# Long run technical change in an energy-environment-economy (E3) model for an IA system

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**Abstract**
A world macroeconomic model is being developed to investigate policies for climate change and sustainable development, as a module of an IAM structure for the UK Tyndall Centre. This requires an economic model for the next 50-100 years, to show how changes in industrial structure and technology change GHG emissions. There is no suitable and generally accepted theory of long term technical change/development (Kondratiev waves) for incorporation in a macroeconomic modelling structure. However, there is now a good descriptive theory, which is intended to provide an economic history perspective of long term change. This is Freeman and Louçv (2001). The objective of our model is to interpret this descriptive theory in quantitative terms, in the context of the macroeconomic analysis. It will model the dynamics of Input-Output coefficients and the implied industrial structure, incorporating endogenous technical change from R&D and investment, with learning-by-doing.

**Keywords:** Macroeconomics, endogenous technical change, Kondratiev waves

## 1. INTRODUCTION

A world macroeconomic model is being developed to investigate policies for climate change and sustainable development, as a module of an IAM. To 'couple' with climate change models, a timescale of 100 years is necessary, because changes in CO2 concentrations, which are now strongly influencing the atmosphere, become significant over a time period of 50-100 years or more. This raises particular difficulties for economic modelling. Looking back over the last 200 years, the socio-economic system seems to be characterised by ongoing fundamental change, rather than convergence to an equilibrium state. Our opinion is that over such a long time, a neo-classical economic model incorporating a long term equilibrium for the world economy is inappropriate. It is necessary instead to consider the dynamic processes of socio-economic development. These processes have been called 'Kondratiev waves' in the literature on long term economic development.

This paper suggests a quantitative theory of long term technical change. It will be part of a global macroeconometric model. Dewick, Green and Miozzo (2002) describe the process of assessing the future technologies to which this theory will be applied. A (descriptive) theory of long term economic change is discussed and an interpretation suitable for incorporation in a macroeconomic modelling framework introduced. The conclusions will relate this work to environmental modelling.

## 2. A THEORY OF INDUSTRIAL REVOLUTIONS

Our central argument is that, since 1750, socio-economic activity has been characterised by a series of fundamental changes in technology, institutions and society. This follows the earlier thinking of Kondratiev, Schumpeter and more recently evolutionary economists (Nelson and Winter (1982), Brian W. Arthur (1994), Silverberg, Richard Day, Dosi) and economic historians (Paul David, Chris Freeman, Carlota Perez). Freeman and Louçv (2001) include a history of economic thought in this area, starting from a critique of cliometrics, the use of econometric methods in economic historical analysis. They cover the ideas of Kondratiev and Schumpeter in particular, who were the leading early figures in economic analysis of long term economic changes. Kondratiev formulated the hypothesis that there were long waves in capitalist development, now called 'Kondratiev Waves'. He undertook one of the first quantified statistical analyses of long term economic data and identified an approximate dating of the long term upswings and downswings with distinctive characteristics in capitalist economies. Schumpeter applied the ideas of economic theory to the study of long term economic change, in a search for an economic theory of the processes of economic change in economic history.

The current (numerical) models of long term technical change have often been developed in the tradition of evolutionary economics, often using the mathematics of diffusion developed for dynamic processes in biology. e.g. Arthur (1994) applied a random process to the cost reduction in a competition between two technologies to demonstrate that one technology would eventually dominate the market with 100% probability and this would not necessarily be the most effective technology, the phenomenon of 'lock-in'.

To summarise, there is no suitable and generally accepted theory of long term technical change for incorporation in a macroeconomic modelling structure.

However, for the first time, there is now a comprehensive descriptive theory, which is intended to provide an economic history perspective of long term change. This is Freeman and Louçv (2001). They argue that Kondratiev waves involve a process of dynamic interaction between 5 subsystems: science, technology, economy, politics and culture. For our purpose of developing a quantitative model, it is only realistic to try and model technology and economy. The impacts and feedbacks with the other subsystems will be reflected qualitatively in the macroeconomic model structure and through scenarios. The objective of our model is to interpret this descriptive theory in quantitative terms, as far as is plausible, in the context of the macroeconomic analysis outlined in the introduction.

## 3. A SUMMARY OF THE THEORY OF FREEMAN AND LOUÇv

They identify 5 waves of technology and socio-economic activity since the industrial revolution in the UK:

1. Water powered mechanisation of industry.
2. Steam powered mechanisation of industry and transport, based on iron and coal.
3. Electrification of industry, transport and the home, with steel as a core input.
4. Motorisation of transport, civil and war economies, with industrial chemicals and oil as core inputs
5. Computerisation of the economy.

Following Perez (1983), they characterise Kondratiev waves as a succession of new technology systems (Freeman and Louçv pp.147-8).

1. For each long wave, there are 'core inputs' e.g. iron for the railway wave, that become very cheap and universally available. This opens up new possibilities of production factor combinations. The sector producing these inputs is the 'motive branch'.

2. New products based on the new factor combinations give rise to new industries whose growth drives the whole economy e.g. railways; associated production of rails, locomotives, railway equipment.

3. There are new forms of organisation of production brought about by the new industries and products, a new 'techno-economic paradigm'.

4. Such a fundamental change will lead to a period of turbulent adjustment from the old paradigm to the new.

Freeman and Louçv identify the following 6 phases in the life cycle of a technology system:

1. Laboratory/invention

2. Decisive demonstration(s) of technical and commercial feasibility. Continuing with the railways example, the opening of the Liverpool and Manchester railway in the UK in 1830 is an good example.

3. Explosive, turbulent growth, characterised by heavy investment and many business startups and failures. There is a period of structural crisis in the economy as society changes to the new organisational methods, employment and skills and regime of regulation, brought about in response to the new technology.

4. Continued high growth, as the new technology system becomes the defining characteristic of the economy.

5. Slowdown as the technology is challenged by new technologies, leading to the next crisis of structural adjustment.

6. Maturity, leading to a (smaller) , continuing role of the technology in the economy or slow disappearance.

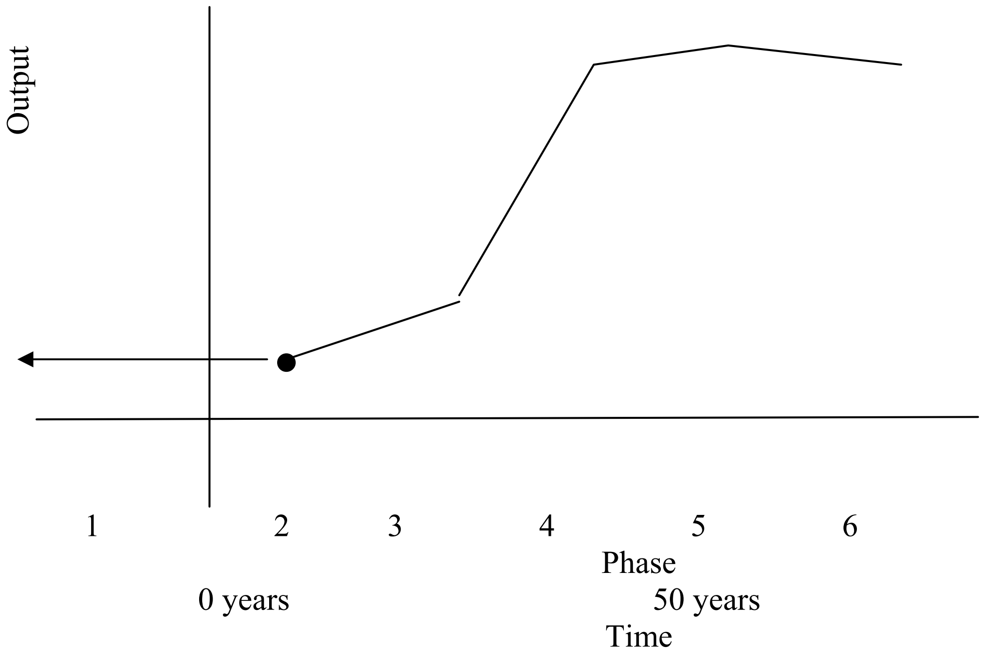


**Figure 1** Phases in the life cycle of a technology system

As can be seen in figure 1, phases 2-5 take roughly 50 years. In phase 1, which is of indeterminate length, there is a negligible macroeconomic effect. The timing of the invention leading to a breakthrough in the technology and the application in a 'decisive demonstration' is more or less random, viewed from a economic perspective. It is phases 2-5 that lead to the Kondratiev waves.

This view of Kondratiev waves leads Freeman and Louçv to the following conclusions / hypotheses:

1. There is a period in which there are technological and/or organisational innovations offering very high profits in a period of general decline in the rate of profit (Phases 2 and 3).

2. There are recurring structural crises of adjustment, structural unemployment, social unrest as society switches from one technology system to the next (phases 3 and 5).

3. The new technological system is associated with a change of regulatory and institutional regime.

4. Each wave generates a new cohort of very large firms, compared to the industrial organisation of the previous wave, in the new sector(s).

5. There is a high level of industrial unrest in 2 phases:
   stage 3: structural adjustment, with a mismatch of skills, as workers in 'old industries are made redundant while new skills are often only acquired by new entrants to the workforce.
   stage 5: decline in rate of profit with strong unions.

## 4. IMPLEMENTATION OF THE DESCRIPTIVE THEORY IN A MACROECONOMIC MODEL

The most difficult challenge in interpreting this descriptive theory of Kondratiev waves is the very large extent to which each wave has unique features of organisation and changes to the industrial structure. This problem has been addressed using the following approach.

The theory of Kondratiev waves is included in the macroeconomic module for Integrated Assessment, as outlined in the introduction. Thus the outputs of the theory have to be compatible with a large scale, dynamic, IO model of a world economy. This implies that it is the IO structure that has to change over time. The current and next Kondratiev waves are characterised by the technologies that form the new technology systems. These technologies are assessed in Dewick, Green and Miozzo (2002). Also, scenarios have been written to identify the impact of these scenarios on the world economy and emissions Berkhout (2002). From these possible new technologies, new economic sectors were identified and used to modify the IO classification as products and sectors. Then the problem is to write a (simple) model of the dynamics of the new sectors which will determine how I-O coefficients associated with the new sectors will change over time.

The necessary features of the technology model are:

- It should generate the output path over time in the 6 phases.
- Following the ideas of Patrick Criqui (Criqui et al., 1999) on how to model endogenous technical change, it should incorporate or at least take into consideration exogenous inventions, supply (R&D, technological opportunities) and demand (new products, markets) inducement factors. It should model path dependency (learning by doing, increasing returns).
- Have declining production costs in the new sectors, incorporating endogenous technical change through R&D expenditure, investment and learning by doing i.e. investment impacts, following e.g. Grübler et al. (1999).

The key assumptions of the theory are:

- The new technology is taken up by a ‘Carrier branch’ of industry, to use Perez’ terminology.
- The new technology is embodied in a ‘Core input’ , whose price suddenly drops dramatically, to say 1/10 previous price.
- This leads to ‘super normal’ profits in the carrier branch, which then leads to an expectation of high profits, resulting in many startups of firms with high R&D expenditure and investment.
- Output is function of market size and relative prices
- R&D and investment are a function of expected profits

In the longer term, the structure of economic activity changes. There are new products, new organisations and new institutions. There is a lagged process of diffusion of the new technology in the following order:

1. industry producing core input
2. carrier branch (new sector)
3. other industries

Thus there is a lagged diffusion process across sectors and countries, including international spillovers, Foreign Direct Investment, international trade. The initial version of the theory does not consider these diffusion processes, this will be incorporated in the next stage of development.

**4.1 Theory**

The theory will form part of a dynamic macroeconomic model and must therefore link up with the IO structure of the model. The general macroeconomic model will also provide information in the form of output quantities and prices for this theory, where not explicitly modeled here.

For simplicity of exposition, the economy will be divided into only two sectors, a new sector, dependent on a new general purpose technology and a notional sector, representing the rest of sectoral activity in the economy. This ignores the idea that the new technology gives rise to a cluster of associated industries, which form the fast growing part of the economy. The usual macroeconomic identity for a time period t (and dropping the t subscript) can be written in matrix notation as:

$$Y_t = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}_t \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}_t = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}_t + \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}_t ( + G + X - M) \qquad (1)$$

where

$Y_t$ = output
$a_{xx}$ = IO coefficient
$q_x$ = total output in sector x
$d_x$ = final demand for the products of sector x
$I_x$ = investment in sector x
and G (government spending), X (imports) and M (imports) will be suppressed for this description.

There are two sectors, 1 is the current economy, 2 is a new sector that will arise following a fundamental scientific/engineering advance. Sector 2 represents some new ‘General purpose technology’, following Perez’ terminology.

At $t = 0$, $q_2 << q_1$

Freeman and Soete (1997) describe the process by which R&D expenditure is chosen as a complex process of engineers' beliefs about their new ideas, an expressed desire for new products from customers and a social/organizational as well as economic process of decision making within a firm. In particular, there is no strong correlation between what might be described as 'rational economic expectations' of potential markets or prices. So, R&D expenditure ($R\&D_{2t}$) will not be explained in detail. It could be modeled as a stochastic fraction of output, or taken as a deterministic proportion of output, calibrated on data for e.g. the computer hardware industry in the 1950s and '60s.

R&D expenditure generates a probability of a major breakthrough, with a step reduction in the costs of production. Following the work of IIASA in particular (e.g. Grübler et al., 1999) there is, after this breakthrough, a dynamic cost reduction function of production, dependent on cumulative R&D expenditure and cumulative investment.

Thus the cost function has two parts, a continuing decrease:

$$c_{2t} = \alpha 1 \varepsilon \exp[-\alpha 2 \Sigma_0^{t-1} (R\&D_2 + I_2)] \qquad (2)$$

with constant $\alpha 1$ calibrated on historical data as the initial price level in the sector before a technological breakthrough.

and a probability of a step decrease, dependent on both cumulative R&D expenditure and current R&D expenditure:

$$\varepsilon = \{1, \delta<1\}; P[\delta|R\&D_{2t}, \Sigma_0^{t-1} R\&D_2] = \alpha 3\, R\&D_{2t} + \alpha 4 \Sigma_0^{t-1} R\&D_2 \qquad (3)$$

Investment depends on the depreciation rate $\nu$ of the current capital stock, interest rate r, expected profitability ( (p-q)*c) and Keynes' 'animal spirits' i.e. an exogenous factor.

$$I_{2t} = \alpha 5[\nu K_2 + p_{2t}q_{2t} - c_{2t}q_{2t} ]/1+r \qquad (4)$$

The macroeconomic model will provide a time path of overall economic activity Y and historical information for $q_1$. Note, however, that the macroeconomic identity includes investment as a component of total demand. Thus this theory by determining $I_{2t}$ partly determines output. Historically, when a new general purpose technology reaches phase 3 (turbulent growth) and then 4 (continued high growth) c.f. section 3, $I_2$ and $d_2$ become the main drivers of growth in the economy. $q_2$ can be found from the IO relationship and is therefore dependent on the IO coefficients $a_{12t}$ $a_{22t}$ . The paths of these coefficients over time will be defined, dependent on relative prices. This is a departure from most IO models, which assume constant IO coefficients or rely on historical data to track the movements of these coefficients over time.

By construction, the IO coefficients sum to 1 for each sector:

$$a_{11t} + a_{21t} = 1; \qquad a_{12t} + a_{22t} = 1 \qquad (5)$$

assuming that the new sector will determine the changes in these relationships, it is then necessary to define the time paths of $a_{21t}$ and $a_{22t}$.

Given that sector 2 subsumes all the new industries in the cluster for the new general purpose technology, $a_{22t}$, the proportion of production of the new sector for its own inputs can be assumed to be high and constant. The increase in $q_2$ will then come from the assumed rate of growth of Y and the change over time of $a_{21}$. This growth rate must be consistent with both the very high rate of investment in the new sector and the rapid growth of final demand for the new sector's products.

This initial version of the theory will concentrate on supply side issues. A future development could be the modelling of the changing pattern of final demand. Note, however, that while final demand does respond to relative prices, the pattern of consumption is also dependent on many other variables. This will be an output of the general macroeconomic model, but the change in consumer tastes and associated lifestyles which embed the new technology in a new pattern off consumption cannot be modelled by economic factors alone. Therefore, writing a purely economic model of the change in consumption due to say the introduction of cheap PCs or in the previous Kondratiev wave of cheap motor cars would be misleading. Therefore, the most productive approach would probably be to use data on consumption patterns from previous waves.

$a_{12t}$, is assumed to be dependent on relative prices, as an increasing logistic function, and is a measure of the diffusion of the new technology into the rest of the economy in this formulation of the model. There are a series of diffusion processes that take place if more sectoral detail is included, both between the new sectors that spring up around the new technology and into the 'old' sectors (with a time lag) as they adopt the new technology in their production processes.

$$p_2/p_{average} = p_2/[(p_{2t}q_{2t} + p_{1t}q_{1t})/(q_{1t} + q_{2t})] \quad (6)$$

$$\Delta a_{12t} = \exists(a_{12max} - a_{12t})\, p_2/p_{average} \quad (7)$$

The (exogenous) changes in Y allow the changes in IO coefficients to generate a dynamic expansion of the market.

$p_{1t}$ can be taken either from historical data or as an output of the macroeconomic model. While $p_{2t}$ could be taken from the model, there will be little basis in historical data for this price. It is more plausibly found from the patterns of growth presented in section 3 above. So, the cost is found from the above theory and $p_{2t}$ can be calculated as a markup over this cost $c_{2t}$. Before the breakthrough, a 'typical' or historical level of prices can be assumed. When a breakthrough occurs and the cost drops, Freeman and Louçv imply that there is no immediate drop in prices. This presents a (temporary) opportunity to make an exceptional level of profits. This encourages many new entrants, leading to the 3rd phase of turbulent growth and in the longer run a reduction in the level of profits as the technology spreads through more firms. Thus there is a slow and lagged decline in the markup.

The markup $m_{2t} = p_{2t} - c_{2t}$ can be modelled as a declining ( logistic) function in output in terms of the current model.

$$m_{2t}/m_{2min} = 1- 1/\{1+\exp(-(1 -(2q_{2t})\} \quad (8)$$

## 5. CONCLUSIONS

This theory formalises assumptions and processes required to generate Kondratiev waves, or long term structural changes to the world economy in a world of continuing technological revolutions. This has been undertaken because the modelling of climate change and the associated policy issues has to consider timescales of 50-100 years at least. Current general macroeconomic models do not take into account these long term structural changes.

These changes – technological, organisational and eventually cultural - have a fundamental impact on anthropogenic GHG emissions. The new technologies have very different emissions characteristics, and cause the combinations of production processes and hence the balance of emissions from different economic sectors to change. In order to guide socio-economic activity, in particular policy to encourage environmentally beneficial technological development, it is necessary to model these dynamic processes of technological and economic change. The next step will be to incorporate this theoretical approach into a macroeconomic model of world emissions, disaggregated into the major world economies and sectors. This will also enable the processes of international diffusion of technology to be considered.


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