention will lie between these two extremes (Hepburn, 2010).

Applying the above to our results, in an active policy scenario, a government might incentivise markets to achieve higher rates of substitution between non-renewable and renewable capital in order to achieve the first and fourth objectives above. This could for instance be through structural support measures to renewables: an example would be through support of renewable projects developed through Contracts-for-Difference schemes, under which a government might hold an auction to develop a solar or windfarm at a 'strike' price with winning bidders — with the proviso that when the project is operational, any difference between the strike price and market price of electricity would be either subsidised by government (if the strike price was below the market price) or returned as a pass-through to consumer prices (if the strike price was higher than market prices), thus ensuring a reliable revenue stream for investors in renewables (vis-a-vis investors in fossil fuels). This has for instance been the case in the development of the UK offshore wind industry, which has grown manifold in the last 10 years, with the costs of electricity produced from them dropping as a result of learning curves and scale effects.

Higher substitution could also be achieved with active policy signals that explicitly disincentivise the extraction of new fossil fuels: for instance, some countries, including Denmark, Costa Rica, France, and Sweden, have pledged to end fossil fuel extraction completely in their jurisdictions as part of the 'Beyond Oil and Gas' alliance led by Denmark and Costa Rica.

5. Conclusion

In this paper, we established a simple neoclassical growth model that integrates three pillars in economics: the net zero carbon target in environmental economics, the circular economy in resource economics, and sustainable growth. We described the dynamics between these three pillars, offering policymakers a framework of analysis with which to pursue these objectives. Our results show that measures to incentivise faster substitution between renewable and non-renewable capital, and to mandate higher rates of recycling and pollution abatement, will be needed to reach net zero carbon emissions faster, while ensuring that economies converge to a sustainable growth path. This suggests that an 'active' form of policy intervention – standards, mandates and regulation – may be preferred by policymakers seeking to a balance between growth, net zero and circular economy.

Our results lend themselves to further research. Future work could explore the optimal parameters for the four policy instruments, based on empirical observation, enabling a context-specific understanding of the nexus between growth, net zero targets and circular economy. Second, one could consider the fiscal implications of the transition to a renewable economy — for instance through the inclusion of a cost function and the government budget constraint. Third, future work can also explore the relationship between productivity and the circular economy with and without net zero targets, in order to develop a deeper understanding of the relative effectiveness of environmental policy in carbon-constrained economic growth. Finally, we could explore the effect of a climate shock on the aggregate economy and compare the mitigation of such adverse shocks when government more aggressively follows pollution abatement and waste management policies.

CRediT authorship contribution statement

Parantap Basu: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Methodology. **Tooraj Jamasb:** Conceptualization, Investigation, Writing – review & editing. **Anupama Sen:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tooraj Jamasb acknowledges financial support from the Copenhagen School of Energy Infrastructure (CSEI). The CSEI are funded jointly by Copenhagen Business School and energy sector partners.

Acknowledgments

The paper benefitted from valuable comments from Avinash K. Dixit on an earlier draft. The participants from the Annual Conference on Growth and Development at the Indian Statistical Institute in New Delhi in 2023, Loughborough University's ECO Seminar Series, and IEB Symposium are gratefully acknowledged. We also thank an anonymous referee for comments. The usual disclaimer applies.

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