Trilemma or Trinity? The nexus between economic growth, circular economy and net zero emissions *

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Abstract

How can economies achieve economic prosperity without negative environmental externalities? A first-best solution is for economies to replace fossil fuels with renewable energy sources, eliminating carbon emissions. A second-best solution is for economies to also adopt efficient waste management methods, recycling residual waste and pollutants (including hard-to-abate carbon) from the production environment (circular economy). In this paper, we establish a simple growth model that integrates three fundamental pillars of economics: (i) the net-zero carbon target, (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 an active environmental policy achieves net-zero faster than one with a passive policy. In contrast with a passive policy, an active policy is also capable of eliminating carbon from the environment.

Key words: net zero, growth, circular economy, pollution, capital, recycling, substitution

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1. Introduction

How can economies achieve economic prosperity 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 (for e.g. oil, gas, coal) are a non-renewable, depletable resource; for e.g., extracting a barrel of oil from the ground today would leave fewer barrels available for extraction and use by future generations. The theory also proposes an optimal 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 been disproven, as theory does not account for the role of technological innovation. Namely, fossil fuel producers/firms have continue to invest in 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 hypotheses on 'peak oil supply' or claims that "the oil will run out".

The second aspect of sustainable growth is particularly relevant in a climateconstrained world: negative environmental externalities. Conventionally, these refer to the pollution of the natural environment resulting from economic growth – for e.g. air, water and soil – and 'sustainable growth' is growth with minimized (ideally eliminated) pollution (e.g. through reducing waste, and recycling). Specifically, carbon emissions from fossil fuels and their 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 CO2 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 1.5oC to avoid dangerous climate change would require 'global net human-caused emissions of CO2 to fall by about 45% from 2010 levels by 2030, reaching "net-zero" around 2050.' This is 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 offsetting any residual emissions (for 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 catastrophic 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 (for e.g. through Carbon Capture and Utilisation - CCUS)[3] and reintroduce them into the production process in a circular loop. 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 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) an active policy, where the government mandates that emissions

[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.

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 has 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; in other words, substitution is a necessary but not sufficient condition. We find that it is essential to have efficient waste management, and technologies and environmental policies that prioritize waste recycling. This can be achieved through circular economy. This might include adaptation 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 pre-empt 'mitigation' as the first-best solution (Burton, 2014).

- 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 more rapidly than one with a passive government policy (e.g. a singular economywide net zero emissions target). Governments may rely on either market-based approaches, or on regulation while designing environmental policies.

The next section of the paper reviews literature on the nexus between net zero, circular economy and sustainable growth. Section 3 develops the model and main findings, and Section 4 contains a discussion of 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. At the end of this section, we 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. 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 is 420-770 GtCO2. 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) has its origins 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 (Benyus, 1997); the industrial ecology (Lifset and Graedel, 2002); 'natural capitalism' (Hawken and Lovins, 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 maximizing the utilization capacity of goods (for example by means of product-sharing, or the product-as-a-service) (Stahel, 2016; Ferasso et al., 2020). Closing material loops in industrial ecosystems in this way can create a continual use of resources; this can, in theory, be achieved through long-lasting design, proactive maintenance, recycling, repairing, refurbishment, and remanufacturing (Geissdoerfer et al., 2018; Ferasso et al., 2020). For e.g., as around 25% of global energy use is estimated to serve the production of major materials, the more efficient use of these materials 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) (see Figure 1).

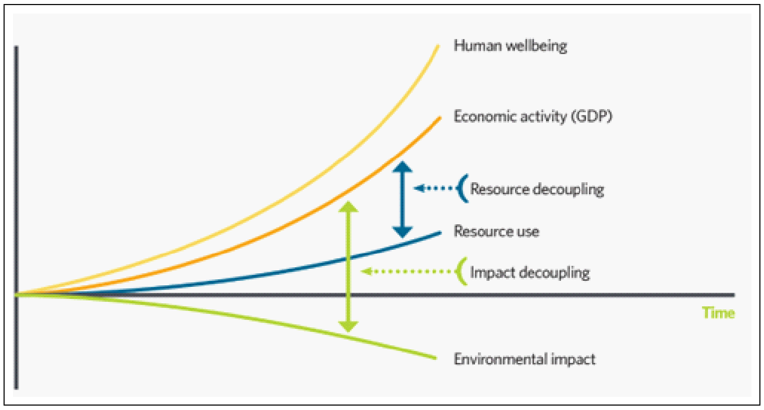

Fig 1: Circular Economy and environmental impact (Source: Popplewell et al.,2019)

Whether or not economic growth is 'sustainable' in the long run depends crucially on substitutability between natural capital and other forms of capital (e.g. physical or human) in the production process (Cohen et al., 2018). Unless natural capital is sufficiently substitutable, long-run economic growth cannot be sustainably maintained, without continued technological progress, since exhaustible natural resources will ultimately deplete (Solow 1974; Dasgupta and Heal, 1974; Weitzman 1976; Dasgupta and Heal, 1979; Arrow et al., 1995; Dasgupta and Maler 2000; Ruta and Hamilton, 2007; Arrow et al. 2012, Hallegate et al., 2012; Cohen et al., 2018).

There is a long standing theoretical and policy debate on whether growth is possible with a 'green' technology by substituting away from fossil-fuel intensive capital or 'dirty' capital hereafter. The proponents of strong sustainability (Daly, 1997; Ayres, 2007), hold the view that there is limited scope for such substitution. Sustainability is, however, not a binary concept. Solow (1974) and Nordhaus and Tobin (1972) take a weak sustainability view that suggests some degree of substitution is possible between green and dirty capital.

Intuitively, when there is a high degree of substitutability between 'clean' and 'dirty' inputs (in the context of climate policy – between clean or renewable energy, and non-renewable energy), certain types of policies to combat climate change are likely to prove more effective – for example, policies improve the relative price difference between non-renewable energy and renewable energy technologies such as carbon taxes. For example, Acemoglu et al. (2012) consider two inputs, clean and dirty, and demonstrate that if clean and dirty inputs are highly substitutable, a temporary carbon tax is sufficient to shift the direction of technical change towards clean technologies and avert an environmental disaster. On the other hand, the shift would occur much more slowly and require a permanent carbon tax, if the two inputs are less substitutable or complements. Similarly, the level of optimal subsidy to 'clean' research to reduce its cost is also lower and it is only temporarily needed in the high-substitutability case, while it is higher and lasts longer in the low-substitutability case because the switch to clean technologies also occurs much later.

Golosov et al. (2014) note from their calibrated model that a high degree of substitutability between different fuels induces the temperature to decline in the middle of the next century, while lower substitutability involves a continuous increase in the temperature even with optimal policy in place. Gans (2012) explicitly discusses the cases of an elasticity of substitution between clean and dirty energy, smaller and larger than one, in studying how a tighter emissions cap would affect innovation. It finds that with a substitution elasticity below one, the emission cap would reduce innovation incentives for factor-augmenting technologies.

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2.2. Net zero emissions, circular economy and sustainable growth

There is little to no theoretical or empirical literature that directly address the interaction between these three concepts across the three pillars of economics discussed above. Most macro-level studies are qualitative 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 some of the fundamental issues related to 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. 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 that 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 mobilize 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 form of the generation and recycling of solid municipal waste (MWG), globalization, linear economic growth and renewable energy consumption on CO2 emissions growth from 1990 to 2020 for seven major CO2-emitting countries. It argues that top emitters should consider waste as a solution toward sustainable development but not as a problem for growth and stability. These emitters should lean more toward developing sustainable and scientific solid waste management practices that can help tackle the waste problem.

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, a nd 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) and innovation-led growth phase (called the Romer regime) 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).

The studies above all suggest that some form of policy intervention (e.g. pollution abatement measures) may be required to ensure that net zero and circularity are not just necessary, but sufficient conditions for sustainable growth.

2.3. Illustration of circular economy framework: the hydrogen economy

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. A electricity production comprises the largest single source of CO2 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. decarbonization 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 globalization of trade (e.g. supply chains), and spatial dissociation between places of extraction, production, and consumption. International trade enables the costs of decarbonization 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:

1 Renewables-to-hydrogen can be achieved with utilising renewable electricity to split water (H2O) 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.

2 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). Some countries like Japan are exploring the burning of green ammonia in turbines for power plants.

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 homogenous 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 3 entails the possibility of some carbon as ‘waste’ that can only be recycled if appropriate Carbon Capture, Utilisation and Storage (CCUS) technologies exist 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 (and which in the case of green ammonia, already have a globally accessible market e.g. in the fertiliser sector) – these therefore require an expansion in investment to rapidly increase their deployment. 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. Figure 2 illustrates how a circular economy in hydrogen could work.

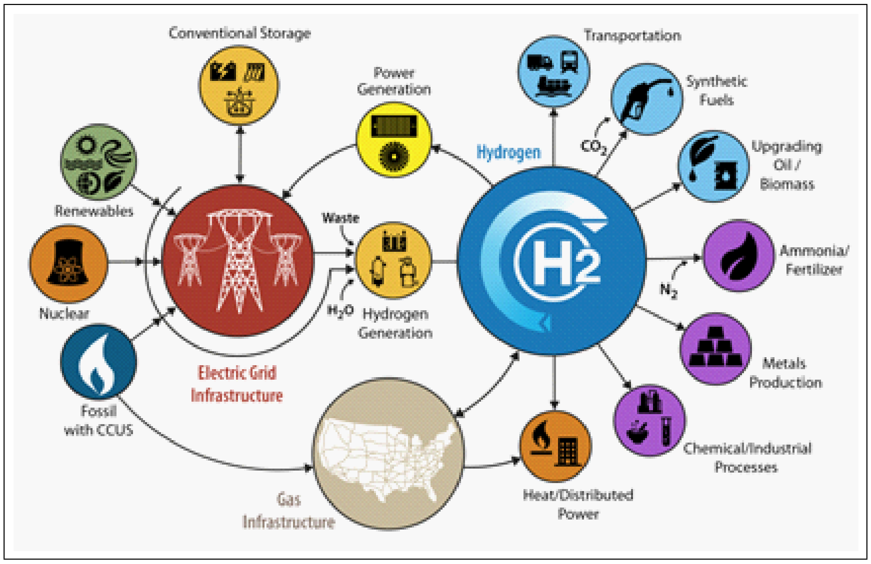


Fig 2: Circular economy in hydrogen – an illustration (Source: Kish, 2022)

3. A Growth model of a Net Zero Carbon Circular Economy

Time (t) is discrete 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 normalizing 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. As in DICE models, the stock of pollutants (P_t) adversely affects current TFP. 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 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). In other words,

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

Let a fraction θ_t of the waste is 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. ρ is the rate of investment in renewable which is determined by the private sector.[4]

[4]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.

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 natural oil). The rate of extraction (ς) is based on the principle of Hotelling's rule and it is a policy instrument.[5] Let I_t^N rises at the rate of the real interest rate. In other words.,

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

The time path of nonrenewable is thus:

$$K_{t+1}^N = \overline{K}^{EX} - I_t^N \tag{5}$$

In other words, as more investment in nonrewable happens, it draws down the fixed exhaustible resource.

The dynamics of pollution is given by

$$P_{t+1} = (1 - \delta_p) P_t + (1 - \theta) W_t \tag{6}$$

where δ_p is the pollution depletion rate which is primarily determined by a pollution abatement policy of the authority. The second term, $(1 - \theta) W_t$ on the right hand side of (6) is the hard-to-abate pollutants which goes to the landfill. Ideally, we want θ to be someday which means all waste is recycled. Until this happens the stock of pollutants will be on a rising trend.

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

3.1. Net zero carbon and pollution abatement

Net zero carbon target means that the net emission must go to 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 or carbon capture, utilization and storage). In the context of our model, the net emission (call, NETCO2) is given by:

$$NETCO2_t = (1-\theta)W_t - \delta_p P_t \tag{7}$$

The first term, $(1-\theta_t)W_t$ is the waste output which cannot recycled (hard-to-abate) and adds to the pollution pool. The second term, $\delta_p P_t$ is the extent of carbon capture.

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

$$\frac{P_t}{Y_t} = \frac{(1-\theta)\nu}{\delta_p} \tag{8}$$

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

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

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 have the following key result.

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

$$Y_t = A[\omega^{\frac{\sigma}{\sigma-1}}]K_t^R \tag{9}$$

and the balanced pollution free growth rate is given by: ()

$$G = 1 - \delta_R + (\nu\theta + \rho)A\omega^{\frac{\sigma}{\sigma-1}} \tag{10}$$

Proof. Use (1) to verify that

$$Y_t/K_t^R = Z_t \left[(1-\omega)(K_t^N/K_t^R)^{\frac{\sigma-1}{\sigma}} + \omega\right]^{\frac{\sigma}{\sigma-1}} \tag{11}$$

The first term in the square bracket in (11) approaches zero if and only $\sigma > 1$. Since P_t in (6) approaches the steady state zero, so is Z_t which means (11) approaches (9). . Next rewrite (4) as

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

■

Few observations are in order. First the long run growth rates seen in (10) is rising in σ. In other words, the greater the substitutability between nonrenewable and renewable capital, the higher the long run growth rate. Second, the long run growth rate is higher if recycling rate θ is higher. Third, the long run growth rate in a circular economy (with $\nu > 0$) is higher than in a linear economy with $\nu = 0$.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 tun (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:

$$\frac{Y_{t+1}}{Y_t} = \left(\frac{Z_{t+1}}{Z_t}\right) \left[\frac{(1-\omega)\left(\frac{K^N_{t+1}}{K^R_{t+1}}\right)^{\frac{\sigma-1}{\sigma}} + \omega}{(1-\omega)\left(\frac{K^N_{t}}{K^R_{t}}\right)^{\frac{\sigma-1}{\sigma}} + \omega}\right]^{\frac{\sigma}{\sigma-1}} \left(\frac{K^R_{t+1}}{K^R_t}\right) \tag{12}$$

Over time as the economy traverses along the short run path, as 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 decrease 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 aggressiveness of policy to eliminate nonrenewable which is summarized by the parameter (ς) in (**??**). .

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 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 doesn't necessarily mean that the economy converges to long run growth path in year 2050.

To fix ideas, 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, $\zeta = 1.02$, $\delta_p = 0.9, \theta = 0.9, \sigma = 2$. For such an economy the long run growth rate is 2.28% and the steady state carbon intensity is 0.0077. 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. Fig 1 through 4 plot the time paths of GDP, renewable and nonrenewable. Overtime the economy grows and approaches the balanced growth path. Nonrenewable resource declines in use both in level and in proportion to renewable.

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

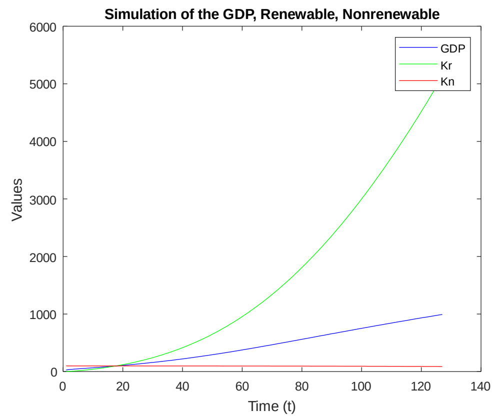


Figure 1

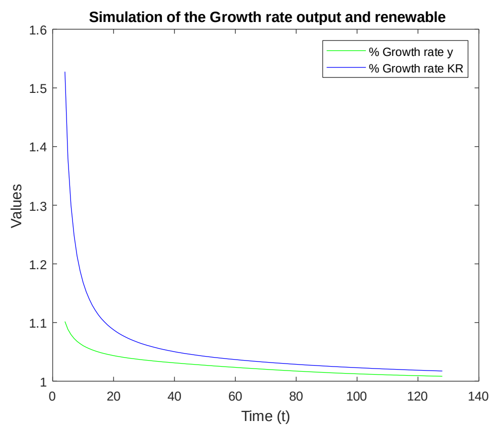
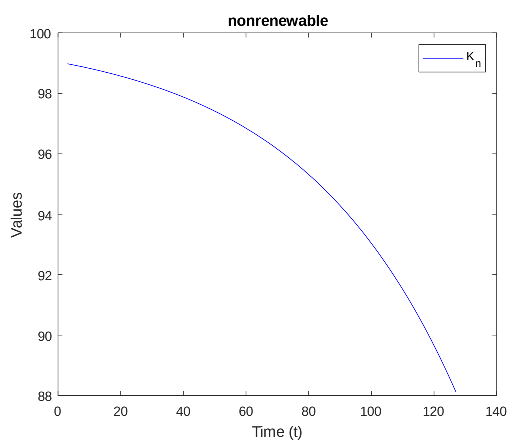


Figure 2



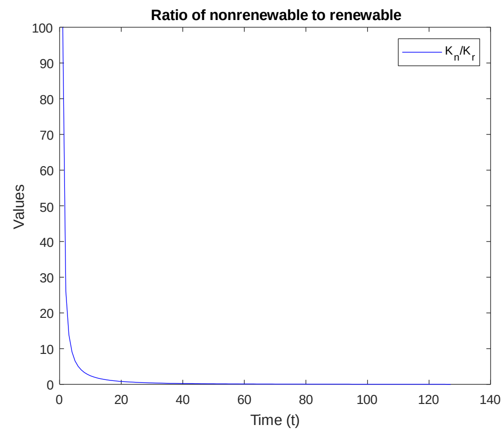


Figure 1: Figure 4

Figure 3

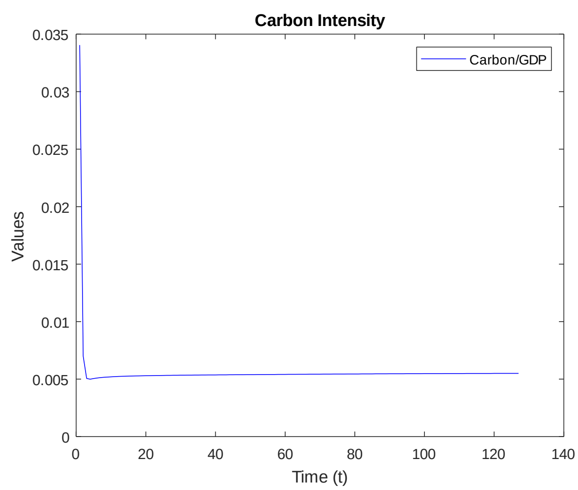


Figure 5

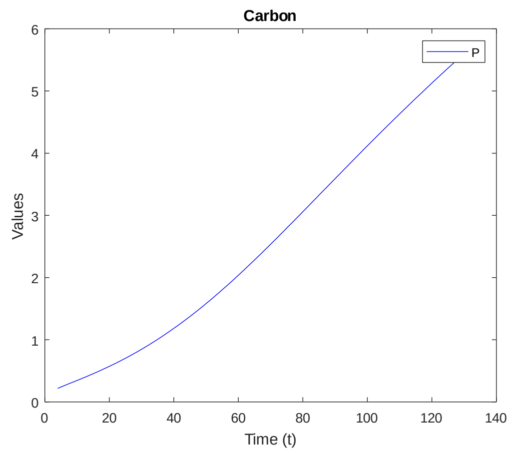


Figure 6

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.

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

Table 2 reports the sensitivity of the long run growth rate of GDP with respect to θ. Greater recycling has significantly positive growth effect. The sensitivity of growth to recycling highlights the importance of circular economy in influencing growth. Table 3 reports the sensitivity of growth to increase in the elasticity of substitution between nonrenewable and renewable. The greater degree of substitution boosts the long run growth rate.

Table 2: Sensitivity of growth rate to recylcing 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%

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

As of now, 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 lesson is that waste management in a circular economy environment is quite 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 authority lays out a path for θ_t and δ_{pt} as follows:

$$\delta_{pt} = 1 - \frac{1}{\lambda_1^t} \tag{13}$$

and

$$\theta_t = 1 - \frac{1}{\lambda_2^t} \tag{14}$$

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 actually a first best environment because the long run growth rate (10) is maximized when θ_t approaches unity. To illustrate this, 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 Fig 5 through 8. The economy smoothly lands in the long run carbon free growth path. What is noteworthy is that the stock of carbon (Fig 8) also declines to zero in this environment.

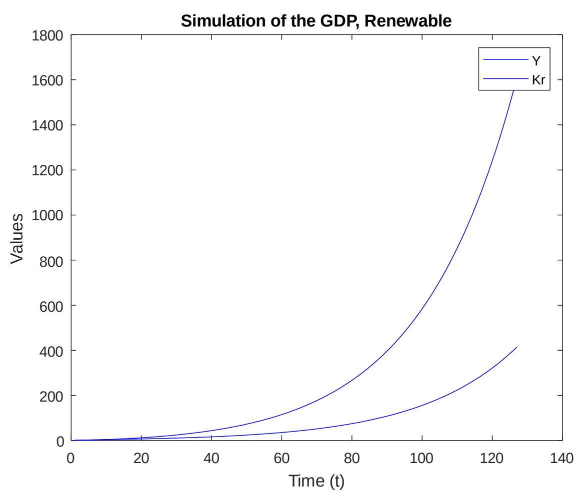


Fig 5

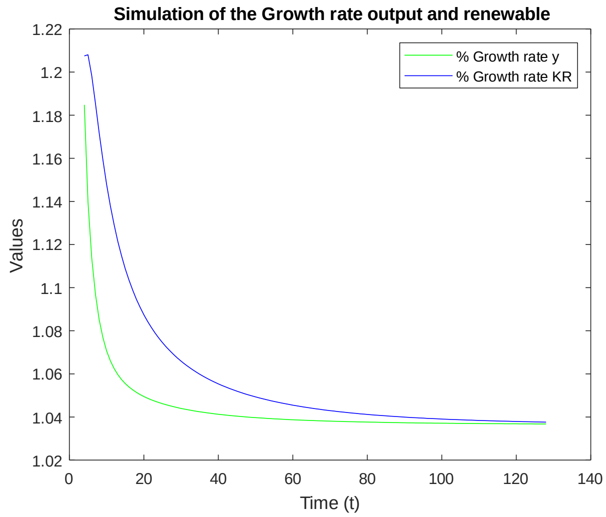

Simulation of the Growth rate output and renewable
% Growth rate y
% Growth rate KR
Values
Time (t)

Fig 6

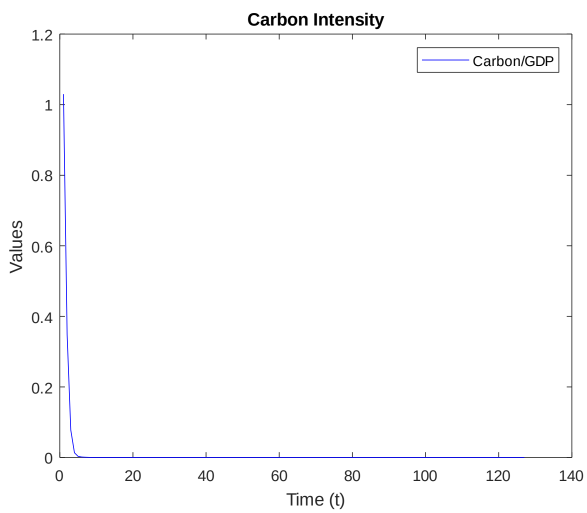

Carbon Intensity
Carbon/GDP
Values
Time (t)

Fig 7

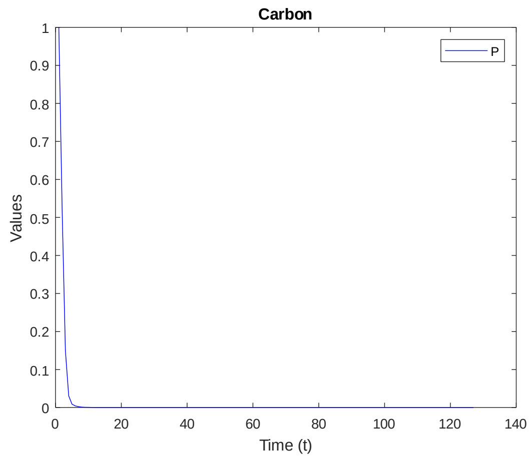


Fig 8

4. Discussion

Our model provides a representation of the dynamics between these net zero carbon, sustainable growth and circular economy, offering policymakers a framework of analysis with which to think about policy design that can balance trade-offs and priorities, and 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 non-renewables.

We can consider 1 and 4 above as interchangeable objectives; a higher elasticity of substitution might reflect lower investment in non-renewables, and vice versa.

Governments face choices in the types of instruments they may adopt to achieve their policy objectives: in neoclassical economics, a distinction has been made between 'market-based' approaches and 'command-and-control' approaches (Swaney, 1992). In theory, both approaches should lead to the same outcome. In practice, command-and-control approaches assume that a policymaker has access to perfect information in order to set policies that result in optimal outcomes, whereas this is not always the case; the costs of compliance to command-and-control 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 are thought to 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). Over 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 might be another example of a command-and-control 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.

The 'markets versus command' dichotomy has however, been challenged (Jeanrenaud, 1997; Swaney, 10992). 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, nationalizing 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 objectives 1 and 4 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 developed a solar or windfarm at a 'strike' prices 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-à-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.

Policymakers may also introduce mandatory standards on recycling and pollution abatement – for example, emissions standards introduced on coal power generation in India and China; or Electric Vehicle sales mandates and gasoline and diesel vehicle sales bans in the US and the UK, which are imposed on original equipment manufacturers (or 'OEMS' in the automotive industry which refer to all the large car manufacturing firms). These have been set with progressively tightening targets. For e.g. the UK has instituted a ban on the sales of new gasoline and diesel vehicles from 2035. Similarly, the EU strategy for plastics in a circular economy proposes that all plastic packaging placed on the EU market should contain a certain minimum amount of recycled content recovered from post-consumer plastic waste (European Parliament, 2023).

Our results show that measures to incentivise a faster substitution between renewable and non-renewable capital, and to mandate higher rates of recycling and pollution abatement, suggest that the 'active' form of policy intervention – standards, mandates and regulation – will be needed, in order to get to net zero carbon emissions faster, while also ensuring that economies converge to a sustainable growth path.

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