The Australian growth miracle:
An evolutionary macroeconomic explanation

by

John Foster
School of Economics
University of Queensland

j.foster@uq.edu.au

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I. Introduction

The purpose of this article is to understand the drivers of Australian economic growth since its Federation in 1901. Australia is an interesting case study given that it seems not to have been affected by the ‘natural resource curse’ like many other natural resource dependent countries. Indeed, at time of writing, it has been 23 years since it experienced a recession and its GDP per capita is now amongst the very highest in the World. At the end of the 19th Century it also had one of the highest per capita incomes in the World and, although there were economic difficulties between the World Wars, it did not fall into relative economic decline like, for example, Argentina, also a European immigrant country producing and exporting natural resources.

Australia has exhibited very strong and persistent economic growth, even in the face of major international upheavals, such as the 1970s Oil Crises, the 1990s Asia Crisis and the 2008 Global Financial Crisis. But it has not always been thus. From the mid-1880s to the mid-1930s, Australia exhibited little growth in GDP per capita. But, as McLean (2013) pointed out, this can be somewhat misleading because Australia started the 20th Century with a very high level of GDP per capita relative to all other countries. Many of these countries experienced little, or even negative, growth over the same period. So, as he observes, by the late 1930s the standard of living in Australia was still very high by international standards. However, there is little doubt that the First World War (WWI), unlike the Second (WWII), was a difficult period. It involved a large diversion of economically active males and significant reductions in international trade. The latter were also a problem in the Great Depression. Yet, despite these setbacks, Australia’s growth surged after WWII and it now enjoys one of the highest levels of GDP per capita in the OECD, bettered only by Luxembourg, Norway and Switzerland in 2012. Also, in 2013, it had the highest median wealth per adult in the World according to Credit Suisse.

McLean (2013) provides a compelling account of how Australia’s post-war ‘growth miracle’ came about. He argues that Australia is, and always has been, primarily a ‘natural resources and services’ economy. Thus, he views the significant shifts that have occurred in the balance of natural resources produced, both for export and domestic consumption, as very important. Such shifts have enabled Australia to adapt to changing global economic circumstances. This has been crucial to the maintenance of persistent economic growth. McLean (2013) also argues that Australia has
gone through distinct phases of development since the late 19th Century when it was still very strongly connected to the British Economy. Reading his book, it becomes clear that any study of Australian economic growth should be preceded by extensive study of the institutional, organisational and technological features of the country. Unfortunately, modern studies of economic growth often tend not to start with such historical investigations but, instead, with timeless ‘neoclassical’ theoretical foundations, originally provided by Robert Solow (Solow, 1957).

These days, an extension of Solow’s approach, namely, ‘endogenous growth theory’, usually the ‘second generation’ variant pioneered by Aghion and Howitt (1998), is the favoured starting point for studying economic growth. Studies using endogenous growth theory focus on hypotheses concerning the roles of ‘knowledge’ variables, such as patents and R&D expenditure. Now it makes a great deal of sense to believe that the ‘growth of knowledge’ has an important place in determining economic growth and those applying endogenous growth theory should be applauded for highlighting this. However, the evidence provided in support of endogenous growth theories cannot be decisive because of the presence of ‘observational equivalence.’

For example, Ayres and Warr (2009) have argued persuasively that Solow’s neoclassical production function approach omits a key input into all productive processes, namely, energy. They show that adding energy, or more precisely, ‘useful work,’ into an aggregate production function, either of the familiar Cobb-Douglas form, or the more realistic LINEX form that they prefer, can explain most of multi-factor productivity growth in the countries that they have studied. So we have two very different hypotheses finding support in the same data sets. Foster (2014) has argued that such a result is not surprising because, from a non-equilibrium thermodynamic perspective, growth must be the outcome of a co-evolutionary process that involves the parallel growth of both energy consumption and the application of new knowledge.

In this article, a different approach is taken. An ‘evolutionary macroeconomic’ methodology is applied which begins in the actual processes that give rise to historical growth trajectories. This methodology, originally developed in Foster and Wild (1999a), has been used to explain long term economic growth in the United Kingdom in Foster (2014). Models constructed, using this

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2 There are very few recent studies that attempt to model Australia’s long term economic growth. One is by Banerjee (2012) who models productivity growth using a second-generation endogenous growth approach as specified by Madsen et al (2010). Using variables such as R&D expenditure and patents, support is found for the hypothesis that productivity growth is driven by the level of research intensity. Population growth, on the other hand, is found to have a negative effect on productivity growth.
methodology, are stylised representations of the non-equilibrium (historical) processes that result in economic growth. They recognise, explicitly, that economic processes involve a degree of time irreversibility and are subject to structural change, which can be either radical or incremental in character. Although Joseph Schumpeter never told us how to specify an evolutionary economic model so that it could address historical data, beyond the discussion of descriptive statistics, the evolutionary macroeconomic methodology is identifiably ‘Schumpeterian’. This methodology is radically different to that used in modern ‘endogenous’ models of economic growth, despite the fact these are often claimed to also have ‘Schumpeterian’ features (Aghion and Howitt (1998)).

Although the modelling is similar to that used in Foster (2014), there was no expectation that similar results would be obtained. The United Kingdom and Australia have very different histories, despite sharing a similar culture and many common institutions. The former is an advanced industrial country that has moved towards maturity over the past century after previous centuries of economic development. Australia, which was still dominated by hunter-gatherers two and a half centuries ago and started out as a penal colony when the British settled there, has been heavily dependent on the production and export of natural resources for its economic development. Our results confirm that significant differences exist but, importantly, that these can be clearly understood from an evolutionary macroeconomic perspective.

II. A Look at History

Foster (2014) found evidence that supported the hypothesis that the UK, as an industrialised country, has moved up a ‘super-radical’ innovation diffusion curve, driven by the large scale utilisation of fossil fuels, over the past two centuries. However, it is clear from McLean (2013) that Australia’s economic evolution has been quite different. It has not been a manufacturing powerhouse but, rather, mainly a producer of natural resources and services, both for consumers and producers. The manufacturing sector has been relatively small, predominantly meeting local needs, rather than export demand. Capital goods have been very important in the natural resource sectors and most of them have been imported. These capital goods have been essential to provide the capacity for GDP to grow. In the mines and on the farms they provided dramatic increases in labour productivity.
McLean (2013) noted that the economy of Australia has gone through two distinct developmental phases. There was fast growth up to the 1890s slump and virtually no growth in per capita GDP until the end of the 1930s, with significant take-off after WW2. Some also argue that the mid-1970s was a watershed in the shift away from the domination of wool and other agricultural products towards more minerals in the export mix. The microeconomic reforms, initiated in the 1980s are also viewed by many as having a positive impact upon economic growth, particularly after the recession ended in the early 1990s.

Australia, up until the interwar years, was predominantly a natural resource exporter, mainly feeding British demand. As MacLean (2013) observes, it was, in effect, a distant region of the British Economy. He views this strong British connection as very important because, in addition to providing strong economic institutions, it prevented the emergence of ‘squatter power’ in the political system and consequent severe inequalities, as was the case in natural resource based countries that broke loose from their colonial masters in the 19th Century, such as Argentina.

It was WWII that gave a big push to manufacturing, which reached an all-time peak of 25% of GDP. This was, essentially, an artificial war-time condition but it was not fully reversed afterwards. The manufacturing sector continued to be protected in the immediate post-war era and used strategically as a vehicle for the employment of immigrants and to promote core industrial skills. There was increasing investment in capital goods that used cheap and powerful fossil fuels, in agriculture, mining, manufacturing, power generation and transportation. In particular, the severe shortages of electrical power experienced in WWII gave rise to large investments in power stations, transmission and distribution lines across the states, as well as hydroelectricity.

Although there was strong dependence upon trade with, and investment from, Britain for a long time, the capacity of Australia to deliver GDP growth was the same as in any other economy. It depended upon work done using human and non-human physical energy combined with knowledge, embodied in capital goods and in the human ingenuity and skills that are involved in production of all kinds. Like the rest of the developed world, growth was made possible by the increasing use of capital goods, driven by cheap and plentiful fossil fuels. However, this was less so before WWII when Australia’s natural resource sector was still dominated by labour effort, assisted by animals such as horses and oxen, and supported by labour engaged in service delivery in the urban areas and in transportation. Of course, capital goods were important but they tended to be
labour, or animal, augmenting rather than labour replacing. Manufacturing was mostly dedicated to
the immediate needs of mining, agriculture and construction and so, in a sense, people engaged in
such activities were also involved in a form of service delivery.

**Figure 1**

Australian Real Capital Stock Index (1901-2008)

1901 = 100

In Fig. 1 it can be seen that the net capital stock was small and slow growing before WWII. During
the war, the capital stock became inadequate, resulting in very high capital utilization and
accelerated deterioration. After the war, capital investment increased significantly to compensate
for overuse and the new capital stock embodied technologies that relied much more upon fossil
fuels. Thus, it was WWII that sparked a fundamental shift of the Australian economy towards fossil
fuel driven growth. Although barely discernible in Fig.1, the shift to greater fossil fuel dependency
and associated capital intensity really began in the 1930s. However, Australia, without a significant
manufacturing base at that time and with only a small population was not in a position to move
very quickly towards a fossil fuel driven economy.

In the 19th Century, Britain had chosen to use Australia as a source of natural resources rather than
to develop it industrially. Capital goods that were required could be imported and paid for with
revenue from exporting natural resources. When Australia did, finally, begin to engage in significant
industrial activity, this involved much ‘retooling’ in agriculture, mining and manufacturing for two
decades after WWII. In Fig. 2 we can see how the ratio of GDP to energy consumption fell on a fluctuating path after the first decade of the 20th Century. The sharp drop up to WWI was because of the rapid substitution of capital goods for animal power, mainly, in the natural resource sector, to produce a given quantity of GDP. The second sharp drop after WWII can be attributed to the fact that there were long lags before large capital investment projects, both public and private, yielded their full GDP potential. It was not until 1963 that this trend reversed, in contrast to the UK where the reversal occurred around 1880. The productivity of energy has risen steadily since 1963, as in most developed countries, because of a rise in capital good productivity.

Figure 2

Ratio of Australian GDP to energy consumption (1901-2008)

1901=1

In the post-WWII era, with increased reliance on fossil fuel powered capital goods, capital-labour substitution became significant but, unlike the UK, this did not result in total labour hours ceasing to grow (Fig. 3). This is because Australian annual population growth has been about nine times higher than the UK since 1901.³

³ Average annual population growth in the UK from 1901 to 2010 was 0.46% per annum. For Australia it was 4.2% per annum from 1901 to 2008.
We can see in Fig. 4 that GDP growth began to take off in the 1930s and, after WWII, it became slightly exponential, tending to linear over the last two decades.

**Figure 3**
Australian Total Labour Hours (1901-2008)

**Figure 4**
Australian Real GDP Index (1901-2008)
Fig. 5 confirms McLean’s (2013) observation that there was little labour productivity growth before WWII. GDP per labour hour has risen on a roughly linear trend since WWII. Energy consumption has also grown linearly since WWII (Fig 6) fuelling a capital stock that has grown exponentially (Fig 1).

**Figure 5**

Australian GDP per Labour Hour Worked (1901-2008)

1901=1

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**Figure 6**

Australian Energy Consumption (1901-2008)

1901=100
What becomes very clear in these charts is that the growth experiences before and after WWII are very different. As we can see in Fig. 7, the capital to labour ratio increased dramatically after WWII.

**Figure 7**
Ratio of Capital to Labour in Australia (1901-2008)

1901=1

**Figure 8**
Australian Capital to GDP Ratio (1901-2008)

1901=1
Correspondingly, the capital/output ratio, often assumed constant in conventional studies of economic growth, surged from its pre-war average of about 0.7 to about 3.0 in 2008 (Fig 8).

So, in summary, there are strong indications in these historical charts that the ‘engine room’ of post-war Australian economic growth was the rise in the scale and quality of a capital stock powered by fossil fuels. Economic activity always involves some combination of human work time and work yielded by a flow of non-human energy. The increasing size of the capital stock required more energy consumption. In 2008, the latter was 13 times greater than in 1938, in contrast to labour time which was only 3 times greater. Casual examination of the historical record suggests that increases in the size of the energy-using capital stock have had a key role to play in this growth story. But can we provide econometric evidence that this has been a systematic evolutionary process and, if, so what are Australia’s prospects looking ahead?

III. The Evolutionary Macroeconomic Methodology

The evolutionary macroeconomic methodology is embedded in history rather than an abstract, timeless economic theory. It is presumed that there is always productive structure in place at any point in historical time that is, to some degree, irreversible. Any economic model of growth that presumes full reversibility fails to capture a fundamental stylised fact of reality. The Second Law of Thermodynamics tells us that all productive structures, being, to some degree, irreversible, must continually deteriorate. This is partly offset via maintenance, repairs and capital replacement expenditures. There is also new (net) investment expenditure. All investments, replacement or net, tend to embody new technologies that provide new opportunities to re-organise and extend productive processes and to produce new products. In other words, if we think of the economy as a complex network, more connections between both old and new elements are being continuously forged. The economy becomes more complex and total value added increases (Hausmann and Hidalgo (2011)).

Beginning in history, following Foster (2011), we can start with a macroeconomic identity, expressed in real terms:

\[ Y_t = Y_{t-1} + Z_t - W_t \]  

(1)

As the scale of the capital stock increases so does its technological complexity and, thus, its range of uses.
or

$$Y_t - Y_{t-1} = Z_t - W_t$$  \hspace{1cm} (2)$$

Where $Y_t$ is the economic value that flows from the output of a complex economic system, $W_t$ is the loss of real value due to wear and tear, breakdowns, bankruptcies, etc., and $Z_t$ is the increase in real expenditure of all kinds. Clearly, if $Z_t$ exceeds $W_t$ then there must be growth.

Part of $Z_t$ offsets $W_t$ and part of it is a new flow of value, either from the production of greater output from existing structure (productivity growth) or from increased production using more factor inputs. Increased supply has to be demanded so $(Z_t - W_t)$ is, in Keynesian terms, the change in effective demand and this will determine how much capacity will be utilised.

This identity makes explicit the time irreversibility that must exist in any dissipative system. And it is this time irreversibility that renders much of standard economic analysis, where time is fully reversible, i.e. history does not exist, invalid. In such a historical economic system, all growth is ultimately due to the diffusion of radical innovations, made possible by entrepreneurship which opens up niches that are entered by incremental innovations, both in processes and products, and productivity improvements due to learning-by-doing effects. In the presence of a niche, output grows in a sigmoid manner towards a limit (Foster and Wild (1999a)). This is so commonly observed in the large literature on innovation diffusion that it is almost axiomatic. So, we can hypothesise that $(Z_t - W_t)$ in Eq. (2) follows a sigmoid curve. If we choose a Gompertz specification we get:

$$Y_t - Y_{t-1} = aY_{t-1} \left[1 - \frac{\ln Y_{t-1}}{\ln K}\right]$$  \hspace{1cm} (3)$$

Where:

- \( Y \) is GDP
- \( K \) is the diffusion limit of GDP
- \( a \) is the innovation diffusion rate

Thus, there is a \( K \)-limit that provides a niche into which GDP can grow, via increased expenditures on new products and/or processes in all sectors of the economy. So \( \ln Y / \ln K \) falls as GDP rises and when this ratio reaches unity, there are no further diffusion effects on growth. But what is the process going on behind this growth curve?
Long term economic growth is, necessarily, the outcome of a co-evolutionary process involving both the application of knowledge, via innovation diffusion, and increases in energy use. So, in Eq. (3), diffusion must include the growth of energy application, both human and non-human. So the diffusion rate must have two components, \( a' \) and ignoring, for the moment, lags in impact, \([\text{edln}E_t + \text{fdln}L_t]\) where \( E \) is total energy consumption (enabling work to be done by capital goods) and \( L \) is total hours worked. This captures the growth of aggregate expenditure due to parallel increases in spending on energy and increases in labour hours, weighted by their relative impacts on GDP growth, \( e \) and \( f \). The \( a \) parameter remains on \([\ln Y_t / \ln K]\) and, being also long term in nature, is an average, \( [a' + (\Sigma edlnE_t)/s + (\Sigma fdlnL_t)/s] \), where \( s \) is sample size.

So, rearranging Eq. (3) and expanding on \( a \), we get:

\[
d\ln Y_t = [a' + (\text{edln}E_t + \text{fdln}L_t)] - a[\ln Y_{t-1} / \ln K] + u
\]  

(4)

Where: \((Y_t - Y_{t-1})/Y_{t-1}\) is approximated by \(d\ln Y_t\)

\(d\) denotes an annual first difference

\(u\) is a quasi-random error term

\(E\) is energy consumption

\(L\) is total hours worked

At the \(K\)-limit, only deviations of energy growth and growth in labour hours from their mean values impact on GDP growth. So fluctuations in GDP at the \(K\)-limit can only occur due to stochastic shocks.

Constant returns to scale are frequently assumed with regard to input flows in conventional growth models that are based upon aggregate production functions. Here this implies that \( e + f = 1 \). What this restriction does is push all productivity growth into to a ‘growth residual’ in a conventional Solow model and, here, into \([a' - a[\ln Y_{t-1} / \ln K]]\). However, from a historical perspective, there is no reason why there should be constant returns to scale. This depends on how the economy-wide productive network structure changes as inputs grow. Diminishing returns to scale \((e + f < 1)\) are likely to exist when the rises in structural complexity that accompany an increase in scale or scope result in rising maintenance costs, congestion, bottlenecks, etc., in a relatively mature economic

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5 As Foster and Wild (1999b) point out, although the residual errors in such a model can exhibit some Gaussian properties, their oscillatory structure should change over time. However, this is not discernible when using annual data.
Increasing returns to scale \((e + f > 1)\) are likely to be observed when we are dealing with an economy still with significant expansion opportunities.\(^6\)

We have not included the growth of the capital stock in Eq. (4), as would be normal in a conventional aggregate production function specification. Instead, the growth of energy consumption has been used. This is viewed as a more accurate proxy for the use of capital services. However, this does not imply that the capital stock is unimportant. On the contrary, although we have eliminated the capital stock as a proxy for capital services, the capital stock, being the physical embodiment of knowledge as to how non-human energy can be deployed to do work, can be viewed as the variable that determines, most strongly, the \(K\)-limit that a diffusion process tends towards. So, as the capital stock increases in size, the \(K\)-limit must also rise. Since the use of the capital stock is accounted for by the growth of energy consumption in Eq. (4), the level of the capital stock should not have any quantitative effect on growth. Instead, it is hypothesised that it has a qualitative effect: a larger capital stock embodies more technical innovations and this raises the \(K\)-Limit that GDP can attain. This limit is not just determined by embodied technical innovations but also organisational and institutional innovations that are made possible with more advanced capital equipment. So our hypothesis is that \(K\) is dependent on the size of the capital stock. Keeping to the Gompertz specification, \(K\) is assumed to be linearly related to \(\ln C\), where \(C\) is defined as the capital stock: \(K = n \ln C\).

Capital has another potential role to play: its short term fluctuations can lead to short term fluctuations in GDP. This Keynesian multiplier effect of capital investment can be captured by adding the first difference of the growth of the capital stock, \(d(\ln C_t - \ln C_{t-1})\), to Eq. (4). So we get:

\[
d\ln Y_t = a' + e d\ln E_t + f d\ln L_t - (a/n)(\ln Y_{t-1}/\ln C_{t-1}) + g d(\ln C_t - \ln C_{t-1}) + u
\]

As noted, \(n \ln C_{t-1}\) is a ‘soft’ limit. Short term positive expenditure shocks to GDP growth can push the ratio above unity, as seems to have been the case in WWII, but the resultant negative effect will eventually return it to unity unless there is an emergent tendency for GDP to move towards a new \(K\)-limit. Correspondingly, Negative aggregate investment expenditure shocks will result in the temporary under-utilization of capacity.

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\(^6\) In the endogenous growth literature, increasing returns arise because of the expansion possibilities offered by the non-rivalrous nature of ‘ideas’. This is a ‘growth of knowledge’ hypothesis but specified quite differently to the innovation diffusion hypothesis used here.
Our historically grounded theory of economic growth is now complete. Unlike standard ‘timeless’ growth models, its application has to be history specific. We can only model periods when historical investigation suggests that there have been steady diffusions of radical innovations and, thus, it is valid to hypothesise that a sigmoid growth path existed. When there are structural transitions between phases of sigmoid growth, such modelling cannot be conducted (Foster and Wild (1999a)). The economic history provided by McLean (2013) suggests that the developmental experiences of Australia before and after WWII were quite different and, thus, should be modelled separately.

So we have a very different macroeconomic characterization of economic growth to that in a Solow model of economic growth. It centres upon the diffusion of innovations – technological, organizational and institutional and the necessary co-evolutionary role of human and non-human energy consumption. Constant returns to scale are not assumed. They are a special case that is unlikely to be in evidence. Solow built his discussion of the role of “technical progress” upon a neoclassical model of aggregate production and exchange. Here, the relationship between inputs and outputs is an outcome of the complex, networked structure of production. It is not an aggregation of homogenous, constrained-optimizing decisions but, rather, an outcome of the adoption of productive rules, or routines, determined by prior decisions to invest in technological, organisational and institutional innovations (Nelson and Winter (1982), Dopfer, Foster and Potts (2004)). So what we have is a model representation of growth based upon a non-equilibrium process of order and change. In conventional terms, there is an ever changing state space as new processes and products are made possible at higher levels of economic complexity.

**IV. The Evidence**

In testing the hypotheses contained in Eq. (5), data from 1901 to 2008 were used. Given Australia’s economic history, it made sense to split our data into two periods: 1901-1938 and 1948-2008. This omits the special effect of WWII and its immediate aftermath on the Australian Economy. In estimating Eq. (5), one contemporaneous and three lagged variables were included for each independent variable and ‘general to specific’ elimination was conducted. Because we are dealing with a complex economic system in historical time we cannot have any *a priori* view concerning the dynamics involved in the processes determining overall growth. The stability of the results was

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7 The sample employed stops short of the global ‘Great Recession’ so that there were not end years that included large negative macroeconomic shocks.
checked using one-step and N-step forecasts derived from recursive estimation. Outliers were identified and, when historical investigation confirmed that an exceptional event had occurred, an impulse dummy was added to remove ‘outlier bias.’ The presence of endogeneity was checked using two-stage least squares estimation.

As an initial step, the model was estimated using the whole sample, even though historical investigation suggests that this is not appropriate. The results, after general-to-specific variable selection and the inclusion of historically justifiable impulse dummies, are reported in Table 1. There is no significant $a/n$ term, energy growth is significant but has a near zero cumulative impact but growth in labour hours is strongly significant. A 1.24 estimated coefficient on $d\ln L_t$ indicates the presence of economies of scale. However, recursive estimation revealed that the estimated coefficient on growth of labour hours is not stable. The rate of change of the growth of the capital stock was also insignificant. Thus, the whole sample result does not support all of the hypotheses specified in Eq. (4).8

Table 1
OLS Estimates of Eq. (5): 1904-2008

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-Statistic</th>
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<tbody>
<tr>
<td>$a'$</td>
<td>0.16</td>
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<td>$d\ln E_t$</td>
<td>0.24</td>
<td>2.63</td>
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<td>$d\ln E_{t-2}$</td>
<td>-0.27</td>
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<tr>
<td>$d\ln L_t$</td>
<td>1.24</td>
<td>5.85</td>
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<tr>
<td>$DUM1922$</td>
<td>-0.21</td>
<td>-4.41</td>
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<tr>
<td>$DUM1940$</td>
<td>0.14</td>
<td>2.93</td>
</tr>
<tr>
<td>$DUM1948$</td>
<td>0.16</td>
<td>3.17</td>
</tr>
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Adj. R-squared 0.54
Durbin-Watson 1.77

8 As a check, growth in the capital stock, in line with standard production function logic, was included in all specifications but there was no significance on lags 0 to 3.
The 1901-1938 Period

In Table 2, the results of estimating Eq. (5) from 1903-1938 are reported.

### Table 2:
OLS Estimates of Eq. (5): 1903-1938

<table>
<thead>
<tr>
<th>Dependent Variable: $d\ln Y_t$</th>
<th>Coefficient $a'$</th>
<th>Coefficient $\ln Y_{t-1}/\ln C_{t-1}$</th>
<th>Coefficient $d\ln L_t$</th>
<th>Coefficient $d(\ln C_t - \ln C_{t-1})$</th>
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<tr>
<td>$a'$</td>
<td>1.20</td>
<td>-1.16</td>
<td>1.54</td>
<td>1.87</td>
<td>3.11</td>
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<td>$\ln Y_{t-1}/\ln C_{t-1}$</td>
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<td>0.52</td>
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<tr>
<td>Durbin-Watson</td>
<td>2.40</td>
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Figure 9:
Recursive Estimates of Coefficients in Table 2

Once again, general-to-specific elimination was applied to obtain a parsimonious representation of the lags involved. There is support for the hypothesis that a sigmoid innovation diffusion process of the Gompertz type, with a limit determined by the size of the capital stock, was operative. Growth
in labour hours is very significant, but not growth in energy consumption. The rate of change of capital stock growth is also significant and correctly signed, supporting the hypothesis that ‘Keynesian’ short term capital investment multiplier effects existed. With an estimated coefficient of 1.54 on the growth of labour hours, there is evidence that strong economies of scale were operative. Recursive estimation was conducted to ascertain the stability of these results. The recursive coefficients were always significant and of the same sign but unstable (Figure 9).

Using one-step and N-step forecast results, historically justified impulse dummies were introduced to eliminate the effects of outliers. The results are reported in Table 3.

Table 3
OLS Estimates of Eq. (5): 1903-1938

<table>
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<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-Statistic</th>
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<tr>
<td>( d_{\Delta \ln Y_t} )</td>
<td>1.03</td>
<td>3.57</td>
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<td>( \ln Y_{t-1} / \ln C_{t-1} )</td>
<td>-0.98</td>
<td>-3.53</td>
</tr>
<tr>
<td>( d\ln L_t )</td>
<td>1.69</td>
<td>6.87</td>
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<tr>
<td>( d(\ln C_t - \ln C_{t-1}) )</td>
<td>1.08</td>
<td>2.52</td>
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<tr>
<td>DUM1921</td>
<td>0.12</td>
<td>2.76</td>
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<tr>
<td>DUM1922</td>
<td>-0.19</td>
<td>-4.15</td>
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<td>DUM1927</td>
<td>-0.11</td>
<td>-2.56</td>
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<tr>
<td>DUM1930</td>
<td>-0.09</td>
<td>-2.13</td>
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</tbody>
</table>

The inclusion of impulse dummies stabilises the coefficients when estimated recursively. Their inclusion also alters the estimated coefficients with the largest effect on the rate of change of the growth of the capital stock (from 1.87 to 1.08) which is unsurprising given that this variable is a second difference and likely to be affected by the inclusion of impulse dummies. The estimated diffusion rate \( a' \) falls from 1.2 to 1, but the calculated value of \( n \) is 1.070, which is close to its value derived from the results in Table 2. The calculated \( K \)-limit \( (n\ln C_t) \) and \( \ln Y_t \) are plotted in Fig. (10).

What we observe in Fig. 11 is that GDP reached its \( K \)-limit by about 1910 where it stayed until about 1920 after which adverse economic conditions led to negative expenditure shocks that lowered GDP. This was followed, in the 1930s, by a sharp reversal and a return of GDP to its \( K \)-limit by 1937.
As McLean (2013) observed, in the first three decades of the 20th Century, the Australian economy was sluggish. However, GDP did grow, on average, by 2.4% over this period but this was largely due
to growth in the labour force employed, driven by the demands of a fast-growing population. As can be seen in Figure (1), the capital stock also grew somewhat, providing embodied technical benefits. But these seem to have manifested themselves mainly as increasing economies of scale in the employment of labour, rather than from innovation diffusion. In other words, there is little evidence that organisational and institutional innovations opened up a significant niche for GDP to enter. This is what might be expected in a sparsely connected economy with large developmental potential.

So the strength of labour hours growth and the lack of significance of energy consumption growth suggest that Australia may have been at the $K$-limit of a diffusion process that involved the augmentation of labour by capital goods rather than its replacement.\(^9\) The sharp dip and recovery observed in Figs. 10 and 11 is consistent with a temporary drop in capacity utilization rather than an innovation diffusion process at work. Although advantage was clearly taken of the innovations embodied in, mostly imported, capital goods, resulting in proportional increases in GDP, there is little sign that capital investments opened up niches for GDP because of compatible organisational and institutional innovations. Nothing much changed in three decades.

**The 1948-2008 Period**

Turning to our second period, 1948-2008, where history suggests that a different phase of development was in operation, the results are reported in Table 4. These results are very different to those in the earlier sample. Now, the growth of labour hours is not significant but the cumulative estimated coefficient on energy consumption is 1.36 and very significant.\(^{10}\) So there is support for the hypothesis that economies of scale continued to be in operation but the evidence suggests that growth was now primarily driven by the use of capital equipment to substitute for labour which was released into an ever-expanding services sector. The short term multiplier effects of capital investment are significant and similar to those in Table 3 but spread over two periods.

---

\(^9\) Energy consumption and labour hours were found to be collinear with the latter dominating which provides some indirect support to this hypothesis.

\(^{10}\) Shahiduzzaman and Khorshed (2013) found there to be a bi-directional relationship between energy consumption and GDP in Australia so Eq. (5) was also estimated using two-stage least squares. However, there was little or no change in the estimated coefficients. The bi-directionality they found in levels does not seem to carry over to rates of growth.
Table 4

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a'$</td>
<td>0.29</td>
<td>2.04</td>
</tr>
<tr>
<td>$\ln Y_{t-1} / \ln C_{t-1}$</td>
<td>-0.32</td>
<td>-2.05</td>
</tr>
<tr>
<td>$d\ln E_t$</td>
<td>0.83</td>
<td>4.05</td>
</tr>
<tr>
<td>$d\ln E_{t-3}$</td>
<td>0.53</td>
<td>2.47</td>
</tr>
<tr>
<td>$d(\ln C_t - \ln C_{t-1})$</td>
<td>0.89</td>
<td>2.50</td>
</tr>
<tr>
<td>$d(\ln C_{t-2} - \ln C_{t-3})$</td>
<td>0.94</td>
<td>3.12</td>
</tr>
</tbody>
</table>

Adj. R-squared 0.37
Durbin-Watson 1.68

Figure 12
Actual to Predicted Plots for Table 4

Recursive estimation yielded stable coefficients from 1980 onwards, i.e., when the small sample maximum of 32 observations was exceeded (Fig. 13). One step and N-step forecasts suggested that there are no significant outliers so no impulse dummies were required. The parameter $n$ was calculated to be 1.168. However, what Fig. 12 shows is that there are quite noticeable variations in the actual-to-predicted plots during the 1970s. McLean (2013) pointed out that: large fluctuations...
in commodity prices, Britain’s entry into the Common Market and a political crisis in 1975 had macroeconomic impacts in that decade.

**Figure 13**
Recursive Estimates of Coefficients in Table 4

Impulse dummies were introduced in mid-1970s to assess the impacts of the sharp residual fluctuations visible in Fig. 12. The results are reported in Table 5.
Table 5
OLS Estimates of Eq. (5): 1948-2008, with impulse dummies

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>t-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>0.29</td>
<td>2.33</td>
</tr>
<tr>
<td>ln$Y_{t-1}$/ln$C_{t-1}$</td>
<td>-0.33</td>
<td>-2.36</td>
</tr>
<tr>
<td>$dlnE_t$</td>
<td>0.83</td>
<td>4.49</td>
</tr>
<tr>
<td>$dlnE_{t-3}$</td>
<td>0.58</td>
<td>3.03</td>
</tr>
<tr>
<td>$d(lnC_t - lnC_{t-1})$</td>
<td>0.91</td>
<td>2.81</td>
</tr>
<tr>
<td>$d(lnC_{t-2} - lnC_{t-3})$</td>
<td>0.99</td>
<td>3.63</td>
</tr>
<tr>
<td>DUM1974</td>
<td>0.08</td>
<td>2.23</td>
</tr>
<tr>
<td>DUM1975</td>
<td>0.07</td>
<td>2.23</td>
</tr>
<tr>
<td>DUM1977</td>
<td>-0.08</td>
<td>-2.47</td>
</tr>
</tbody>
</table>

Adj. R-squared 0.49
Durbin-Watson 2.07

Impulse dummies for 1974, 1975 and 1977 were significant but they made very little difference to the other estimated coefficients, leading to the conclusion that the mid-1970s experience involved only temporary shocks, not a shift in the evolutionary economic trajectory. This is consistent with the view of McLean (2013). Another noticeable feature of Fig 12 is that the variation of growth and also actual-to-predicted deviations are lower from the early 1980s onward. The Australian Dollar was floated (an institutional innovation) in 1983 and this was the most likely reason for the stabilization of these fluctuations.

Support for the hypothesis that Australia has been on the same developmental growth path since WWII contradicts the view that recent strength in economic growth can be attributed only to the microeconomic reforms that commenced in the mid/late 1980s. It seems more likely that these involved institutional innovations that were part of a longer term evolutionary process. Again, this concurs with the view held by McLean (2013). Also, some economists have argued that the ongoing shift towards service activity has handicapped economic growth because the service sector is perceived as exhibiting low productivity. But Hughes and Grinevich (2007) found that key parts of the services sector have recorded the highest rates of productivity growth since the 1990s. So,
again, the shift to services can be viewed as been no more than part of a longer term process of economic evolution. Many service activities are entirely novel and there is no reason to believe that, overall, their emergence has dampened productivity growth.

Although manufacturing has not been a long term driver of Australian economic growth, it provided a ‘launching pad’ for the uptake of fossil fuel dependent capital goods in the early post WWII period. An evolutionary niche opened up for GDP because of a growing capacity to enact organisational and institutional innovations. We can see from Figs. 14 and 15 that this niche has widened over time. Initially, the ratio of GDP to its $K$-Limit dropped sharply over two decades. This was due to the commencement of heavy capital investment, particularly in public infrastructure, after WWII (Fig.1). From the mid-1960s to the late 1990s, the ratio remained fairly stable at about 0.8, except in the unusual 1970s. After about 1998, the ratio, once again, dropped sharply. This was a period of high capital investment (see, again, Fig.1), which opened up a significant niche for GDP to enter via innovations of all kinds. Australia has become an economy with significant growth potential because of the innovative opportunities that capital investment has made possible, combined with a well-developed capability for organisational and institutional innovations.

Figure 14

$\ln Y_t$ and the $K$-Limit, 1948-2008
In addition to strong support for the presence of an innovation diffusion process driven by fossil-fuel using capital equipment, we also observe significant economies of scale in post-WWII Australia, unlike the finding of Foster (2014) for the UK. A 1% increase in energy use led to a 1.40% increase in Australian GDP, on average over the post WWII period. The UK has been a leading mature economy for some time and, therefore, we would not expect economies of scale to have been in operation there. In contrast, Australia remains a country with many expansion capabilities and it is in such conditions that we tend to observe economies of scale. Indeed, because of strong innovation diffusion and economies of scale effects, the Australian economy has been impervious to recession for two decades. By 2008, the prevailing capital stock provided very strong growth potential and even the Global Financial Crisis could not cause a significant reversal and, by 2011, Australia was exhibiting high rates of labour productivity growth because of the diffusional benefits made available by the capital stock.

By 2008, innovative potential had become very significant – Australia now had a very strong capacity to take capital goods and use them to generate organisational, institutional and product innovations. To be sure, as Cutler (2008) found, Australia’s national innovation system seemed not to be as developed as in other industrialised countries but this was, to a large degree, because its
innovation system was unusual, concentrated in the natural resource and service sectors, rather than in manufacturing and, therefore, difficult to measure.

So our findings suggest that the growth in consumption of energy, largely from fossil fuel sources, in tandem with the application of new knowledge via innovation diffusion, has driven economic growth since WWII. As was found to be the case in Foster (2014) for the UK, Australia has been on a long term innovation diffusion curve driven by the growth of knowledge embodied in capital goods powered by cheap fossil fuels. However, it began to climb this curve much later than the UK and did so with a different mix of productive activities. We also have a Keynesian element to the story: shifts in net capital investment, captured here by the growth in the net capital stock, have had a strong effect on the oscillations of economic growth.\textsuperscript{11} No significant role was found for growth in labour hours, even though these have grown steadily over the post-war sample period. Time spent in work has not been a constraint upon the innovation diffusion process even though the level labour input clearly remains fundamentally important in determining the level of GDP. Growth in employment has been principally in the service sector which has been the main beneficiary of the process whereby capital goods, using cheap energy have substituted for labour hours. What has been very important has been the capacity of the labour force to apply new skills, in combination with increasingly advanced capital goods, to allow the innovation diffusion process to occur. Much of this ‘invisible’ effect has occurred in the delivery of services, both within and beyond firms.

\textbf{V. Conclusion}

Strong support has been found for the hypothesis that, since WWII, an innovation diffusion process, involving the expanding use of capital goods fuelled largely by fossil fuels, has enabled the strong and sustained economic growth that has been observed in Australia. Before WWII, Australia had an economy that was still largely dominated by the application of labour and animal power. The relatively small capital stock was labour and animal augmenting, rather than labour substituting. The evidence suggests that a capacity limit was reached early in the 20\textsuperscript{th} Century. WWII induced a sharp increase in the use of productive capacity. The result was overuse and exhaustion of the capital stock but it also heralded a fundamental structural transition in the Australian economy. The evidence presented here indicates that Australia, building on a growing capital stock that used

\textsuperscript{11} These fluctuations in capital investment have tended to be associated with fluctuations in commodity prices in the Australian case.
cheap fossil fuel energy, became an innovative economy with a rising $K$-limit. Technical innovations embodied in capital goods were important but so were applications of new knowledge in organisational, institutional, and product innovations, particularly in the service sector which came to dominate employment.

Sitting at an estimated 76% of its estimated GDP capacity limit in 2008, Australia shows great potential for further growth after a long period of heavy capital investment. This ongoing strength is why Australia has not experienced a recession in two decades, why it weathered the Global Financial Crisis so well and why it is resuming strong economic growth as the global economy recovers.\footnote{It is worth pointing out that the successful enactment of a stabilization policy in the wake of the GFC is, of itself, evidence of significant institutional innovation in the area of policy.} So why has the gap between GDP and its $K$-limit grown so much since 1990?

With rapidly increasing computing power and innovations in information and communications technologies, both the quantity and technical quality of capital stock has increased markedly enabling new kinds of innovations, both in organisational structures and in product offerings. At the same time, the capacity of the population to participate in, and contribute to, such innovation processes has also increased. According to Perez (2002), a Schumpeterian long wave, driven by radical innovations in ICTs, commenced in advanced countries in the mid/late 1980s and reached an inflexion phase in the 2000s. However the evidence here suggests that the ‘inflexion effect’ that may have slowed growth in many developed countries has been minimal in Australia because it has, increasingly, traded with a fast-expanding Asian economy which has had significant production cost advantages. In the next decade we might expect Australia’s GDP to $K$-limit gap to narrow somewhat as the hypothesised ICT-based long global upswing comes to an end. In the meantime, it is likely that Australian economic growth will remain very strong. Such a positive result might suggest that Australia would do well to continue the policies that it has been pursuing. However, the path that is being followed, although successful, may not be very resilient in the longer term.

For example, in this study, we have not distinguished growth of output per capita and population growth, which sum to GDP growth. Of course, inward migration, boosting population, has been important in providing human knowledge and skills and in stimulating effective demand but, in Australia, economic growth is highly correlated with growth of output per capita but not with
growth of population.\textsuperscript{13} In addition to not being effective in generating economic growth, more population increases pressure on Australia’s very fragile natural environment. So, in looking ahead, Australia would do well to stabilise its population.

Paradoxically, the greatest threat that Australia faces is complacency concerning its economic success. In recent decades, this success has been founded very strongly on the exploitation and use of fossil fuels: almost all electricity generation and transportation is powered by them; over a period of forty years, Australia has gone from a net exporter of oil to a major importer; at the same time, it has gone from exports dominated by agricultural products to a heavy dependence on coal exports. So the Australian ‘growth miracle’ has relied heavily upon fossil fuel exploitation but the World is now beginning to transition away from such fuels, both because of carbon mitigation policies and because fossil fuels are anticipated by many to become much more expensive as the cost of extracting them increases in coming decades. In other words, many of the economic advantages of access to very cheap fossil fuels may slowly disappear and heavily dependent countries such as Australia will become vulnerable.

Molyneaux et al (2012) have provided evidence that Australia already lacks long-term resilience because of its unusually heavy dependence on fossil fuels. So it would make good economic sense to have an explicit long-term policy to reduce dependence upon fossil fuels in generating electricity, powering transportation and in earning export revenue. Fortunately, Australia has a demonstrated history of being able to meet such adaptive challenges but it did require a major war to spark a full transition towards a successful fossil fuel economy. Economic conditions today are radically different to those prevailing in Australia in the late 1930s, so there is no immediate urgency to adapt. However, the very high level of wealth per capita offers a great opportunity to enact a structural transformation without being forced to do so because of a political crisis. As Dodgson et al (2010) argue, Australia needs to assign a very high priority to formulating a bi-partisan innovation policy to take advantage of new radical innovations, both domestic and foreign, that can open up new niches for economic growth that is sustainable in the longer term.\textsuperscript{14} It seems vital that such a policy pays particular attention to radical innovations that raise energy efficiency and induce

\textsuperscript{13} Banerjee (2012), using an endogenous growth methodology, comes to an even more negative conclusion concerning the impact of population growth on productivity growth.

\textsuperscript{14} Banerjee (2012) also stresses the importance of promoting innovation based upon evidence concerning, for example, the estimated impacts of patents and R&D expenditure. However, no attention is paid to either the role of the capital stock or energy consumption in his modeling.
significant shifts to non-fossil fuel energy sources. For a country such as Australia, with its very heavy reliance on fossil fuels, the benefits of such developments would seem to be particularly marked.

References


Data Sources

All series are annual, computed for the purpose of estimation as index numbers.

GDP

The gross domestic product series from 1901 to 1990 is taken from Snooks (1994) Table 7.9 p. 181. The remaining 18 years of data are obtained from the ABS national accounts figures, given in current prices, but converted to constant prices by chaining the relevant ABS deflator with the Snooks (1994) deflator. Chaining these series does not lead to a significant break.

Capital Stock

Snooks (1994), Table 7.9 p. 181, combined private and public capital stock figures (as ‘market capital stock’) to 1990, using ABS national accounts figures, and reporting the combined series in constant (1967) prices. He adopted the perpetual inventory method (PIM) and assumed depreciation of 8 per cent per annum for plant and equipment and 1.5 per cent per annum for structures. This is the chosen a consistent long term source of capital stock statistics until 1990. The remainder of the series (from 1991 to 2008) is computed by appending the end-of-financial-year net capital stock data from the ABS national accounts, deflated to constant (1967) prices and subject to the same depreciation assumptions imposed by Snooks (1994).

Labour

Labour supply is represented as the index of total annual labour hours worked. From 1901 to 2008, annual labour hours data for Australia is drawn from the Total Economy Database for 2011 maintained by the Groningen Growth and Development Centre.
Energy

The 2011 *BP Statistical Review of World Energy* contains annual data on the production and consumption of coal, oil, gas, hydroelectricity and other renewables in Australia since 1901, courtesy of the International Energy Agency.

Population

Source: Maddison (2009).