An introduction to REXS a simple system dynamics model of long-run endogenous technological progress, resource consumption and economic growth.

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Abstract
This paper describes the development of a forecasting model called REXS (Resource EXergy Services) capable of accurately simulating the observed economic growth of the US for the 20th century. The REXS model differs from previous energy-economy models such as DICE and NICE (Nordhaus 1991) by replacing the requirement for exogenous assumptions of continuous exponential growth for a simple model representing the dynamics of endogenous technological change, the result of learning from production experience. In this introductory paper we present new formulations of the most important components of most economy-energy models the capital accumulation, resource use (energy) and technology-innovation mechanisms. Robust empirical trends of capital and resource intensity and the technical efficiency of exergy conversion were used to parameterise a very parsimonious model of economic output, resource consumption and capital accumulation. Exogenous technological progress assumptions were replaced by two learning processes: a) cumulative output and b) cumulative energy service production experience. The initial results of simulation for the period 1900-2000 shed light on the historical causes of economic growth and downturn. They also have considerable implications when simulating future output for scenario analysis. Over the past century, the dominant long-term productivity improvements can be associated with efficiency improvements of primary exergy use. Economic downturns were the result of strong and sudden depreciation during the 1930s due to overcapacity and a similar rapid drop in the level of investment end energy consumption in the early 1970s. The REX modules are the focus of ongoing research. We discuss briefly the many possibilities for elaboration of each module that will enrich the feedback dynamics, policy levers and post-scenario analyses.

Introduction

Simulation models are at the heart of many efforts to evaluate the prospects for the future. The relationships between economy and global environment are the focus of most of this research. The simplest and best known to date is DICE (Dynamic Integrated model of Climate and the Economy, (Nordhaus 1991)[1]. The DICE model was the first integrated-assessment model of the economics of climate change, wherein the costs of mitigating climate change today were measured against the future 'benefits' to be derived from economic growth. Results from this model led Nordhaus to claim that global warming might not actually be such a big problem (Nordhaus 1991). In turn, the DICE model has received much criticism (Ayres and Walter 1991; Cline 1992; Fankhauser 1995). Many consider that it underestimates the costs of abatement at \$7.3 per tonne of carbon emitted by assuming constant GHG emissions (Cline 1992) and a simple linear relationship between damage costs, GHG concentrations and warming levels (Fankhauser 1995). However after corrections to include a climate module and damage sector which fed climate changes back into the economy (Nordhaus 1992; Nordhaus 1993; Fankhauser 1995) the results were similar and ranged from \$5.3/tC in 1995 \$10/tC in 2025[2]. Other criticisms concern the choice and sensitivity of the model to the discount rate. Cline (Cline 1992) suggested that 3% may be an underestimate, while (Frankhauser 1995) highlighted the sensitivity of the results to the value of this 'unobservable' parameter.

Perhaps the most useful insights into the assumptions underlying the DICE model have been provided by Tom Fiddaman who is responsible for many modifications resulting in the NICE and more recently the FREE[3] system dynamics models (Fiddaman 1996; Fiddaman 1997; Fiddaman 1998). The core changes he first made were to the capital growth loop, the energy supply and pricing system and the production function. Fiddaman recognised the importance of energy as a component of the system and added feedbacks between energy consumption and capital accumulation. It is now widely accepted that the consumption of energy is as much a cause as a consequence of growth, and to the layman it is apparent that without a source of energy to power the economy there would be no economic activity (Ayres and Warr 2003).

In both the NICE and FREE models a constant elasticity of substitution (CES) production function replaced the standard two factor Cobb-Douglas production function thereby introducing a "composite capital-energy good" as a factor of production (Fiddaman 1996).The energy-intensity of capital is controlled by the relative marginal returns to energy and capital in the short run and autonomous technological progress in the long. Long run cost reductions due to cumulative production experience (learning and scale economies) provide considerable scope for lock-in of fossil fuels vis-à-vis alternatives. Both models include stocks, flows, nonlinearities and disequilibrium feedback mechanisms[4], and require a certain degree of rational bounded decision making to control certain parameters. These modifications have considerably enriched the feedback dynamics that are modelled. The abatement costs simulated using NICE or FREE are typically higher than those predicted by DICE and the range of uncertainty is considerably wider (~\$15-\$135/tC optimal carbon tax in 2105), (Fiddaman 1996).

Nevertheless, the central problem with the DICE and NICE models and many integrated energy-economy models remains the requirement for exogenous assumptions of continuous exponential growth. This is the focus of our interest and the topic of this report. Numerous modelling studies have shown the sensitivity of mid- and long-run climate change

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[1] An updated version of the model RICE-99 (Regional Integrated model of Climate and the Economy) has since been published (Nordhaus 1998).

[2] These figures are current value estimates and denote the social costs valued at the time of emission.

[3] Discussion is limited to the former here. FREE can be downloaded from **http://home.earthlink.net/~tomfid/models/models.html**

[4] For arguments favouring the use of disequilibria models see Ayres, R. U. (2001). "The minimum complexity of endogeneous growth models: the role of physical resource flows." Energy, The International Journal **26**: 817-838.

mitigation cost and benefit projections to assumptions about technology (EMF 1996). In all of the models mentioned above technological change increases outputs without increases in productive inputs, effectively reducing the cost of GHG abatement policies. Whether formulated as multifactor productivity or technological progress the requirement of an exogenous multiplier is troublesome. The difficulty can be restated: if we cannot account for historical growth rates, having observed the technological progress that took place over the past century, how can we expect to parameterize models to account for technological progress? If a considerable fraction of the observed growth can only be accounted for by a fudge factor, then it is very likely that important mechanisms are missing from the model. Existing energy-economy models place emphasis on showing the mere effect of technological change, not on how the technology develops or the specific effects that it may have on productivity. We suggest that as a result many of the most important feedbacks between output and technological progress are ignored or glossed over.

Technological Progress

Attempts to endogenise 'technological progress' or 'multifactor productivity growth' have proliferated since the mid 1980s. Logically, the majority focus on the contribution of the accumulation of knowledge. Unfortunately, while elegant conceptual models are informative, a quantitative measure of knowledge or human capital is unavailable (Ayres and Warr 2003). Theory and practice are two facets of the same coin. To arrive at meaningful conclusions production theory and growth accounting should coincide at an interface defined simultaneously by our fundamental knowledge of the dynamics of economic growth but also the reliability with which we can parameterize and validate the models that represent the underlying concepts.

Alternative attempts to endogenise the 'prime residual' have therefore focussed on improving the accounting methods used via explicit differentiation of factor services**.** In his original application of the Cobb-Douglas production function (Solow 1957) Solow used the number of hours worked as a measure of the factor services provided by labour. However, labour, defined simply as the number of hours worked poorly reflects the diversity of the labour services provided by the workforce. Consider the following extract from a Bureau of Labor Statistics publication,

> "Labour productivity measures have traditionally defined labour input as the sum of all hours worked by employees, proprietors and unpaid workers. As a result, an hour worked by a highly experienced surgeon and an hour worked by a newly hired teenager at a fast food restaurant are treated as equal amounts of labour. It does not matter who was actually working or what kind of job workers held. All workers are treated as if they were identical" (Bureau of Labor Statistics, 1993).

Defining labour simply as the number of hours worked also completely fails to capture improvements in the overall quality of the services provided by the labour force. Yet, the quality of labour has certainly increased over the past 100 years. Therefore, a quality-adjusted measure of labour services will grow faster than its quantity counterpart. By representing changing worker quality in the production function, the magnitude of the residual, the productivity growth attributed to exogenous technological progress, will be smaller and that attributed to labour larger.

The factor service model is based on the observation that explicit differentiation of factor inputs is required a) to account for disparities in the quality between inputs and b) to capture their productivity changes over time. The traditional factors of production are indeed services that are considered proportional to the aggregate measures that describe them. Standard methods to measure factor services and their productivity effects are described in a range of OECD manuals (OECD 2001). Explicit differentiation of factor service contributions to output can be described by three characteristics: quantity, quality and intensity. Commonly used labour quality and intensity adjustments are presented in *Table 1.*

Measure	**Differentiation**	**Input**
Quantity (minimum level)	None	Labour force
Quantity (robust)	Status	Employed
Quantity and quality (robust)	Wages	Employed x hours worked x total labour costs per hour
Quantity, quality and intensity	Industry differentiation	Employed per industry x hours worked per industry x wages per hour by industry

Table 1. Different levels of explicit labour differentiation possible as a function of data availability, and consequently the scale of observation.

A more elaborate model would stratify labour or capital into groupings that reflect these characteristics (e.g. cohorts). Jorgenson and Stiroh (Jorgenson and Stiroh 2000) were able to identify ICT investment productivity effects by adjusting aggregate ICT capital stock estimates to better reflect the capital services they provide. This is an example of a 2-level stratification (ICT and non-ICT capital). A fraction of the formerly 'unexplained' residual was therefore attributed to ICT investments. Yet there is a problem is a similar methodology is used to estimate the services provided by the factor energy (or exergy) using monetary measures of investment (or consumption). Estimates of improvements in capital and labour quality based on their returns to factor payments, for example capital costs or wages, fail to assign an unbiased quality improvement to all three essential factors of production capital, labour and energy, because the full costs of the latter are not accounted for explicitly in the historical national accounts (Ayres and Warr 2002).

The fundamental problem seems to centre on two issues i) how to empirically allocate productivity improvements correctly amongst the factors of production, and ii) how to compare different types of progress on a unique linear scale over time. The problem can be illustrated by an example. Consider the process of harvesting a crop. Photos from the start of the century show clearly the large quantity of human and animal labour that was essential. With the introduction of steam powered belt driven machinery some of this labour was substituted and the productivity of those that remained increased. Today a sole individual is capable of harvesting thousands of hectares single-handedly in a GPS controlled combine harvester, at night. How can the productivity increases be allocated correctly between the improved knowledge skills of the labourer now filling a supervisory role, the machinery that is capable of doing more work per unit time, and the energy source that powers the machinery? It is apparent that without the correct combinations of labour, capital and energy to power and supervise the machinery the system is not productive at all. The productivity gains that have been achieved result from the synergy of efficiency improvements occurring to all three essential factors of production and resulting from various cumulative effects on technological progress.

Experience and technology

Technological progress results from either the incremental improvement of existing technologies as well as through the invention of new technologies. The idea of a technology life-cycle as an ageing process goes back to the economist Julius Wolf (Wold 1912), who noted the tendency of incremental improvements to increase in cost as a technology reaches its long-run

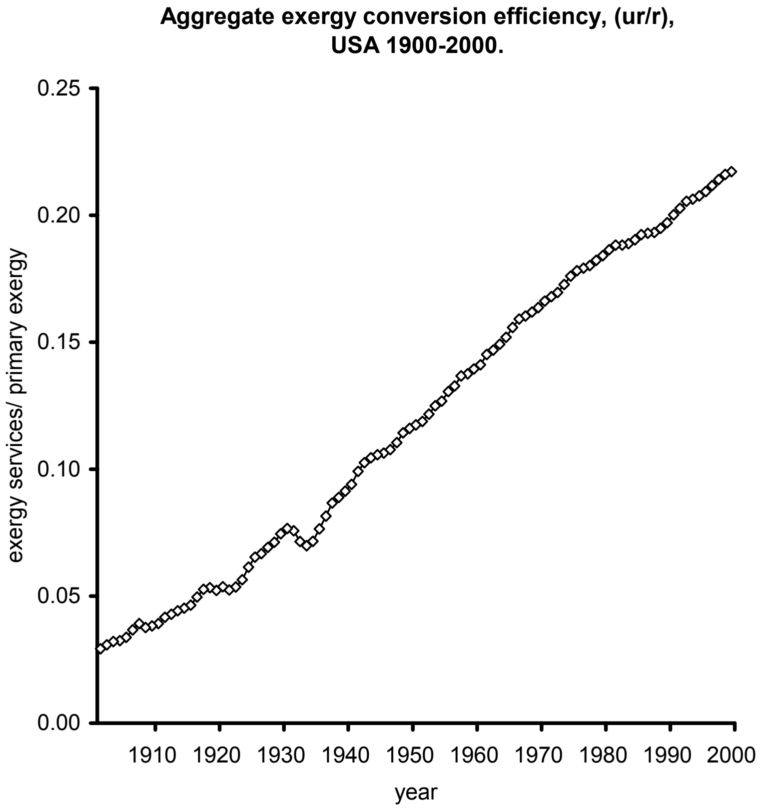


Figure 1. Technical efficiency of natural resource exergy conversion to work

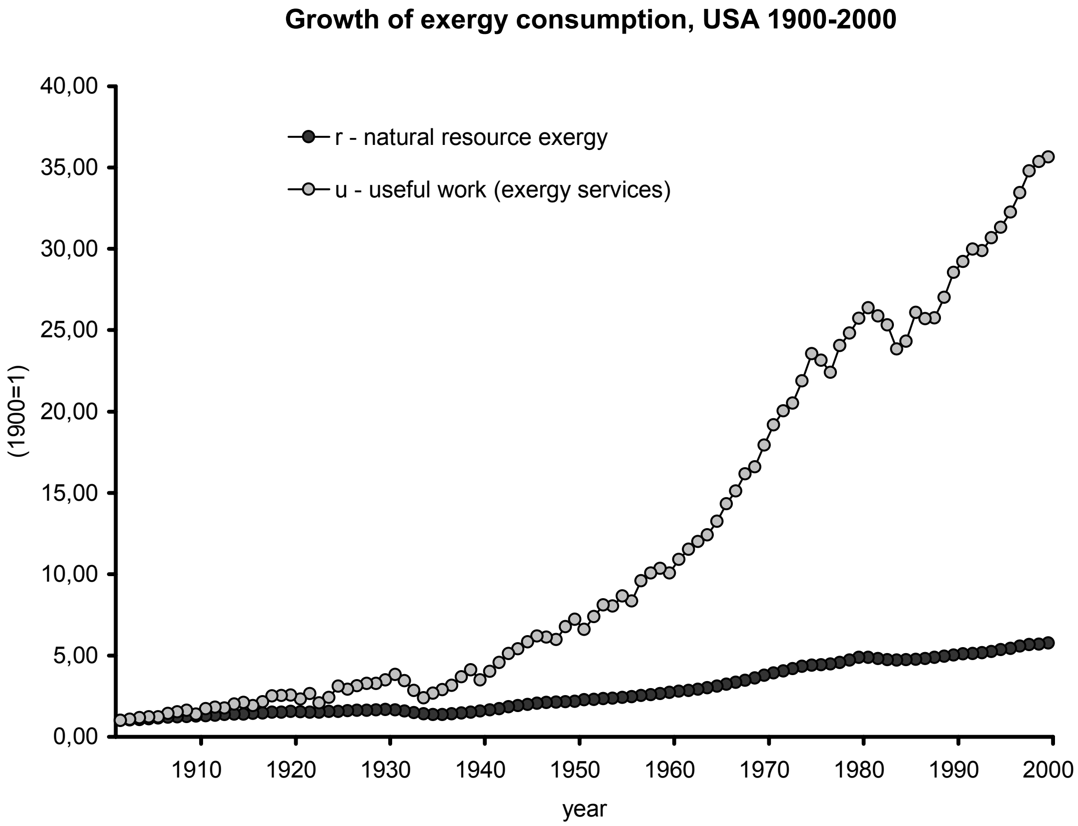


Figure 2. Primary natural resource exergy (*r*) and exergy services (*u*), US 1900 - 2000.

performance level (Ayres and Martinas 1992). Schumpeter (Schumpeter 1942) and other economists in the 1940s – Kuznets, Burns, Hansen, Hoffman - distinguished in business cycles, political institutions, and social processes three stages of technological change: invention, innovation and diffusion. These stages are entirely consistent with the commonly observed behaviour modes of radical fast change through the introduction of new technologies and subsequent incremental progress through experience. Technological change is cumulative; the second stage of Usherian incremental improvements presupposes the first stage of radical Schumpeterian innovations or 'breakthroughs' (Ayres 1994). New technologies, which are often more costly or inferior to existing technologies, improve more or less slowly, through 'learning-by-doing' and 'learning-by-using'.

At about the same time, as Schumpeter presented his ideas, Wright (Wright 1936) introduced and quantified the 'learning' or 'experience curve', from empirical studies of output and labour costs in the aircraft industry. Numerous studies have illustrated a broader range of learning relationships in many industry sectors with cumulative investment and time as alternative causes of learning by doing (Arrow 1962; Rapping 1965; Sheshinski 1967; Stobaugh 1975; Lieberman 1984), as well as applications in other areas (Group 1970). There is overwhelming support for the unit cost / price-experience relationship from many economic, social and political activities. While for predictive purposes it is not essential to define the identify the causal relationship it is widely agreed that the accumulation of production experience typically improves the efficiency of production processes; the implications are that experience and learning do not directly impact price, but that price (unit) costs fall because of efficiency improvements in production processes.

Monetary measures are just one possible surrogate measure of efficiency improvements. We can consider a much wider range of measures suitable to describe 'technological distance', or distinguishability. The evolutionary path of technology is influenced by 'configuration-dependent' limits, reflecting the specific properties of the materials and best represented by a form of 'barriers and breakthroughs' model (Ayres 1988). For accounting purposes, and useful as indicators of the technological state of unit processes or activities, a whole suite of distance measures can be imagined and evaluated relative to specific configuration dependent performance limits (*see Concept Sheet, Technological Distance*). Learning curves describing the evolution of technological distance have been used to examine the effects of cumulative R&D investment (Watanabe, Zhu et al. 2001), adoption and diffusion processes, incremental improvements on price/unit cost and the resultant climatic/economic impacts (IEA 2000). To date no study has tackled the central but missing essential feedback that permits examination of dynamics between output, natural resource consumption and endogenous technological change.

Technical Efficiency and Exergy Services

Human capital lies at the heart of the learning process. It is people who learn through experience and who are therefore the repository of knowledge and source of innovation that drives the efficiency process. Technology can be considered as, "knowledge combined with the appropriate means to transform materials, carriers of energy, or types of information from less to more desirable forms", (Ayres 1994). The most general definition of technological distance is information content in the technical (Shannonian) sense. For thermodynamic systems this information content is exactly proportional to the general thermodynamic potential also referred to as 'useful work' (Ayres and Martinas 1992). The ratio of useful work U, delivered to primary natural resource exergy supplied R, describes the aggregate technical efficiency f, (*see Concept Sheet, Technical Efficiency and Exergy Services*) of natural resource exergy conversion. The technical efficiency ($f = U/R$) is a fraction equal to the thermal efficiency of the conversion process of raw primary exergy (for example oil, gas, coal, metals) into useful work (for example electricity). It is a physically quantifiable index of the combined impacts of hu-

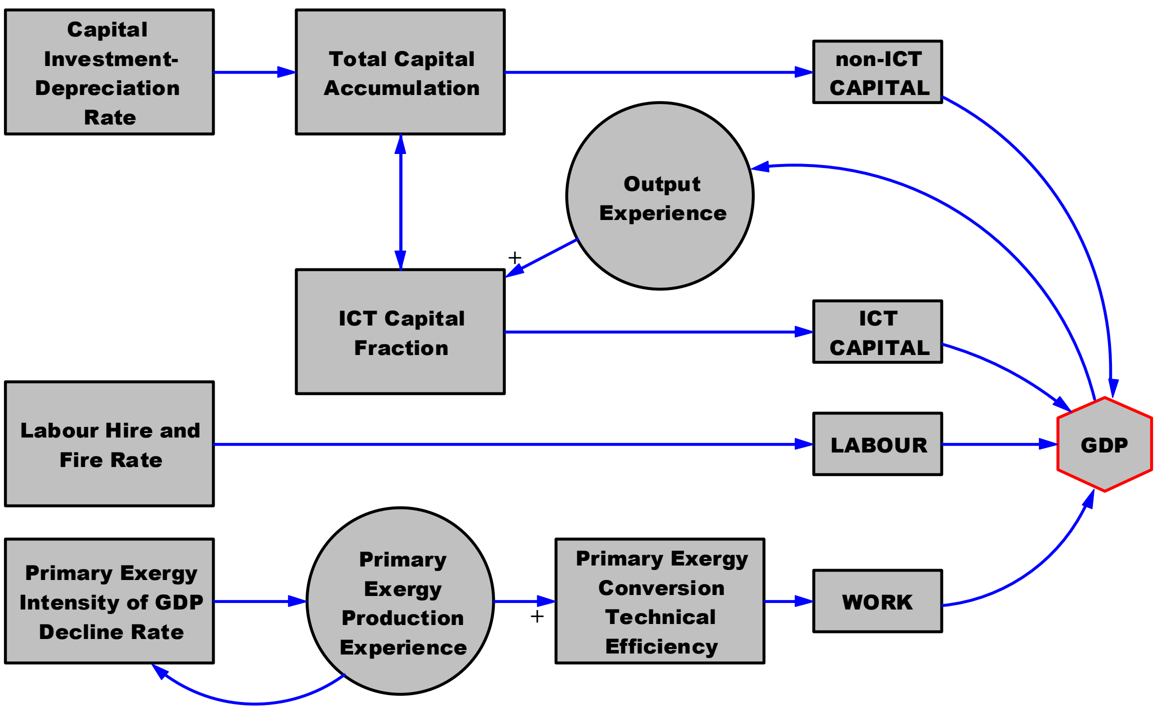


Figure 3. Simplified diagrammatic representation of the structure of the REXS Level 1 model.

man innovations, capital and labour quality improvements on the 'quality' of the flows of useful work.

This bold statement leads us to the introduction of a new concept: exergy services (see *Concept Sheet, Technical Efficiency and Exergy Services*). Exergy services flow from aggregate natural resource exergy in proportion to the technical efficiency of exergy conversion. Exergy services are mostly synonymous with 'useful work'[5] and we shall use the expressions 'work and 'exergy services' interchangeably throughout this paper. The concepts of useful work are discussed in detail and an explanation of how time series of useful work were derived from statistics describing the historical uses of all major fuels, mineral, metals and biomass for the US are provided in (Ayres, Ayres et al. 2003). Figure 1 illustrates the aggregate technical efficiency for the US over the last century. The five-fold improvement in the flows of exergy services provided per unit if raw natural resource exergy (from 0.03% in 1900 to 0.15% by the end of the century) is dramatic and encouraging. The technological progress (represented by the technical efficiency f) that has made this possible have meant that the exergy services that flow through the economy have increased at a much faster rate than the natural resource exergy required to provide them (Figure 2**)**.

Exergy services are an essential factor of production. Without power, the economy would come to a standstill. If we consider the total raw exergy consumed by the economy R or only that fraction coming from commercial fuels E, it is evident that a considerable fraction of the resource exergy is not used productively and actually goes to waste W, ($W = R - U$). It is more probable that wasted exergy actually hinders economic output. Therefore, exergy services are the correct factor input for energy dependent production functions not the total raw exergy consumed. Coincidentally, when exergy services are included in a three-factor production function the need for any exogenous technology multipliers are removed (Ayres and Warr 2003). The conclusions are that the major technological advances that have occurred in the US over the past century are proportional to the increase in technical efficiency of primary exergy conversion and effectively summarised in the exergy service factor. The Resource Exergy Services (REXS) model represents a first attempt to implement the use of exergy services in an energy-economy model and thereby overcome requirement for exogenous assumptions of continuous exponential growth. The rest of this paper is devoted to an overview of the model, followed by a discussion of the results in light of the historical evidence. Finally, in the conclusions we shall suggest briefly how the model may be modified to more accurately represent the causality between resource consumption, technological progress and economic output.

The REXS Level 1 model: An overview

The REXS model stems from research into the role of resource consumption on economic growth (Ayres & Warr, 2002) for the US over the period 1900-2000. The REXS - level 1 module was developed to investigate the role of technological progress and resource consumption as drivers of growth (Ayres and Warr 2002) and the sensitivity of the model to changes in each. It draws on a unique empirical database of historical resource consumption and flows of exergy services (useful work) through the economy (Ayres, Ayres et al. 2003), to provide important reference mode information and for parameter identification. A diagram of the essential structure of the REXS model is shown in Figure 3. The model consists of capital accumulation, population growth, resource consumption and technological change dynamics. The diagram shows that exergy services or work is used as a factor of production (Ayres & Warr 2002). The model combines a minimum of empirically determined constant parameters to control labour, capital accumulation dynamics. The variable rate of decline of output exergy intensity is regulated by a self-referencing feedback. Cumulative output experience and defines the increasing information-communication technology (ICT) fraction of the total capi-

[5] See Concept Sheet, Useful Work – Exergy Services

tal stock. Incremental improvements in the aggregate technical efficiency of primary exergy conversion are driven by the accumulation of primary exergy production experience.

When constructing the model both simplicity and a strong correspondence between model and observed behaviour were considered essential[6], following the precept that it is better to start simply and complicate if necessary. Simplicity or complexity are relative terms and clearly depend upon the type of behaviour and in particular, the scale and resolution of the phenomena being modelled. A simple way to compare the complexity of similar models is to use the measure proposed by Jeffreys (Jeffreys 1939). The complexity C, given by C = O +D +S, where O is the order of the equation, D the degree of the equation and S is the sum of the absolute values of the parameters after setting one coefficient to one. Using this measure a highly non-linear differential equation involving few terms can be less complex than a high order linear differential equation (Zellner 2002).

The REXS model was developed iteratively. Each sub-module was developed independently using exogenous data to identify appropriate parameters. The sub-modules were then combined and the model was tested again in terms of their ability to explain past data. The dynamics of the model were developed around robust and regular reference modes *(see concept sheets, Resource Use Reference Modes)*. The criteria when choosing reference modes included relevance, availability and the interpretability of suitable empirical time series. We shall discuss each of these time series in detail as each module is presented.

A standard optimisation procedure was adopted throughout the model calibration to ensure a degree of quantitative independence in the choice of parameters. When fitting model parameters, empirical data replaced important input parameters not relevant to the calibration in question and parameter values were allowed to vary simultaneously across the full range of plausible values.

The REXS model is composed of four sub-modules: economy, resources, capital and labour. We start by briefly presenting the ‘standard’ components; the capital accumulation and labour supply modules. The dynamics of either were not the focus of this study. Nevertheless present an overview for completeness and because some interesting insights into future modifications were identified. We main body of this report presents the resource consumption sub-module, designed to reflect trends in the resource intensity of output (the environmental Kuznets curve), to simulate exergy service dynamics and endogenise technological progress. We finish by piecing the various components of the model together around the production function and comparing the simulated time series of important reference modes with their empirical counterparts.

Labour Supply

The labour supply module operates like a birth and death process, where births are considered equivalent to hiring and deaths to firing (Figure 4). This is a very simple formulation but adequate to provide simulated time series of the labour supply without the need for exogenous inputs, complex parameterization or strong assumptions that could influence the core components of the model (i.e. the exergy or economy modules), in unexpected ways. The fractional hire and fire rate parameters were constants. To correctly reproduce the empirical time series it was necessary to allow these parameter values to change only once over the entire 100 year period. Optimisation methods were used to identify the years when the constant parameter values should change. The empirical and simulated results are presented in Figure 5 . The overall trend in one of ever increasing rapid labour hire and fire dynamics, interrupted by sudden readjustments. In 1920, the fractional fire rate shifted from 0.10 to 0.12. In 1959, the fractional hire rate increased from 0.124 to 0.135. These independent shifts generate three identifiable periods of relatively constant labour dynamics, from 1900-1920, 1920-1959 and 1959 to the present day. We shall come back to discuss these findings after presenting the

[6] This is not to exclude strong departures from past behaviour during future scenarios.

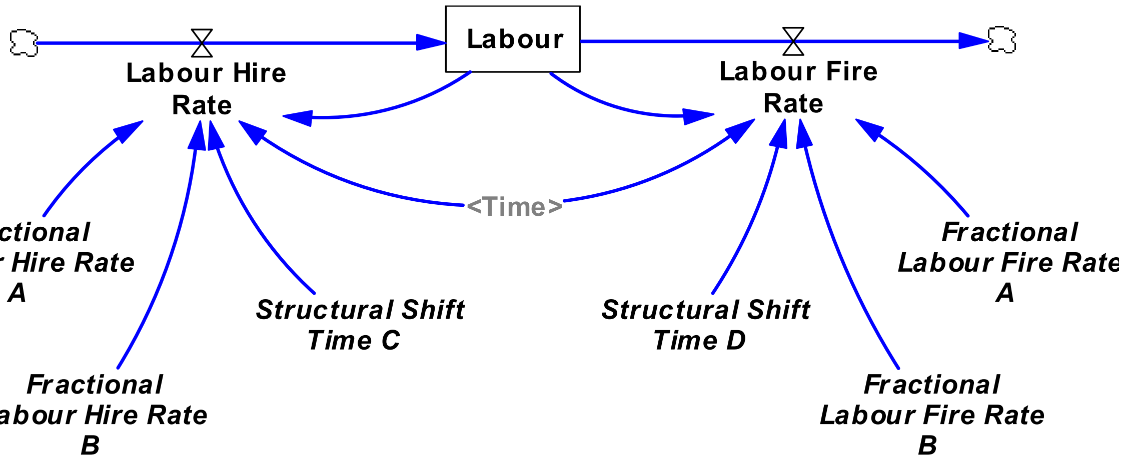
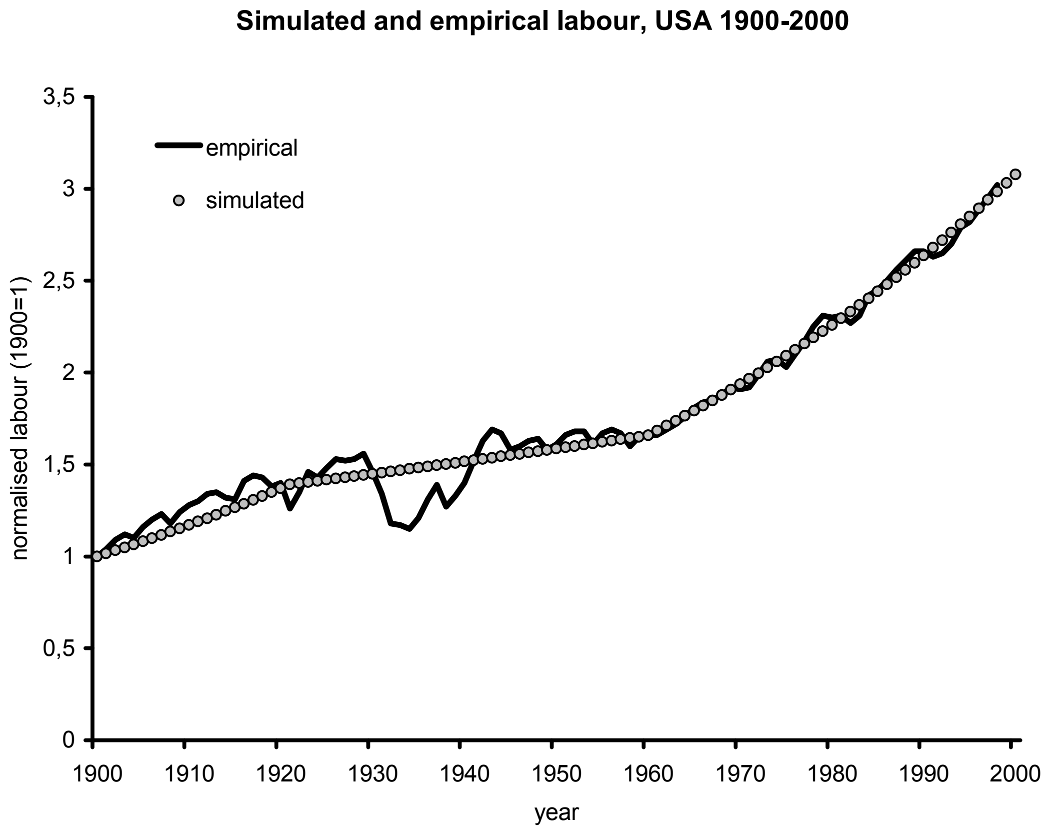


Figure 4. REXS level 1 Labour supply feedback dynamics.

Labour supply equations:

Labour Hire Rate=IF THEN ELSE(Time<=Structural Shift Time C, Fractional Labour Hire Rate A*Labour, Fractional Labour Hire Rate B*Labour)
Labour=INTEG (Labour Hire Rate-Labour Fire Rate,1)
Structural Shift Time C=1959
Structural Shift Time D=1920
Fractional Labour Fire Rate A=0.10886
Fractional Labour Fire Rate B=0.120208
Fractional Labour Hire Rate A=0.124721
Fractional Labour Hire Rate B=0.135787



(a)

(b)

Figure 5. Labour simulation results, US 1900-2000.

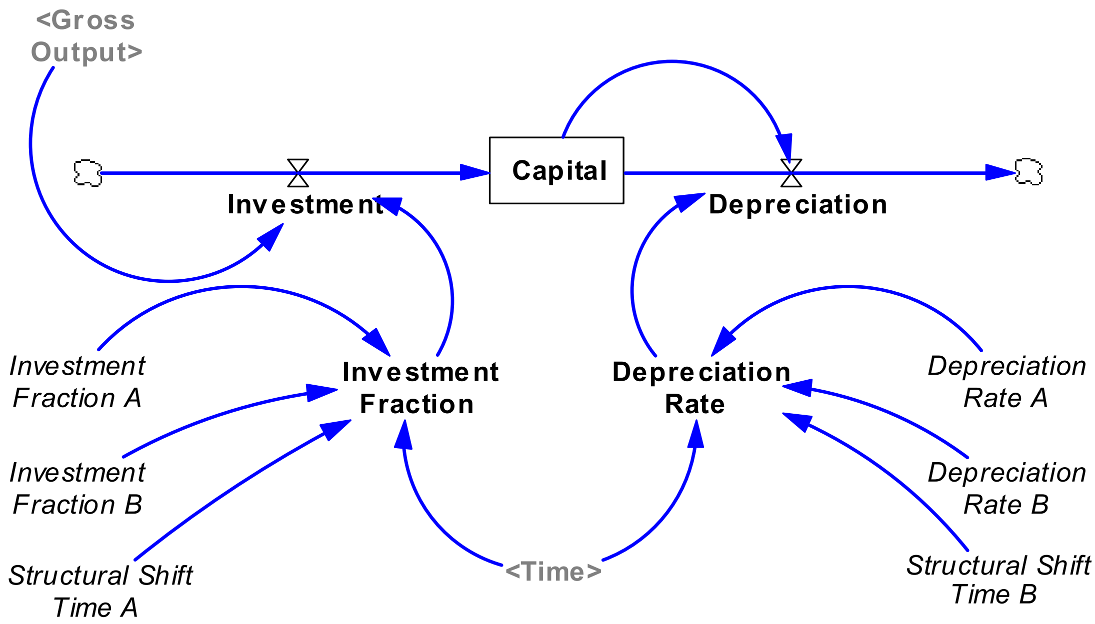
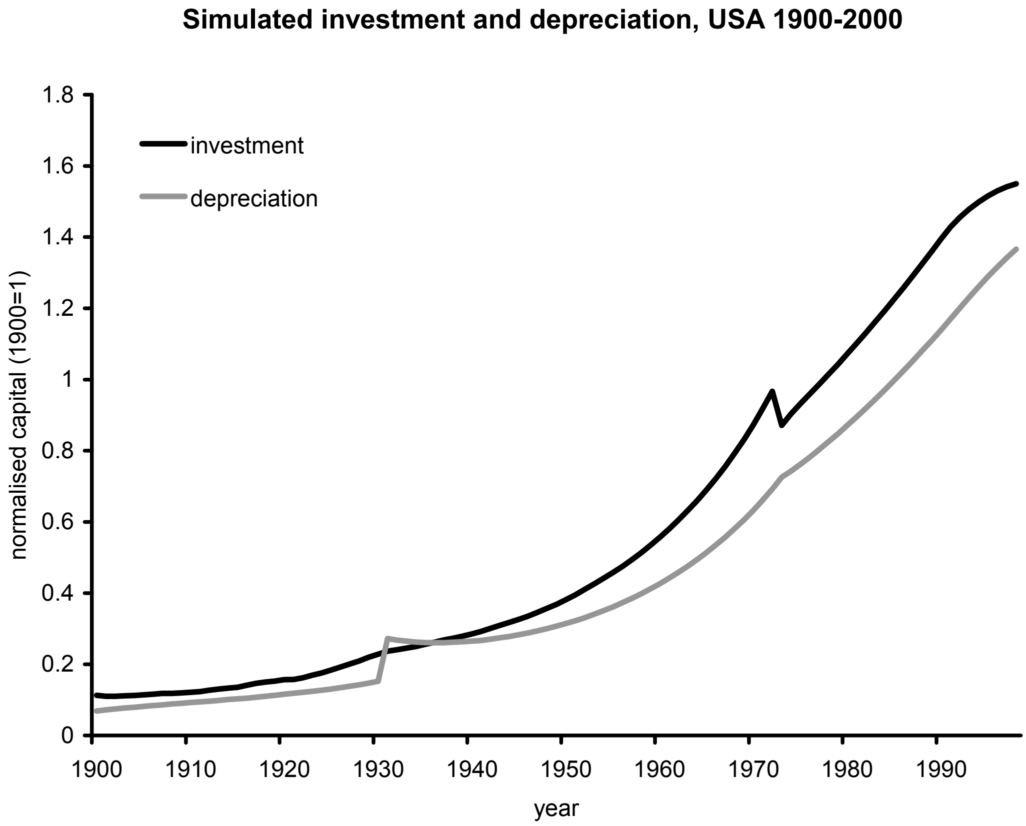


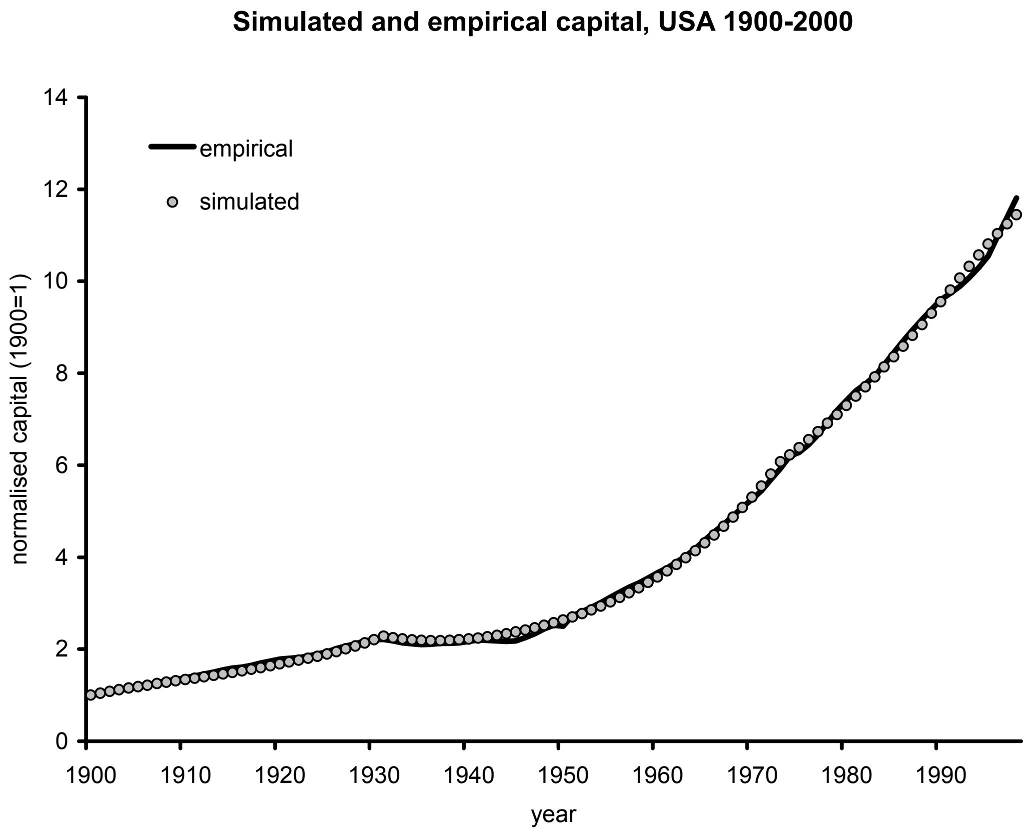
Figure 6. REXS level 1 capital accumulation feedback loop.

<u>Capital accumulation equations:</u>

Capital= INTEG (Investment-Depreciation, 1)
Investment Fraction=IF THEN ELSE(Time<=Structural Shift Time A,Investment Fraction A , Investment Fraction B)
Investment Fraction A=0.0809601 - Determined by optimisation (1900-1928)
Investment Fraction B=0.0741895 - Determined by optimisation (1928-1998)
Depreciation Rate=IF THEN ELSE(Time<=Structural Shift Time B, Depreciation Rate A, Depreciation Rate B)
Depreciation Rate A=0.0590329 - Optimised over period 1900-1950
Depreciation Rate B=0.106435 - Optimised over period 1950-1998
Depreciation=Capital*Depreciation Rate
Structural Shift Time B=1930
Structural Shift Time A=1970



(a)



(b)

Figure 7. Simulated and empirical capital accumulation, US 1900-2000.

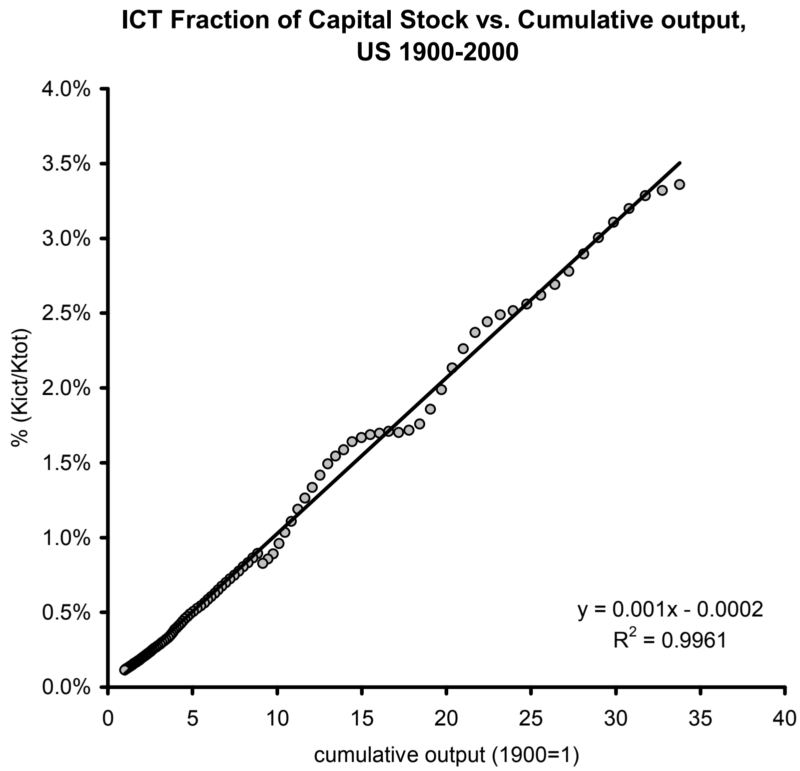


Figure 8. Relationship between cumulative output (GDP) and the ICT fraction of capital stock (K_{ICT}). Capital stock data from (Jorgenson and Stiroh 2000), regressed values for cumulative GDP<10.

other modules.

Capital Accumulation

In the REXS model total fixed capital is stratified into two types, non-ICT and ICT capital. The capital accumulation module bears strong similarities to that for labour supply. Investment in total capital is a fixed percentage of gross output, proportional to the savings rate. The depreciation rate is self-referencing (Figure 6). As was the case in the labour supply module, abrupt changes to the investment fraction and depreciation rate were required to accurately reproduce the empirical time series (Figure 7a**)**. In 1930 the depreciation rate parameter doubled from 0.06 to 0.11. In 1970 the investment fraction fell slightly from 0.081 to 0.074. Both parameter changes are subtle, interpretable and entirely adequate to provide a very accurate estimate of capital for the entire century (Figure 1b**)**. The overall trend is over ever increasing levels of investment and faster rates of depreciation, and is entirely consistent with historical observations. The fraction of total capital that is ICT capital was estimated using a simple but robust relationship, identified from empirical data provided by (Jorgenson and Stiroh 2000). Figure 8 plots (a) cumulative output (GDP) vs. the ICT fraction of capital and (b) the simulated and empirical time series of ICT capital stock. Again the estimates are accurate. The very simple but precise linear relationship served to endogenise this ICT investment, until more elaborate capital investment dynamics are developed and included in subsequent versions of REXS.

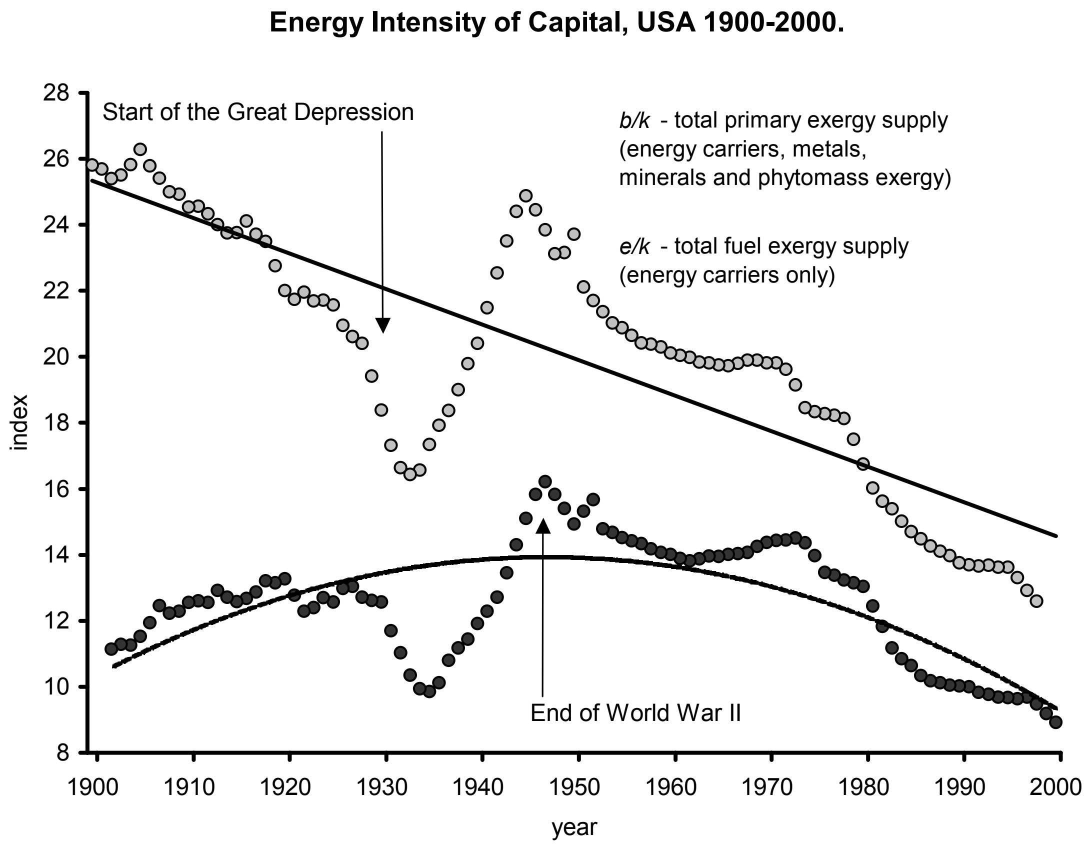
Exergy Flows

Natural resource exergy intensity of output

In the DICE system dynamics model (Fiddaman, 1997), exogenous assumptions of multifactor productivity and estimates of two constant parameters, the capital elasticity of output and capital energy elasticity, determine the rate of change of the energy intensity of capital over time. Therefore, output and subsequently capital investment determine energy consumption. In the REXS model the level of exergy consumption is determined directly by the accumulation of production experience. This served two purposes: firstly, we avoided assumptions of constant capital-energy elasticity for which there is no evidence; secondly we were able to more reliably and simply parameterise the model using this alternative reference mode.

In the DICE model, and others relying on a CES production function, the *E/K* ratio is assumed as a monotonically decreasing function of time. However, empirical evidence suggests that the energy (exergy) intensity of capital is not necessarily the case. Figure 9 shows the exergy intensity of capital for two definitions of exergy (*R/K* and *E/K*) for the US (1900-2000). For commercial fuel definition of exergy, swings in the trends occur over relatively short, but increasingly long time spans (1900-1910, 1935-1950 and 1975-), simultaneously with well-documented structural changes in the way that energy has been supplied and used. Transition periods signal shifts to new levels of capital energy intensity that remain relatively constant over several decades (1910 to 1930 and 1950 to 1975), revealing the historical sensitivity of the commercial exergy intensity of capital to structural changes in an industrialising economy. Only since the early 1970s has the commercial fuel exergy intensity of capital steadily fallen, because of innovative and productive uses of energy in less energy intensive-capital rich service sectors. If all primary exergy is considered (*R/K*) a decreasing trend is more apparent (~0.1%per annum), but only if the entire period is considered. However, the marked breaks of slope in years 1930, 1940 and 1970 are again evidence of the sensitivity of the rate of change of the energy intensity of capital to structural shifts in the economy.

In stark contrast the monotonic decline of the primary resource exergy of output (*r/y,* see Figure 9b) with cumulative output (*GDP*), identified from empirical data for the US, is very stable. In the REXS model, we used this very general relationship between GDP to define the total natural resource exergy requirements. Our definition of total primary resource exergy included commercial and non-commercial fuels, metals, minerals and biomass. Impor-



(a) (b)

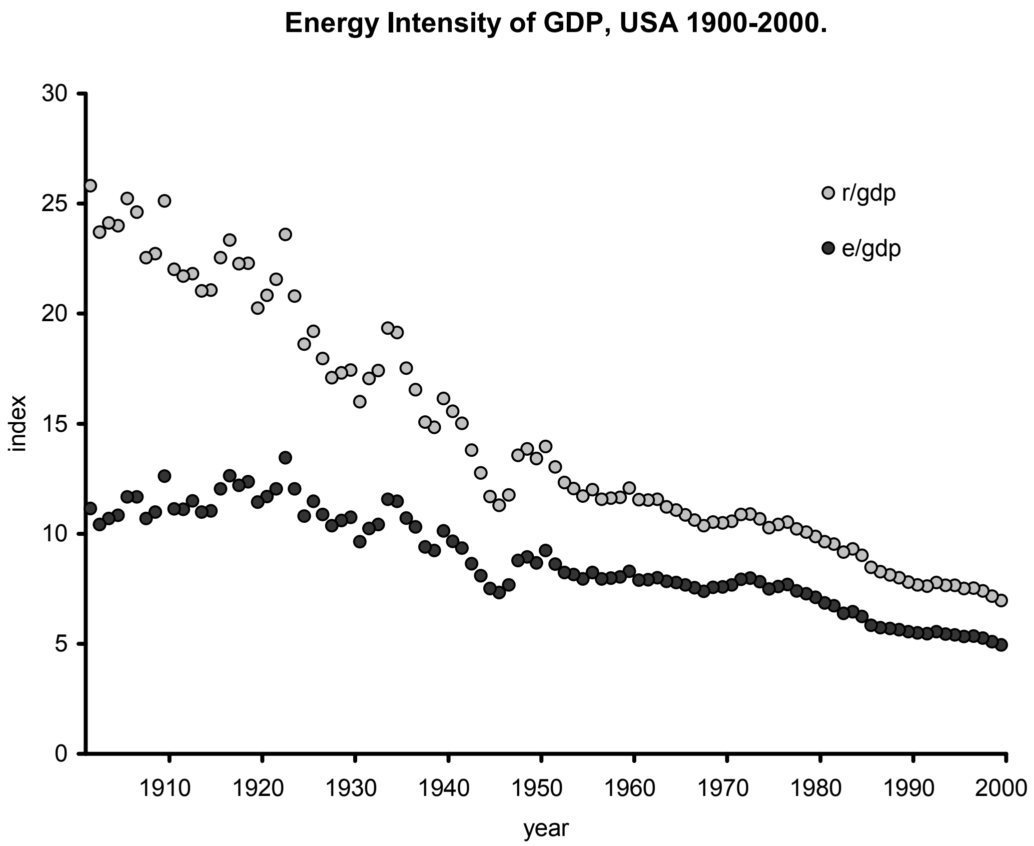


Figure 8. The exergy intensity of (a) capital and (b) output for two definitions of exergy.

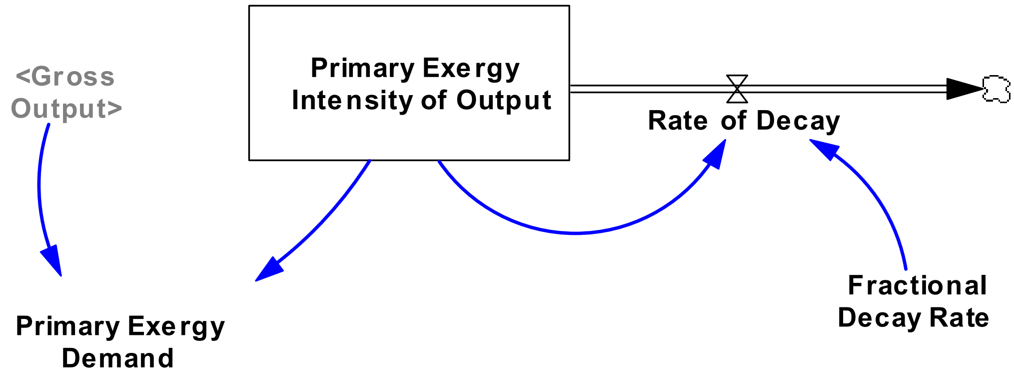
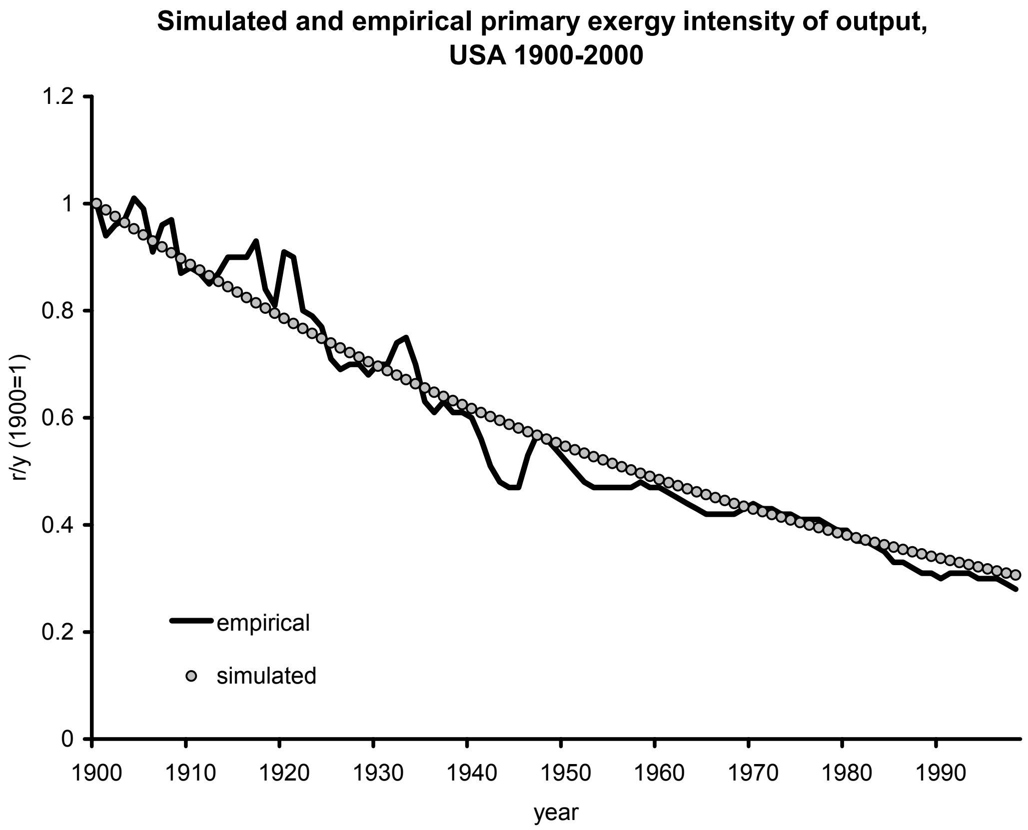


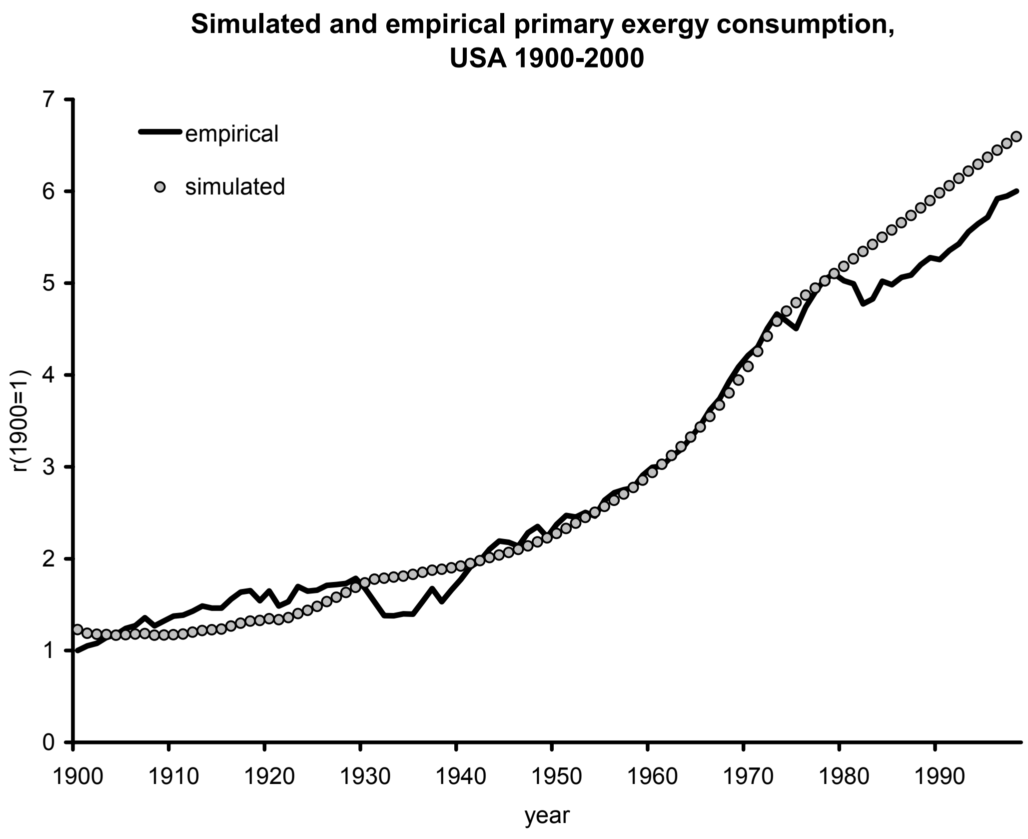
Figure 10. Primary exergy intensity (*R/GDP*) of output decay feedback mechanism.

<u>Primary exergy intensity of output (*R/GDP*) equations:</u>

Primary Exergy Demand=Primary Exergy Intensity of Output*Gross Output
Primary Exergy Intensity of Output= INTEG (-Rate of Decay, Initial Primary Exergy Intensity of Output)
Rate of Decay=Fractional Decay Rate*Primary Exergy Intensity of Output
Fractional Decay Rate=0.012



(a)



(b)

Figure 11. Empirical and simulated primary exergy of intensity, US 1900-2000.

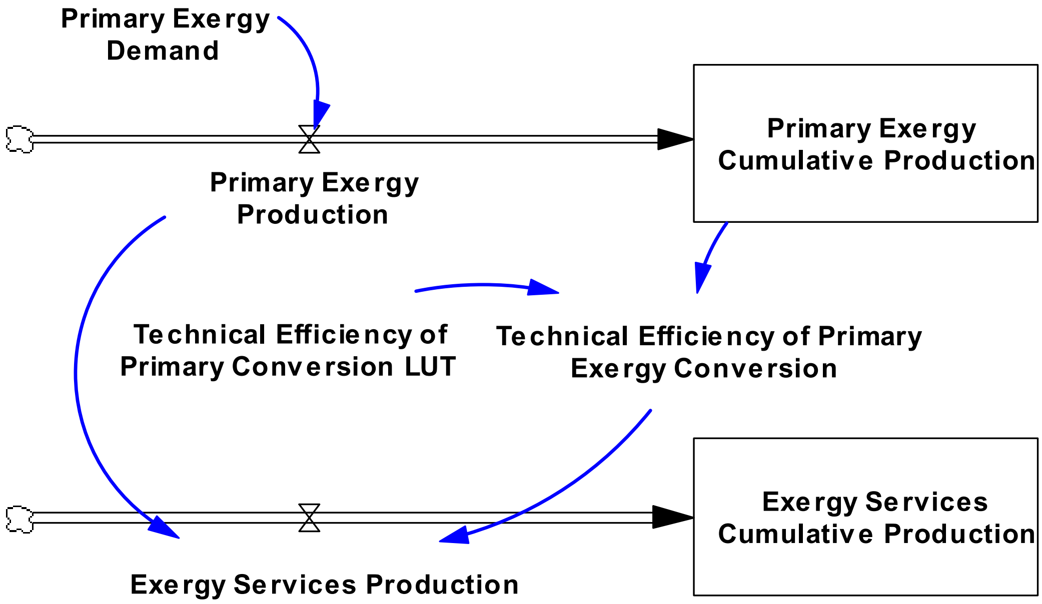


Figure 12. Technical efficiency feedback mechanism (Type I: Experience curve), and exergy services supply dynamics.

<u>Technical efficiency look-up table equations:</u>

Exergy Service Production $\propto$ Primary Exergy Cumulative Production

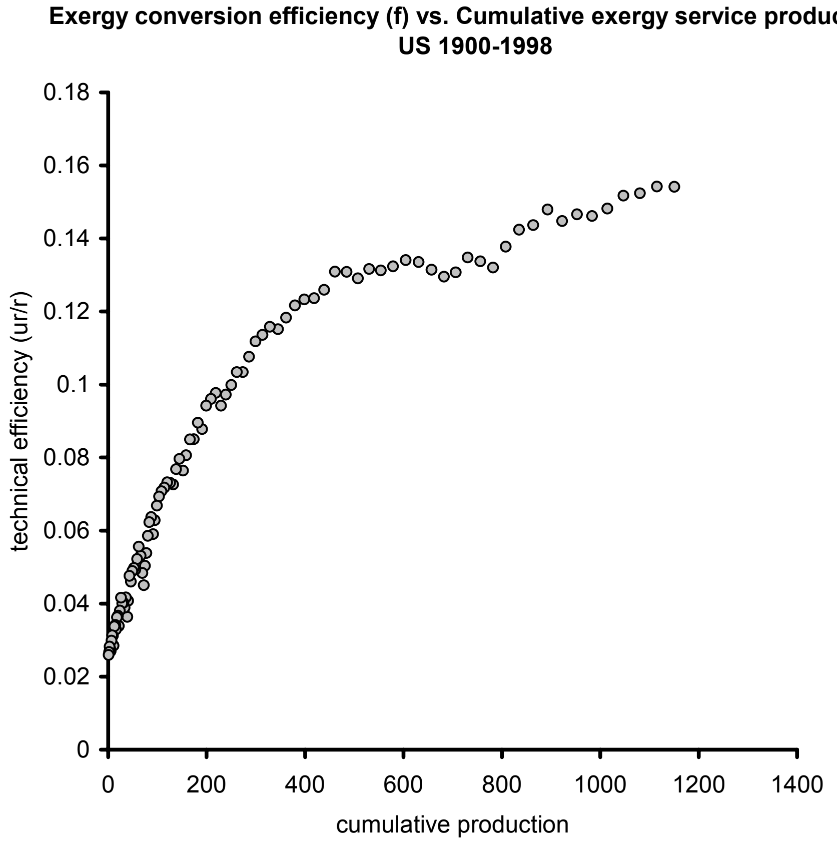


Figure 13. Exergy conversion efficiency look-up table, US 1900-2000.

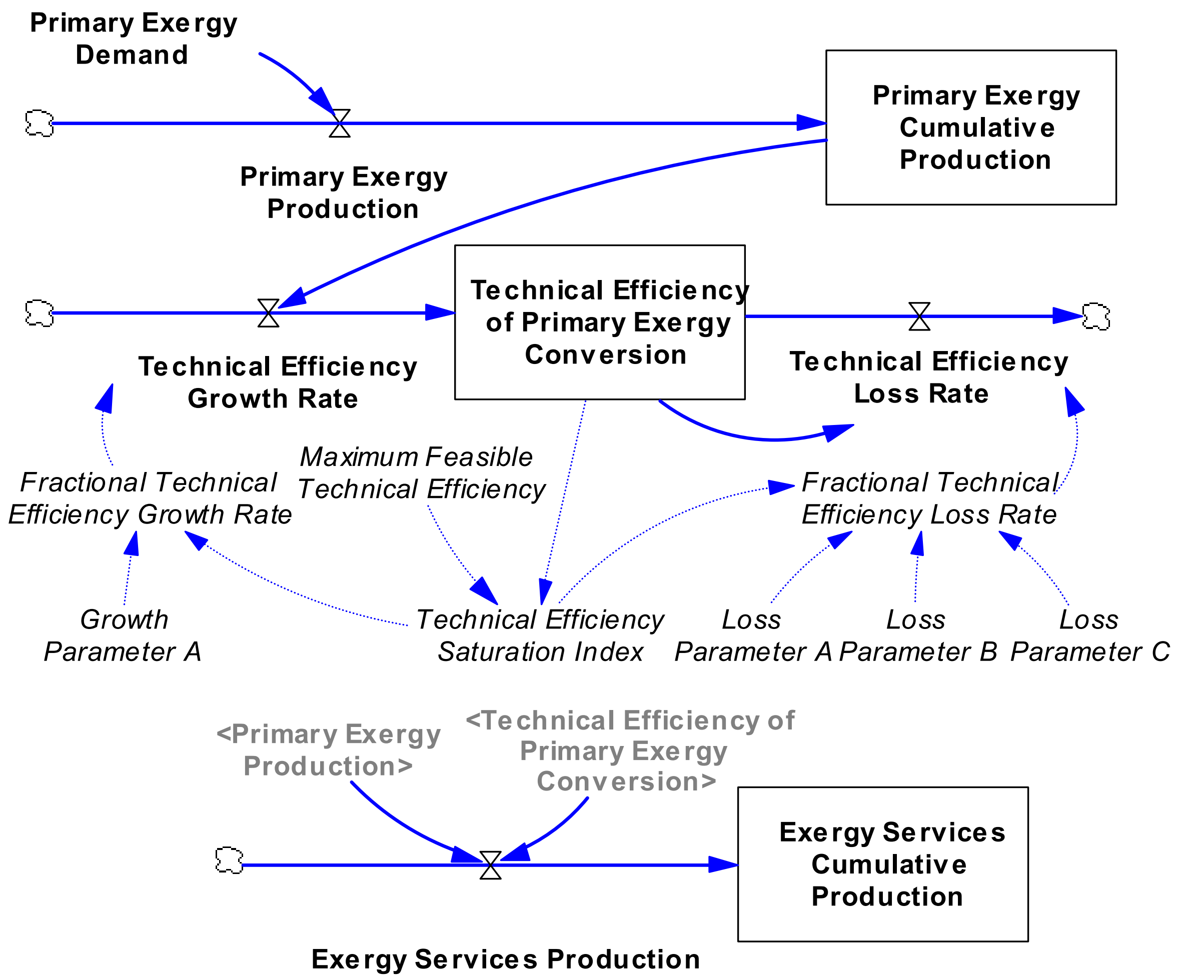
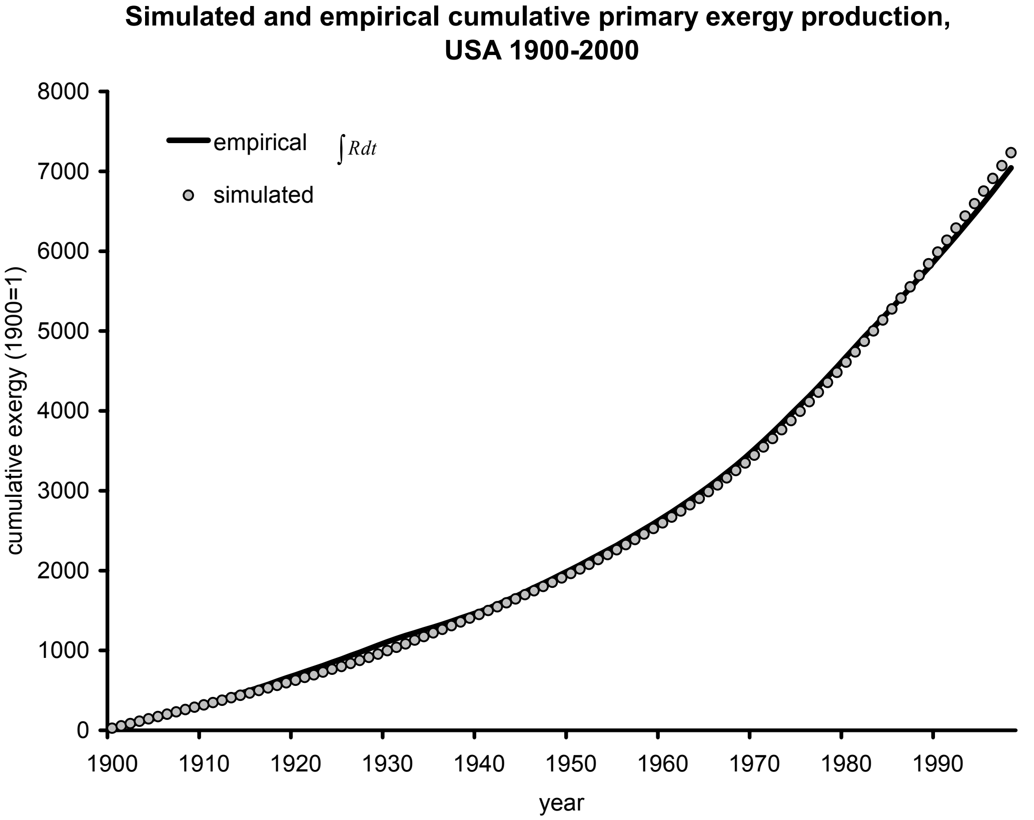


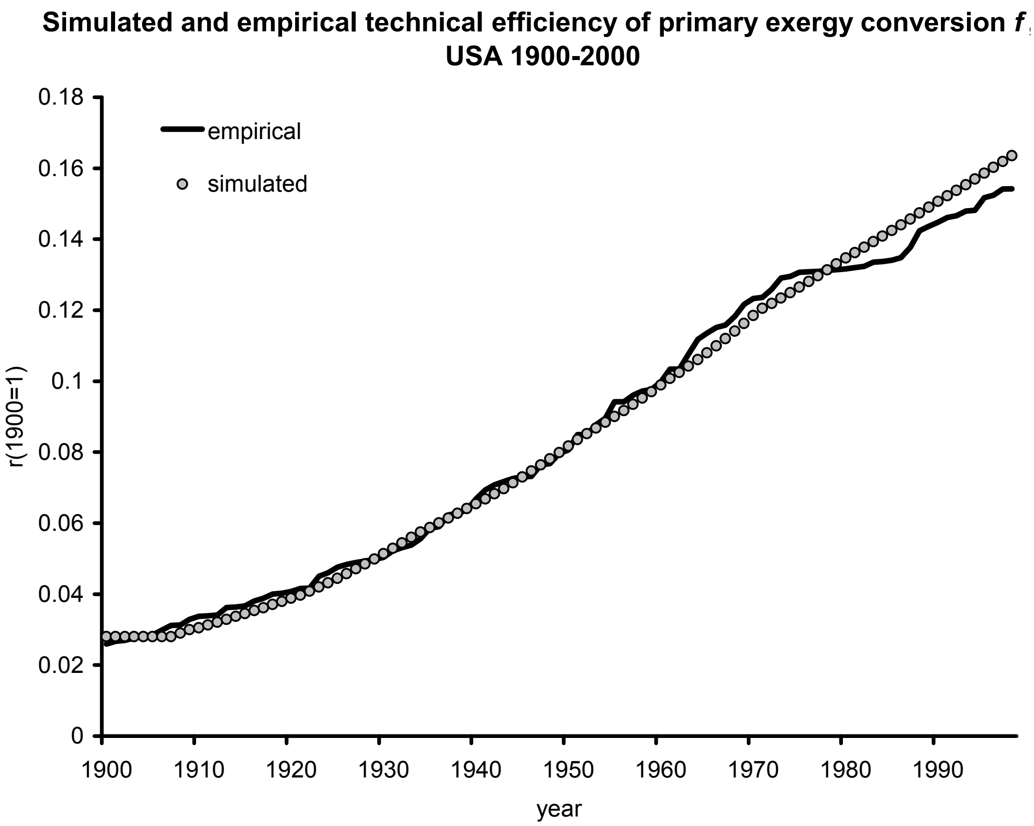
Figure 14. Technical efficiency feedback mechanism (Type II: Birth and Death of Ideas), and exergy services supply dynamics

<u>Technical efficiency growth feedback mechanism (Type II) equations:</u>

Growth Parameter A=12
Loss Parameter A=-0.0203786
Loss Parameter B= 3
Fractional Technical Efficiency Growth Rate= 1-(1/(1+EXP(Growth Parameter A*(Technical Efficiency Saturation Index-1))))
Fractional Technical Efficiency Loss Rate=Loss Parameter A+Loss Parameter C*Technical Efficiency Saturation Index^Loss Parameter B
Loss Parameter C=23.8718
Maximum Feasible Technical Efficiency=1



(a)



(b)

Figure 15. Technical efficiency reference modes, US 1900-2000.

tantly, if we were to use the more commonly used definition, which includes only commercial fuels, this trend of 'output dematerialisation' does not start to have serious effect until the mid 1920s. The primary exergy intensity of output mechanism was modelled very simply using a constant fractional decay rate (0.012), causing the absolute rate of decay to be proportional to the intensity measure, here represented as a stock (Figure 10a). The minimum feasible resource exergy intensity of output value was set to zero. Tests using values greater than zero did not alter the empirically fitted results significantly. We shall come back to this point later.

The empirical and simulated environmental Kuznets curve (*R/GDP*) are presented in Figure 11a. The correspondence is excellent. Tests using functions that are more complex were less successful. The simulated and empirical primary exergy demand is plotted in Figure 11b. It rises to over 150 exajoules by the end of the century. The simulation underestimated exergy demand over the period 1900-1930 because the empirical dematerialisation rate of output slowed with the advent of new inefficient technologies for fossil fuel and electricity use. Other deviations from the empirical trend occur during the period the first half of the century are the result of the Great Depression and World Wars. The sudden drop in primary exergy demand in 1972 is readily interpreted as a reaction to the oil shocks and OPEC actions to stabilise the price of crude oil at a higher level.

Much of the primary exergy consumed is wasted during the conversion process to physical work, particularly during the early part of the century. Only the exergy supplied as work and delivered at the point of use can be considered productively active in the economy: the rest is waste and could even hinder growth. The aggregate technical efficiency *f*, is a measure of the ratio of work (exergy service) delivered per unit of primary exergy consumed. This measure is a monotonically increasing function of time, an S-shape describing the underlying learning process that it reflects (Figure 1). This trend is compatible with van Duijns' (van Duijn 1977) hypothesis for the life cycle of industry "which combines the innovation theory of Schumpeter and Mensch, …and Forrester's multiplier accelerator mechanism of investment, which intensified the growth and saturation of basic innovation", (Watanabe, Zhu et al. 2001). We shall come back to this point later.

Two methods to control the technical efficiency dynamics were tested, to similar effect. The first shown in Figure 12 relied on empirically determined look-up curve (Figure 13) describing the effect of cumulative production experience on technical efficiency. In the second perhaps more elegant mechanism, the technical efficiency growth rate is a function of cumulative production experience and the 'loss' of technical efficiency is level relative to the maximum feasible technical efficiency (Figure 14). The maximum feasible technical efficiency was unity.

Modelling the technical efficiency as a birth and death process reflects the innovation and operationalization process of efficiency measures. It is an acceptance that not all innovations are made operational and that existing technologies are replaced by newer ones. This formulation could be considered a learning and forgetting model (Benkard 1999). Assume that the space of possible efficiency ideas is infinite, i.e. that human beings are capable of innovating infinite combinations of technologies to achieve efficiency improvements. It is therefore consistent to expect certain technologies to replace others. We can consider the innovation of new efficiency improvements as resulting from the birth of new technologies and the process of successful replacement as the cause of the loss of memory of the previous ones. Of course, this is a very simplistic interpretation as existing ideas may be subsumed in new ones, may continue to be used or may simply be stored as unused but alternative solutions.

Regardless of the underlying model used to represent the accumulation of technical experience, using a look-up table or a dynamic learning and forgetting process[7], the simulated

[7] It was also possible to provide equally accurate results using a fitted bi-logistic function, a learning curve involving only learning (no forgetting). These results are presented along with other examples in Concept Sheet: Barriers and Breakthroughs.

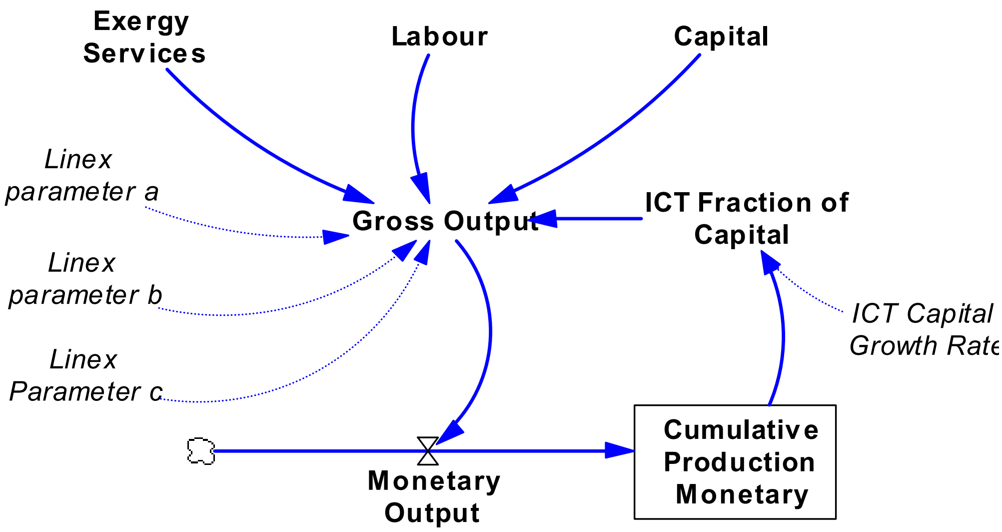


Figure 16. REXS economic output module.

Economic output module and production function equations:

Investment = A FUNCTION OF(Gross Output,Investment Fraction)
Investment=Gross Output*Investment Fraction
ICT Fraction of Capital=ICT Capital Growth Rate*(Cumulative Production Monetary/7315.2)
Capital Intensity of Output=Capital/Gross Output
Constant Returns To Scale Check=Marginal Productivity of Capital+Marginal Productivity of Exergy Services+Marginal Productivity of Labour
Labour Intensity of Output=Labour/Gross Output
Marginal Productivity of Labour=Linex parameter a*((Labour+Exergy Services)/Capital)
Gross Output= ACTIVE INITIAL (Exergy Services*((Labour/Exergy Services)^(Linex Parameter c*ICT Fraction of Capital))*EXP(Linex parameter a*(2-((Labour+Exergy Services)/Capital))+Linex parameter a*Linex parameter b*((Labour/Exergy Services)-1)),1)
Linex Parameter c=-0.0378207
ICT Capital Growth Rate=0.00105

cumulative primary exergy production (Figure 15a) drove technical efficiency growth to produce a result that accurately reproduced the empirical data (Figure 15b**)**.

Economic output

At the heart of the economy module is a four-factor service adjusted LINEX production function (Kummel, Strassl et al. 1985; Ayres and Warr 2003) taking as inputs the outputs of the three modules described above (*K* – nonICT / ICT capital, *L* labour and *U* – exergy services). The form of the production function was chosen specifically to reflect the synergistic relationships that exist between work and the other factors. The relationships between exergy services (work), capital and labour are complex. Capital equipment is required to extract and process natural resource exergy to provide necessary work. However, substitution between work and capital are possible through investments in 'energy efficient' capital. Exergy services and labour are also complementary. For example, labourers supplied with additional exergy services to power tools are more productive than those without. Yet, there are significant possibilities for the substitution of processed exergy from fuels to replace human muscular effort. In the service adjusted LINEX model (Ayres and Warr 2003) the fraction of ICT capital is the fourth factor of production. It is probable that information technology effectively increases labour productivity, while correspondingly reducing the productivity of exergy services. More thorough descriptions of the LINEX function and justifications for its application to prediction of long-run economic output can be found in the reference articles and in *Concept Sheets - Macro-economic production functions.*

The fitted LINEX parameter values presented in these papers were used directly in the REXS model. No subsequent adjustments to these parameters were made. The LINEX function was originally fitted using empirical time series of capital, labour and exergy services (work) not simulated variables. Therefore, any error in the simulated GDP resulted from inaccuracies in the other modules and the factor estimates they provided as inputs. The empirical and simulated time series of GDP are presented in Figure 17. The results are as accurate as those provided using empirical time series of the factors (Ayres and Warr 2003), testament to the accuracy of the inputs provided by the other modules. The model predicts output accurately over the entire century without the need for any exogenous assumptions of technological progress. The effects of technological progress are represented a) by endogenous improvements of the technical efficiency of exergy conversion and b) by the increasing prevalence of ICT capital.

Discussion

Arguably, the results of the REXS model fitting procedure show two important characteristics: i) structural changes represented by abrupt changes in parameter values; ii) deviations of the simulated primary exergy consumption from the empirical data over two historically important time periods, 1920-1940 and from 1970 onwards Figure 11b. The period 1920-1929 corresponds to a period of particular rapid economic overextension when the US economy was working at capacity under inflationary pressures. Stock market failure, investment and capital collapse of the Great Depression and the subsequent failure to establish new equilibrium points, restore stability and create the conditions for recovery caused a sudden but sustained fall in primary exergy consumption reflecting the new lower level of capacity utilization. The model itself provided the explanation for this sudden downturn, having identified by purely objective means an abrupt rise in the depreciation rate of capital in 1930 and a preemptory reduction in the labour hiring rate in 1920 (Figure 7b).

The REXS model identified a marked drop in investment in 1970 coincident with the start of OPEC efforts to stabilise oil prices at a higher level (Figure 18). Scrutinising Figure 10a we see that the simulated primary exergy intensity of output is very slightly larger than the empirical value since 1970. Reduced rates of capital accumulation and higher fossil fuel prices heralded a shift to a lower level of primary exergy consumption that has prevailed

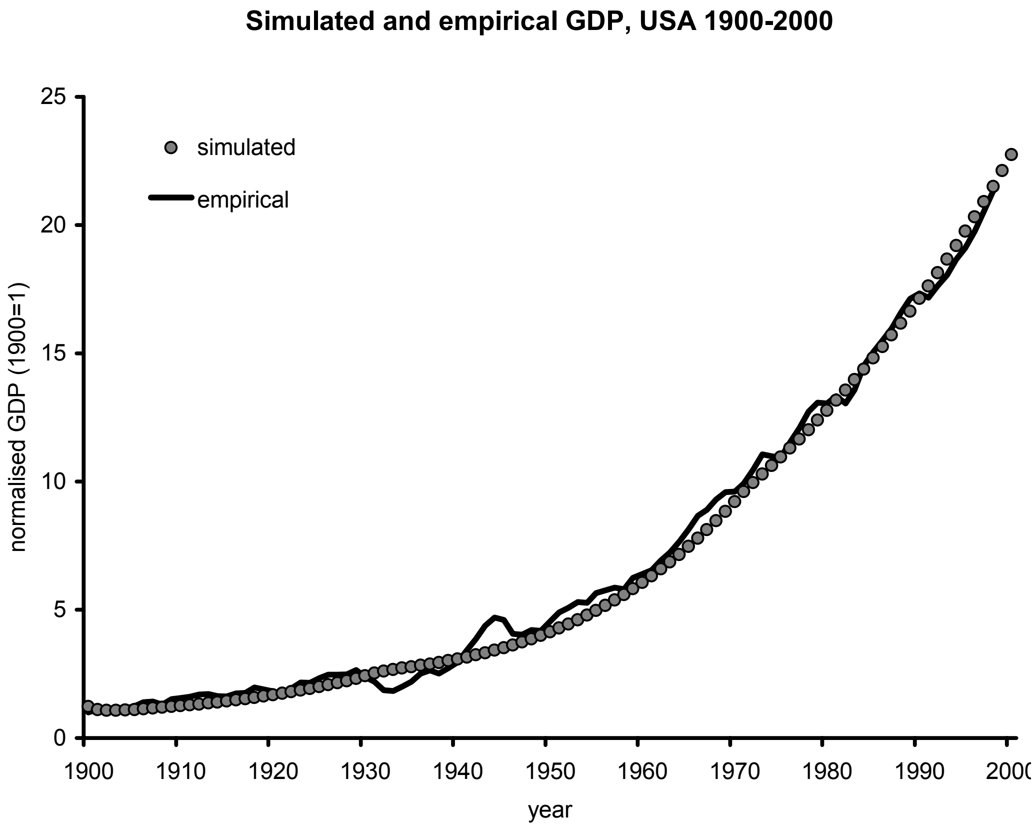


Figure 17. Simulated and empirical GDP (y), US 1900-2000.

since. From 1970 onward, the simulated primary resource exergy consumption runs parallel, but at a higher level to the empirical time series. The constant parameter value, the fractional decline rate of output primary exergy intensity, was fit over the period 1900-2000. Equal weight was assigned to the empirical value in each year. It is likely that by weighting the contribution of the empirical data to the model error on the basis of the empirical data reliability would cause the fit to approximate better the values in later years, at the expense of the fit in earlier years. This would reduce the level of simulated primary exergy consumption for a given level of economic avtivity. An alternative would be to model a variable capital utilisation level that could be used to impose sudden and short-term effects on the fractional decay rate of dematerialisation. Capacity utilisation could in turn be determined by price effects and so on. Such modifications are the subject of ongoing work.

Conclusions

The REXS model is a simple system dynamics model capable of providing accurate estimate of long-run historical growth. The REXS model is endogenous. It contains relatively few parameters and can be calibrated using empirical data, unlike models that involve measures of human capital to parameterize technological progress. The REXS model does this by recognition that natural resource consumption is both a cause and effect of past economic growth, and that the rate of the improvement of the aggregate technical efficiency of exergy conversion of an economy is a realizable measure of its technological progress. Cumulative production and output provide operational measures to control the long-run dynamics of energy intensity the efficiency of energy use.

We accept that there are many important dynamics that determine the short-term behaviour of the economy, not included in the REXS model. Nevertheless, the framework as we have presented it here has proved sufficiently flexible to accommodate both long-term trends and important structural changes. In this version of the model, structural changes were simply modelled using abrupt and imposed changes in parameter values. The past century has witnessed important structural changes to all aspects of the socio-economic system and in particular in the quantity with which energy and materials are supplied and the ways in which it is processed and used productively. The abrupt changes in the empirical time series discussed above are testament to this. However, in REX the growth of technical efficiency is modelled as a continuous process. This is consistent with the observation that the aggregate technical efficiency *f*, of the US is a simple increasing function of time. A ten-year moving average of the derivative of *f*, (Figure 19a) reveals two periods of more rapid change. This behaviour results from the sum of revolutionary and incremental engineering improvements and behavioural changes that determine the efficiency of primary exergy conversion. Figure 19b shows the technical efficiency of primary exergy conversion *f* for the major fossil fuels (coal, oil and gas). Each is quite distinct from the others, reflecting the specific learning experience for each fuel. These dynamics will be the focus of later realisations of the REXS model. Here we briefly outline how these trends will be used in future elaborations of the exergy resource consumption and exergy services supply dynamics. These modifications will include:-

a) The disaggregation of primary fuel mix and lock-in price effect (supply side),
b) A distinction between carbon and non-carbon fuels and carbon tax effects,
c) The influence of available fossil fuel reserves on price,
d) A disaggregation of technical efficiency by exergy carrier (demand side),

These changes will permit greater flexibility to control supply and demand side dynamics and allow us to explore various energy-economy-efficiency scenarios. Sensitivity tests will be used to evaluate the behaviour of the model under various conditions. We are aware the model represents only a single country at present. We cannot yet discuss climate effects, taxes and utility, or extend the specific conclusions and parameter interpretations that were possible using the DICE or NICE models. However, we do suggest that the dynamics represented in the model are generally applicable to energy-economy models of individual countries, regions and the World. The inclusion of exergy service dynamics removes the need for exogenous assumptions of continuous exponential growth, reveals the full importance of energy in the economy and provides an operational representation of technological progress, suitable for the generation and analysis of scenarios of the future.

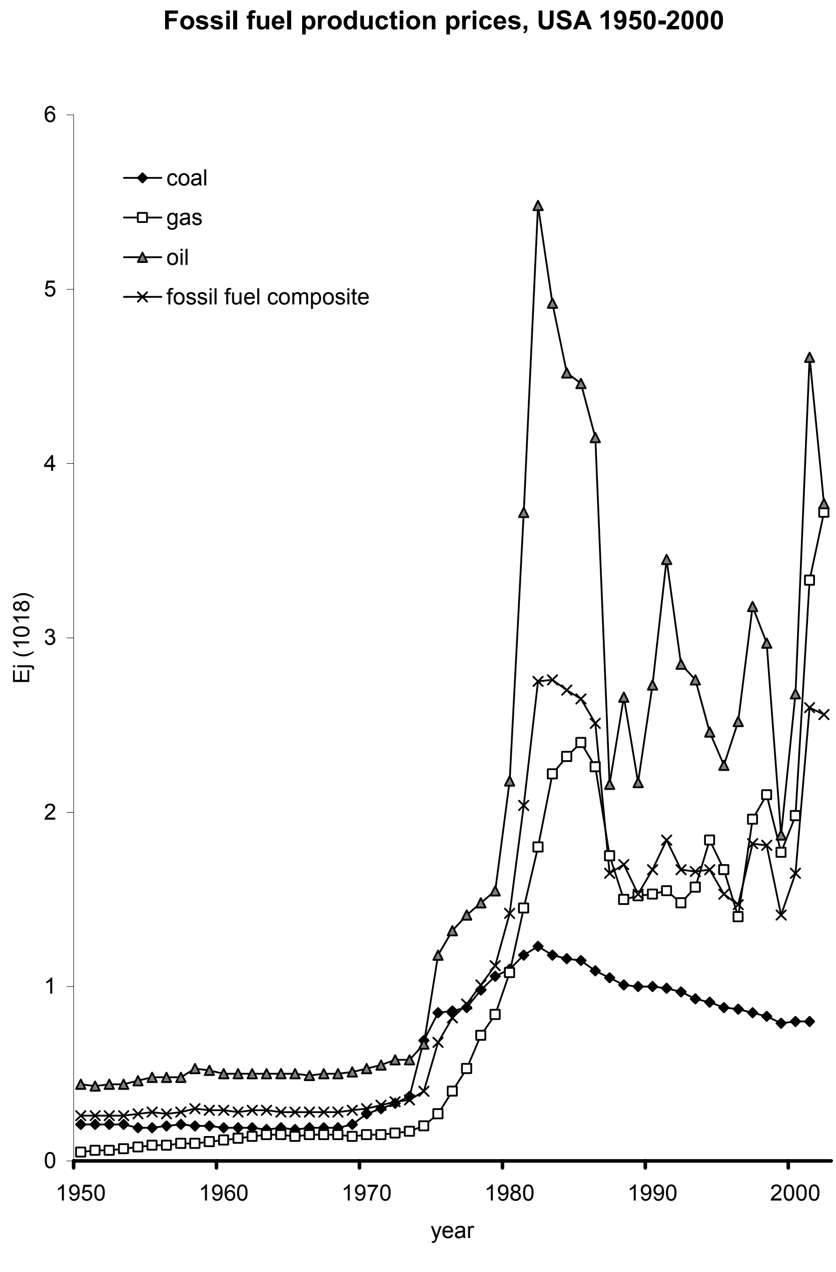
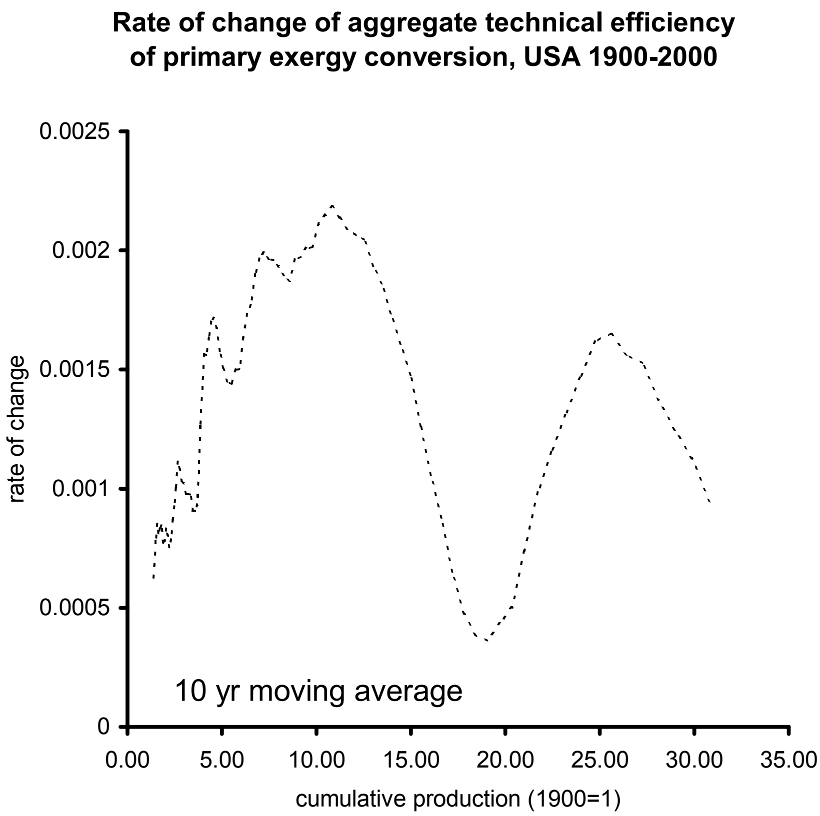
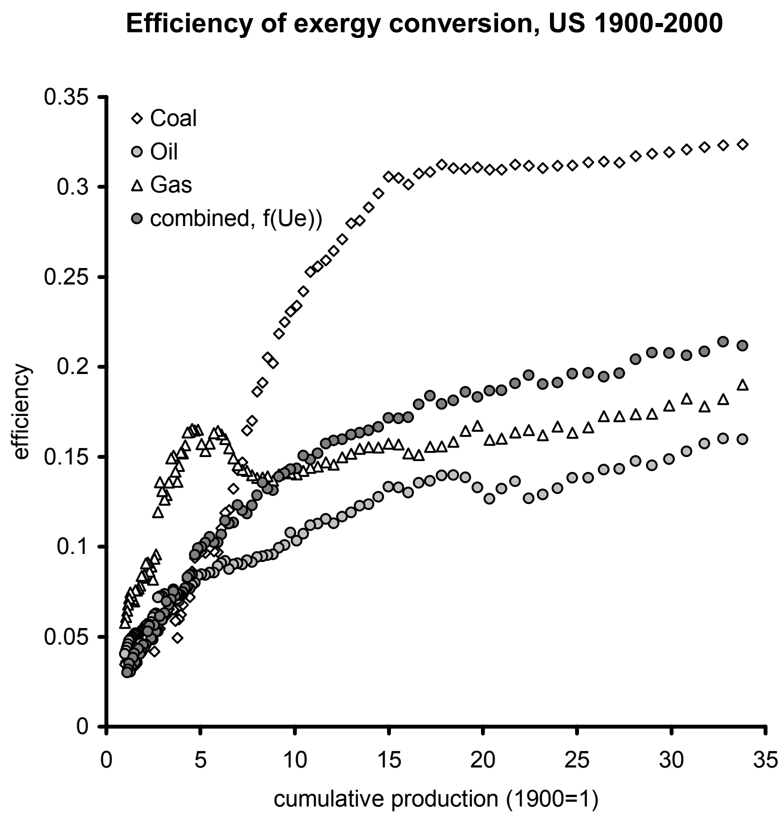


Figure 18. International average fossil fuel production prices (Source : IEA).



(a)



(b)

Figure 19. (a) Derivative of the aggregate technical efficiency *f*, (b) nested experience curves of exergy conversion technical efficiency for major fossil fuels.

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