# Investing in a New Regime: Confidence and Uncertainty in a Low-carbon Transition

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**Abstract.** There is growing consensus that acting now to effectively mitigate climate change will bring social benefits, both the in the near and short term, yet action is far below what is required. An explanation is provided by the carbon lock-in hypothesis, which proposes that economies are in a high-emitting socio-technological regime. Viewing the economy as a complex adaptive system (CAS), a regime is a self-stabilizing state that emerges from underlying economic and social dynamics. We present a “North-South” dataset to describe global trends from 1970 through 2010, and use the idea of the economy as a CAS to interpret changes in capacity utilization, proposing a stochastic threshold model for medium-term cycles. We then use the dataset to construct a simple macroeconomic model, and combine it with a green-brown capital model developed in an earlier paper to explore the macroeconomic consequences of a low-carbon transition. With the models as guides, we use the Shared Socioeconomic Pathways (SSPs), one component of a recently developed global climate scenario framework, to construct a narrative of the initial stages of the launch of a low-carbon transition and explore the challenges it raises.

## 1. Introduction

Several recent reports, among them the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGIII 2014) and the New Climate Economy report (Global Commission on the Economy and Climate 2014), have pointed out that serious action to mitigate greenhouse gas emissions is likely to be beneficial, and will certainly be less costly than delay. This is not a new idea, having been pointed out already in the 1990s (Ha-Duong et al. 1997). Some countries have taken action, for example Germany (Dehmer 2013) and China (Garnaut 2014), yet they stand out because they are rare, and China’s policy is driven as much or more by local air pollution problems as by the global challenge of mitigating climate change. This combination of opportunity and inertia is consistent with the carbon lock-in hypothesis (Unruh 2000; Mattauch et al. 2012), which proposes that our current, high-emitting, global economy is maintained by strong institutional, technological, and economic stabilizing forces. That is, we are in a high-emitting socio-technological regime (Geels and Schot 2007).

This paper combines macroeconomic analysis from a post-Keynesian perspective with a view of the economy as a complex adaptive system (Rosser

1999; Foster 2005; Gallegati and Kirman 2012) as a way to understand a regime transition. Complex adaptive systems are made up of interacting heterogeneous agents whose combined actions lead to properties for the system as a whole that are not present at the individual level. Structures are therefore liable to change, sometimes abruptly and substantially. Even in "normal" times, economic life is characterized by fundamental uncertainty (Shackle 1949; Davidson 1991), in part because economic actors shape the environment in which they operate. However, a low-carbon transition is likely to be far from normal as governments, investors, and citizens make choices without clear knowledge of how technologies will develop, how trading partners and other businesses or investors will act, whether funding for government programs will be sustained, and the prospects for existing and future jobs. In these circumstances, economic actors must search for new rules to govern their behaviour (Loasby 2013). Any transition between socio-technological regimes is unsettling, which can lead to resistance, but transitions nevertheless occur because strong private economic incentives align with the direction of change. A transition to a low-carbon economy will be different, because the economic motivation is social, not private, and resistance can be more effective.

To better understand the macroeconomic consequences of a low-carbon transition, this paper develops a two-region North-South model, in which a more developed "North" interacts through trade with a developing "South". There is a well-established literature on such models (Darity and Davis 2005). Until recently, they typically assumed a resource-exporting South with abundant labor that must import investment goods and intermediate manufactures from the North. Given the dramatic changes in developing countries in the late 20th century, recent papers make different assumptions. Several (e.g., Dutt 2002; Botta 2009; Cimoli and Porcile 2014) close their models using Thirlwall's law (1979; 1997), which states that over the long run growth is constrained by the need to maintain an average zero balance on the capital account. There is ample evidence that Thirlwall's law applies in high-income countries (McCombie 1997) and some evidence that it also applies in developing countries (Thirlwall and Hussain 1982; Perraton 2003). However, we do not invoke Thirlwall's law in this paper because we are interested in a transition, during which constraints that hold in the long run may be violated.

We first construct a North-South model with a single category of capital, focusing on capital accumulation. We then apply both it and a green-brown capital model to explore the macroeconomic implications of a low-carbon transition. In a green-brown model, "green" capital is less productive than "brown" capital in today's economy, but becomes relatively more productive as green capital displaces brown capital, thereby capturing one aspect of lock-in. The model draws on an earlier working paper by the author (Kemp-Benedict 2014), but departs from it in some ways. The most significant departure is the way in which it is closed. The working paper used a Kaleckian closure, in which utilization adjusts to satisfy savings-investment balance in response to changes in the functional income distribution. Such a closure is appropriate at national scale, but does not perform well with the large regions we use for the present paper. Instead, we find that utilization is best described as evolving independently of distributional variables in a quasi-cyclical fashion. Utilization and distributional variables then explain changes in investment rates, and we close the model by having savings adjust to the level required to satisfy the balance of payments constraints. The result is a rather stylized version of an endogenous finance model in which savings adjust to accommodate desired investment.

We use the model to explore alternative pathways for a low-carbon transition. To ground both the model and scenario development, we begin with an exploration of historical trends in a North-South dataset.

## 2. Trends in North and South, 1970-2010

We constructed a data set using the Penn World Table (PWT) version 8.0 (Feenstra et al. 2013) and the World Development Indicators (WDI) (World Bank 2015). We included only those countries with a complete series from 1970 to 2010, defining the North as OECD member states as of 1990, and the South as the rest of the countries in the data set. Because the dataset starts before and ends after the fall of the Berlin Wall, the former Soviet Union is not represented. The countries in each region are shown in Figure 1.

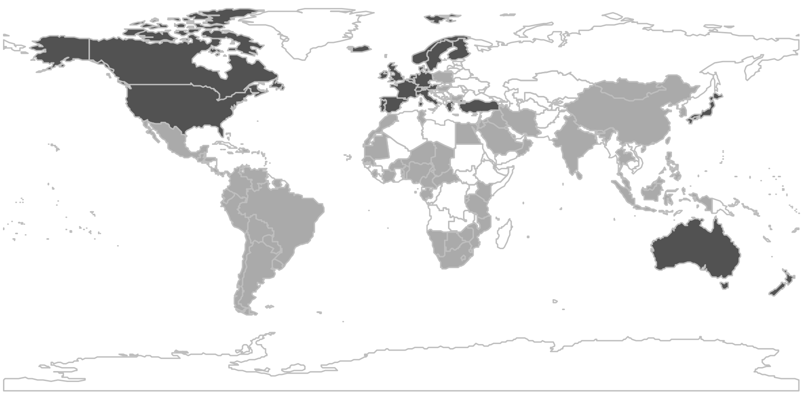

Figure 1: Countries in the North (dark) and South (light) regions

In a standard Kaleckian formulation, GDP in North and South, $Y_N$ and $Y_S$, are assumed to be proportional to the capital stock,

$$Y_{N,S} = u_{N,S} v_{N,S} K_{N,S}. \quad (1)$$

In this expression, $u_{N,S}$ is capital utilization in each region, scaled so that it equals one at a normal level of utilization, $v_{N,S}$ is capital productivity at normal utilization, and $K_{N,S}$ represents accumulated capital stocks in each region. GDP is allocated entirely between wages and profits, so gross profits are equal to GDP less the wage bill. Because the real wage is proportional to the wage share, wage earners notice the functional income distribution between profits and wages. The profit share is given by the ratio of gross profits $\Pi_{N,S}$ to GDP,

$$\pi_{N,S} = \frac{\Pi_{N,S}}{Y_{N,S}}. \tag{2}$$

While wage earners react to the functional income distribution, investors react to the profit rate, or return on investment expressed as profits per unit of capital stock, given by

$$r_{N,S} = \frac{\Pi_{N,S}}{K_{N,S}} = u_{N,S} v_{N,S} \pi_{N,S}. \tag{3}$$

**Utilization: A Minsky-Holling interpretation**

An essential variable in the post-Keynesian model above is the level of capital utilization. Data on utilization are reported in some countries, but are unavailable for most. We used a Hodrick-Prescott filter (Hodrick and Prescott 1997)[1] to separate the slow-moving and rapidly-moving components of GDP per unit of capital. The Hodrick-Prescott filter has a single parameter representing a frequency cut-off (Baxter and King 1999; Gómez 2001). The value used most often was selected by Hodrick and Prescott (1997, p.4) based on their expectation of what a moderately large deviation would be. Others (Baxter and King 1999; Gómez 2001) use a time period of about eight years, following work on business cycles at the US National Bureau of Economic Research (NBER) (Burns and Mitchell 1946). However, taking the definition of utilization in equation (1) literally, we are looking for deviations from capital productivity at normal levels of utilization. The relevant time scale in this case is the turnover time of capital, or the inverse of the depreciation rate; from PWT data, typical values in both North and South are about 25 years.[2]

[1] We used the mFilter package for R ver. 0.1-3 (http://cran.r-project.org/web/packages/mFilter/index.html). Unless noted otherwise, all statistical analyses in this paper were carried out using R ver. 3.1.3.

[2] Comin and Gertler (2006) and Borio (2014) also filter using longer time scales. Relative price changes can alter output per unit of capital (*Y*/*K*) over short time

Time series for the variables defined above are shown for the North in Figure 2 and for the South in Figure 3. Periods of falling utilization or profit rate are shaded grey in the figures. Because we use annual rather than quarterly data, the periods in grey as marked on the figures may be off by one year from the official start and end years of different recessions and crises. That caveat aside, some major economic events are evident in the graphs. In the North, it is possible to identify the 1973 and 1979 oil crises and ensuing recessions, the early and late 1990s recessions, the 2000 recession, and the most recent 2007-2009 recession. In the South, the 1973 oil crisis is evident, as are the 1980s debt crisis, the 1995 "peso crisis", the 1997 Asian financial crisis, and, as in the North, the recessions in the 2000s. The increasing degree of interaction between the highly industrialized and developing countries is illustrated by the coincidence of cycles in North and South from the mid-1990s onward.

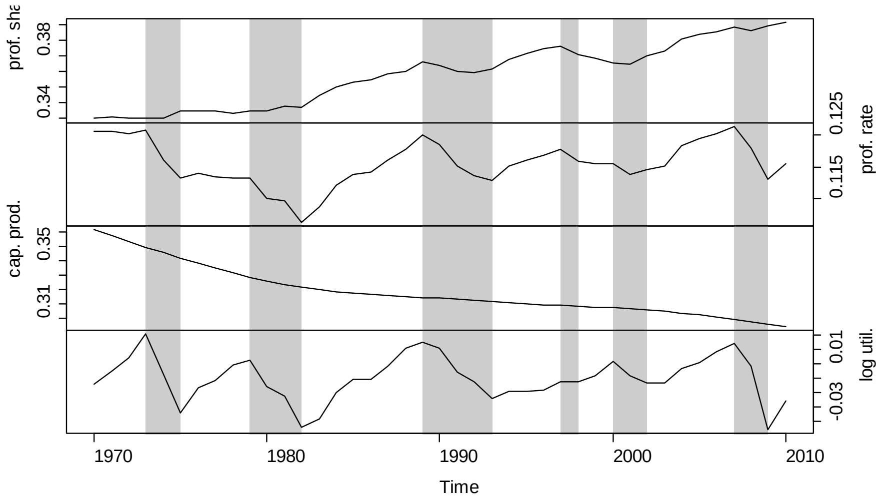


Figure 2: Trends in macroeconomic indicators for the North; periods of falling utilization or profit rate are shaded gray

scales. We implicitly factor this into utilization. Long-term compositional trends (e.g., a shift toward services) are captured in capital productivity.

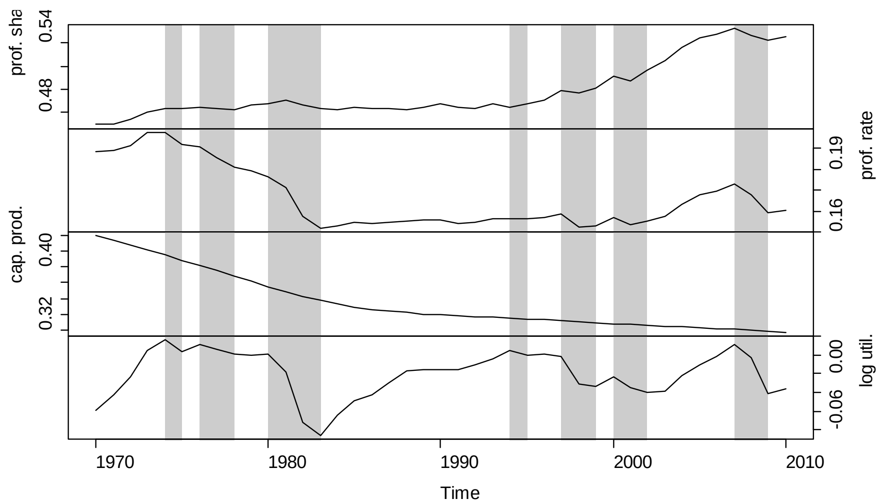


Figure 3: Trends in macroeconomic indicators for the South; periods of falling utilization or profit rate are shaded gray

Utilization in both regions and in both periods is quasi-cyclical. Considerable study has been devoted to cycles of different duration, both empirically and through models such as Hicks' (1950) multiplier-accelerator model.[3] In our filter we have selected for medium-term variations, which combine features of both business and financial cycles (Comin and Gertler 2006; Borio 2014). In this paper we use Minsky's (1977; 1980; 2008) financial instability hypothesis as a reference point for model construction.

According to the financial instability hypothesis, firms and investors are cautious after a crisis, and take on little debt. Nevertheless, they do invest, which boosts aggregate demand, leading to subsequent profits. The profits more than validate the incurred debts, encouraging firms to increase their leverage. By the end of the cycle the boom is in full swing and firms are highly leveraged. The system is now fragile, in that a small fall in output can lead some firms to miss their payments, which makes lenders nervous and call in debt. This leads to a general fall in output, perhaps ending in rescue by the government in its role as lender of last resort. In this view, crises are endogenous to the financial system. In Minsky's (1977, p.24) words, "the fundamental instability of a capitalist economy is upward". While every cycle is different, Minsky argued that the precise form does not matter. If, using established mechanisms, firms and lenders cannot finance the investment they

[3] The dominant approach today is real business cycle (RBC) theory. However, it views cycles as driven by exogenous shocks rather than endogenous dynamics, and its methodological assumptions are inconsistent with the post-Keynesian notion of fundamental uncertainty.

think is justified, then they will find other ways to do it (Minsky 1980, pp.511–512).

From the perspective of ecological economics, Minsky's theory appears as a special case of Holling's "figure-eight" adaptive cycle (Gunderson and Holling 2001). Across an adaptive cycle, complex adaptive systems aggregate resources and then release them, thereby creating opportunities for innovation and restructuring. Such systems tend to release resources in "cascades" of an indeterminate size (Bak et al. 1988), where the sizes of cascades typically follow a power-law distribution (that is, they appear as a straight line on a log-log plot). Release happens when the system has become highly interconnected and has aggregated considerable resources. In that state it is fragile, and vulnerable to events that it could have withstood previously. After resources are abruptly released, the system loses some of its interconnections and becomes simplified. Resources are then reassembled, and new structures are built. As in Minsky's view, the fundamental instability is upward, as complex adaptive systems, starting from a simple form but with ample resources in their environment, begin to grow in complexity as they aggregate resources, leading almost always to a complex and interconnected, but also fragile and vulnerable, state.

## Capital productivity, return on investment, and income distribution

Setting cycles aside, long-term trends in capital productivity, profit share, and profit rate are evident in Figure 2 and Figure 3. Following Kaldor (1957), it has long been conventional to assume constant capital productivity. However, while capital productivity exhibits no noticeable long-term trend, it can vary considerably within wide bounds (Maddison 1994). Moreover, as argued in detail by Piketty (2014), the variations matter a great deal in daily economic life. The essential link is between the profit share, capital productivity, and the profit rate at normal utilization. Setting utilization equal to one (and dropping the $N$ and $S$ subscripts), from equation (3) we have

$$r = v\pi. \tag{4}$$

As noted earlier, wage earners react to changes in the functional income distribution, $\pi$, while investors react to the changes in the profit rate $r$. Variations in capital productivity $v$ – whether through changing technology or economic structure – alter the relationship between the two variables and force a renegotiation of the allocation of income.

Such a renegotiation can be seen in the trends for profit share, profit rate, and capital productivity in the North (Figure 2). Capital productivity fell steadily, although at a slowing rate, from 1970 through 2010. In the first decade the profit share remained roughly constant. This was a time of relatively strong unions that protected the wage share of income and the real value of wages. However, falling capital productivity combined with a fixed wage share led to a falling profit rate, so the value of investments declined sharply. Northern finance, mostly from commercial banks, was increasingly directed toward the South over this period, ending with the Southern debt crisis. After the crisis the distributional conflict was resolved in the North by weakening unions. Union density fell in many OECD countries between 1980 and 1990 (Visser 2006, table 3), and starting in the 1980s, the profit share rose in the North, while the profit rate returned, by the late 1980s, to the level it had been in the early 1970s.

The profit rate remained higher in the South than in the North throughout the 1970-2010 period. Around 1970 it was very high because capital productivity was high, but that might better be described as a time when capital intensity was very low. The diversion of Northern investment toward the South rapidly drove up capital intensity, thereby driving down capital productivity, and the profit rate began to fall. There was considerable convergence in capital productivity between North and South over the period, and they are now nearly identical. The profit rate stabilized after the debt crisis, while capital productivity continued to fall; the profit share nevertheless remained steady because utilization rose for a decade after the crisis. After utilization hit a peak in the late 1990s, the profit rate was sustained by virtue of a rising profit share.

In both North and South, the period before 1985 is distinctly different from the period that followed, while the Great Recession has perhaps ushered in a new period. In subsequent analysis we therefore split the data set into two periods: Period I, from 1970-1985, and Period II, from 1985-2007. Period II corresponds to what has been called the “Great Moderation” in the US, as well as the “stakeholder value era”. It is characterized by weak unions and rising income inequality in the North, but also by comparatively mild recessions and low inflation. The same period in the South has been characterized by the emergence and rapid growth of some developing countries.

### The balance of trade

The data set collected for this paper does not include all countries in the world so net exports do not sum to zero (see Figure 4). Nevertheless, some trends can be discerned. The trade deficit in the North in the 1970s was driven, on the current account side, by rising petroleum prices. On the capital account, “petrodollars” earned by oil-exporting states were “recycled” and invested by Northern commercial banks, with many of these investments directed toward the South. The two regions remained more or less in parity well into Period II. It was not until after the Asian financial crisis in the late 1990s that the large volume of savings available in the South began to be directed towards relatively safe investments in the North, driving the capital account in the North sharply downward. Thirlwall's law reminds us that this state of affairs cannot continue indefinitely, and the reduction in the Northern trade deficit after the 2007-2009 financial crisis may signal a return to parity. However, at present the Northern trade deficit remains large.

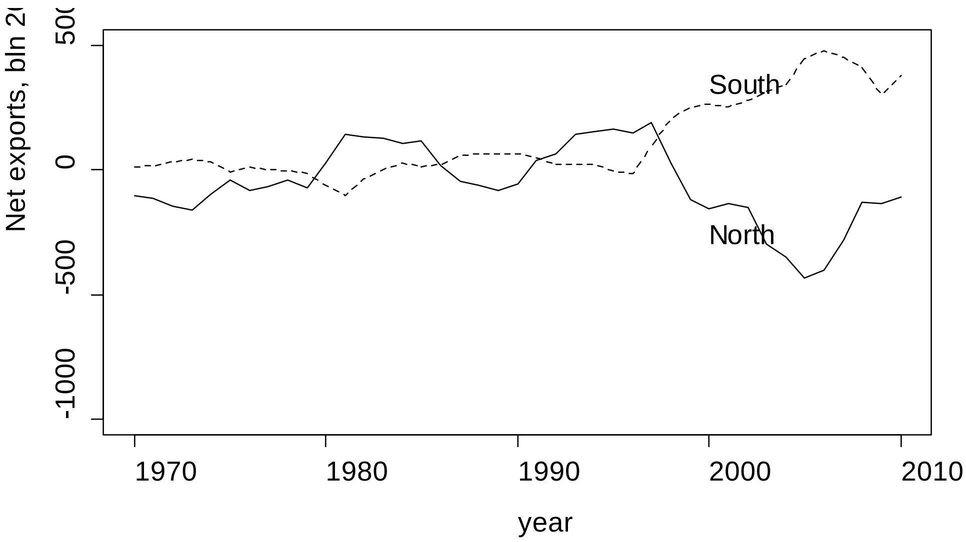


Figure 4: Net exports in North and South

## 3. A North-South model

Based on the observations in the preceding section and statistical tests in this section, we develop a post-Keynesian North-South model. Throughout, we use the logarithm of utilization rather than utilization itself. To keep expressions more compact, but at the risk of some confusion, we represent log utilization by $u_{N,S}$, the same symbol we used for utilization in the previous section.

The causal structure of the model is illustrated in Figure 5. In Kaleckian fashion, prices are assumed to be determined from costs. Both relative price and utilization feed into the trade balance. Utilization then drives investment, and savings emerges from the trade balance.[4]

[4] Granger causality tests showed that utilization Granger-causes investment in the North, but not vice versa. In the South, Granger-causality operates in both directions.

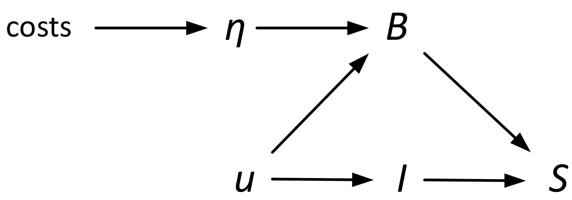


Figure 5: Causal connections in the proposed model

### Trade balance

Extending the single-country formulation of Blecker (2002), we propose a balance of payments constraint in each region,

$$S_N - I_N = K_N b_N(\underset{+}{\eta}, \underset{-}{u_N}, \underset{+}{u_S}), \tag{5}$$

$$S_S - I_S = K_S b_S(\underset{-}{\eta}, \underset{+}{u_N}, \underset{-}{u_S}). \tag{6}$$

In these expressions, $I_{N,S}$ is investment in North and South, $S_{N,S}$ is saving, and $\eta$ is the ratio of the price level in the South to that in the North. As indicated, we expect net exports from North to South to increase when prices in the South increase relative to those in the North or when utilization rises in the South (thereby increasing demand for intermediate goods). By the same argument, we expect net exports from North to South to decrease when utilization increases in the North. In the model we treat North and South as comprising the world, so trade must be in overall balance,

$$K_N b_N + K_S b_S = 0. \tag{7}$$

As trade is not balanced in our data set, we separately test a specification for net exports in the North and in the South. Our model is

$$b_N = b_{0N} + b_{\eta N} \log\eta + b_{NN} u_N + b_{NS} u_S, \tag{8}$$

$$b_S = b_{0S} + b_{\eta S} \log\eta + b_{SN} u_N + b_{SS} u_S. \tag{9}$$

The results are shown in Table 1.[5] During Period I the link between North and South was weak. However, the signs in each period on the significant terms are consistent with expectations: higher utilization in the North is associated with increased Northern imports and Southern exports. The insignificance of the price ratio and utilization in the South in Period I is

[5] We use the dynlm package ver. 0.3-3 for R (Zeileis 2014) for this and other dynamic linear regressions.

consistent with the trade patterns of the time, in which the South mainly exported raw materials to the North. In Period II the links are stronger. Relatively lower prices in the North are associated with increased exports, but not the other way around, while the changes due to utilization in either region are significant and of the expected sign.

Table 1: Regression coefficients for net exports per unit capital in North and South, all variables in first differences*

| | North | | South | |
|---|---|---|---|---|
| variable | Period I | Period II | Period I | Period II |
| constant | 0.005 * | 0.000 | -0.001 | 0.001 |
| | (2.26) | (-1.50) | (-0.82) | (1.56) |
| log $\eta$ | 0.003 | 0.005 ** | -0.027 | 0.000 |
| | (1.17) | (3.26) | (-1.78) | (0.03) |
| $u_N$ | -0.046 ** | -0.085 *** | 0.193 * | 0.158 * |
| | (-3.12) | (-4.22) | (2.26) | (2.66) |
| $u_S$ | 0.008 | 0.051 ** | -0.109 | -0.117 * |
| | (0.73) | (3.59) | (-1.61) | (-2.77) |
| $R^2$ | 0.57 | 0.57 | 0.51 | 0.36 |
| adj. $R^2$ | 0.45 | 0.50 | 0.37 | 0.26 |

* Lagged differences were not significant.

**Investment**

We next propose a behavioural relationship for investment. We started with a fairly standard Kaleckian specification for the investment rate per unit of capital,

$$\text{Propose: } \frac{I_N}{K_N} = \gamma_N + \alpha_N r_N^e + \beta_N u_N + \varphi_N \left( r_N - r_S \right), \tag{10}$$

$$\text{Propose: } \frac{I_S}{K_S} = \gamma_S + \alpha_S r_S^e + \beta_S u_S + \varphi_S \left( r_S - r_N \right). \tag{11}$$

The first term expresses overall expectations for growth (or “animal spirits”). The second captures the investment response to changes in expected returns, independent of any developments in the other region, where expected returns are defined as returns at normal utilization, to separate the effects of utilization from profitability (Bhaduri and Marglin 1990; Blecker 2002). The third term reflects changes in the pace of investment, mainly by business from retained profits, due to fluctuations in utilization. The final term is an "international arbitrage" term that captures the diversion of investment from one region to the other depending on performance. This term is assumed to depend on observed returns, which depend on utilization.

We found that the coefficient on expected returns was not significantly different from zero at the 10% level, while the gap in profit rates was only significant in the South, and only in Period I. We therefore use the following behavioural relationships,

$$\frac{I_N}{K_N} = \gamma_N + \beta_N u_N, \tag{12}$$

$$\frac{I_S}{K_S} = \gamma_S + \beta_S u_S. \tag{13}$$

The estimated values of the coefficients (including for the gap variable in Period I) are provided in Table 2.

Table 2: Regression coefficients for investment rate (*I*/*K*), all variables in first differences

| | | North | | South | |
|---|---|---|---|---|---|
| variable | lag | Period I | Period II | Period I | Period II |
| constant | | -0.001 (.)<br>(-1.82) | -0.001 **<br>(-3.32) | 0.001<br>(0.95) | 0.000<br>(0.25) |
| log util. | 0 | 0.307 ***<br>(6.60) | 0.282 ***<br>(9.15) | 0.129 **<br>(4.31) | 0.269 ***<br>(7.22) |
| gap ($r_S - r_N$) | 1 | | | 0.682 ***<br>(4.96) | |
| $R^2$ | | 0.77 | 0.80 | 0.84 | 0.71 |
| adj. $R^2$ | | 0.75 | 0.79 | 0.81 | 0.70 |

**Utilization**

An essential feature of the model described above is the quasi-cyclical change in utilization. As a nonlinear process, it cannot be represented by a linear model (Blatt 1978). Nonlinear models include Hicks' (1950) multiplier-accelerator model, a piecewise linear model with thresholds; and those of Goodwin (1951) and Minsky (1957), with endogenously changing rates. In this paper we propose a model with an upper and lower threshold on utilization.

The main theoretical challenge with threshold models is to specify the threshold values. We address this point explicitly below, but for testing against historical data, we use the observed downswings and upswings illustrated by the shaded and unshaded regions in Figure 2 and Figure 3. We used a dummy for the phase of the cycle and allowed for dependence on utilization. Because there are few cycles in the data set, we did not split it into periods.

The results are shown in Table 3. In the upswing, utilization grows at a steady rate. In contrast, in the downswing a large positive coefficient, when multiplied by a negative deviation, leads to a strong acceleration as utilization falls. Interestingly, the constant terms in upswing and downswing are nearly identical, suggesting that early in the downswing the pattern is symmetrical. However, the downturn accelerates, leading to an abrupt and substantial fall, so the two halves of the cycle are not symmetrical.

Both the upswing and downswing are explosive, with steady increase in the upswing and accelerating decrease in the downswing. We assume an upper threshold is active in that expansion stops when a capacity constraint is reached slightly above the normal rate of utilization, while the lower threshold is not uniquely determined. To construct a model we return to the idea of the economy as a complex adaptive system, and propose a stochastic model for the lower threshold.

Table 3: Regression coefficients for change in log utilization

| phase | variable | North | South |
|---|---|---|---|
| upswing | constant | 0.008 *** | 0.009 *** |
| | | (4.26) | (-0.66) |
| | log *u* | -0.002 | -0.113 |
| | | (-0.02) | (-0.85) |
| downswing | constant | -0.009 *** | -0.010 *** |
| | | (-4.64) | (-3.94) |
| | log *u* | 0.613 *** | 0.397 *** |
| | | (5.93) | (4.46) |
| | $R^2$ | 0.67 | 0.57 |
| | adj. $R^2$ | 0.64 | 0.52 |

**Complex adaptive systems and cascades**

As noted in the Introduction, complex adaptive systems release resources in cascades whose size follows a power law distribution. As the data set described earlier has too few observations to test for this, we used monthly utilization data for the US from the Federal Reserve Bank's FRED database (2013) (see Figure 6) and computed the difference between a peak and the subsequent trough. The rank-size distribution of peak-to-trough differences is shown in Figure 7 on a log-log plot. The plot is roughly linear in the tail, suggesting an approximate power-law distribution in that region, but is truncated at large drops in utilization.

These observations lead us to propose a stochastic lower bound, representing the size of the cascade of firms that curtail operations or shut down.

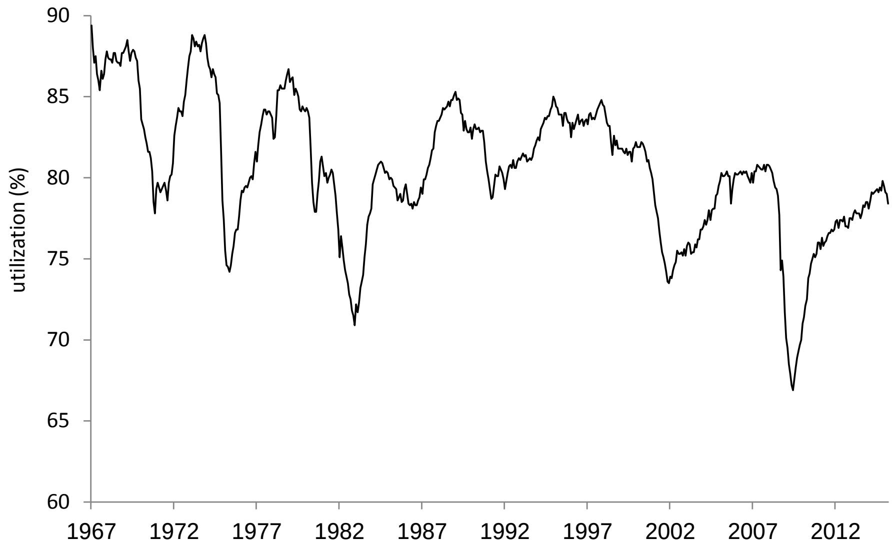


Figure 6: Monthly utilization in the US, total industry, seasonally adjusted

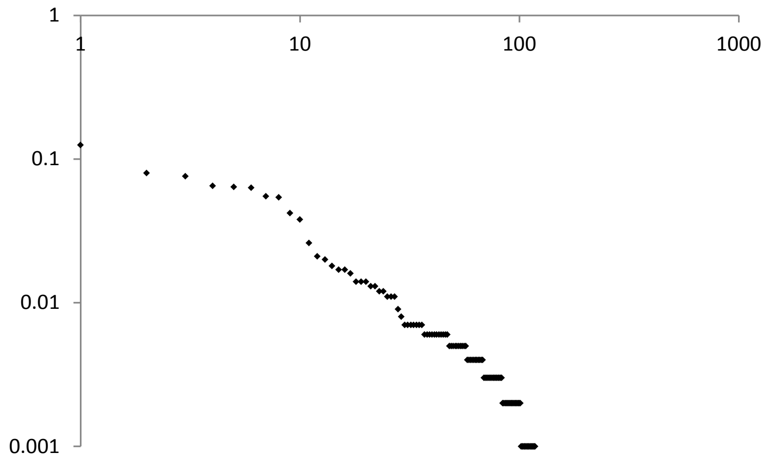


Figure 7: Rank-size plot for peak-to-trough differences in utilization

## A numerical example

Putting the different elements from the foregoing together, we give an explicit numerical example. For this example, we assume that both regions are in an upswing simultaneously. We also simplify the model by assuming instantaneous rather than lagged response of investment in the South to a change in relative returns. For (log) utilization we have

$$u_{N,S} = u_{0N,S} + \sigma_{N,S} t. \tag{14}$$

In this expression, $t$ is the time in years since the last trough, and the initial value, which will normally be negative, depends on the depth of the preceding trough. Inserting this expression for utilization into the investment functions, and using the capital accumulation equation

$$g^K_{N,S} \equiv \frac{\dot{K}_{N,S}}{K_{N,S}} = -\delta_{N,S} + \frac{I_{N,S}}{K_{N,S}}, \tag{15}$$

the investment rate is a linear function of time in both North and South. We write it as

$$g^K_{N,S} = a_{N,S} + c_{N,S} t, \tag{16}$$

where

$$a_{N,S} = -\delta_{N,S} + \gamma_{N,S} + \beta_{N,S} u_{0N,S}, \quad c_{N,S} = \beta_{N,S} \sigma_{N,S}. \tag{17}$$

The solution to this equation is

$$K_{N,S} = K_{0N,S} e^{a_{N,S} t + \frac{1}{2} c_{N,S} t^2}, \tag{18}$$

so capital grows super-exponentially over time.

Typical values of parameters in Period II are shown in Table 4. Using those values for illustrative purposes, and supposing that log utilization at the bottom of the last trough, is -0.02 in both North and South, from equation (16) the capital growth rates are

$$g^K_N = 0.024 + 0.0022t, \tag{19}$$

$$g^K_S = 0.046 + 0.0024t. \tag{20}$$

Over a five-year run, the growth rate in the North rises from 2.4% per year to 3.5% per year. In the South, it rises from 4.6% per year to 5.8% per year.

Table 4: Typical parameter values from Period II

| variable | North | South |
|---|---|---|
| $v$ | 0.32 | 0.33 |
| $\gamma$ | 0.07 | 0.09 |
| $\beta$ | 0.28 | 0.27 |
| $\sigma$ | 0.008 | 0.009 |
| $\delta$ | 0.040 | 0.039 |

Trade can be determined from either the North's or South's trade balance, but using both over-determines the model. We use the parameters for the North, and find, from estimates above and the data set, that

$$b_N = 0.006 + 0.005 \log \eta - 0.085 u_N + 0.051 u_S. \tag{21}$$

Assuming that relative prices remain fixed, using the observed value for log $\eta$ of -1.4, and again assuming that log utilization at the last trough was -0.02 in both North and South, this equation becomes

$$b_N = -0.00032 - 0.00023t. \tag{22}$$

Over the upswing, $b_N$ decreases, becoming more negative, so the trade gap in the North is widening. Over a five-year period, it rises by a factor of 3.6. This is, indeed, the pattern that can be seen in Figure 4, where the trade gap widened during expansions and shrank during contractions since 1997.

## 4. Green and brown capital in the North-South model

In this section we apply the North-South model developed above to the case in which either the North, or the South, or both, embarks on a transition to a low-carbon economy. We expand upon the single-country green-brown capital model presented in Kemp-Benedict (2014), which assumes both "carbon lock-in" and "carbon lock-out". That is, in a brown capital-dominated world, green capital is relatively unproductive due to network externalities, as well as norms and institutions geared toward a brown capital economy; the opposite is true in a green capital-dominated world. Also, labour productivity of green capital is assumed to be lower initially. This assumption is motivated by two arguments. First, the literature claiming that green investment creates jobs (e.g., UNEP 2008) appears to bear it out: more labour per unit of capital investment means lower labour productivity. Also, it is a reasonable expectation, in that new capital normally has a lower labour productivity than older capital, a difference that is erased more or less rapidly through learning-by-doing (Yelle 1979).

In the model, prices are determined by the costs of a price leader. In a brown capital-dominated economy the price leader is the brown capital sector, while it is the green capital sector in a green capital-dominated economy. As prices are passed through the economy they receive accumulated markups across supply chains. As a consequence, a carbon price translates into an increasing profit share, as well as increasing prices.

Finally, a low-carbon strategy may feature early retirement of brown capital, or even of green capital to allow for innovations and technical development in the green capital sector.

## Exploring implications: scenarios

With reference to the North-South model presented above, these features of the green-brown capital model lead to the following implications: introducing green capital without a price on carbon results in a falling capital intensity and a falling profit share (due to lower labour productivity); introducing green capital with a price on carbon leads to a falling capital intensity, a rising price, and an indeterminate change in the profit share. If, in addition, a policy to retire capital early is introduced, then it will increase the depreciation rate.

In this model, utilization and the depreciation rate affect capital accumulation, while utilization and price determine the trade balance. Capital productivity affects growth, and the profit share affects the real wage. Both variables together determine the profit rate at full utilization.

The effect of these changes depends on the larger context in which they play out, about which we face fundamental uncertainty. There are well-known techniques of strategic foresight to deal with uncertainty about the future (Bezold 2010; Coates 2010). These include scenarios (Bishop et al. 2007), which are used often in climate mitigation and impact studies (Nakićenović et al. 2000), as well as ecological economics (Raskin 2008). A new generation of climate scenarios is now being developed (Moss et al. 2010). One component is a set of Shared Socioeconomic Pathways (SSPs) (Kriegler et al. 2012; O'Neill et al. 2015), which can provide the context we seek.

There are five SSPs, differentiated by the degree to which socio-economic developments create challenges to mitigation and to adaptation. This two-category distinction leads to four narratives at the extremes, with a fifth presenting mid-range challenges. The names of the scenarios are revealing, although they certainly do not completely characterize the pathways: SSP 1: Sustainability, or Taking the Green Road; SSP 2: Intermediate Challenges, or Middle of the Road; SSP 3: Regional Rivalry, or A Rocky Road; SSP 4: Inequality, or A Road Divided; and SSP 5: Fossil-fueled Development, or Taking the Highway. The SSPs are meant to describe the world in the absence of explicit climate policy, so they provide a context in which to explore the implications of a low-carbon transition.

**Trends in the Shared Socioeconomic Pathways**

Expectations for key trends in different SSPs are described in O'Neill et al. (2015). Table 5 provides a summary. As shown in the table, the pathways tend to pair up in two ways, either SSP 1 & 4 vs. SSP 3 and 5, or SSP 1 and 5 vs. SSP 3 and 4, depending on whether the distinguishing feature is technology or society.

Table 5: Summary trends in SSP narratives

| | SSP 1 | SSP 3 | SSP 4 | SSP 5 |
|---|---|---|---|---|
| International institutions | effective | ineffective; barriers to trade | effective | ineffective |
| Domestic institutions | focus on sustainability | ineffective | unequal | focus on growth |
| Technological change | low-carbon | slow, high-carbon | low-carbon | high-carbon |
| Inequality | reduced | increased | increased | reduced |
| Human capital | high | low | low | high |
| Development | rapid | slow | slow | rapid |

Corresponding trends for the model parameters are proposed in Table 6, which is split into two sections. The first four rows show assumed trends based on the SSP narratives, while the last two rows are implied by the first four. There are two determinants of average capital productivity: the intrinsic productivity of capital and "capital ubiquity". The first captures technical change while the second captures structural change. The two factors operate in opposite directions: an increase in intrinsic productivity will, for a fixed structure, increase average capital productivity, while increasing ubiquity with fixed technology results in falling average capital productivity.

In SSP 1: Sustainability, profit rates may be maintained, although the profit share falls in favour of wages. This is accomplished by a falling capital intensity, which, combined with increases in the intrinsic productivity of capital, translates into rising average capital productivity. In short, there is less to invest in, but those who do invest see reasonable returns. Technological change may be rapid or slow, depending on the particulars of the narrative. The assumption of effective international institutions suggests a greater parity in the trade balance, without the wide swings seen in recent decades.

SSP 3: Regional Rivalry sees the world moving toward regional blocs of greater or lesser degrees of autarky. Along this pathway the increasing integration of North and South observed at the end of the 20th century is reversed, and technological development is slow. Autarky within regional blocs would lead to very low net trade, but this pathway could see a re-emergence of regional arbitrage, with investment flowing to the North or South depending on which region is showing greater returns.

SSP 4: Inequality features greater inequality both between and within countries, but also effective international institutions and the development of low-carbon technologies. This occurs through the emergence of a global elite community that is separated from its compatriots. Low-carbon technological development is a response to uncertainty in fossil fuel markets.

Finally, SSP 5: Fossil-fueled Development, sees rapid investment, driving capital intensity upward. This is offset by technological improvements, so average capital intensity is either stable or falling. Wage inequality is reduced by building human capital, thereby improving labour productivity. This compresses the wage distribution, while the average wage increases in proportion to productivity. Together with stable or falling average capital productivity, this implies a stable or falling profit rate.

Table 6: Proposed trends in model parameters in the SSPs

| | SSP 1 | SSP 3 | SSP 4 | SSP 5 |
|---|---|---|---|---|
| Trade balance | moderate fluctuations | close to zero or large swings | moderate fluctuations | large swings |
| Intrinsic capital productivity | slow to rapid increase | slow increase | increased | rapid increase |
| Capital ubiquity | reduced | slow increase | increased | rapid increase |
| Profit share | reduced | increased | increased | stable |
| Capital productivity | increase | little change | indeterminate | stable or falling |
| Profit rate | indeterminate | rising | indeterminate | stable or falling |

**A low-carbon transition in SSP 5**

As an illustration, we consider a possible trajectory for a low-carbon transition under SSP 5: Fossil-fueled growth, or Taking the Highway, using the model developed in this paper to ground the discussion. This pathway places its faith in competitive markets, which supply energy-intensive lifestyles. It is an inclusive faith that recognizes the need for public investment in human capital. Global markets are increasingly integrated.

We start the narrative from the present, in which the world is recovering unevenly from a severe crisis. Utilization is rising, driving an increase in the trade deficit in the North. As utilization increases, firms increase the pace of investment in both regions and take on more debt. The recent success in Latin America with reducing inequality through broadening access to education (Cornia 2012) is noted and emulated in other countries. Labour productivity improves and wage inequality declines. Following observed patterns (Galbraith 2011), wage distributions are compressed further during the upswing. The emphasis on markets leads to broad support for ensuring stable profit rates, but this is somewhat in conflict with the goal of broad-based growth, if capital productivity were to fall.

Part-way through the recovery there is a global push toward a low-carbon economy. It enjoys public support, and emphasizes market mechanisms, including a carbon price and certified “green” investment vehicles. However, a carbon price alone cannot be set high enough to make green investments inherently more attractive (Foxon 2010, p.3477). Also, investment in the shared infrastructure required for a low-carbon transition is below the social optimum. Policy initiatives therefore feature a mix of private incentives and direct public investment.

The result is that average capital productivity and labour productivity begin to fall. The fall in labour productivity, combined with wages that are sticky downwards, initially drives the wage share upward. Counteracting that trend is that the carbon price, passed through supply chains, increases the profit share. The net effect is ambiguous, but in this narrative we suppose it results in a rising profit share. As capital productivity is declining, the consequences for the profit rate are also uncertain. Utilization is rising, which leads firms to seek funds for investment, and profits begin to increase, but uncertain prospects for returns raise doubts in the minds of investors.

The response to this situation is crucial for the success of the transition. Until green capital has penetrated sufficiently to compete on its own with brown capital, forward motion depends on the perceptions of investors, in particular whether public policies will be effective and what other investors will do. Investors must decide whether to back the currently less profitable green sector in the expectation that it will become dominant in future. Observing that low-carbon policies have not threatened the recovery boosts investor confidence, but the deterioration of real wages because of the carbon price leaves a sour taste in the mouths of consumers.

Success also depends on the timing and severity of the next crisis, when it comes. When the economy encounters capacity constraints, some firms will not be able to cover their debts, leading to a wave of failures. If those are mostly in the green capital sector, or if the contraction is widespread and deep, it could make investors nervous, leading them to pull out of green investments and shift back toward apparently safer brown investments. As it is quite likely that a crisis, large or small, will occur before green capital has penetrated very far into the economy, this is a serious risk to the success of a low-carbon transition.

## 5. Discussion

The global economy today has peculiarities that will not persist. The large imbalance in trade between North and South cannot persist indefinitely, and eventually will reverse or return to parity. Also, the current high level of interconnectedness may not be sustained, if climate impacts and other changes make today's extended supply chains untenable (Curtis 2009). However, the need to minimize the risk of dangerous climate change (World Bank 2013) means that a low-carbon transition must be launched in today's world. The present policy environment favours market solutions and maintaining economic growth, even as it recognizes the need to reduce environmental impacts and socio-economic disparities.

As illustrated in the narrative of a low-carbon transition within the SSP 5 narrative, this combination of market incentives with socially progressive goals brings different policy goals into conflict. Also, there is a risk is that a downturn – a normal part of the operation of a capitalist economy – is likely to occur before green capital has penetrated sufficiently for its benefits to be felt. Thus, carbon lock-in is likely to be reinforced by the perceived failure of publicly-led low-carbon initiatives, even if they enjoy broad support initially, and even if the downturn had little or nothing to do with low-carbon investment in fact.

A central theme of the paper is that economies are complex adaptive systems. Such systems feature quasi-stable regimes that emerge from underlying dynamics rather than external structures. The dynamic nature of regimes means that they can change abruptly. Even within their quasi-stable state, they are subject to periodic fluctuations in which they alternately amass and release resources. Release occurs in cascades whose size cannot be predicted. The quasi-stable nature of regimes creates carbon lock-in, while the normal, quasi-cyclical behaviour of economies introduces fundamental uncertainties that inhibit investment in a new regime.

## 6. Conclusion

A low-carbon transition is likely to provide net social benefits, and even private benefits. However, lock-in into a high-carbon socio-technological regime erects significant barriers. Those barriers are amplified by the uncertainties around a low-carbon transition, because it requires investors and consumers to support the transition for some time before the low-carbon regime is sufficiently attractive in itself to drive investment.

Lock-in is a feature of complex adaptive systems, such as economies. Another feature is the presence of adaptive cycles, in which such systems alternately collect and release resources. We propose a partially stochastic model for medium-term cycles with this characteristic, and note that cycles will be superimposed on a low-carbon transition. How different economic actors interpret those cycles in the context of a low-carbon policy will affect the policy's success. Whether confidence can be maintained in the face of uncertainty will be a determining factor for successful action on climate.

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