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Long Run Technical Change in an Energy-Environment-Economy (E3) Model for an IA System: A Model of Kondratiev Waves

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ABSTRACT

A world macroeconomic model E3MG is being developed to investigate policies for climate change and sustainable development, as a module of a new IAM structure. As climate change is a long term phenomenon, a model of long term economic changes is required. There is no suitable and generally accepted theory of long term technical change, but Freeman and Louçã [1] have developed a good descriptive theory. This paper interprets this theory in quantitative terms, in the context of the macroeconomic analysis. It will outline a model of the changes in economic structure via Input-Output coefficients and the growth of new technology industries, incorporating endogenous technical change from R&D and investment, with learning-by-doing.

Keywords: macroeconomics, endogenous technical change, Kondratiev waves.

1. INTRODUCTION

As part of the research programme on Integrated Assessment at the Tyndall Centre, a world macroeconomic model (E3MG environment-energy-economy global) is being developed to investigate policies for climate change and sustainable development, as a module of an Integrated Assessment Modelling system or IAM. This system will provide a flexible platform to combine or 'couple' different models to undertake Integrated Assessment of climate change policy. To couple economic models with meterological and atmospheric chemistry models of climate change, a timescale of 100 years is necessary, because changes in CO_2 concentrations, which change the climate through the Greenhouse Gas effect, exert this influence 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, following Freeman and Louçã [1], is that over such a long time, the approach of the usual macroeconomic models is inappropriate. These 'neo-classical' models (so-called because they use ideas of equilibrium from 19th century economists such as Marshall and Walras) incorporate the idea of equilibrium in perfectly competitive markets for the world economy. It is necessary instead to consider the dynamic processes of socio-economic development. The economic processes of long term growth and structural economic change have been called 'Kondratiev waves.' Not only do these Kondratiev waves characterise long term economic development, but they embody changes in economic structures that have major impacts on the forms of energy use and hence climate change. The internal combustion engine and the diffusion of motor cars is an obvious example.

Thus, in order to build an appropriate module for an Integrated Assessment of climate change, we consider that an economic model should have the following characteristics:

- It should model the relevant anthropogenic emissions, of which the most important is CO_2.
- A world model is necessary, since CO_2 and the other Greenhouse Gases (GHGs) are a global phenomenon.
- It should provide simulations out to 2100, to allow the analysis of policy impacts over the timescales in which changes in CO_2 and the climate are significant.
- The model should be dynamic, not necessarily converging to an equilibrium. Changes in economic structure and consequent changes in patterns of greenhouse gas emissions must be modelled.
- Differentiated geographical regions and industrial sectors should be part of the model structure. Although highly aggregated, this model must be able to distinguish between the world regions with different time paths of development and of emissions and pollution. The same argument holds for different industrial sectors, since e.g., the transport sector has very different characteristics to

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e.g., food. Also, the study of long term socio-economic change requires a specific model of research and development (R&D) and investment, which is also very different in different industrial sectors. An Input-Output (IO) structure accounting for sectoral activity is a convenient way to consider the interrelationships between the different sectors.

- The model should be checked against historical data as far as possible, with validation using time series data based methodology. Over the long term, there is inadequate detailed data against which to parameterise the model. Econometric methods can be used to a certain extent, to ensure that the model recreates recent data, but for the longer term elements, a statistically based analysis will not be feasible, however, the results can be checked against historical patterns of prices and production.

There is a considerable literature on modelling technical change in economic models used for climate change policy analysis. A recent review is that of Grubb et al. [2]. Most economic models have assumed constantly improving technologies, where the improvement is exogenous to the model. New work is now beginning to incorporate dynamic increasing returns to scale in these models: as investment in a new technology takes place, production costs decrease as processes are improved and new engineering innovations are made, as described in [3]. However, these new models in the climate change literature address energy technologies only. As argued above, it is also necessary to consider the changes in the general economic structure in the long term. As far as we are aware, the current work is the first attempt to address this issue in the context of the economic modelling for climate change policy.

This paper suggests a quantitative theory of long term technical change, that can reproduce the features of a notional Kondratiev wave. It will be part of a global macroeconometric model. Dewick et al. [4] describe the process of assessing the future technologies to which this theory will be applied, in the context of the new global model. 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 the IAM system being developed by the Tyndall Centre in cooperation with other IA centres and describe the planned development of the current outline model for incorporation into a full macroeconomic model.

2. A THEORY OF INDUSTRIAL REVOLUTIONS

These considerations lead us to the conclusion that there is a requirement for a detailed analysis of the macroeconomics of long term changes.

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 [5, 6] (Silverberg, Richard Day, Dosi) and economic historians (Paul David, Chris Freeman, Carlota Perez).

Freeman and Louçã [1] includes 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 economic theoretical ideas 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 developed for dynamic processes in biology. E.g., Arthur [6] 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.’

The problem with the models in this field is that they are theoretical and conceptual, rather than dependent upon empirical analysis. They are not based on the standard or ‘mainstream’ assumptions of economic rationality (that economies consist of agents self-interested calculators who maximise a payoff or utility function) or a Walrasian economic structure (in which the whole economy consists of perfectly competitive markets with one single equilibrium point at which supply equals demand in all markets). While this departure from the heavily idealised mainstream assumptions is both necessary and desirable, there is no consensus about what a reasonable theoretical structure might be.

Also, this field has concentrated on industrial structure, studying competition between firms, often with different technologies. This is vital for an understanding of the processes of change, but there has been very little work in this tradition on macroeconomic models. Robert Boyer is one of the few macroeconomic modellers in this area; Boyer [7] analysed the interactions between new institutions and the macroeconomy.

Empirical analysis in the normal sense (for economists) of econometrics has some serious limitations for this analysis. Indeed, the econometric approach initiated by Kondratiev is specifically rejected by Freeman and Louçã. Econometric models depend on looking backwards to develop the model and then can only extrapolate from past trends into the future. The data for long term economic change is necessarily sketchy and econometric methods are therefore ill suited to such broad analyses, particularly when a view of the long term future is needed and fundamental changes in the socio-economic system are postulated.

To summarise, there is no suitable and generally accepted theory of long term technical change for incorporation in a macroeconomic modelling structure. However, there is now a good descriptive theory, Freeman and Louçã [1], which is intended to provide an economic history perspective of long term change. 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 through 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 LOUÇÃ

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.

The features of these waves are summarised in Table 1, taken from Freeman and Louçã [1] table, p. 141. Following Perez [8], they characterise Kondratiev waves as a succession of new technology systems ([1], pp. 147–8).

1. For each long wave, there are one or more scientific and technical discoveries that make a ‘core input’ e.g., iron for the railway wave, very cheap and universally available. The process by which these discoveries are made is partly dependent on firms’ R&D expenditure, but also on cultural and even personality factors [9]. 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.

Table 1. Condensed summary of Kondratiev waves source: Freeman and Louçã [1], p. 141.

Wave	Decisive innovations	Carrier branches	Core input(s)	Infrastructure	Management; organisation	Upswing (boom) Downswing (crisis of adjustment)
1. Water powered mechanisation of industry	Arkwright’s mill 1771	Cotton spinning, Iron	Iron, Cotton, Coal	Canals Turnpike roads Sailing ships	Factory systems Entrepreneurs Partnerships	1780s–1815 1815–1848
2. Steam powered mechanisation of industry and transport	Liverpool and Manchester railway 1830	Railways, Steam engines, Machine tools, Alkali industry	Iron, Coal	Railways Telegraph Steamships	Joint stock companies Sub-contracting to craft workers	1848–1873 1873–1895
3. Electrification of industry, transport and the home	Bessemer steel process 1875 Edison’s electric power plant 1882	Electrical equipment Heavy engineering Chemicals Steel products	Steel, Copper, Metal alloys	Steel railways Steel ships Telephone	Specialised, professional management systems ‘Taylorism’ giant firms	1895–1918 1918–1940
4. Motorisation	Ford’s assembly line 1914 Burton process for cracking oil 1913	Cars Aircraft Internal combustion engines Oil refining	Oil, Gas Synthetic materials	Radio Motorways Airports Airlines	Mass production and consumption ‘Fordism’ Hierarchies	1941–1973 1973–?
5. Computerisation of the economy	IBM computers 1960s Intel processor 1972	Computers Software Telecommunications equipment	Silicon ‘Chips’ (integrated circuits)	Internet	Networks: internal, local, global	Approx. 1980–?

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 Louçã 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 outstanding 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 (with unemployment and social unrest).
6. Maturity, leading to a (smaller) continuing role of the technology in the economy or slow disappearance.

As can be seen from Table 1 and illustrated in Figure 1, phases 2–5 have been found to 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.

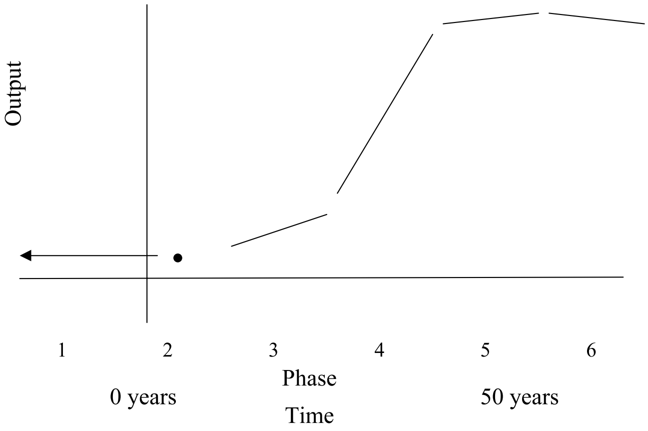

Fig. 1. Phases in the life cycle of a technology system.

This view of Kondratiev waves leads Freeman and Louçã 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 QUANTITATIVE 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 sectoral activity, as can be seen in Table 1. 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 [4]. They assess three pervasive technologies – biotechnology, information technology and nano-technology and outline an assessment of the impact of these technologies on energy use and hence CO_2 emissions. Also, scenarios have been written to identify the impact of these technologies on the world economy and emissions [10]. These scenarios are based on the IPCC SRES scenarios, but give more detail on the directions of technological change for each scenario. 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 of a Kondratiev wave over time in the 6 phases, as described in Section 3 above.
- Following a presentation of Patrick Criqui [11] 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).
- It should 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. [3].

The theory will incorporate some novel features compared to previous models of economic growth, which are discussed below. These features should enable the model to generate patterns of growth for a sector in which the new technology is discovered roughly according to Figure 1. The fundamental assumption is that for some sector of industry or economic productive activity, there is a scientific or engineering breakthrough. More recent waves have involved a long period of scientific research, leading to some fundamental discovery, which then takes some time before a new device or method has a significant impact on economic activity. The new technology is taken up by a ‘Carrier branch’ of industry, to use Perez’ terminology. The model outlined in this paper is therefore intended to model this carrier branch, which experiences a boom in the demand for the new technology. The new technology is embodied in a ‘Core input’ to some industrial sector.

Because of the new breakthrough, the price of this core input drops suddenly and dramatically, to between $1/2$ and $1/10$ of the previous price. This has several effects. Firstly, the drop in the price of the input causes other sectors to start to change their production processes to use much more of the input. This causes a rapid expansion in the demand for the input. This substitution effect is also captured by conventional economic models if a large change in the price of the input relative to other goods is assumed. However, in the present model, which in contrast to conventional models does not assume that firms and prices adjust output and price instantaneously to reflect the new situation, this leads to ‘super normal’ profits in the carrier branch. These high profits for the first few firms to exploit the new technology then lead to an expectation of high profits, resulting in many startups of firms with high R&D expenditure and investment. Thus, R&D and investment in the sector are a function of expected profits. This process can result in a boom, of which the ‘dot com’ bubble is the most recent example.

The overall output of the sector depends upon the potential market size and relative prices. Thus demand from other parts of the economy or sectors and the overall size of the whole economy, together with growth within the sector from the rapid investment in the early part of the wave (phase 3. explosive, turbulent growth), all interact to generate the rapid sectoral growth patterns of a Kondratiev wave as shown in phase 3 of Figure 1. In the longer term, the structure of economic activity changes. There are new products, new organisations and new institutions that exploit and reinforce the new technology [1]. This implies a (lagged or delayed) process of diffusion of the new technology from the industry producing the core input into a carrier branch (new sector) and eventually to other industries. There is also diffusion between countries, in the 19th century as well as in the modern globalized economy. These diffusion processes cause a further and continuing expansion of the original sector; the phase 4 – continued high growth – in Figure 1. Thus the present structure presented here will have to be expanded to include international spillovers (indirect transfers of technology and knowledge), Foreign Direct Investment and international trade. The initial version of the theory does not consider these diffusion processes, but they should be incorporated in later stages of development.

5. THEORETICAL IMPLEMENTATION

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:

$$Y_t = A_t Q_t = [d_1] + [I_1] \quad (+G + X - M) \qquad (1)$$

where

Y_t = output
$A_t = a_{11}a_{12},\ a_{21}a_{22}$ = IO coefficient matrix
$Q_t = q_1,\ q_2$ = vector of total output in sectors 1 and 2
$D_t = d_1,\ d_2$ = vector of final demand for the products of sectors 1 and 2
$I_t = I_1,\ I_2$ = vector investment in sectors 1 and 2
G = government spending
X = exports
M = imports

G, X and M 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.

$$\text{At } t = 0, \quad q_2 \ll q_1$$

Freeman and Soete [9] 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 ($R\&D_2$) 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. [3]) 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:

$$c_{2t} = \alpha 1 \varepsilon \exp\left[-\alpha 2 \sum_{j=0}^{t-1} (R\&D_{2j} + I_{2j})\right] \tag{2}$$

where

$\alpha 1, \alpha 2$ = constants calibrated on historical data as the initial price level in the sector before a technological breakthrough.

$R\&D_{2j}$ = R&D expenditure in sector 2 at time j.

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

$$\varepsilon = \{1, \delta < 1\}; P\left[\varepsilon = \delta | R\&D_{2j=t}, \sum_{j=0}^{t-1} R\&D_{2j}\right]$$
$$= \alpha 3 R\&D_{2j=t} + \alpha 4 \sum_{j=0}^{t-1} R\&D_{2j} \tag{3}$$

where

$$\alpha 3, \alpha 4 = \text{constants}$$

This linear function of the benefits of current and cumulative R&D expenditure might also be modelled to reflect decreasing returns to scale.

Investment depends on the depreciation rate ν of the current capital stock, interest rate r, expected profitability ((price-cost)*output) and Keynes' 'animal spirits' i.e., an exogenous factor.

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

where

$$\alpha 5, \nu = \text{constants}$$

The macroeconomic model will provide a time path of overall economic activity Y and historical information for output q_1. Note, however, that the macroeconomic identity includes investment as a component of total demand. Thus this theory by determining investment 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 demand 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} and 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:

$$a_{11t} + a_{21t} = 1, \qquad a_{12t} + a_{22t} = 1 \tag{5}$$

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 output 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 concentrates 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 of 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. The most productive approach would probably be to use data on consumption patterns from previous waves.

IO coefficient 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.

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

$$\Delta a_{12t} = \alpha 6(a_{12max} - a_{12t})p_2/p_{average} \quad (7)$$

where

$$\alpha 6 = \text{constant}$$

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

Price 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 of production drops, Freeman and Louçã argue 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.

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

6. CONCLUSIONS AND CONNECTION TO THE MACROECONOMIC MODEL IN THE IA SYSTEM

As part of the research programme on Integrated Assessment at the Tyndall Centre, a world macroeconomic model is being developed to investigate policies for climate change and sustainable development, as a module of an Integrated Assessment Modelling system or IAM. To couple economic models with meterological and atmospheric chemistry models of climate change, a timescale of 100 years is necessary. Current general macroeconomic models do not take into account the structural changes over this long term.

The theory outlined here 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. The work is based on the characterisation of Kondratiev waves of Freeman and Louçã [1]. The theory models an industrial sector in which there is a scientific or technological breakthrough, which leads to a dramatic and sudden one off-drop in production costs. This leads to a few market leaders making exceptionally high profits, which then initiates an investment boom. Because of learning effects, as described for energy supply technologies in [3], costs reduce further, feeding back to further investment. This rapid growth in investment leads to a growth in supply and also a growth in demand as new markets are found and new products developed. The sector enters a stage of sustained growth such that it becomes one to the major components of the economy.

Why is this significant for climate change policy assessment? There are two, interrelated reasons. Firstly, as argued in the introduction, a model of the economy for 100 years into the future will generate much more plausible economic results if it takes account of the possible changes in the structure of the economy in this timescale. Secondly, these structural changes may well have dramatic impacts on the pattern of energy use and hence CO_2 emissions.

Finally, how will the abstract theory outlined here be applied to current climate change policy issues and incorporated into an IAM? Firstly, the theory will be built into a dynamic macroeconomic of the world (E3MG). This E3MG model has a production structure based on input-output tables to describe the structure of intermediate demand in the production chain for consumption and export goods in industrial production. The Kondratiev theory will generate changes in the input-output structure in the long term. However, this also requires calibration of the theory to real world data. Furthermore, this Kondratiev theory is technology specific. Each wave is a unique event for each technology, although with the general features common to Kondratiev waves. Therefore, the Tyndall Centre is combining technology analysis as reported in [4] together with scenarios of future technological development, starting from an elaboration of the SRES scenarios [10]. Their analysis of the future directions of technologies, particularly in Information Technology, biotechnology and nano-technology provide a basis for estimating the features of the next possible Kondratiev waves. The potential growth and possible impacts of these technologies on other industrial sectors make feasible an assessment of how industrial production may change in the future, and data on current emissions provides a basis for assessing possible future changes in emissions as a result of the structural changes.

Hence the economic model, incorporating the model of the particular Kondratiev waves identified from the technology analysis, can indicate future potential changes in industrial structure and the consequent changes in GHG emissions. When coupled to models for climate and ecosystem change due to GHG emissions and then to climate impacts models, this provides the basis for a considerably improved modelling of climate change policies.

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