Ecological Macroeconomics in the Open Economy: Sustainability, Unequal Exchange and Policy Coordination in a Center-Periphery Model

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Abstract

This article introduces a novel (environmental) interpretation of a “Keynesian Coordination Game” and develops four potential scenarios to remaining within a global carbon emissions constraint. With inspiration from research on “ecologically unequal exchange” (EUE), we demonstrate the drawbacks of present “green growth” strategies by considering how pollution- and resource-intensive industries are distributed unevenly in the world economy, with large and increasing negative impacts on the Periphery. The situation may only be exacerbated if the reduction of emissions in the center is based on shifting heavy industries and extractive enterprises to low-cost producers in the periphery. In this way, existing research likely overemphasizes the capacity of “green” investment policy to achieve sustainable outcomes. Our scenarios show that achieving global sustainability and improving global equity will require an impressive level of coordination between the Center and Periphery, as well as a significant reduction in the rate of growth (“degrowth”) in the Center.

Keywords: ecological macroeconomics; open economy; ecologically unequal exchange; balance of payments constraint; environmental policy coordination; Center-Periphery model

JEL code: E12, F43, Q55, Q56, Q57, Q58

1. Introduction

As global average temperatures continue to exceed year-to-year record highs, the negative impacts of climate change are increasingly apparent. To deal with the rapidly unfolding crisis, policymakers, international organizations, and academics have rallied behind a global push for “green growth” (OECD\textsuperscript{2011} UNEP\textsuperscript{2011} World Bank\textsuperscript{2012} Dale et al.\textsuperscript{2016}). Green growth
strategies apply pricing mechanisms and (Green) Keynesian-style demand management, to re-
solve the present socio-environmental by promoting more efficient forms of economic growth.
A combination of environmentally-minded price, fiscal and monetary measures are put forward
to supporting efficiency-enhancing investments and break the connection between global GDP
growth, resource use and emissions production.

In theory, green growth policies can result in a virtuous shift towards high value-added sectors
(e.g. in renewable technologies or services) with limited environmental impact, thereby raising
economic growth to improve employment, sustainability, and even global equality (Altenberg
and Assmann 2017). For this reason, economic growth is thought to remain an acceptable,
and even desirable, method of enhancing social and environmental sustainability for all nations
(Alexander et al. 2017) Pollin 2019). The fundamental obstacle to solving the climate challenge
is understood as a lack of adequate demand for sufficiently “green” investments (Peake and Ekins
2017) Espagne 2016). As long as investment can be shifted to increasingly efficient technolo-
gies, there should be no inherent contradiction between economic growth and socio-technical
“harmony with nature” in any part of the world (Hickel 2019).

The emerging field of “ecological macroeconomics”, spearheaded by post-Keynesians, has
also prioritized the climate-mitigating potential of greener economic growth. Many of the avail-
able models utilize fiscal and monetary policies as instruments for channelling investments to
accumulate “green”, as opposed to “brown”, forms of capital (see Svartzman et al. 2019). As the
stock of efficient technologies increases, greenhouse gas emissions are reduced such that continued
economic growth no longer poses a considerable threat to socioeconomic and environmental
well-being.

Recent research, however, has raised serious doubts as to whether such growth-based ap-
2016). Thus far, a full in the absolute level of emissions relative to GDP has remained elusive on
a global scale. Achieving climate objectives in the time needed to avoid increasingly catastrophic
scenarios would require global emissions reductions at multiple times historical rates of decar-
bbonization, even in the absence of population and income growth (Hickel and Kallis 2019) 1
Moreover, while there are signs of emissions reductions at the country-level, trade-weighted
measurements of environmental impacts reveal that “successful” instances of growth-based de-
coupling have nearly always been achieved by outsourcing pollution and resource-intensive ac-
tivities to poorer countries (Teixidó-Figueras et al. 2016) Verones et al. 2017) Wiedmann and

Indeed, trade frequently enables technologically advanced countries offload the most socially
and environmentally destructive aspects of production to the Periphery (Hornborg 2001, 2006,
Rice 2007) Frey 2018). Relationships of “ecologically unequal exchange” have allowed the Cen-
ter to maintain its own environmental quality and satisfy domestic resource demands at the ex-
 pense of the Periphery (Bunker 1985) Bunker and Cicciantell 2005). As such, policies that appear
environmentally advantageous from the domestic perspective may actually reinforce globally un-
sustainable trends. This suggests that addressing the structure of the international political econ-
omy and the relations between economic and environmental inequalities in different regions will
be key to guarantee any successful transition. For instance, environmental justice movements,

1The Paris climate accords set individual-country and global emissions targets, seeking to limit temperature increases
to “well below” 2 degrees Celsius above pre-industrial levels, with the hope of limiting warming to 1.5 degrees. If
implemented in full, established measures are still insufficient to prevent climate destabilization, pushing warming above
3 degrees Celsius (Steffen et al. 2018). Few countries are now on track to comply with their national commitments.
and the UNFCCC itself, acknowledge the principle of common but differentiated responsibilities to tackle climate change (Roberts and Parks 2009, Brunée and Streck 2013).

These findings raise a number of fundamental questions for ecological macroeconomics, which has been relatively silent about the prospects for the global sustainability transition in an open economy context (Guarini and Porcile 2016). By focusing primarily on wealthy, industrialized nations in the closed economy, available models likely project overly optimistic scenarios for global climate mitigation. Present mitigation pathways rely heavily on (uncertain) future innovations to decarbonize and neglect the way technological developments restructure the geographic distribution of environmental benefits and burdens (Bonds and Downey 2012). In light of the uneven structure of global trade, ecological macroeconomics may need to seriously consider the limits of its present methodological toolbox to address the deeper technical, institutional and ethical dimensions of truly sustainable economic pathways (Røpke 2016, Svartzman et al. 2019).

This paper seeks to address these limits by investigating possible pathways to social and environmental sustainability in a Keynesian “environmental coordination game”. We depict a world economy characterized by a technologically advanced industrial “Center” and lagging “Periphery”. While technical change and green fiscal strategies can enhance domestic environmental efficiency, some portion of pollution reductions in the Center are assumed to be achieved at the expense of rising emissions in the Periphery.

We explore four different scenarios for achieving a successful transition to negative global emissions growth using a balance-of-payments constrained growth model. The model highlights the difficulties of achieving global social and environmental goals while maintaining long-run macroeconomic stability: countries must stay within the global carbon budget while also avoiding fiscal and balance of payments disequilibria. The scenarios are as follows: First the “Global Unsustainability by Business-as-Usual” scenario depicts a situation in which no intervention occurs and world economic growth and emissions exceed the sustainable limits. Second, the “Local Sustainability by Accumulation” scenario shows how a “green growth” strategy from the Center can enhance local efficiency at the expense of emissions efficiency of the Periphery. The world drastically overshoots the available carbon budget and global sustainability would imply a reduction in growth from the Periphery. A third scenario, “Global Sustainability by Accommodation”, describes a situation in which wealthy countries purposefully reduce growth. This allows developing countries the opportunity to improve their material consumption, while global emissions are falling, albeit at a reduced rate of economic growth. Finally, “Global Sustainability by Cooperation” describes an ideal scenario; global sustainability is achieved via a major coordinated international effort. Here, the Center both agrees to degrow and shares its technology with the Periphery such that a sustainable development program in the Periphery can improve income growth and efficiency without significantly overshooting the carbon budget.

By considering global emissions in an open-economy framework, this paper highlights how technological developments can result in an increasingly unequal distribution of environmental benefits and burdens that can reinforce global inequalities (Rice 2007, O’Hara 2009). Domestic technology and investment policies do not a priori present clear “win-win” pathways, making them perhaps necessary but insufficient steps to meet global targets. Green investments alone cannot, therefore, be counted on to automatically bring about greater socio-ecological harmony and equality (Hickel and Kallis 2019, Hickel 2019). Sustainability will likely require a reduction in investment (e.g. degrowth) in many presently wealthy countries, as well as a major change in lifestyle and social needs provisioning. Moreover, much closer coordination between countries will be necessary to raise material consumption in the Periphery without overstepping global emissions limits. While such policies are highly unlikely in the current political setting, they
may be the only option for improving equality while safeguarding long run socioeconomic and environmental stability.

The rest of the paper continues as follows: Section 2 briefly surveys the literature on ecologically unequal exchange to incorporate key insights into the existing post-Keynesian ecological vision. Special focus is placed on reevaluating green investment strategies in the open economy, and the utility of existing Center-Periphery models to demonstrate unequal environmental relations. Section 3 provides the analytical background of the Center-Periphery framework by introducing the classical Keynesian coordination game and highlighting its main limitations. Section 4 updates the model to incorporate a global environmental constraint and pollution displacement to analyze the potential for global economic sustainability under conditions of ecologically unequal exchange. Section 5 describes each of the four scenarios outlined above in an “environmental coordination game”. Section 6 summarizes findings and draws conclusions.

2. Sustainability in an Unequal World System: Reconsidering Green Growth in Ecological Macroeconomics

Recent attempts from post-Keynesians and heterodox researchers to incorporate ecological considerations in their models have tended to exclude open-economy issues (Guarini and Porcile 2016, pg.15). Considering economies in isolation, however, is a major abstraction from the present day world ecological system (Hornborg 2003, Moore 2015). Local natural systems are under increasing pressure to fulfill ever-larger global demands as the scale and speed of trade expands (Bunker and Ciccantell 2005, Ciccantell and Smith 2009). Moreover, the costs and benefits of these pressures are distributed unevenly across the world. Capturing the dynamics of these ecological inequalities is an important step for the nascent field of ecological macroeconomics. As researchers seek for sustainable solutions to ongoing environmental and social crises, “green” policies must be understood holistically, or risk reinforcing unsustainable patterns.

A growing literature on ecologically unequal exchange (EUE) has identified the ways in which global trade is hierarchically structured along both economic and environmental lines. EUE theorists argue that by capturing higher stages of value-added production, some regions are systematically provided with a greater claim on global resource stocks and natural sinks (waste assimilation capacity) (Hornborg 2001, 2006, Ciccantell and Smith 2009). Resources flow “vertically” upwards through chains of value production towards the industrial Centers. Those regions which export natural resources or specialize in pollution-intensive production face increasing environmental costs, while global Centers of demand offset their environmental footprints via imports (Bunker and Ciccantell 2005, Rice 2007, 2009, Jorgenson et al. 2009). This has led to a conspicuous inverse relationship between a country’s demand for natural resources and its degree of domestically felt environmental burdens (Hornborg 2001, Roberts and Parks 2009, Srinivasan et al. 2008, Jorgenson et al. 2009). Trade enables technology leaders to preserve domestic environmental quality while using Peripheries as waste sinks or resource pools (Bunker and Ciccantell 2005, Rice 2007). Those at the bottom of value hierarchies must suffer the consequences of extractive, resource- and pollution-intensive production (Boons et al. 2012, Selwyn 2016, Ciccantell and Smith 2009). As resources are depleted and natural systems undermined, inter- and intra-country income distribution worsen (Srinivasan et al. 2008, Bunker 1985).

This situation is increasingly counterproductive for efforts to meet global social and environmental objectives. Despite increasing alarm over the need to significantly reduce greenhouse gas emissions, the systematic displacement of environmental loads may be provoking an increase in
the global emissions and material intensity of production (Thombs 2018, Plank et al. 2018, Hao 2019). As pollution intensive production concentrates in global Peripheries, lax environmental regulations, low levels of enforcement, and the use of less efficient production technologies have resulted in a global re-coupling of emissions and resource use with economic growth. In this light, even seemingly “green” attempts at growth must therefore be scrutinized for exacerbating global asymmetries of economic and environmental quality (Bonds and Downey 2012).

This represents an intriguing challenge to post-Keynesians, for whom directed investments in technological efficiency have come to form the backbone of their contributions to ecological macroeconomics (Svartzman et al. 2019). In the post-Keynesian tradition, investment demand is the key driver of technical change, productivity, employment and income growth. Investments in resource-efficient technologies can raise productivity and lead to cumulative cycles of economic expansion (Myrdal 1957, Kaldor 1970). Increased resource efficiency has historically been an important driver of economic growth (Sakai et al. 2019). In the open economy, specializing in increasingly resource-efficient capital goods enhances productivity and export demand, thereby also relieving the balance of payments constraint with greater foreign currency inflows (Guarini and Porcile 2016). Countries can then seemingly undergo a virtuous shift towards higher rates of growth, even while domestic emissions production falls.

As such, “green growth” policies are commonly viewed as “win-win” solutions to environmental and social crises (Hickel 2019). Not only will resources be more efficiently and effectively used, but incomes should also rise while unemployment falls. Sustainable development programs also consider “green structural change” and “green industrialization” (Altenberg and Assmann 2017) to be inherently beneficial mechanisms to bridge the technological divide between developed and developing countries. Doing so should allow the Periphery to specialize in clean, high value-added production stages, while reducing inequalities and environmental pressure.

Seen from a global perspective, however, increased income and demand growth may simply improve access to resource- and emissions-intensive goods abroad (Hornborg 2001, 2003, 2006). In essence, improvements in technical efficiency and productivity are more likely to raise a country’s capacity to import resources and outsource pollution (Bonds and Downey 2012). Investment policy - green or otherwise- may not so much increase global efficiency as evolve new ways of distributing material and energy resources and the locations of production (Ciccantelli and Smith 2009). Even seemingly “dematerialized” services are heavily dependent on raw material and energy inputs and may be better regarded as drivers of global emissions growth than methods for reduction (Cahen-Fourot and Durand 2016, Fix 2019). Becoming a technological leader can improve a country’s position in the hierarchy of value and resource transformation (Andersson and Lindroth 2001), but cannot fundamentally reduce environmental pressure under present socio-ecological relations.

For this reason, despite major technological changes and enhanced efficiency, income growth has in no way been separated from demands for resources or emissions production at the global level (Dahmus 2014, Schröder and Storm 2018, Hickel and Kallis 2019). As climate change and environmental degradation worsen, additional calls for investment growth - green or otherwise - are more likely to generate a zero-sum game than a progressive march towards sustainability and development (Hornborg 2009).

Indeed, the socioeconomic and ecological costs of environmental degradation continue to fall hardest on the developing world, particularly affecting the poor (Adger et al. 2005, Thomas and Twyman 2005, ECLAC 2012, 2016). The consumption and production capacities of many Peripheral countries are already constrained by deteriorating environmental quality (Rice 2007, Wackernagel et al. 2019), a situation that will only worsen with climate change. Improving the
material standards of living for many of the poor in the developing countries may be impossible if global emissions are not significantly reduced in the near future (Daly 1991, Wackernagel et al. 2019).

Formal macroeconomic models, however, have thus far yet to make explicit the effects of unevenly distributed environmental damages between unequal regions, focusing instead on potential synergies for growth and convergence (Guarini and Porcile 2016). This represents an opportunity for ecological macroeconomics to incorporate key insights from fields like human geography, political ecology and environmental sociology (Harvey 2001, Smith 2010, Jorgenson 2016) to highlight that vulnerability to environmental harms, and their distribution between groups and regions, are a symptom of the structure of social relations (Hornborg 2006, 2009).

A wealth of research, particularly amongst post-Keynesians, already exists for modeling the relationship between interconnected yet unequal regions in an open economy. The most commonly used is the Balance-of-Payments-constrained growth model (BOPCG). BOPCG models identify the structural impediments to growth faced by developing countries while trading with already technologically advanced trading partners. Interestingly, the BOPCG framework was heavily influenced by Latin American Structuralist thought (Thirlwall 1997, 2011), particularly the ideas of Raul Prebisch, which later inspired notions of unequal exchange in Dependency and World Systems theories (Roberts and Parks 2009). The dynamics of ecologically unequal exchange therefore provide a useful new avenue for ecological macroeconomics to better incorporate nature into existing heterodox frameworks.

Furthermore, sectoral transformations resulting from technical change can be linked to changes in the geography, quantity and quality of resource use and degradation in different regions of the World System (Hornborg 2003, Bunker and Ciccantell 2005). Since the open-economy framework found in BOPCG models focuses on long-term structural dynamics, these models are able to investigate the relationship between technological development and resource flows. Ecological macroeconomics is thus well-placed to integrate the economy-wide mechanisms that underpin environmental distribution conflicts into existing models of the open economy.

In the following section, we introduce a classical “Keynesian Coordination game” to more fully outline the Center-Periphery (BOPCG) framework. Afterwards, we extend the model to include a carbon budget constraint and a mechanism of pollution displacement from the Center to the Periphery. We then develop four alternative scenarios to find pathways to sustainability in an uneven world system, particularly focusing on ways to improve the material living standards of the poor, without overshooting environmental limits.

3. The Classical Coordination Game in a Center-Periphery setting

**Keynesian Coordination Game**

Open economy models in the Keynesian tradition, such as the BOPCG, argue that in the long run the current account-to-GDP ratio should be constant. Otherwise, the country would be following an explosive path, piling up reserves of foreign exchange or raising its external debt to GDP ratio. Since the focus of this model is on convergence and environmental sustainability, we will make the simplifying assumption of zero capital flows in the international economy, which implies that the current account balance should always be zero. Based on export and import demand functions with constant price and income elasticities, it is possible to show that the dynamic condition for equilibrium in the current account is the following:
\[ y^p = \frac{\epsilon}{\pi} y^c + \frac{(\mu_x - \mu_M - 1)}{\pi} \hat{R}, \]

(1)

where \( y^p \) represents the proportional rate of growth of the Periphery \( (y^p \equiv \frac{\dot{Y}}{Y}) \), \( y^c \) is the rate of growth of the Center, \( \epsilon \) is the income elasticity of exports, \( \pi \) is the income elasticity of imports, \( \mu_x \) is the price elasticity of exports and \( \mu_M \) the price elasticity of imports of the Periphery. The variable \( \hat{R} \) represents the rate of growth of the real exchange rate, \( R \), defined as

\[ R = \frac{P_C}{P_P} \]

where \( P_C \) refers to the price level in the centre, \( P_P \) prices in the Periphery and \( E \) the nominal exchange rate (price of the foreign currency in terms of the domestic currency). As Equation 1 implies equilibrium in the external sector, then \( y^p^* \) is the rate of economic growth of the Periphery which is consistent with such equilibrium—a Balance-of-Payments-constrained rate of growth (the superscript * in the variables indicates equilibrium). In the long run, the real exchange rate should be stable and hence \( R = 0 \). This gives the long-run rate of growth of the Periphery consistent with equilibrium in current account, which is the following:

\[ y^p^* = \frac{\epsilon}{\pi} y^c^* \]

(2)

Equation 2 is known as Thirlwall’s Law (see Thirlwall 1979, 2011). The ability of the Periphery to diversify its production base and move towards more dynamic sectors in the international markets (e.g., high-tech manufactures and services), allows the Periphery to change the elasticity of demand for exports and imports \( (Nassif et al. 2016) \). To do so, the Periphery should boost its technological capabilities, which means reducing the technology gap with respect to the Center.

In the short run, the equilibrium and the effective rate of growth may differ. The effective rate of growth is given by the Kaldorian Equation 3:

\[ y^p = \alpha a + \beta x \]

(3)

\( y^p \) in the short run depends on the growth of autonomous expenditure \( a \) and the growth of exports \( x \). The parameters \( \alpha \) and \( \beta \) are a function of the relative weight of autonomous expenditure and exports, respectively, in total income, along with the income elasticity of demand for imports \( \pi \) which for simplicity is assumed constant in the paper. The effective and the equilibrium rates of growth converge based on changes in the rate of growth of autonomous expenditure (for a discussion of the mechanisms leading to this convergence, see Guarini and Porcile (2016)). The latter variable endogenously adjusts to ensure that the external constraint is not violated.

The dynamics of the Center-Periphery system can be described by a simple two-country model based on McCombie and Thirlwall (1994), Blecker (2013), Cimoli and Porcile (2011) and Bárceca and Porcile (2018). Figure 1 represents different scenarios of adjustment in the Center-Periphery system. The curve \( P \) represents the effective rate of growth of the Periphery \( (y^p) \) as a function of the growth in the Center \( (y^c) \), while the curve \( C \) represents the effective rate of growth of the Center as a function of growth in the Periphery. The \( BP \) schedule represents the equilibrium rate of growth, defined by the rate of growth which keeps the current account
in balance (Balance-of-Payments constrained growth). Beginning at the initial position $z$, both the Center and Periphery grow in line with external equilibrium. $z$ is on the $BP$ schedule, which gives all the combinations of the effective rates of growth in Center and Periphery that comply with the Balance of Payments constraint, i.e. satisfies $y_P = \epsilon \pi y_C$.

Assume now that—with a view to improving employment and income distribution—the Periphery raises autonomous expenditure and the curve giving the effective rate of growth shifts from $P$ to $P'$. The new (transitory) position of the economy is $z'$, where both Center and Periphery grow at a higher rate than before. At point $z'$, however, the Periphery experiences a trade deficit that raises the external debt-to-GDP ratio. This deficit cannot be easily or safely sustained in the long run.

![Figure 1: Classical Keynesian coordination game](image)

If Center and Periphery coordinate fiscal policies, then the Center responds to the expansion of fiscal policy in the Periphery by increasing its own rate of growth of autonomous expenditure. $C$ shifts to $C'$ and the new equilibrium position is $z'$. This position implies higher growth with external equilibrium in both Center and Periphery. This classical coordination game, however, is no longer possible in a world in which current patterns of growth compromise the stability of the planet. A more complicated coordination game emerges, which is the topic of the next sections.

4. The Missing Constraint: The environment in a Center-Periphery System

**Environmental Coordination Game**

The previous analysis presented the mutually beneficial effects of adopting expansionary policies for two interdependent economies. The classical Keynesian coordination game, however, takes place outside of environmental constraints. Accounting for a planet with finite resources and pollution absorption capacities, policies with positive effects on growth and income distribution may harm global sustainability efforts in the long run. In other words, even if perfect Keynesian coordination were possible (with full employment and convergence between Center and Periphery), such coordination would be compromised by environmental disequilibria. Both the causes and
effects of these environmental disequilibria, as has been stressed, will overwhelmingly impact the poor and populations in the Periphery.

For simplicity, in the rest of the paper we refer to the challenge of stabilizing the earth system simply as avoiding “climate change”, keeping in mind that it encompasses several other environmental limits to growth along current patterns of production and consumption (Steffen et al. 2018). There is now an international consensus that rapid reductions of global emissions are necessary to stabilize the earth’s climate system and avoid increasingly catastrophic damages. At current rates of emissions production, the global carbon budget needed to avoid a 1.5 degree Celsius temperature change above pre-industrial levels will be surpassed in little over a decade, with 2 degree Celsius change coming swiftly afterwards (5-10 years). At 2 degrees Celsius, most reports indicate massive increases in the number of poor and starving people, large cross-border migrations, and growing domestic and international conflict as ecological crises devolve into humanitarian disasters (IPCC 2018). Reducing the absolute level of emissions should therefore be a high national and international priority, given the fast approaching carbon deadline.

In the rest of this section, we update the Keynesian coordination game to highlight both the environmental constraints to growth and the distribution of environmental burdens in an unequal world system. This framework provides a macroeconomic tool for depicting unsustainable growth patterns as a function of trade between regions with divergent economic and technological capabilities. Even seemingly sustainable patterns of growth must therefore be scrutinized for exacerbating global asymmetries (Hornborg 2009, Bonds and Downey 2012).

**Emissions Growth and “Green Efficiency”**

To see how climate change constrains the Keynesian coordination game, we take as a point of departure a simplified version of the IPAT identity, assuming constant population (normalized for simplicity to one).

\[
H = Y \left( \frac{H}{Y} \right)
\]

where \( H \) is global pollution, \( Y \) is global output, and \( \frac{H}{Y} \) is the stock of CO2 emissions per unit of output. In a two-region system (see ECLAC 2019), this becomes:

\[
H = H^C + H^P = Y^C \left( \frac{H^C}{Y^C} \right) + Y^P \left( \frac{H^P}{Y^P} \right)
\]

\[
Q^i = \frac{Y^i}{H^i}, \text{ with } i = C, P
\]

\[
H = H^C + H^P = Y^C \left( \frac{1}{Q^C} \right) + Y^P \left( \frac{1}{Q^P} \right)
\]

Equation 6 gives the variable \( Q \), defined as the inverse of \( H \). \( Q \) represents “green efficiency”, denoting the technology-driven relationship between the level of output per unit of pollution (e.g., tons of CO2). Taking logs and differentiating with respect to time, we obtain the rate of

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4The IPAT identity (Commoner 1972) represents a measurement of the environmental Impact; the original formulation is Impact = Population x Affluence x Technology where each component can be measured by pollution, population, GDP per capita, and pollution per unit of GDP, respectively.
growth of the global emissions as a function of growth in Center and Periphery and the rate of technical change driving improvements in emissions growth relative to the growth of output:

\[
h = h^C (1 - s) + h^P s = (1 - s)(y^C - q^C) + s(y^P - q^P)
\]  

(8)

In the previous equation, \( q \) is the rate of growth of output per unit of emissions, and superscripts C and P are Center and Periphery. \( q \) is therefore the rate of growth of the “green efficiency”, \( s \) is the share of total global emissions produced in the Periphery, making \( 1 - s \) the share of the Center. In turn, \( h \) is the rate of growth of global emissions, now shown to depend on the evolution of technical change in each country. The following equation describes the rate of growth of green efficiency in the Periphery as depending on technological developments, social capabilities in the Periphery, and emissions exported by the Center:

\[
q^P = f(G, w) - by^C, f_G > 0, f_w > 0, b > 0
\]  

(9)

Following the Schumpeterian literature on the evolution of the technology gap, the higher the technology gap \( G \), the higher the potential for technological spillovers from the Center to the Periphery (for a discussion see Verspagen [1991]. For this reason, the rate of growth of green efficiency \( q^P \) is positively associated with \( G \). A large technology gap offers more opportunities for catching up based on the existing technology in the center. A small (green) technology gap indicates that the Periphery is already near the technological frontier; closing the technology gap at the margins becomes more difficult, and this is the reason why improvements in efficiency tend to slow down. In turn, \( w \) represents what Abramovitz [1986] calls “social capabilities” and the neo-Schumpeterian literature calls “absorption capabilities” (Narula [2004], which refers to the ability of the Periphery to master, diffuse, improve and adapt foreign technology. The extent to which potential green technological spillovers become effective spillovers depends on these social capabilities. \( w \) depends on the strength and coordination of public and private institutions for green science and technology - the National System of Innovation (see Lundvall [2007]). A more detailed analysis of the evolution of green efficiency as it relates to the technology gap and social capabilities can be found in the mathematical Appendix A.

Finally, the term \( by^C \) is a measure of pollution transfers to the Periphery. Part of the pollution emissions and resource use by the Center is effectively off-shored to the Periphery. Empirical data show that decoupling of domestic emissions and resource use from output growth has coincided with rising pollution- and resource-intensive production elsewhere (Jorgenson et al. [2009], Jorgenson [2012], Thoms [2018], Plank et al. [2018], Hao [2019]). Including the pollution transfer term is therefore a necessary addition to capture the global “rebound effects” of decarbonization efforts (Wei and Liu [2017]). If technological developments translate into greater production of resource- and emissions-intensive goods abroad, then counting solely on efficiency improvements to resolve environmental crises is unwise.

**The Center-Periphery Environmental Frontier (CPEF)**

In order to achieve an absolute reduction in the level of emissions, the growth rate of emissions output must be negative. The pathway towards a zero-carbon economy begins with a negative-carbon-growth economy. Moreover, such a pathway must be achieved in the context of competing regions with divergent technological capabilities, institutional power, and resource availability. This section develops the modeling framework to consider situations that can bring the global economy within a declining carbon growth budget.
Assume that the level of emissions output ($H$) is required to fall at a rate $e$ in order to prevent global temperatures from rising more than 1.5 degrees Celsius above pre-industrial levels. Therefore, $e$ is the environmental target rate of emissions decline consistent with the internationally agreed-upon maximum safe limit of emissions output. From Equation 4 it is possible to find all the combinations of output and emissions growth in the Center and Periphery that are consistent with this target (i.e. that makes $h = -e$). We call this a Center-Periphery Environment Frontier (CPEF):

$$y^P = \frac{(s - 1)y^C}{s} + \frac{(1 - s)q^C - e}{s} + q^P,$$  \hspace{1cm} (10)

$$y^P = \frac{(s - 1)y^C}{s} + \frac{q^C - e}{s} - \frac{(q^C - q^P)}{c}$$  \hspace{1cm} (11)

Equation (11) considers the growth rate of the Periphery as a function of three components: the rate of growth of the center ($A$), the rate of growth of green innovations (represented by the rate of growth of green efficiency in the center) as compared to the rate of growth of green efficiency required to stabilize the planet ($B$), and the rate of growth of the green efficiency gap between center and periphery ($C$). Technological innovations allowing for an increase in green efficiency $q^C$ are assumed to be produced in the Center. To simplify notation, we also assume that all technical change is directed to improve $q$ in the Center and Periphery; we therefore assume complementarity between green and standard innovation processes. Technical change in the Center grows at an exogenous rate. Both technical change and the growth of green efficiency in the Periphery, however, are endogenous to the model.

Note that the growth rates of the Center and Periphery ($y^{C,P}$) consistent with $h = -e$ must follow strict criteria. Growth rates can increase under the condition that (i) the growth of green efficiency $q^{C,P}$ is sufficiently large and increasing through time out of technical change, and (ii) the rate of growth of the “green technology gap” $(q^C - q^P)$ is small. Transfers of emissions from Center to Periphery can improve $q^C$ at the expense of $q^P$. From an analytical perspective, pollution transfers make the CPEF curve steeper and imply less growth in the Periphery for any rate of growth in the Center. In turn, a reduction in the technology gap or an improvement in the absorption of technology spillovers shifts the CPEF to the right, implying that the Periphery can grow at a higher rate without overstepping climate boundaries.

Efforts to maintain global climate goals and promote sustainable development will likely require an impressive level of coordination between the Center and Periphery. For the Periphery to grow at a higher rate without overshooting the global carbon budget, the Center’s growth should not result in a transfer of pollution to the Periphery. In addition, if technical change does not reduce emissions levels fast enough, a second sustainable economic pathway for the global economy that allows for a growing Periphery would require a zero or negative growth condition for the Center, i.e $y^C \leq 0$.

A negative-growth-of-emissions constraint likely entails a fall in trade such that the Center is no longer importing raw materials and pollution-intensive goods from the Periphery. This condition does not rule out the possibility for positive growth in the Center, as long as that growth is achieved without any increase in domestic emissions or offsetting emissions in the South. The possibilities of doing so are severely restricted.
Below we show how the addition of the environmental constraint \((C_{PEF})\) can shed light on available scenarios for achieving a globally negative rate of pollution growth.

5. Environmental Coordination Games: Four Scenarios for Global (Un)Sustainability

The previous section has detailed the modeling framework to develop different scenarios in which the global economy feasibly reaches a sustainable point, defined as zero pollution growth. In what follows, we sketch an outline of four potential scenarios with varying degrees of likelihood and Sustainability (from global unsustainability to global sustainability). First, “Global Unsustainability by Business-As-Usual” describes a situation in which no direct actions are taken to improve domestic or global sustainability. Second, “Local Sustainability by Accumulation” shows the potential effects of a “green growth” agenda in the industrial Center. Third, “Global Sustainability by Accommodation” depicts what may happen as a result of a strong degrowth policy in the Center to accommodate higher levels of output in the Periphery. Fourth, “Global Sustainability by Coordination” shows how international cooperation to raise income growth in the Periphery and decrease growth in the Center could improve material well-being for the poorest.

**Scenario 1: Global Unsustainability by “Business-As-Usual”**

The first scenario describes the actual situation of the present global economy, shown below in Figure [2]. Here, both the Center and Periphery grow at different rates with respect to each other as shown by their respective curves, \(C\) and \(P\). Moreover, both regions are growing in line with the global long-run balance of payments equilibrium \((BP)\). However, Center-Periphery environmental frontier \((C_{PEF})\) is well below equilibrium growth rate. This means that the growth rate of the world economy is out of sync with global sustainability. In the “business-as-usual” scenario, there is no coordination and no “green” fiscal efforts from each country. Moreover, there are no automatic mechanisms which force global economic growth into the negative emissions growth territory. Business-as-usual therefore implies long run instability as climate change and other ecological crises worsen. It is necessary to turn towards public policy to stabilize the earth system.
Scenario 2: “Local Sustainability by Accumulation”:
*Green Growth in the Center brings Global Unsustainability*

In this scenario we assume that the Center initiates a “green growth” strategy that successfully makes domestic emissions growth negative. Such strategies have already been explored in much of the existing literature in post-Keynesian ecological macroeconomics (see Svartzman et al. 2019). While approaching the subject in multiple different ways, these studies detail the negative impacts of climate change on output, income, employment and even inequality. Green Keynesian fiscal and monetary policies are put forth to counteract emissions growth and improve both environmental and social outcomes. However, such “win-win” solutions are not easily found. Domestic growth and technology-based policies are conducted in the absence of intervening measures, thereby resulting in a transfer of pollution to the Periphery and a continuation on a globally unsustainable path.

Seeking to improve domestic sustainability and environmental efficiency, the Center implements green fiscal and monetary measures to channel investments towards efficient technologies and raise its rate of growth, seen in Figure 3 as a move from C to C'. Green policy incentives allow the Center to set $y_C = y_C^e$, where $y_C^e$ is given by the equality $y_C^e = q_C - e \Rightarrow h_C = -e$.

With a higher rate of technical efficiency, the Center can now obtain a rate of growth, $y_C^e$, on $C'$, consistent with a negative rate of emissions growth. This implies that green investment policy in the Center effectively shifts production towards “decoupled”, low-emission high-tech industries and services such that emissions growth domestically is negative, reflecting an instance of absolute decoupling of domestic emissions from GDP growth in the Center.

3In reality, the most likely result under a “Business-As-Usual” Scenario is that the rate of growth for the Periphery required by the CPEF is negative for any positive value of the rate of growth in the Center. However, to keep the figures simple, we assume that the Center always attains a positive growth rate.

4Note in Figure 3 that the $C'$ curve is now primarily determined by the desire to maintain the environmental target rate of growth $y_C^e$, and is thus a vertical line. While the Periphery’s rate of growth depends on the growth of the Center, the Center no longer depends on growth in the Periphery.
At the same, however, a higher rate of growth in the Center is matched by an increase in
the growth of demand for resource- and pollution-intensive goods. The CPEF curve becomes
steeper due to an increase in the pollution transmission mechanism (an increase of $b$). The new
CPEF' curve reflects that, while local production is more environmentally efficient, the Center’s
output expansion must be partially fed by an increase of imported goods and resources, extracted
and processed in the less-efficient Periphery.

Figure 3 draws attention to this important caveat built into domestically oriented “green
growth” policies. Locally efficient growth in the Center has led to a rise in the scale and inten-
sity of pollution-intensive production in the Periphery. Export demand in the Periphery therefore
increases, raising its rate of growth. The $P$ curve shifts upwards to $P'$, meeting the $C'$ curve at $z'$. However, $z'$ is not on CPEF'. Emissions growth in the Periphery is not negative, and thus $y^p > q^p – e$. The decoupling strategy of the Center has produced a domestic drop in emissions
that is balanced by an increase in the growth of emissions globally. There has been no absolute
decoupling of emissions on a global scale; depending on the size of the transmission term, global
emissions intensity may have increased.

Furthermore, the external-constrained equilibrium rate of growth in the Periphery is higher
than the rate of growth required for achieving a decline in global emissions (point $z'_e$). With a steeper CPEF' curve, it is now more difficult for the Periphery to remain in line with the
global carbon budget for any rate of growth of the Center. Achieving global sustainability in this
scenario would require a strong downward shift in the effective rate of growth in the Periphery
to meet the CPEF' curve at $z'_e$.

Figure 3: “Local Sustainability by Accumulation”

Scenario 2 demonstrates that global emissions may rise both in spite of and because of an
emphasis on purely technological fixes to environmental problems. The Center’s emissions are

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7We have abstracted from changes in the BP curve to keep the story simple.
displaced spatially via the pollution transmission mechanism. The institutional and political economy requirements for achieving global sustainability are therefore more demanding than changing fiscal expenditure and/or implementing policies in support of technological innovation. Sustainability transitions must be contextualized for the ways that they redistribute social and ecological inequalities. If the Center wishes to focus on a growth-enhancing policies alone to improve efficiency, staying within the global carbon budget would require a major reduction in growth from the Periphery. Given that much of the population in the Periphery consumes an insufficient quantity of resources, and the Periphery is least responsible for accumulated environmental demands, such a situation is untenable. The following two scenarios present alternative pathways that can promote global sustainability, focusing in particular on redistribution and equality.

Scenario 3: “Global Sustainability by Accommodation”:
Degrowth the in Center Accommodates Weak Growth in the Periphery

The “Global Sustainability by Accommodation” scenario depicts a Center that takes responsibility for its share of global emissions production. The Center acknowledges that most of the stock of CO2 in the atmosphere was accumulated over centuries during their own process industrial economic growth (Roberts and Parks 2009). Industrialized countries therefore make a concerted effort to reduce pollution-intensive consumption and investment. In this case, green fiscal and monetary policy would support strategic divestments from the most environmentally harmful industries, and would significantly reduce growth in the Center. Scenario 3 further assumes that the Center encourages a large-scale transfer of green technology to the Periphery, and a rise in Peripheral exports, to avoid a major fall in incomes in the Periphery.

Not only would low (zero) or negative growth in the Center reduce domestic emissions production, it could also provide the environmental “breathing room” necessary for the poor to increase material consumption. Such policies have been put forth as a necessary aspect of a global redistribution program to allow the world to remain within ecological limits (Jackson 2009, Daly 1991). Daly (1991, pg. 148) has argued that

the underdeveloped countries are not ever going to develop […] unless the overdeveloped countries moderate their demands on world resources and absorption capacities. […] In addition, underdeveloped countries will have to revise their expectations downward regarding their own growth.

Indeed, widespread environmental degradation is already hindering many poor countries from developing the infrastructure and institutions necessary to meet even basic needs (Rice 2007, Wackernagel et al. 2019). Dependence on resource extraction frequently results in declining environmental quality, as well as vicious cycles of poverty-induced environmental deterioration that can prolong and reinforce underdevelopment (Bunker 1985). Without a degrowth policy in the Center, socially necessary consumption and investment in the Periphery will be increasingly impaired. A warming climate, erratic precipitation, rising pollution and resource extraction

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will also likely worsen domestic and international inequality (Gough 2017). Since resource- and pollution-intensive demands from within the industrialized world tend to exacerbate environmental degradation and vulnerability in developing countries (Jorgenson 2016), finding ways to reduce demand in the Center is also a matter of environmental justice (Martínez-Alier 2002, Martinez-Alier 2012, Schneider et al. 2010).

Under a zero or negative growth condition, \( y_C \leq 0 \), the Center economy is no longer growing and no additional emissions are exported via pollutive imports. This approach would require a major restructuring of the Center’s economy. The degrowth platform suite of policy options provide a useful guide to what would allow a country to reduce growth and emissions in a socially and economically sustainable manner (Kallis 2011, 2017, Sekulova et al. 2013, Videira et al. 2014). While investments in efficiency increases and a national focus on low-impact sectors with high technological capabilities may remain an important aspect of the program, the Center will complement these by instituting policies in line with broader socioeconomic and environmental goals. Such investments would likely include major investments in public infrastructure and public or community provision of goods and services such as health, housing, education and transportation. A reduction in working hours (e.g., via a work-sharing program), alongside investment in projects for natural restoration and other public works with low or positive environmental impact (Forstater 2006), could feasibly reduce unemployment and improve well-being. Nevertheless, degrowth would also require downsizing sectors that are particularly environmentally damaging, as well as an economy-wide negative rate of investment.

Figure 4 reflects a scenario in which the Center significantly reduces its rate of growth, seen here as shifting from \( C \) to \( C' \). At the new rate of growth \( y_C' \) has declined to make room for the Periphery to grow without overstepping the environmental frontier. The Center and Periphery agree on the need to reduce emissions and move from the environmentally unsustainable equilibrium in \( z \) to sustainable equilibrium in \( z'_e \) (which is both upon both the BP schedule and CPEF schedule; see Figure 4). The global economy moves towards the CPEF while at the same time “accommodating” rising emissions and material consumption in poor countries.

*For the sake of simplicity, in Figure 4 it is assumed that technical change has shifted the BP curve, but not yet the CPEF schedule.*
However, the decline in growth in the Center would also necessarily shift the BP curve in a way that harms output in the Periphery. While much of the growth of the Center can be traced to socially and ecologically harmful production in the Periphery (Srinivasan et al. 2008, Downey et al. 2010, Bonds and Downey 2012), it nonetheless represents a major source of economic demand and supports socioeconomic stability under existing institutional frameworks. A sudden and significant drop in demand from the Center would result in declining human welfare, higher unemployment and inequality in the Periphery if conducted in the absence of regional policy coordination and improved social policy implementation. Degrowth in the Center must also be considered in relation to its effects on the Periphery (Jackson 2009, pg. 175), a fact that is not frequently discussed in degrowth literature (Weiss and Cattaneo 2017, pg. 224).

To avoid an immediate and major contraction in Peripheral growth, two additional policies are required. First, policies in the Periphery that improve social (technological) learning capabilities can be adopted to speed up technological absorption and catching up with the Center. This shifts the BP curve out to BP′, which represents a more diversified production structure in the Periphery and a higher elasticity ratio of exports to imports. Second, the Center must also be ready to allow higher imports from the Periphery to keep external equilibrium at both Center and Periphery.

In Figure 4 we assume that this coordination is successful and income elasticities adjust to avoid a sudden fall in growth in the Periphery. Note that the new combination of rates of growth is given by point z′. The P curve remains stable in this case, but the Periphery’s rate of growth declines to be compatible with the lower rate of growth of the Center, the CPEF schedule, and external equilibrium (BP′).

The sequence of actions is as follows: the Center reduces its rate of growth; the Center facilitates exports from the Periphery in order to allow for some degree of convergence; the BP curve shifts to the left from BP to BP′; the Periphery grows at a lower rate than before (because it exports less to the Center).

As investment transitions towards meeting better local social and ecological needs, there may also be a large improvement in green efficiency in the Center that reduces (i) import needs from the Periphery, as well as (ii) pollution transmission. Technological upgrading in the Periphery
may affect both the BP and the CPEF curves, as seen in Figure 5. In this case, the CPEF can experience a large change, as both terms in the pollution transmission mechanism change: $b'y^C$, where $b' < b$; $y^C' < y^C$. The CPEF moves to $CPEF'$ which highlights that technological catching up in the Periphery raises competitiveness (and hence economic growth in equilibrium) and reduces the rate of growth of pollution at the same time.

![Figure 5: “Global Sustainability by Accommodation” (with reduced pollution transmission)](image)

Scenario 3 shows that global convergence and sustainability will require a serious transformation in global economic structure and considerable coordination between regions. Most of the change will likely come from the Center, whose negative growth rate leaves sufficient environmental space for the Periphery to grow without overshooting ecological limits.

It should be noted that it would be unwise for Peripheral countries to simply follow in the same footsteps as the Center. Daly (1991) has also warned that world-wide adoption of a Western-style high mass consumption economy would be an environmentally impossible and socially undesirable goal. Emerging Peripheral countries with technologically advanced export structures are presently repeating many of the same environmental mistakes as the Center, pushing environmental degradation into poorer Peripheries (Meng et al. 2018). For Scenario 3 to remain sustainable, developing countries would have to somehow balance developing a high-value export structure and rising effective demand against growing resource needs and imports required for production. If pollution and resource extraction is simply transmitted from one country to another, absolute decoupling on a global level will remain elusive.

**Scenario 4: “Global Sustainability by Coordination”: Degrowth in the Center Permits Green Growth in the Periphery**
The “Sustainability by Coordination” scenario, much like in the previous section, requires a major reduction in growth from the Center to support continued growth in the Periphery. However, in this case global coordination is key. The Center finds ways to reduce growth sufficiently to allow the Periphery ample room to initiate its own “green” industrial change and investment program (Altenberg and Assmann 2017). Not only does the growth rate in the Periphery rise, but the global green efficiency gap closes \((q^C - q^P < 0)\), as the Periphery catches up in technology.

Serious efforts from the Center to share technology and help the Periphery to build endogenous capabilities, combined with other social policies, allow global efficiency to increase alongside improvements in material conditions for the Periphery. This is the most cooperative possible move by both countries, and would likely result in the quickest and fairest policy for reducing emissions growth while improving livelihoods, within our framework. This scenario highlights the benefits of cooperation between the Center and Periphery to both accommodate growth where it is needed while also quickly raising technical standards to meet climate targets.

As shown in Figure 6, a reduction in growth from the Center, mixed with a focus on social and environmental policies that include green economic restructuring in the Periphery, result in a leftward shift of \(C\) to \(C'\), and an upward shift of \(P\) to \(P'\). Differentiated responsibilities imply that the Center will not use its technological capabilities to maximize advantages in trade, but to encourage international technological diffusion (see Appendix A). The Periphery, in turn, invests heavily in building endogenous learning capabilities (including institutional capabilities) to absorb this technology. The increase in global efficiency shifts the \(CPEF\) schedule upwards to the right (from \(CPEF\) to \(CPEF'\)).

In the process, it is likely that (at least temporarily) the income elasticity of imports in the Periphery increases as new technology is imported, which moves the \(BP\) schedule to the right. Regardless, the result of this internationally coordinated strategy are improved socioeconomic performance, greater material well-being for the poorest countries, and global sustainability.
6. Summary and Conclusions

This paper has explored four possible scenarios for global climate mitigation in an “environmental coordination game”: global unsustainability; local sustainability; global sustainability with reduced growth for both the Centre and Periphery; and global sustainability with reduced growth for the Center and a green growth-stimulus for the Periphery. By modeling the possibilities for coordination in an environmentally-constrained Center-Periphery system, we highlighted several important challenges and opportunities for a truly global response to the present environmental crisis. The environmental coordination game presented here demonstrates interesting political economy differences with the traditional Keynesian coordination game. In the Keynesian game, all actors gain from an expansion of aggregate demand and the pursuit of higher levels of employment and capital utilization in the economy. In the environmental game, gains and losses depend on interrelated technological, social and ecological dimensions.

The present work has also extended and deepened the “shallow” lens of ecological macroeconomics in four important ways (Spash 2013, Svartzman et al. 2019). First, we have highlighted the inseparability of socioeconomic and environmental conditions between regions, presenting the economy as a world ecological system, “in which one country’s environmental problems may be the flip side of another country’s growth.” (Hornborg 2003, pg. 215). Second, we have reconsidered the role of green investments from within the post-Keynesian framework, by questioning their sustainability-enhancing properties at the global scale. Successful climate mitigation and adaptation efforts will need to better understand how technical changes distribute environmental risks and rewards unevenly between different regions and social groups. Third, we introduced degrowth as a viable, and perhaps necessary alternative or complement to “green growth” policies. Nonetheless, degrowth in the Center has important implications for the Periphery, and must be balanced with growth-enhancing policies to avoid a negative income shock in Peripheral countries. Finally, we stressed a third dimension that has been underserved by previous research in the ecological macroeconomic framework: environmental justice. The proposed scenarios aimed to capture two key dimensions in environmental justice: the right of future generations to inhabit a stable and healthy planet, and the right of those presently left behind to improve their material well-being. The desire to enhance global equality while restraining pollution presents a major challenge of redistribution both between and within countries (Laurent 2014, Roberts and Parks 2009).

Achieving a sustainable economic pathway under present economic and environmental constraints implies a difficult road ahead for the global community. Many of the institutional changes necessary for achieving social and environmental sustainability are daunting. Political and economic control rests firmly in the hands of rent-seeking elites whose power will not be easily wrested, especially in the Periphery. Even attempts at improving basic social protections face enormous political opposition, let alone policies that would significantly reduce corporate profits, such as liberating patents for international knowledge sharing.

Future researchers may wish to analyze the effects of a large reduction in trade (e.g., “Global Sustainability by Relocalization”) in both the Center and Periphery. In theory, this would be the strongest move towards global sustainability (Cobb and Daly 1990), especially if paired with local development efforts to build resilient communities on the principle of environmental sovereignty and democratic accountability (Fischer 2017). The institutional changes required to achieve such a scenario, however, are far outside the purview of the present modeling framework.

Moving forward, it will be increasingly necessary to account for the ways in which well-meaning economic and environmental policies can exacerbate the vulnerabilities of less advan-
taged groups across geographic space and time (e.g. future generations). Strategies for raising living standards and sustainability often have unseen or unacknowledged negative consequences (Bonds and Downey 2012, Hickel 2019). If efficiency improvements merely alter the location, scale and intensity of environmental pressures (Bunker 1985, Bunker and Ciccantelli 2005, Bonds and Downey 2012), investment policy alone cannot be counted on to resolve ecological conflicts and crises. On a finite and increasingly fragile planet, ecological macroeconomics must make a decisive turn towards identifying other means of securing sustainability and well-being outside of GDP growth.
References


Appendix A. Mathematical Appendix

Appendix A.1. Deriving the effective rate of growth

Aggregate demand is divided in two components, domestic absorption \( A \) and net real exports, \( X - RM \), where \( R \) is the real exchange rate, defined as \( R = \frac{P_C}{P_P} \).

\[
Y^p = A + X - RM \tag{A.1}
\]
The demand for exports and imports are given by constant-elasticity demand functions,

\[
X = R^{\mu_X}(Y^C)^\epsilon \tag{A.2}
\]

\[
M = R^{\mu_M}(Y^P)^\pi \tag{A.3}
\]
where \( \mu_X \) and \( \mu_M \) are price elasticities of exports and imports, respectively, and \( \epsilon \) and \( \pi \) are income elasticities of exports and imports, respectively. Taking logs and differentiating with respect to time, and representing proportional rates of growth with small letters (e.g., \( a = \dot{a} \)), and assuming a constant exchange rate in the long run we get:

\[
y^p = \tilde{\alpha} + \beta_1 x - \beta_2 m \tag{A.4}
\]
In Equation 7, \( \tilde{\alpha} = \frac{\dot{a}}{1 + \beta_2 \pi}, \beta_1 = \frac{\dot{x}}{\pi}, \text{ and } \beta_2 = \frac{\dot{M}}{\pi} \). Using Equations A.2 and A.3 in A.4 gives:

\[
y^p = \frac{\tilde{\alpha} + \beta_1 \epsilon x^C}{1 + \beta_2 \pi} \tag{A.5}
\]
Making \( \alpha \equiv \frac{\tilde{\alpha}}{1 + \beta_2 \pi} \) and \( \beta \equiv \frac{\beta_1}{1 + \beta_2 \pi} \) renders:

\[
y^p = \alpha + \beta \epsilon x^C \tag{A.6}
\]
Since the rate of growth of exports \( (x) \) in the Periphery is given by the income elasticity of exports \( (\epsilon) \) and the rate of growth of income in the Center \( (y^C) \), \( x = y^C \epsilon \), Equation A.6 can be rewritten as Equation 3 from the main text:

\[
y^p = \alpha + \beta x \tag{A.7}
\]

Appendix A.2. Endogenizing the technology gap and the “Green Gap”

Here we present a simple model of the evolution of the Center-Periphery green technology gap \( G \), and its relationship to endogenous changes in environmental efficiency in and between regions. We follow post-Keynesian and Structuralist literature by assuming that improvements in productive structure in the Periphery result from purposeful investments that decrease the "technology gap" between itself and the technological leader (see Cimoli and Porcile 2011, Porcile and Spinola 2018). \( G \) is the technology gap, \( G = \frac{\dot{T}_C}{T_P} \), which indicates the relative distance in technological capacity between the Center and the Periphery. As \( G \) approaches unity, the Center and Periphery operate under similar technical conditions, and have a rate of accumulation of "sustainable" knowledge, learning-by-doing effects, and industrial synergy on par with each other. When \( G \) is high, there is a large (green) technological gap between them, indicating a major discrepancy in efficiency. Closing the technology gap is therefore an important aspect of
the sustainability transition. A smaller technology gap is thus consistent with improved green efficiency in the Periphery.

Recalling from Equation 5, that \( q^p = f(G, w) - by^c \) (with \( f_G > 0, f_w > 0, b > 0 \)), the evolution of the green gap through time, with an exogenous the rate of growth of green efficiency in the Center, will be:

\[
\dot{G} = q^C - q^p = q^C - f[(G, w) - by^c]
\]  \(\text{(A.8)}\)

Assume a linear relationship between the technology gap and green efficiency in the Periphery, \( q^p = w + \sigma G - by^p \). In equilibrium the green technology gap will be:

\[
\dot{G} = 0 \Rightarrow G = \frac{q^C - w + by^C}{\sigma}
\]  \(\text{(A.9)}\)

Recalling that \( y^C = q^C - e \), then Equation A.9 can be rewritten as:

\[
G = \frac{(1 + b)q^C - w - be}{\sigma}
\]  \(\text{(A.10)}\)

The higher the social capabilities in the Periphery \( w \), and the lower the transfer of emissions from the Center (assuming \( q^C > e \)), the lower the green technology gap in equilibrium. Since climate change is a global existential threat, the degree of pollution transmission is an important variable to consider. Finding a globally sustainable growth path is made exceedingly complicated if the presumed efficiency increases from technological improvements are overcome by “rebound effects” at the micro, meso, macro and international scales (Rezai et al. 2013, Wei and Liu 2017).

While \( b \) is positive, \( y^C \) can be either positive or negative. If positive, economic growth in the Center leads to an increase in pollution emissions in the Periphery. Without sufficient increases in “green efficiency” in developing countries, pollution transmission from the Center raises global emissions. This may happen either despite or as a result of policies that reduce pollution in the Center. If \( y^C \) is negative, the Center has a contracting growth rate and therefore demands less imports of pollution intensive production from the South. In equilibrium, \( q^C = q^p \). If the global economy is on the CPEF, then \( y^C = y^p = q^p - e \). During the transitional dynamics, the Periphery converges with the Center since \( q^p > q^C \) which implies (from Equation 7) that \( y^p > y^C \). When \( G \) is in equilibrium, the only avenue through which the Periphery can converge is by changing the parameters that define the green technology gap in equilibrium (\( w, b \) and \( q^C \)).

Note that the above conditions are those required for the world to be upon the CPEF. The technology gap also affects the BP curve, to the extent that it alters the pattern of specialization in the Center and Periphery. While the two schedules (CPEF and BP) co-evolve and are interrelated, there is no automatic mechanism that make them converge. Recall that \( y^p* \), the equilibrium rate of growth in the Periphery, is given by Equation 1 and Equation 2. Convergence of the BOP-constrained rate of growth and the rate of growth consistent with the CPEF should be driven by policy interventions which adjust the responses of exports and emissions so that they are convergent. This explains why Scenarios 3 and 4 imply such a major institutional challenge to existing political and economic relations.