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Frameworks for Formulating Environmental and Climate Change Policies: Perspectives from Environmental-Macroeconomics

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Abstract

The aim of this paper is to demonstrate the significant differences that would emerge in policy formulation, when environmental capital (KN) is explicitly accounted for in macroeconomic analyses. These differences are illustrated with reference to two selected Organisation for Economic Co-operation and Development (OECD) economies namely, Australia and Canada. The main analytic framework considered is a factor utilization function – which traditionally deals with Labour (L) and manufactured Capital (KM). The development of a three-factor function in terms of L, KM and KN enables the display of mistaken notions of economic performance. That is in the absence of KN, policy makers overstate the performance of L and KM. The recognition of mistaken levels of performance with reference to KM and L in standard macroeconomic analyses enables the identification of policy avenues to protect and enhance KN. As illustrated in the paper, the implication of developing and applying environmental-macroeconomic frameworks for formulating environmental and climate change policies is significant.

Keywords and the JEL code(s): E00 – Macroeconomics General, Q51 – Valuation of Environmental Effects, Q54 – Climate Change, Q56 – Sustainability; Environmental Accounts and Accounting, Z18 – Public Policy

I. INTRODUCTION

The measurement and accounting of environmental capital (KN) in Gross Domestic Product (GDP) has not been fully reconciled by National Income Statisticians and is still a subject of debates and differing viewpoints. Although mainstream economics has started to recognise KN, there remains no consensual approach for the measurement of KN[1]. Such complexity does not suggest that the measurement of KN, critical to the development of sustainable macroeconomic policies, is impossible. Unavoidably, however, there will be assumptions and limitations to consider. Daly (1997) argued that outcomes would differ if natural resources were included in the economics of production. A similar view was offered earlier by Nordhaus and Tobin (1972). To illustrate this view, Daly (1997) used a simple example of baking a cake without the ingredients. To bake a larger cake, the cook needs only to stir it faster in a larger bowl and bake it in a larger oven. The bowl and oven are the capital, and the

[1] Wolf, M. (2012) suggests that extraordinary creativity is required to manage the current world with current frameworks.

cook is the labour. However, without the ingredients (natural resources), there will be no cake. Thus, one way to appreciate the function of KN is through the inclusion of KN in the factor income model.

An economy's capacity is defined in terms of the complete utilisation of the labour force (L_f) and is considered in terms of the steady state equilibrium (SSE) as explained in the early neoclassical work of Solow (1956) and Swan (1956). Steady state literature is now outdated. For example, in contemporary macroeconomic models, technology is no longer regarded as exogenous; instead, it is considered endogenous. Nevertheless, the choice of the neoclassical growth model is favoured for reasons of illustrative convenience especially in terms of the analytics of point estimate. Furthermore, it is also noteworthy that the endogenous formulation [see Romer (1986)] is based on the neoclassical Swan-Solow (1956) framework.

The paper is structured as follow. Section II provides the basis for measuring the role of KN in economic growth. A conceptual basis and a methodological framework for measuring KN are discussed in turn. The empirical evidence of KN utilisation for the Australian and Canadian economy from 1990 to 2009 is presented. Section III begins by defining the steady state, followed by a derivation of the steady states for both the standard macroeconomic and environmental-macroeconomics models. The steady states will be operationalised and the empirical evidence based on the two models presented. Section IV concludes the discussion of this paper.

II. FACTOR UTILISATION FUNCTION FROM 2-FACTORS to 3-FACTORS

Existing literature explains the distribution of national income between 2 factors, namely capital (KM) and labour (L). A widely used model is the Cobb-Douglas (C-D) factor utilisation function which describes the relationship between income and the inputs KM and L. Assuming that this function displays constant returns to scale ($\theta + \lambda = 1$) [Hartwick, (1978, 1991), Solow (1986), and Nordhaus (1992)], the C-D function takes the following form:

$$Y = \alpha KM^{\theta} L^{\lambda} \qquad (1)$$

where α is the total factor productivity coefficient, θ is the share of income to capital, and λ is the share of income to labour. This is based on the assumption that the factors are paid their respective marginal products.

The coefficients θ and λ of the assumed functional forms can be estimated using point estimate data on the premise that equation (1) is valid. Income statements in national accounts contain an identity that allows for this estimation. This identity is:

$$Y \equiv OS + CE \qquad (2)$$

where OS is the operating surplus, which is the sum of the payments to KM and CE is the compensation to the employees, which is the sum of the payments to L.

Therefore, it follows that:

$$\theta = [\frac{OS}{Y}] \qquad (3)$$

$$\lambda = [\frac{CE}{Y}] \qquad (4)$$

The contention in environmental-macroeconomics is that income, Y is not purely attributed to KM and L. KN must also be accounted for because it plays an important role in the formation of Y, similar to the above cake-making example from Daly. This relationship suggests that the contributions of KM and L in the standard factor utilisation function are overstated.

In terms of this premise, there is a need to revise the C-D factor utilisation function to the 3-factor utilisation function as follows:

$$Y = \alpha \, KM^{\theta'} L^{\lambda'} KN^{\phi} \quad (5)$$

where α is the total factor productivity coefficient, θ' is the share of Y to KM, λ' is the share of Y to L, and ϕ is the corresponding share of Y that accrues to KN. When KN is considered as a third factor, the same level of income would then be attributed three-ways to KM, L and KN. As a result, income in the 3-factor income model will fall below that of the 2-factor income model (Thampapillai, 2012). The following discussion on the conceptual basis for measuring KN follows that of Thampapillai (2012) and Thampapillai and Sinden (2012).

A. CONCEPTUAL BASIS FOR MEASURING ENVIRONMENTAL CAPITAL (KN)

Figure 1 below displays both the 2-factor and 3-factor income models[2]. This figure also displays two horizontal scales. The first is KM, which is the accumulated stock of manufactured capital. The second is K, which is a composite measure that comprises the amount of KM accumulated and the amount of KN utilised. Thampapillai & Sinden (2012) assumed that KM and KN can be measured with the same numerical scale and, hence, can be aggregated.

[2] The income definition in the 2-factor model does not make any allowance for depreciation for KN (D_{KN}). However, the definition in the 3-factor model makes an allowance for D_{KN}. With this consideration for D_{KN}, the 3-factor income model will fall below that of the 2-factor income model as indicated in Figure 1.

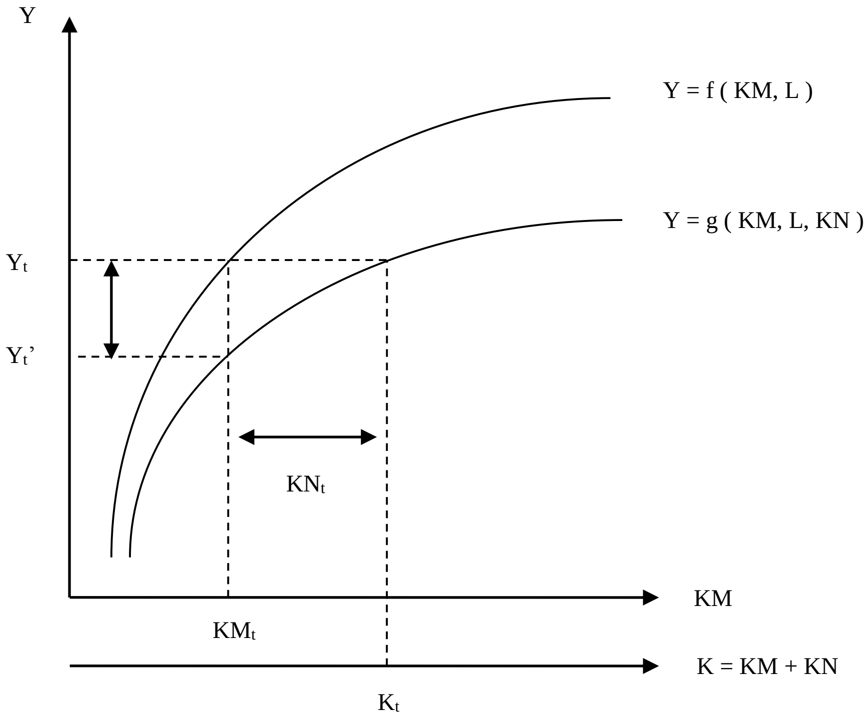


Figure 1: Conceptual Basis for Measuring Environmental Capital[3]

The role of KN in determining Y can be explained by comparing Y = f (KM, L) with Y = g (KM, L, KN). In the 2-factor model, the amount of KM that is required for Y_t is KM_t. However, the same level of Y_t in the 3-factor model is explained by K_t, which is larger than KM_t. This observation suggests that KN_t can be estimated as the difference ($K_t – KM_t$). The utilisation of KN represents the depreciation in the level of existing KN stock. When Y_t is explained by the 3-factor model, the following two observations can be made:

i. KM_t is responsible for a lower value of Y_t' (known as sustainable Y) and not Y_t, in other words, $Y_t' < Y_t$. Hence, there is an over-estimation of the income ($Y_t – Y_t$')

ii. At the level of Y_t, more of the aggregated capital K_t (greater than KM_t) is required to maintain this level of income

[3] Figure 1 is reproduced from Figure 13-2 of Thampapillai & Sinden (2012).

To achieve a given rate of growth, the amount of KN used towards production will increase. However, there are two challenges associated with this: one is to ensure that KN increment is constant; and two, use KN saving technology process.

To recognise the depreciation for KN (D_{KN}), the income Y must be adjusted to the sustainable income, Y', by adjusting for the depreciation of the KN stock. In other words, Y' = Y – D_{KN}. Suppose that D_{KN} is a proportion of Y, as follows:

$$\phi = [\frac{D_{KN}}{Y}] \quad (6)$$

Thampapillai & Sinden (2012) assume that ϕ can be regarded as the share of Y that accrues to KN. Hence, it follows that a sustainable income, Y' would be adjusted accordingly by a factor of (1-ϕ) as follows:

$$Y' = \alpha' \, KM^{\theta'} L^{\lambda'} KN^{\phi} \quad (7)$$

where $\alpha' = (1-\phi)\,\alpha$[4].

Now that both Y and Y' are ascertained, an expression for KN can be obtained by dividing Y by Y' as follows[5]:

$$KN = KM^{\frac{\theta-\theta'}{\phi}} L^{\frac{\lambda-\lambda'}{\phi}} \quad (8)$$

[4] The time series point estimate is assumed valid in each year of the time series. The analysis of point estimates capture productivity changes for each year of the time series. Therefore, any change in multi-factor productivity (MFP) is made through α and α' as point estimates for each year.

[5] The variables which constitute KN, that is capital KM (GCF), operating surplus (OS) and compensation to employees (CE) have been smoothed by the Hodrick-Prescott filter. This ensures that KN is not contaminated by business cycles.

The methodology (steps) taken to measure KN is detailed in Appendix 1.

B. EMPRICAL EVIDENCE OF ENVIRONMENTAL CAPITAL FROM 1990[6] TO 2009

Based on the definition of KN given in equation (8), the utilisation of KN was empirically measured and presented in Table 1 below, and displayed in Figures 2 and 3. Australia and Canada are selected and compared as both are commodities driven economies.

[6] Complete data for all GHG were not available before 1990.

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
AUS	108202107	25411289	12985800	11150858	17266359	29393107	31470808	30571983	47594727	57894233
CAN	127981303	61453246	51209796	52017339	64261203	91397252	84342665	101035918	122646876	146442320

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
AUS	81098958	51242209	64545566	77742171	101501023	138548986	173217127	235092605	271059660	115890459
CAN	233305598	183433035	143167319	164301093	183171564	213102020	230757057	257940982	237759724	84919409

Table 1: Environmental Capital Utilisation (in Year 2005 Constant National Currency) for Australia and Canada from 1990 to 2009

The historical display of KN utilisation in the two figures below show that Australia and Canada are displaying an increase in the use of KN. Note that KN utilisation is plotted on the vertical axis with time on the horizontal axis. Based on Figures 2 and 3, Australia and Canada showed similar progressive increase in the utilisation of KN from 1991 to 2008. A steep decline in the utilisation of KN after 2008 may be attributed to the Global Financial Crisis 2007 – 08.

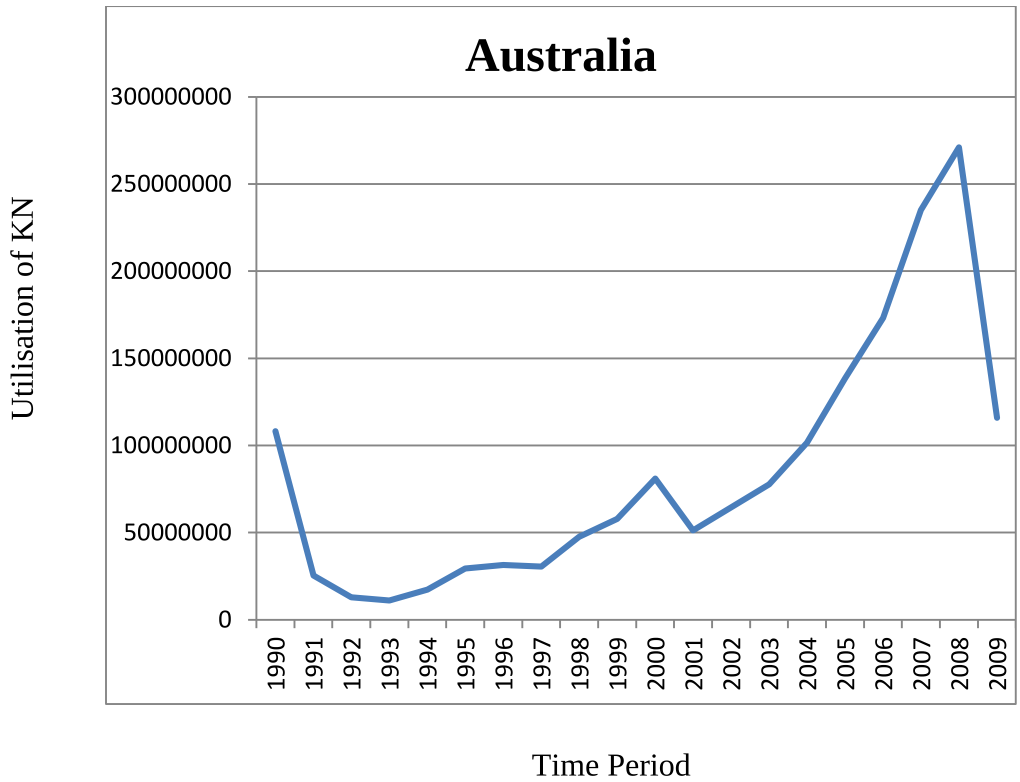


Figure 2: Environmental Capital Utilisation for Australia from 1990 to 2009

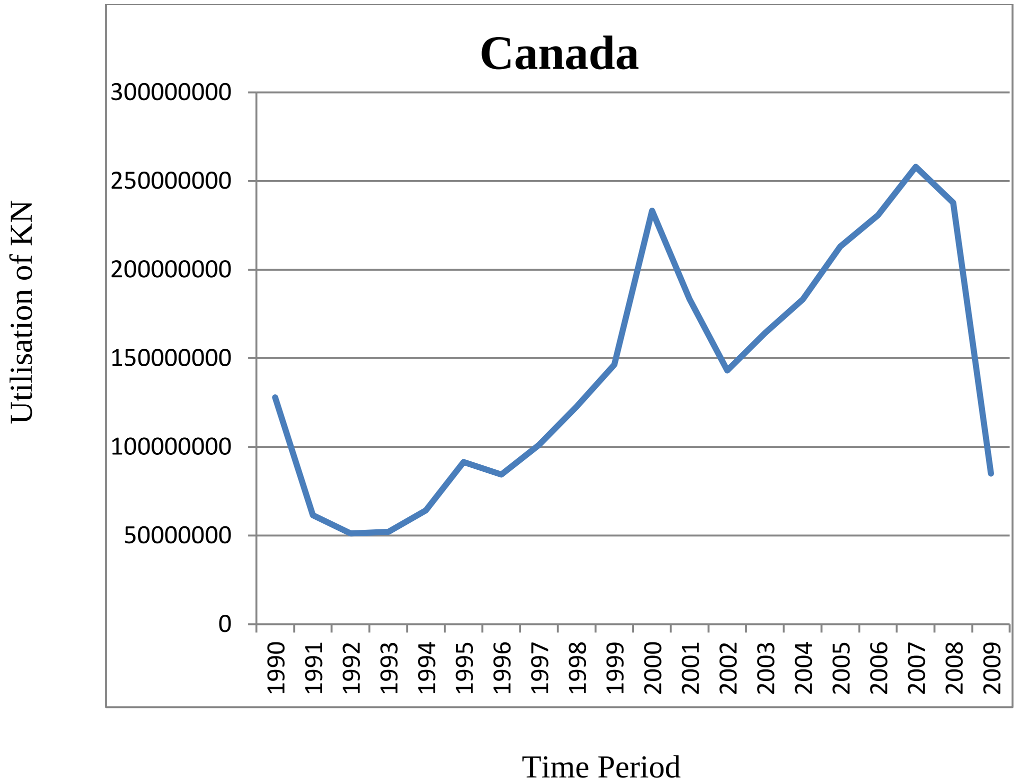


Figure 3: Environmental Capital Utilisation for Canada from 1990 to 2009

Figure 4 shows the level of unemployment rates for Australia and Canada over the same time period. The unemployment rates for both economies are displaying a decreasing trend. That is, more people are employed over the observed time period.

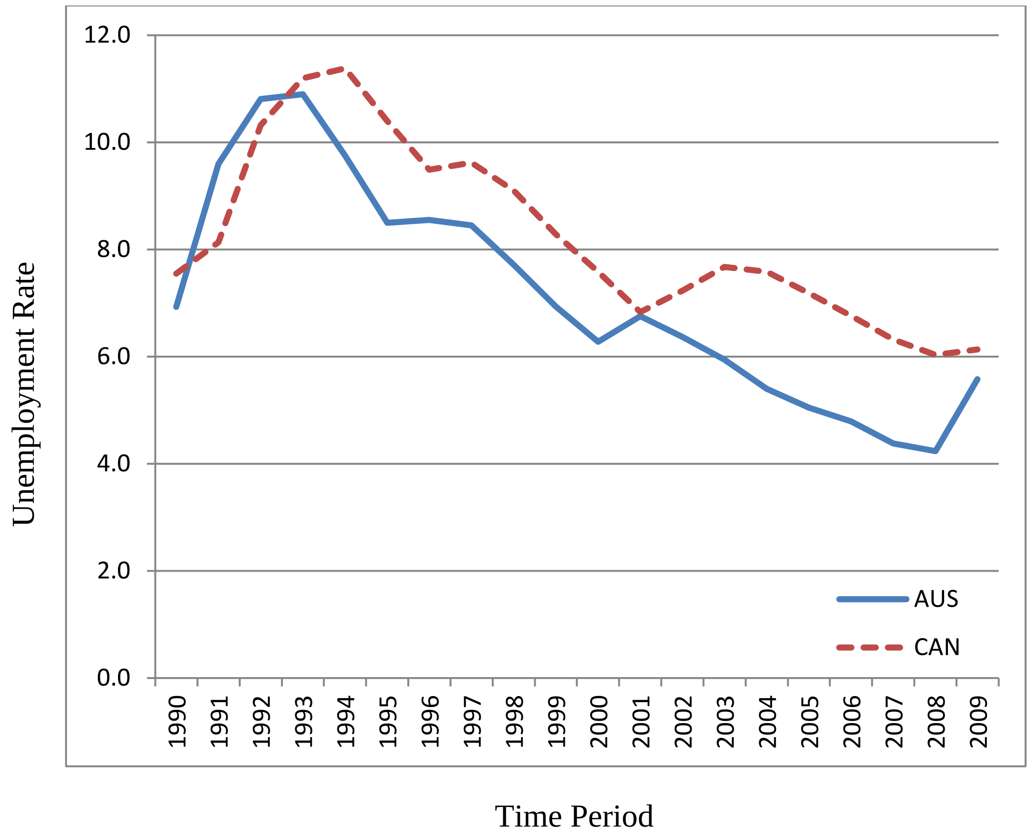


Figure 4: Unemployment Levels for Australia and Canada

From Figures 2, 3 and 4, the utilisation of KN increases when unemployment is decreasing. Note that the reverse also holds true. In the observed period of 1990 to 1992, utilisation of KN in both economies is decreasing and this corresponds to levels of rising unemployment. Hence, it can be concluded that the utilisation of KN is required for the growth of both economies studied.

III. STEADY STATE EQUILIBRIUM (SSE)

The SSE in the Swan-Solow framework is the amount of capital accumulated that is just sufficient to meet the needs of capital (KM) depreciation and the entry of new workers. Capital accumulation is assumed to emerge directly from savings. In other words, savings (S) is equal to investment (I), S = I. Furthermore, the pertinent variables in the framework are described in per worker terms. These variables are as follows:

i. Capital per worker $k = \left[\frac{KM}{L}\right]$ (9)

ii. Savings per worker $s = \left[\frac{S}{L}\right]$ (10)

iii. Output per worker $y = \left[\frac{Y}{L}\right]$ (11)

The 2-factor [Y = f (KM, L)] C-D model is used to explain the relationship between *k* and *y*; and between *k* and *s*. That is,

$$y = \alpha k^{\theta} \tag{12}$$

$$s = \alpha \rho k^{\theta} \tag{13}$$

where α is the total factor productivity and ρ is the savings rate per worker.

The SSE can be derived in terms of a point estimate as:

$$\left[\frac{KM}{L}\right]^{*} = \left[\frac{\rho\alpha}{\delta + \eta}\right]^{\frac{1}{1-\theta}} \tag{14}$$

where ρ is estimated as the savings rate per worker and the national savings (S) is defined as S = GDP – C – G thus ρ = (S / GDP); α is the total factor productivity; δ is the rate of depreciation of KM; η is the entry of new workers into the workforce (or the annual growth of labour).

The above scenario is illustrated in Figure 5 below.

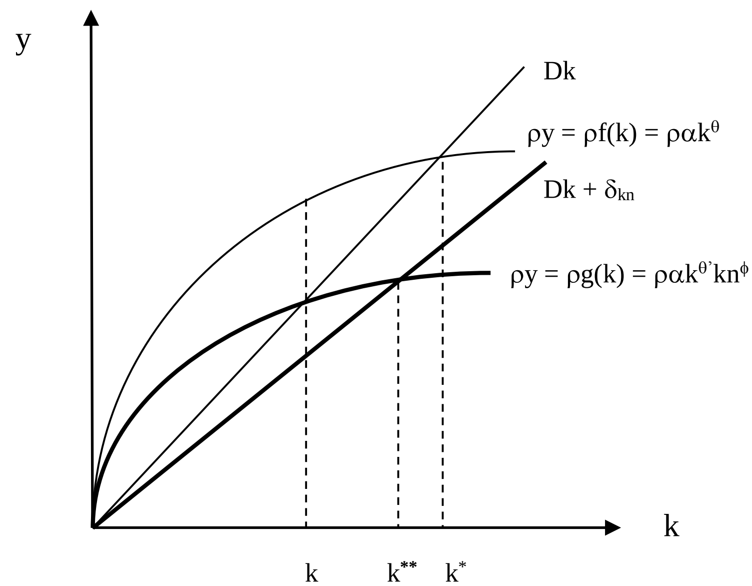


Figure 5: Steady State Equilibrium of the 2-Factor C-D Model (k^*) and the 3-Factor Model (k^{**})

In Figure 5, the curve labelled y = f (k) shows how the output per worker (y = Y / L) increases when the capital per worker (k = KM / L) is increased. When y = f (k) is multiplied by the savings ratio (ρ), the curve $\rho\alpha k^{\theta}$ is the result. The straight line from the origin describes the amount of KM stock replacement that is required for the depreciation of existing KM. It corresponds to the equation Dk, where (D = $\delta + \eta$), δ is the rate of KM depreciation and η is the rate of entry of new workers. The point of intersection between the straight line Dk and the curve describing savings $\rho\alpha k^{\theta}$ is the SSE, k^*. The SSE is defined by the quantity of KM per worker as shown in equation (11) above. The derivation of the SSE is presented in Appendix 2. Comparing k^* and k, k is the current level of KM per worker.

When the 3-factor [Y = g (KM, L, KN)] model is used, there will be one more variable in addition to the three variables (9, 10, 11) discussed earlier. The result is the KN per worker, kn = (KN / L). Because KN is measured on the same scale as KM (assumed), it can be costed and depreciated in the same way as KM. In this revised model, the curve (bold) $\rho\alpha k^{\theta'} kn^{\phi}$ is the result when y = g (k) is multiplied by the savings ratio (ρ). Please refer to Figure 5. With a new variable kn, there is a new parameter ϕ which is the share of income that accrues to KN. The straight line (bold) from the origin corresponds to the equation Dk + δ_{kn}, where δ_{kn} is the depreciation of KN. The SSE is the point of intersection between the straight line Dk + δ_{kn} and the curve $\rho\alpha k^{\theta'} kn^{\phi}$. The SSE is defined by the quantity for KM per worker:

$$\left[\frac{KM}{L}\right]^{**} = \left[\frac{\rho\alpha\gamma^{\phi}}{D + \gamma\delta_{KN}}\right]^{\frac{1}{1-\theta'-\phi}} \qquad (15)$$

The new parameters in Equation (15) are the following: ϕ is the share of Y that accrues to KN; D is a constant, that is (δ + η); γ = KN / KM, where KN is a factor of KM; and δ_{KN} is the depreciation of KN which is estimated using a method outlined in Thampapillai and Hanf (2000). Here P_{KN} is defined as (ϕY / KN). Recall that ϕ is the share of Y that accrues to KN. Then δ_{KN} is ($P_{KN} - i_{KN}$) and is based on the premise that the price of any capital is the sum of the interest rate and the depreciation. As in Thampapillai and Hanf (2000), the interest rate was assumed to be the same as that of KM. The derivation of the revised SSE is presented in Appendix 3.

It is apparent from Figure 5 that there are changes to the SSE. In the Cobb-Douglas model, the current level of k and the SSE is (k, k^*). Comparing this model with the 3-factor model, the respective levels are (k, k^{**}). SSE is reached earlier in the 3-factor model relative to the 2-factor model because allowance has been made for KN. It is now fitting to compare the observed trend of k with the SSE. Let's consider three possible scenarios. For scenario A, the economy's observed level of capital accumulation is lower than that required for the SSE ($k < k^*$), that is (k^* / k) > 1. The economy is experiencing savings surpluses and is under-utilising its available resources. There is capacity available in the economy. In scenario B, the economy's observed level of capital accumulation exceeds the SSE ($k > k^*$) and (k^* / k) < 1. In this context, the economy is experiencing a savings deficit and is over-utilising its available resources. The economy may be over-capitalised and have a possibility of rising inflation. In scenario C, the economy is at SSE ($k = k^*$) and (k^* / k) = 1.

Please see Table 2 for the definition of these scenarios.

Scenarios	**Accumulated capital stock relative to SSE in both the 2-factor (k^*) and 3-factor model (k^{**})**	**State of an economy**
A	$(k^* / k) > 1$ / $(k^{**} / k) > 1$	Within SSE – room to build up *k*
B	$(k^* / k) < 1$ / $(k^{**} / k) < 1$	Beyond SSE – need to seek policies to be within SSE
C	$(k^* / k) = 1$ / $(k^{**} / k) = 1$	Steady State

Table 2: Table Illustrating the Three Different Scenarios for an Economy

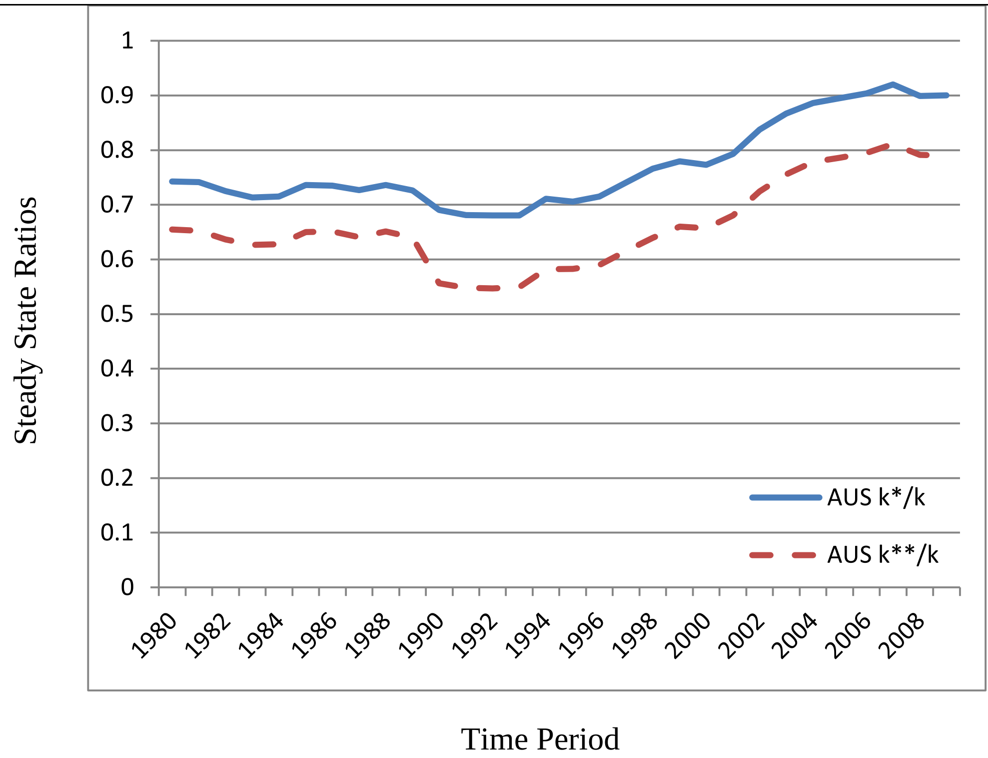
In summary, the steady states for the Cobb-Douglas factor utilisation function (k^*) and the 3-factor utilisation function (k^{**}) and the estimation of KN are reproduced below:

	Estimation of variables
2-factor (k^*)	$$\left[\frac{KM}{L}\right]^* = \left[\frac{\rho\alpha}{\delta+\eta}\right]^{\frac{1}{1-\theta}}$$
3-factor (k^{**})	$$\left[\frac{KM}{L}\right]^{**} = \left[\frac{\rho\alpha\gamma^{\phi}}{D+\gamma\delta_{KN}}\right]^{\frac{1}{1-\theta'-\phi}}$$
KN	$$KN = KM^{\frac{\theta-\theta'}{\phi}} L^{\frac{\lambda-\lambda'}{\phi}}$$

Table 3: Steady states k^*, k^{**}, and Environmental Capital (KN)

A. STANDARD MACROECONOMIC MODEL VERSUS ENVIRONMENTAL-MACROECONOMICS MODEL TIME-SERIES PRESENTATION

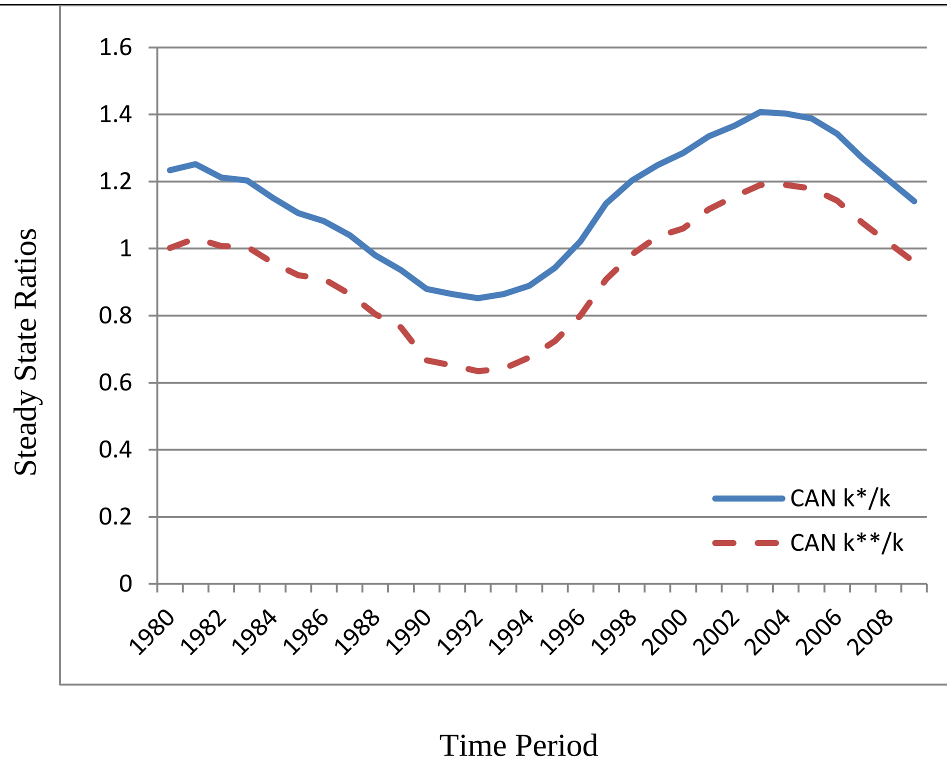
The economies of Australia and Canada are graphed using the steady state ratios of [(k^* / k), (k^{**} / k)]. The ratios are obtained for the economies over the time period of 1980 to 2009. Both ratios [(k^* / k), (k^{**} / k)] are graphed on the same X-Y plot, with the steady state ratio on the vertical axis and time on the horizontal axis. Figure 6 shows Australia's steady state ratios and Figure 7 shows Canada's steady state ratios.



Australia is operating beyond capacity (ratio is less than one) for both the standard macroeconomic and environmental-macroeconomics models. The linear upward trend demonstrates a freeing up of capacity in the economy.

Australia is tending toward steady state (a ratio value of one) in the standard macroeconomic model. However, the Australian economy remains at beyond capacity (at a ratio of less than one) in the environmental-macroeconomics model. Both graphs are displaying a divergence from the year 1990.

Figure 6: Australia Steady State Ratios of (k^{*} / k) and (k^{**} / k)



Canada is displaying a cyclical trend and operating with excess capacity (a ratio of greater than one) before tampering and hovering near steady state (a ratio value of one) in the standard macroeconomic model.

In the environmental-macroeconomics model, Canada is operating at beyond capacity (a ratio of less than one) but accumulated capacity and moved to operating with excess capacity (a ratio of more than one). A slight convergence of the two graphs can be observed nearing 2009.

Figure 7: Canada Steady State Ratios of (k^{*} / k) and (k^{**} / k)

Figures 6 and 7 showed that the ratio of (k^{**} / k) in the environmental-macroeconomics model will always reach a steady state earlier than the ratio of (k^{*} / k) in the standard macroeconomic model. The line of (k^{**} / k) is always below that of (k^{*} / k) shows that the capacity of an economy can be overstated if KN is not taken into consideration. Although this observation has been reviewed for the past 30 years, it does present to the policy maker either one of two possible paths that an economy could have taken at the time of policy making, viz: the path that was (k^* / k) versus the path that should have been (k^{**} / k).

IV. LONG RUN MACROECONOMIC GOALS of INFLATION, EMPLOYMENT, and GDP GROWTH

The long run analysis of the model discussed in this section has been made with respect to the steady state ratios of the selected OECD economies. Based on the discussion, an economy can either operate with excess capacity available, at beyond capacity, or at steady state. The capacity available in an economy can be determined by how an economy's long-term macroeconomic goals (inflation, employment, and per capita GDP) are addressed such as which goal(s) (if any) have priority or whether all of the goals have equal precedence.

Before discussing each of the long run macroeconomic goals, it is important to differentiate the different time periods in macroeconomics. Please refer to Figure 8 below.

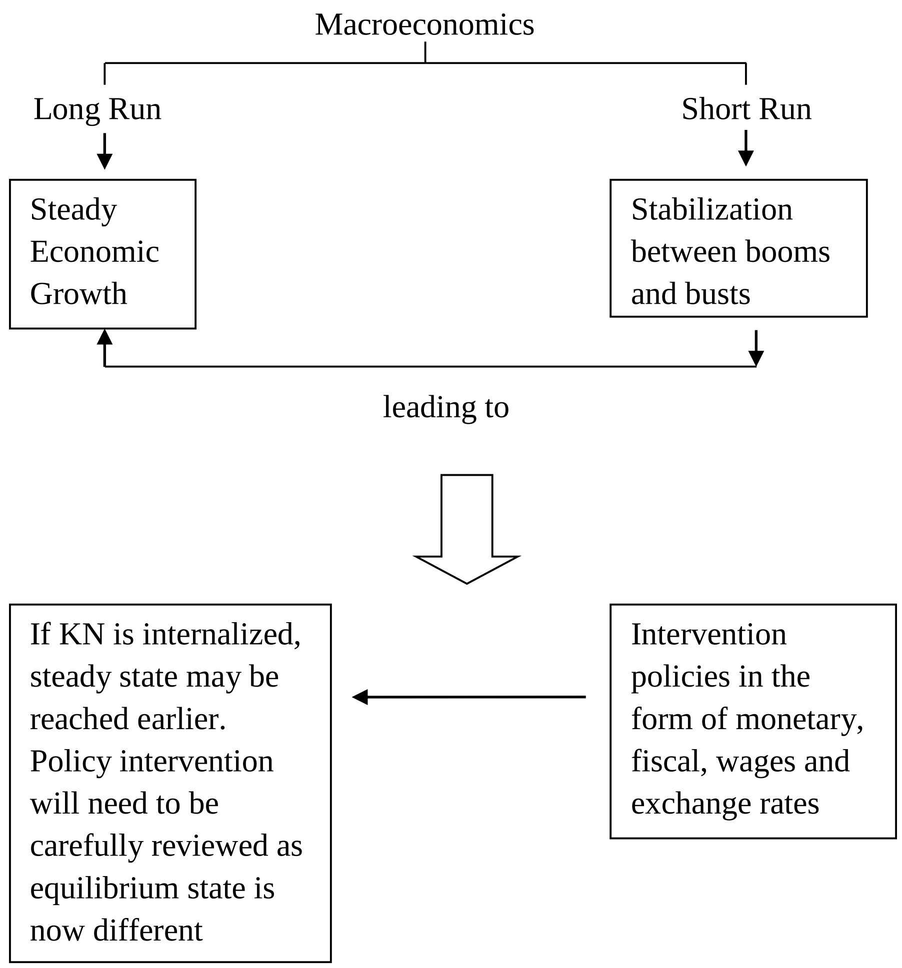


Figure 8: Long Run and Short Run of Macroeconomics

In the long run, an economy is focused on steady economic growth. In the short run, there will be cycles of booms and busts which over the long run are, however, expected to smooth over and result in steady economic growth. Reducing such volatility in the economy will instill confidence and will reduce uncertainty for investors and citizens alike. Effective surveillance and timely analysis of macroeconomic trends ensure that policies are shaped toward macroeconomic stability. Macroeconomic stability lies at the core of economic policy formulation in all economies.

An economy is expected to exhibit steady economic growth in the long run. The factor utilisation functions discussed earlier are the compelling forces that drive this observation. The economics of growth or growth economics are of interest to policy makers. In an ideal situation, equilibrium in the long run would tend toward or be at a steady state. Economic growth would be exogenously determined, with capital accumulation becoming less significant, and technological progress becoming more dominant as a factor for economic growth. Technological progress is often measured by the Solow residual or the total factor productivity (TFP). TFP is enhanced as new capital becomes more valuable than old capital. This is because new capital is based on new technology improving over time. Therefore, it can be argued that technological progress and other external factors may be the main sources of economic growth in the long run by being add-ons to steady state changes, which invariably will affect macroeconomic goals in the long run.

According to Holt (2005), natural capital is based on a dynamic relation between a physical and a biotic environment (which can be unpredictable). The Bruntland Report proposed a change in the exploitation process of resources that would be consistent with future as well as present needs. Hence, there should be moderation of the increase in economic growth. It is crucial to measure the effects of economic activities that are sustainable and resilient with the ecosystems and natural resources. Because of the level of uncertainty, it may be difficult to know the effects of economic growth on the resilience of the environment and natural resources (Holt, 2005).

The challenges for policy makers with respect to macroeconomic goals are as follows. First, is inflation set within acceptable levels for policies to be effective? Second, can greater employment be achieved without significantly impacting inflation? Third, how much is an economy allowed to grow? To sustain natural resources, reduce environmental degradation, and protect a fragile ecosystem for future generations, a steady state should consider KN in addition to the three macroeconomic goals.

V. CONCLUSION

The aim of this paper is to present a steady state analysis of the standard macroeconomic model and the environmental-macroeconomics model. It has been demonstrated that the capacity of an economy can be overstated without appropriate consideration for KN which may result in the policy ranges to be incorrectly identified. However, should KN be taken into consideration, there are two possible paths that an economy could take at the time of policy making namely, the path of the environmental-macroeconomics model and the path of the standard macroeconomic model. In the long run, macroeconomic stability is central to economic policy formulation. Policy formulation must consider the steady state (when allowance for KN is made) of an economy with respect to the long run macroeconomic goals of maintaining inflation within an agreed band and ensuring low unemployment and a smooth GDP growth.

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VII. APPENDICES

Appendix 1: The following details the steps taken to estimate KN[7].

i. The OECD[8] economies selected for this study are Australia and Canada. The variables selected from 1980 to 2009 are the following: Final Consumption Expenditure (C); Final Consumption Expenditure of Government (G); Gross Capital Formation (GCF); Net Balance of Goods and Services; National Income Expenditure Approach (Y); Compensation of Employees (CE); Gross Operating Surplus (OS); Net Taxes (T); Income Approach to National Accounts (IANA); GDP Deflator; and Employment (L). All of the monetary estimates are in the appropriate national currency at current prices

ii. The GDP deflator was used to convert the current value estimates to constant values. Note that the base year is 2005. To smooth any cyclical variations, the Hodrick-Prescott (HP) filter was applied to the variables C, GCF, S[9], CE, and OS

iii. The perpetual inventory method[10] was used to estimate the capital stock (KM). GCF is the Investment (I) and the logarithm of GCF is computed to express the values in a more natural

[7] Thampapillai (2012) estimated KN by apportioning KN from KM and L. This method has limitations because it does not account for changes in ϕ, which is the share of income to KN, as a factor of income. Please refer to point vii. for a proposed response to address this limitation.

[8] The OECD database was selected because it has a full set of national income accounts with data dating to 1980.

[9] Savings (S) = GDP – C – G.

way. The size of the capital at the initial time period of the time series can be determined and estimated by the coefficient ω, which is defined as the ideal rate of increase for KM per annum. The initial size of the capital stock is denoted as $KM_{t=1}$ for the first year and is estimated from the GCF value. This value is defined as follows:

$$KM_{t=1} = GCF_{t=1} / (\delta + \omega) \qquad \text{(A1)}$$

where δ is the rate at which capital stock depreciates over 30 years, which is assumed to be (1/30) = 0.0333. The size of the capital stock for subsequent years can now be estimated by:

$$KM_{t+1} = KM_t + GCF_{t+1} - (\delta * KM_t) \qquad \text{(A2)}$$

iv. The labour (L) is estimated to be the level of total labour force employed. This is obtained directly from the OECD database

v. The value of θ is estimated to be (OS / Y) as in equation (3) and λ is (CE / Y) as shown in equation (4)

vi. The variable ϕ is estimated to be (D_{KN} / Y) as per equation (6). The value of D_{KN} is restricted to the cost of carbon dioxide (CO_2) abatement. The greenhouse gases (GHG) data are obtained from the World Development Indicators (WDI). The GHG are CO_2, methane (CH_4), nitrous oxide (N_2O), and other GHG [which includes hydrofluorocarbons (HFC), perfluorinated compounds (PFC), sulphur hexaflourinated compounds (PFC) and sulphur

[10] The perpetual inventory method is used for the calculation of fixed assets when direct information is difficult to obtain (Eurostat, 1995).

hexafluoride (SF_6)]. All of the gases are converted to tons of CO_2 equivalent, at a cost of USD100 / tonne (2005 constant prices)[11]

vii. With the introduction of ϕ (the share of income to KN), θ and λ must be revised to capture changes in the constituent of income. If the assumption that a constant return to scale holds, then $\theta' + \lambda' + \phi = 1$

Hence, θ and λ must be revised to θ' and λ'. This revision is necessary because the original variables are overstated from the inclusion of the income share from KN.

In this study, θ' and λ' were estimated using shadow pricing. The shadow price is the price of the factor of production when the market is perfect, for example when full employment is observed. Thus, the coefficients θ' and λ' can be defined as follows:

$$\theta' = (1-\phi)\left(\frac{P_{KM}}{P_L + P_{KM}}\right) \quad \text{(A3)}$$

$$\lambda' = (1-\phi)\left(\frac{P_L}{P_L + P_{KM}}\right) \quad \text{(A4)}$$

where P_{KM} is the shadow price of KM, which is estimated to be (OS / KM) and P_{Lt} is the shadow price of CE, which is estimated to be the capital equivalent price of L. The method adopted in Thampapillai (2012) is to convert CE to explain the context of unemployment.

[11] The literature has proposed for a cost of USD100 / tonne of CO_2 emissions. See Stern (2007), Ackerman, et al. (2009), Hope (2011), and Karstad (2012).

This conversion is performed by dividing CE by the labour force to estimate a wage rate that would support full employment. The revised value of CE, namely CE_{St} is then the product of the employment and the shadow wage rate, which is ($L_t^* W_{St}$). Then λ’ is (CE_{St} / Y). P_{Lt} is estimated to be (CE_{St} / KM_t), which is a KM equivalent price.

viii. From equation (8), KN can be calculated by substituting all of the parameters that are described from steps iii. to vii. Note that these parameters are point estimates and not estimation of long-run steady state properties

Appendix 2: Cobb-Douglas Production Function and Steady State Values

The Cobb-Douglas function is one that displays constant returns to scale. In other words

$$Y = \alpha KM^{\theta} L^{1-\theta} \tag{A5}$$

Income, Y is divided by L to express the equation in terms of the output per worker (Y / L) as a function of the capital per worker (KM / L)

$$y = \frac{Y}{L} = \alpha \frac{KM^{\theta} L^{1-\theta}}{L} = \alpha (\frac{KM}{L})^{\theta} \tag{A6}$$

$$y = \alpha k^{\theta} \quad \text{where} \quad k = \frac{KM}{L} \tag{A7}$$

The savings per worker is explained by multiplying (A7) by the savings ratio (ρ)

$$\rho y = \rho \alpha k^{\theta} \tag{A8}$$

Lets assume that there is a need for new workers and that depreciated capital must be replaced. The rate of entry of new workers is η, and the rate of depreciation is δ. The savings per worker is then defined as

$$\rho y = (\delta + \eta) k \tag{A9}$$

To solve for k*, equate (A8) and (A9), as follows:

$$(\delta+\eta)k = \rho\alpha k^{\theta} \tag{A10}$$

Rearranging (A10),

$$k^{1-\theta} = \frac{\rho\alpha}{(\delta+\eta)} \tag{A11}$$

The steady state value of k is

$$k^{*} = \left[\frac{\rho\alpha}{\delta+\eta}\right]^{\frac{1}{1-\theta}} \tag{A12}$$

Appendix 3: 3-Factor Production Function and Steady State Values

The 3-factor production function is one that displays constant returns to scale. In other words

$$Y = \alpha k^{\theta'} L^{\lambda'} KN^{\phi} \tag{A13}$$

Income, Y is divided by L to express the equation in terms of the output per worker (Y / L) as a function of the capital per worker (KM / L)

$$y = \frac{Y}{L} = \alpha \frac{k^{\theta'} L^{\lambda'} KN^{\phi}}{L} = \alpha k^{\theta'} L^{\lambda'-1} KN^{\phi} \tag{A14}$$

For the index of L, $\theta' + \lambda' + \phi = 1, \lambda' = 1 - \theta' - \phi, \lambda' - 1 = -\theta' - \phi, \lambda' - 1 = -(\theta' + \phi)$

Equation (A14) can be expressed as

$$y = \alpha k^{\theta'} L^{-(\theta'+\phi)} KN^{\phi} \tag{A15}$$

Rearranging (A15),

$$y = \frac{\alpha k^{\theta'} KN^{\phi}}{L^{\theta'+\phi}} = \frac{\alpha k^{\theta'} KN^{\phi}}{L^{\theta'} L^{\phi}} = \alpha \left(\frac{K}{L}\right)^{\theta'} \left(\frac{KN}{L}\right)^{\phi} \tag{A16}$$

$$y = \alpha k^{\theta'} kn^{\phi} \quad \text{where} \quad k = \frac{K}{L}, \; kn = \frac{KN}{L} \tag{A17}$$

The savings per worker is explained by multiplying (A17) by the savings ratio (ρ)

$$\rho y = \rho \alpha k^{\theta'} kn^{\phi} \tag{A18}$$

The steady state equilibrium k^{**} can be defined by equating (A18) with the rate of entry of new workers η, the rate of capital depreciation δ, and the rate of environmental capital depreciation δ_{kn}

$$\rho \alpha k^{\theta'} kn^{\phi} = (\delta + \eta)k + \delta_{kn} \tag{A19}$$

Because KN is costed and depreciated in the same way as KM, it can be expressed as a function of KM. In other words

$$kn = \gamma k \tag{A20}$$

Substituting (A20) into (A19)

$$\rho \alpha k^{\theta'} (\gamma k)^{\phi} = Dk + \delta(\gamma k) \tag{A21}$$

where D = $\delta + \eta$

Rearranging (A21),

$$\frac{k}{k^{\theta' + \phi}} = k^{1 - \theta' - \phi} = \frac{\rho \alpha \gamma^{\phi}}{D + \delta \gamma} \tag{A22}$$

The steady state value of k is

$$k^{**} = \left[\frac{\rho \alpha \gamma^{\phi}}{D + \gamma \delta_{KN}} \right]^{\frac{1}{1 - \theta' - \phi}} \tag{A23}$$