CARBON DIOXIDE EMISSION SCENARIOS FOR THE USA

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Abstract

A model of carbon dioxide emissions of the USA is presented. The model consists of population, income per capita, economic structure, final and primary energy intensity per sector, primary fuel mix, and emission coefficients. The model is simple enough to be calibrated to observations since 1850. The model is used to project emissions until 2100. Best guess carbon dioxide emissions are in the middle of the IPCC SRES scenarios, but incomes and energy intensities are on the high side, while carbon intensities are on the low side. The confidence interval suggests that the SRES scenarios do not span the range of not-implausible futures. Although the model can be calibrated to reflect structural changes in the economy, it cannot anticipate such changes. The data poorly constrain crucial scenario elements, particularly energy prices. This suggests that the range of future emissions is wider still.

Key words

Climate change, emissions scenarios, USA

1. Introduction

The emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC) are commonly used for research into climate change, estimates of the impacts of climate change, and analysis of greenhouse gas emission reduction policies. The SRES scenarios (Nakicenovic and Swart, 2000), the latest set of IPCC scenarios, were also used as the basis of the scenarios of the Millennium Ecosystem Assessment (2005) and national scenarios, e.g., in Britain (UKCIP, 2001). The SRES scenarios have been severely criticised (Castles and Henderson, 2003a,b; Castles, 2004; Henderson, 2005), while the improper handling of justified critique (IPCC, 2003; Nakicenovic et al., 2003; Grübler et al., 2004) has cast doubt on the credibility of the entire IPCC (Economist, 2003a,b, 2004; Michaels, 2003; House of Lords, 2005).

The initial critique of the SRES scenarios focussed on economic accounting (Nordhaus, forthcoming). However, the use of market exchange rates rather than the more appropriate purchasing power exchange rates becomes particularly critical if income convergence is assumed (Dixon and Rimmer, 2006), a contestable assumption (Tol, forthcoming). The bias thus introduced is partially offset by the assumption of convergence of energy intensities (Manne *et al.*, 2005), an assumption with some empirical support (Miketa and Mulder, 2005).

The rapid convergence of per capita income is a known characteristic of the modern growth theory developed by Solow (1956, 1987) and Koopmans (1967). Although new growth theory superseded modern growth theory since the work of Romer (1986, 1987, 1990), integrated assessment models have not been updated. New growth theory is distinct from modern growth theory in that technological change is *endogenous*, rather than *exogenous*. As a corollary, convergence of per capita income does not follow, and is indeed not observed (Barro and Sala-i-Martin, 1995).

The fact that a crucial component of the SRES emission scenarios is at odds with the observations is probably because the models used to generate these scenarios have never been validated (see O'Neill and Van Vuuren, forthcoming, for a first attempt). Indeed, the models were calibrated to a recent year and run forward for a century or more. Interestingly, the SRES scenarios typically show a trend break where the data end and the scenario begins.

Criticising the SRES scenarios is easy. This paper is an attempt to offer an alternative, that is better in at least some respects. The model presented here is in line with recent insights into growth and development, and the model is tested against observations for the last 150 years. The work of economic historians, led by Angus Maddison (2001), enables this. The paper is primarily concerned with methodology, and attention is restricted to the USA. Therefore, I do not address my main criticism of the SRES scenarios, namely income convergence. However, the economic model used is a new growth model. An extension to other regions would not imply convergence of incomes.

Besides an improved methodology and a new scenario, this paper offers some estimate of the likelihood of scenarios. Calibration of the model to past observations allows for this. Decision analysis, as it is found in textbooks (Pratt *et al.*, 1995), calls for a complete quantification of the uncertainties. In practical applications, a test of the robustness of insights to alternative assumptions is often sufficient. However, robustness is only meaningful against the full range of non-implausible alternatives. Therefore, also in this case, one needs some idea of the likelihood of the baseline scenario and its alternatives. The confidence intervals presented here are more suited for robustness analysis than for uncertainty analysis, as the dimensionality and non-linearity of the model do not permit a formal estimation of the uncertainties. Yet, the current paper improves on SRES also in this respect, as SRES does not contain any estimate of confidence intervals or relative likelihoods of its alternative scenarios.

The paper is structured as follows. Section 2 describes the model. Except for population, all model parts were developed specifically for the purpose of this paper. Section 3 presents the base scenario. Section 4 shows validation and sensitivity analyses, primarily for developing insights into the behaviour of the model and the scenario. Section 5 concludes.

2. The model

2.1. Data

The list of data and their sources is given in Table 1. The data set is the same as in Tol *et al.* (2006), who analyze the data in some detail.

2.2. Population

The population model used is CHIMP 1.0, described in Fisher *et al.* (forthcoming). Like most demographic models, CHIMP has population cohorts. Every period, the larger part of a cohort is promoted to the next cohort, while the remainder dies. The size of the youngest cohort is proportional to the size of the cohorts of women of child-bearing age. Furthermore, people can migrate between the 16 regions of the model. The USA is a separate region. Unlike most demographic models, fertility, mortality, and migration are partly driven by per capita income. This is particularly pronounced for the poorer regions. For the USA, exogenous trends in mortality and fertility are more important. Migration, however, is driven by the income gap between the USA and other regions.

2.3. Economic growth

The economic model is David Romer's (1996) macro-version of Paul Romer's (1990) micro-based model of economic growth, except for the savings' rate. Production is driven by labour, capital and knowledge:

$$Y(t) = H(t)\left((1-\gamma_K)K(t)\right)^{\lambda}\left((1-\gamma_L)L(t)\right)^{1-\lambda} \tag{1}$$

where Y is production, H is technology, K is capital and L is labour (not population); t denotes times; and γ and λ are parameters.

Capital accumulates as

$$K(t+1) = (1-\delta_K)K(t) + s(t)Y(t) \tag{2}$$

where s is the savings' rate and δ is depreciation.

Knowledge accumulates as

$$H(t+1) = (1-\delta_A)H(t) + \beta\left(\gamma_K K(t)\right)^{\kappa}\left(\gamma_L L(t)\right)^{\kappa} H(t)^{\kappa} \tag{3}$$

where κ, β, and δ are parameters.

The savings' rate follows

$$s(t) = \vartheta + \psi \frac{L(t)}{P(t)} \tag{4}$$

where P denotes the population and φ and ψ are parameters. Earlier versions of the model had a constant savings' rate, but then the technology parameter β in equation (3) has to vary. Calibration did not reveal a regular, interpretable pattern for β.

Equations (1)-(4) have 9 parameters in total, whose values and sources are given in Table 2. Most parameters are set to values that are typical in the literature; the standard deviation is my guess. The parameters of Equation (4) are based on a linear regression. The initial value of the capital stock K is set to its steady state value. The initial value of the knowledge stock H is set such that the predicted GDP matches the observed one for 1850. The capital share of knowledge production κ is set by calibration; the distance between the observed and modelled GDP in 2002 is minimised.

2.4. Structure of the economy

Energy intensity is higher in manufacturing than in agriculture and services. Structural changes in the economy therefore influence energy use. Over a century, structural changes are substantial. Kongsamut *et al.* (2001) present a simple model of secular changes in economic structure. We extended their model to allow for different production functions in the different sectors, and for differential technological progress (see the Appendix). The growth rates of agriculture, manufacturing and services are

$$(5)\qquad \frac{\dot{A}}{A}=\frac{A-\overline{A}}{A}\left((1-\alpha)(g_M-g_A)+g+g_M\right)$$

$$(6)\qquad \frac{\dot{M}}{M}=g+g_M$$

$$(7)\qquad \frac{\dot{S}}{S}=\frac{S+\underline{S}}{S}\left((1-\sigma)(g_M-g_S)+g+g_M\right)$$

where A is production in agriculture, M is production in manufacturing, and S is production in services; $\bar{A}$ and $\underline{S}$ are parameters, denoting subsistence agriculture and household production of services, respectively; α and σ are parameters, denoting the capital share of production in agriculture and services, respectively; g_A and g_S are parameters, denoting technological progress in agriculture and services, respectively.

In (6), g and g_M are parameters, but in the complete model, they equal the growth rate of the population (Section 2.2) and technological progress in the overall economy (Section 2.3), respectively. This implies that manufacturing is the "normal" sector, whose growth rate equals the growth rate of the economy. Without biased technological change, agriculture is subnormal; it grows slower than the economy as the demand for agriculture products saturates. The service sector is supernormal; it grows faster than the economy as it produces luxury goods. Note that this construction essentially allows us to "decouple" economic growth and economic structure – that is, (5)-(7) is calibrated conditional on (1)-(4), not simultaneous with. Note also that (5)-(7) do not necessarily add up to the total economy; rescaling is needed.

There are six parameters in (5)-(7); see Table 2. However, α and σ are indeterminate, and therefore omitted. The other parameters are set by minimum least squares; standard deviations are guessed; $\bar{A}$ and $\underline{S}$ are held constant, g_A and g_S are constrained to vary by less than 1% a year.

2.5. Final energy use

Final energy use is split into five categories: agriculture, manufacturing, services, transport and residential. Tol *et al.* (2006) extrapolate the IEA (2005) data for 1960-2002 back to 1850, constraining the extrapolation with activities levels, primary energy use, and restrictions on the annual change in energy intensities. The energy intensity of transport is here defined as energy use over GDP; residential energy use is per capita. We extrapolate energy intensities to the future as follows. The average intensity is computed for every five-year period between 1852 and 2002. Average annual growth rates are computed for every interval ending in 1997-2002. The mean and standard deviation of these 30 growth rates is used to extrapolate future energy intensity.

2.6. Primary energy use

The ratio of primary energy to final energy grew on average at 0.33% per year between 1850 and 2000. This growth rate is assumed for the future as well.

We distinguish between six sources of energy: coal, oil, gas, nuclear power, hydropower, and other, each with its own capital stock. Capital is depreciated, and new investments are made so that total supply meets primary energy demand. In each period, investment costs are minimised. Investment costs are assumed to be quadratic. The problem is therefore

$$(8) \qquad \min_{I_i} \sum_i \pi_i I_i \text{ s.t. } \sum_i I_i > I$$

where I is investment and π is cost (capital plus operation and maintenance plus fuel), which solves as

$$(9) \qquad I_i = \frac{I}{\sum_i 1/2\pi_i}$$

The life-time of capital is set equal to 40 years, except for hydropower which is 100 year. As energy use varies from year to year, we used the 15-year moving average of primary energy use as the indicator for capacity. For the past, the model was calibrated by inversion. Figure 1 shows the observations and model reconstruction; Figure 2 the prices.

For extrapolation to the future, we followed the same procedure as for energy intensity. Five-year averages of investment costs were computed, and cost trends based on that were extrapolated.

2.7. Carbon dioxide emissions

Carbon dioxide emissions follow from multiplying the primary energy use by fuel with the appropriate emission factor.

2.8. Variances and confidence intervals

Model predictions and observations overlap. Via the sum of squared residuals, this gives a one-step prediction error. Combined with the standard deviations of the parameters specified in Table 2, multiple-step prediction errors follow. The variances are approximated with their first-order Taylor approximations.

The exception is the population scenario. Here, we set the coefficient of variation of the growth rate of the population such that all SRES scenarios just fall in the 67% confidence interval.

3. Emission scenarios

Figure 3 shows the number of people for 1850-2100, as observed and as projected. With 478 million people in 2100, the CHIMP scenario is slightly higher than the A1 and B1 scenarios, lower than A2 and higher than B2. All SRES scenarios fall within the 67% confidence interval, by construction (see above). Section 4 shows sensitivity analyses.

Figure 4 shows per capita income. The Romer-Romer model reproduces the observations for 1850-2000 reasonably well, bar the upheaval of the Great Depression and World War II. For the future, our model project an average income of $100,000 per person per year, which is in between A1 and B1/B2, but much higher than A2. The A2 falls outside the 67% confidence interval, while the other scenarios approach the edges. Section 4 shows sensitivity analyses.

Figure 5 shows the sectoral composition. The KRX model reasonably reproduces the observations. In the projections, the services sector dominates, while agriculture all but disappears. Note that, although the share of manufacturing falls, absolute production in manufacturing continues to increase.

Figure 6 shows observed and projected energy intensities, which are declining everywhere. As the changes in past energy intensity were so regular, the confidence intervals of the projections are rather narrow. See also Table 2.

Figure 7 shows primary energy use. Our model reproduces the observations reasonably well. Our projections are somewhere in between A2, and B2 and A1, but much higher than B1. (Note that GDP is the same for all scenarios in Figure 7, and that the confidence interval is about the energy sector only.) As in Figure 6, our confidence interval is rather narrow, and excludes all SRES scenarios. Section 4 shows sensitivity analyses.

Figure 8 shows primary energy by source for the period 1850-2100. The projection is driven by the relative prices of the energy sources. For coal, nuclear power, and hydropower, we set the annual price change equal to the observed price changes in the past. See Table 2. For oil and gas, we used the mean price change in the past plus the standard deviation. For “other” (wind, solar, biofuels), we used the mean price change minus its standard deviation. Under these assumptions, the share of hydropower, coal and oil are largely stable. This assumes that new sources of exploitable oil will be found, perhaps on the poles or under the ocean, perhaps in tar sands. New sources of hydropower will need to be tapped, as the primary energy use increases (see Figure 7). The share of natural gas declines. Nuclear and to a lesser extent renewables will make up. The absolute numbers (Figure 9) show that the model reasonably reproduces the observations, except for coal which is more volatile that our model allows. Section 4 shows sensitivity analyses.

Figure 10 shows carbon dioxide emissions as observed and as projected. The model reasonably reproduces the past. Our projections are much lower than the SRES ones. (Note that primary energy use is the same for all scenarios in Figure 10, and that the confidence interval is about primary energy use only.) The main reasons are that, under our assumption, oil is not replaced by coal; and gas is replaced by nuclear and renewables.

Figure 11 also shows carbon dioxide emissions as observed and as projected. The difference with Figure 10 is that Figure 11 uses the SRES scenarios proper, and not just the carbon intensity of primary energy use. Similarly, the confidence interval includes all uncertainties, starting with the population. Our projections lie somewhere between A2 and B2, which fall in the 67% confidence interval, and are thus substantially lower than A1 and higher than B1. Note that our projections of energy intensity and carbon intensity deviate from SRES, being on the high side and the low side, respectively. These cancel, so that our emissions projection is well within the SRES range. Section 4 shows sensitivity analyses.

According to the estimated uncertainty about our projection, we can estimate the relative likelihood of the scenarios. We only consider the carbon dioxide emissions in 2100. Including only the SRES scenarios, the probability of A1 is 12%, of A2 is 28%, B1 23%, and B2 37%. Including all five scenarios, our projection has a probability of 33%, A1 8%, A2 19%, B1 15%, and B2 25%.

4. Validation and sensitivity analysis

The confidence intervals reported above already give an idea of the range of scenario results. This range is extended, in a qualitative way, by the validation exercise. In the sensitivity analyses, we rather focus on the workings of the underlying model.

4.1. Validation

A standard way of model validation is out of sample forecasting. With 150 years of observations, there is enough data to re-calibrate the model for a shorter period, and compare long-term projections with observations. We here focus on economic growth and the fuel structure of primary energy supply.

Figure 12 shows the past reconstruction of per capita income for the period from 1850 to 1950(10)2000, and the projections for the remaining period till 2100. The calibration procedure was identical. The models calibrated to 1950, 1960 and 1970 behave very similar; indeed, the results are graphically indistinguishable for 1960 and 1970. Similarly, when calibrated to 1980, 1990 or 2000, the model behaves basically the same. However, if calibrated to 1970 and before, projections are much higher. This suggests that there was a structural break in the 1970s, probably associated with the oil crises. This implies that our projection of per capita income is sound – provided that there are no structural breaks. The model can be recalibrated after a structural break, and performs fine after that. However, the model cannot anticipate structural breaks. This is a humbling conclusion for a 100 year forecast.

Figure 13 shows the past reconstruction and future projection of primary energy sources if the model is calibrated to 1950 and 1975, rather than to 2000. Interestingly, the results are not very different for the year 2000. In the calibration to 1950, coal does not recover from its decline (as it did in the 1970s), and nuclear does not appear; oil takes up this share. In the calibration to 1975, there is too much nuclear and too little coal. Although these differences are relatively small in 2000, they are much larger in the projections. This shows that, in a system with a slow capital turnover, short-term prediction is relatively easy – but that skill at the short term does not imply skill at the long term. The nuclear example shows that history-based projections are not robust to radically new technologies.

4.2. Sensitivity analysis

In Table 3, we report two sensitivity analyses. In the first one, we increased the growth rate of the population by a factor 1.001, so that the 2100 population is roughly 10% larger. We kept the age distribution the same, so that the workforce increases by roughly the same percentage. Income per capita goes up by 5%, as more people of working age implies faster technological progress. The income also has to be share with a larger number of people however. The population elasticity of per capita income is 0.4. Primary energy use and carbon dioxide emissions go up by about 15%, roughly equal to the sum of the population increase and the per capita income increase.

In the second sensitivity analysis, we increased the workforce by roughly 10% in 2100, but kept the population at its original value. Per capita income goes up by 12% as technological progress accelerates. In the current parameterisation of the model, the workforce elasticity of per capita income is greater than unity. Primary energy use and carbon dioxide emissions go up by about 10%. This implies an income elasticity of less than one, which comes about because more rapid economic growth also implies more rapid advancements in energy efficiency. The numbers in Table 3 also reveal that the primary energy elasticity of carbon dioxide emissions is smaller than unity. This is because a greater energy demand would be met with a more diverse portfolio of energy sources; that is, the share of coal and oil falls relative to the baseline.

The changes and elasticities of the two sensitivity analyses are consistent with each other. The “larger workforce” scenario also represents a sensitivity analyses for different economic growth rates.

Figures 8 and 14 show sensitivity analyses around the assumed costs of the six alternative energy sources; Figure 8 shows the structure of the fuel demand, Figure 14 carbon dioxide emissions. In the base case, we set the price development of coal, nuclear and hydro equal to past trends, while we let the price of oil and gas evolve according to the upper end of the 67% confidence interval, and the price of renewables followed the lower end. In the first sensitivity analysis, all price evolves according to past trends. Unsurprisingly, oil and gas expand, at the expense of coal, nuclear and renewables. The latter two dominate the response of carbon dioxide emissions, which are higher than in the base case. In the next six sensitivity analyses, we increase the rate of price change by one standard deviation for coal and oil; and decrease the price change by one standard deviation for the other fuels; in this way, CO_2 emissions always go down. If coal or oil are more expensive than in the base case, they substitute for one another; at the same time, nuclear power expands. Therefore, carbon dioxide emissions fall, relatively to the baseline, and more so if coal is more expensive. If gas is less expensive, it expands at the expense of oil and nuclear. Therefore, CO_2 emissions hardly change. If nuclear, hydro, or renewables are less expensive, they expand at the expense of oil and coal. Carbon dioxide emissions fall relative to the baseline, and in fact start to decline in absolute terms as well.

These sensitivity analyses are based on a single parameter, deviating a single standard deviation from their value in the base scenario. Nonetheless, in three cases (hydro, nuclear, renewables), the alternative projections fall outside the confidence interval for CO_2 emissions derived above. This is partly because, in a full uncertainty analysis, the effects of individual parameter deviations cancel. However, this analysis also suggests that the interval of Figure 11 is overconfident.

5. Discussion and conclusion

In this paper, we present a model of US carbon dioxide emissions. The model contains all the main components: population, income, economic structure, energy intensity, primary energy use, and energy sources. The model reproduces the last 150 years of observations. This is achieved by calibration. Nonetheless, it suggests that the model and its parameters have some relation to reality.

We use the model to extrapolate carbon dioxide emissions for the 21st century. The base scenario is right in the middle of the SRES scenarios. However, the composition of the scenario is different, with a higher energy intensity, and a lower carbon intensity. As the model is calibrated, we do have some idea of the uncertainty of the projection. The SRES A2 and B2 scenarios fall within the 67% confidence interval of our projection for most of the century, while all SRES scenarios are within our 95% confidence range.

However, model validation and sensitivity analyses show that our estimate of the uncertainty is a clear underestimate. Therefore, the confidence range of our scenario, and by implication the range of IPCC scenarios, is too narrow; and we are overconfident in our ability to predict the future. This is not uncommon (Morgan and Henrion, 1990). It is sobering, however, that this effect is so pronounced for the easy case of the USA. Projections for data-scarce and dynamic areas such as sub-Saharan Africa and East Asia are much less constrained by our current understanding. Extending the model to other parts of the world is first on my list of priorities.

The overall conclusion is therefore one of humility. Clearly, the only way forward in improving the models used to generate emissions scenarios, is to systematically test the models in their ability to “predict” changes in the past. The results here show that this ability is limited, particularly with regard to structural breaks; and that alternative models that reconstruct the past equally well may have radically different forecasts. This calls for further research on the one hand, and a wider range of scenarios at the other.

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Table 1. Data: Coverage and sources.

Variable	Coverage	Period	Source
Energy			
Primary energy consumption	Coal, oil, gas, hydro, wood	1850-1955	Schurr *et al.* (1960)
Primary energy consumption	Coal, oil, gas	1900-1987	Liesner (1989)
Primary energy consumption	Coal, oil, gas, nuclear, hydro, other; Industrial, commercial, transport, residential	1949-2004	EIA (2005)
Primary energy consumption	Coal, oil, gas, nuclear, hydro, other	1960-2002	IEA (2005)
Final energy consumption	Coal, oil, gas, electricity, other; Agriculture, manufacturing, services, transport, residential	1960-2002	IEA (2005)
Population			
Size	-	1850-2003	Maddison (2003)
Economy			
GDP		1850-2002	Maddison (2003)
Structure of GDP	Agriculture, manufacturing, construction, transport and communication, commerce	1869-1993	Mitchell (1998)
Structure of GDP	Agriculture, manufacturing, services	1971-2001	WRI (2005)
Emissions			
Carbon dioxide	Coal, oil, gas, flaring, cement	1800-2002	Marland *et al.* (2005)

Table 2. Parameters of the model.

Symbol	Description	Value		Source
Growth				
γ_K	Share of capital in production	.0263	(.0026)	WRI
γ_L	Share of labour in production	.0074	(.0007)	WRI
λ	Capital share in production	.20	(.002)	This paper
κ	Capital share in knowledge production	.29	(.003)	Calibration
φ	Constant savings' rate	31.2	(6.1)	Regression
ψ	Shift factor in savings' rate	-28.4	(5.6)	Regression
δ_K	Depreciation of capital	.100	(.010)	This paper
δ_H	Depreciation of knowledge	.020	(.002)	This paper
Structure				
$\bar{A}$	Subsistence agriculture	485	(49)	Least squares
$\underline{S}$	Household services	1003	(100)	Least squares
$(1-\alpha)(g_M-g_A)$	Technological bias agriculture	Fig A1		Least squares
$(1-\sigma)(g_M-g_S)$	Technological bias services	Fig A1		Least squares
Energy				
	Annual energy intensity decline, agriculture, percent	0.79	(0.41)	This paper
	Annual energy intensity decline, manufacturing, percent	0.84	(0.63)	This paper
	Annual energy intensity decline, services, percent	1.10	(0.52)	This paper
	Annual energy intensity decline, transport, percent	0.79	(0.31)	This paper
	Annual energy intensity decline, residential, percent	0.54	(0.20)	This paper
	Conversion efficiency decline, percent	0.33	(0.17 10^{-4})	Regression
	Annual relative price change, coal, percent	-0.45	(1.15)	This paper
	Annual relative price change, oil, percent	-2.01	(1.69)	This paper
	Annual relative price change, gas, percent	-1.36	(2.70)	This paper
	Annual relative price change, nuclear, percent	-1.38	(4.96)	This paper
	Annual relative price change, hydro, percent	-1.79	(4.80)	This paper
	Annual relative price change, other, percent	0.22	(2.35)	This paper

Table 3. Values of selected characteristics in 2100 in the base case and two sensitivity analyses.

		Base	Population			Workforce		
		value	value	change	elasticity	value	change	elasticity
Population	People (10^6)	478	528	10.5%		478		
Workforce	People (10^6)	193	212	9.8%		212	9.8%	
Per capita income	Dollar (10^3)	106	111	4.7%	0.45	118	11.6%	
Primary energy use	BTU (10^{15})	246	283	15.0%	1.43	272	10.5%	0.91
CO_2 emissions	g CO_2 (10^{12})	11.5	13.1	14.6%	1.39	12.6	10.2%	0.88

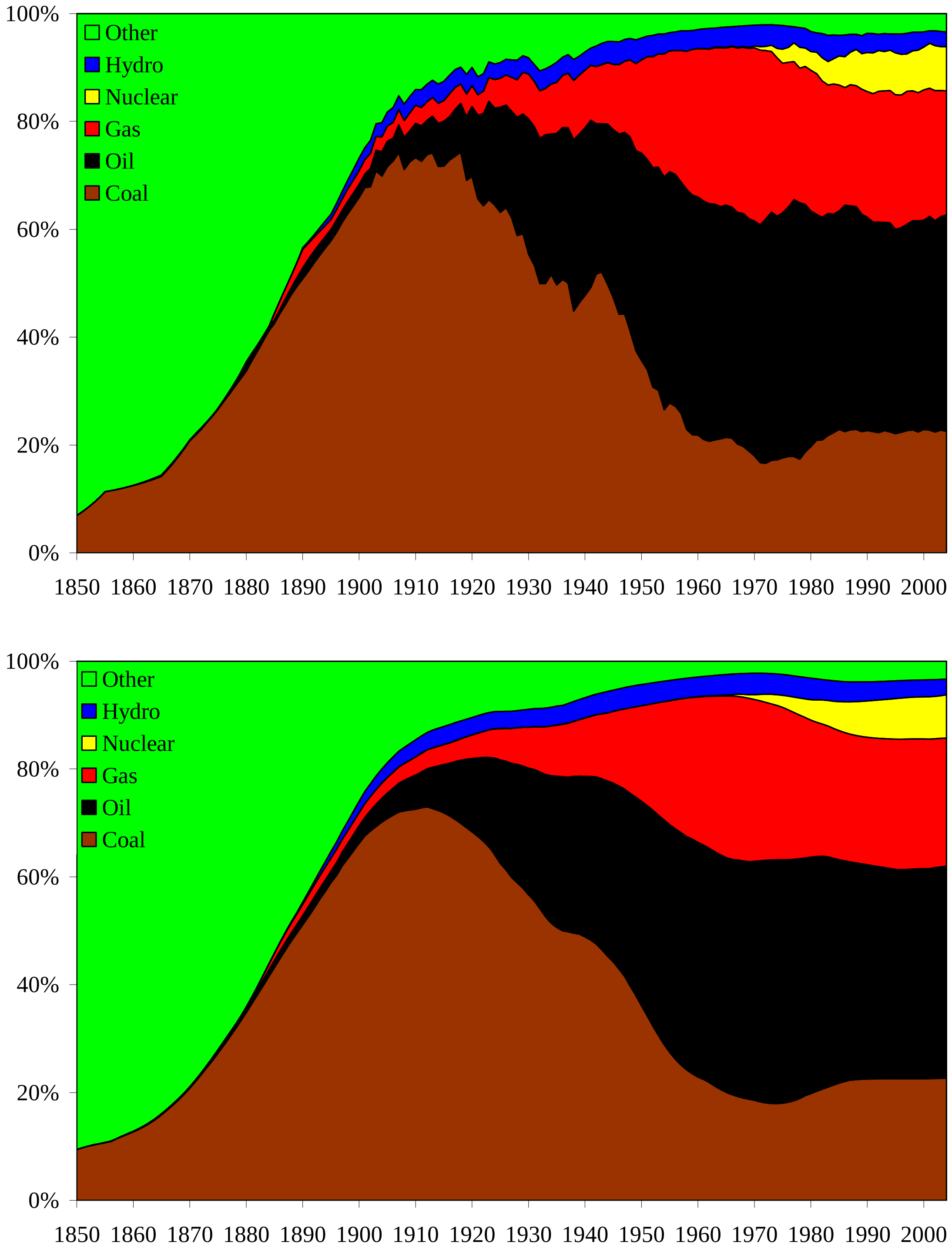


Figure 1. Primary energy use by source as observed (top panel) and as modelled (bottom panel).

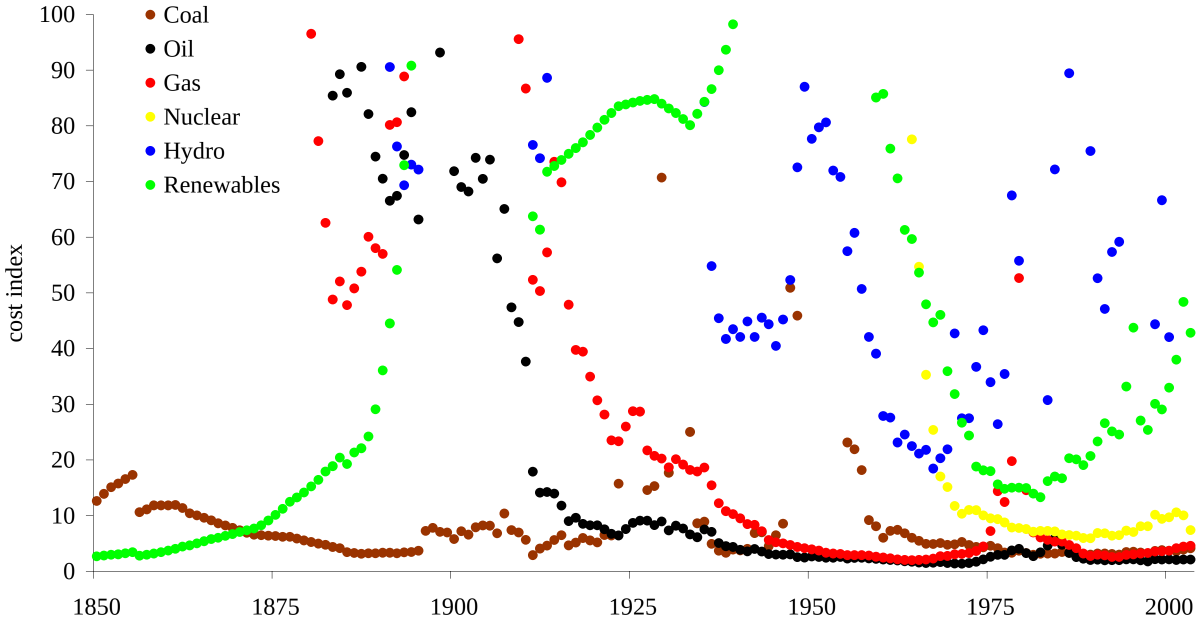


Figure 2. The assumed costs of energy investment, by source.

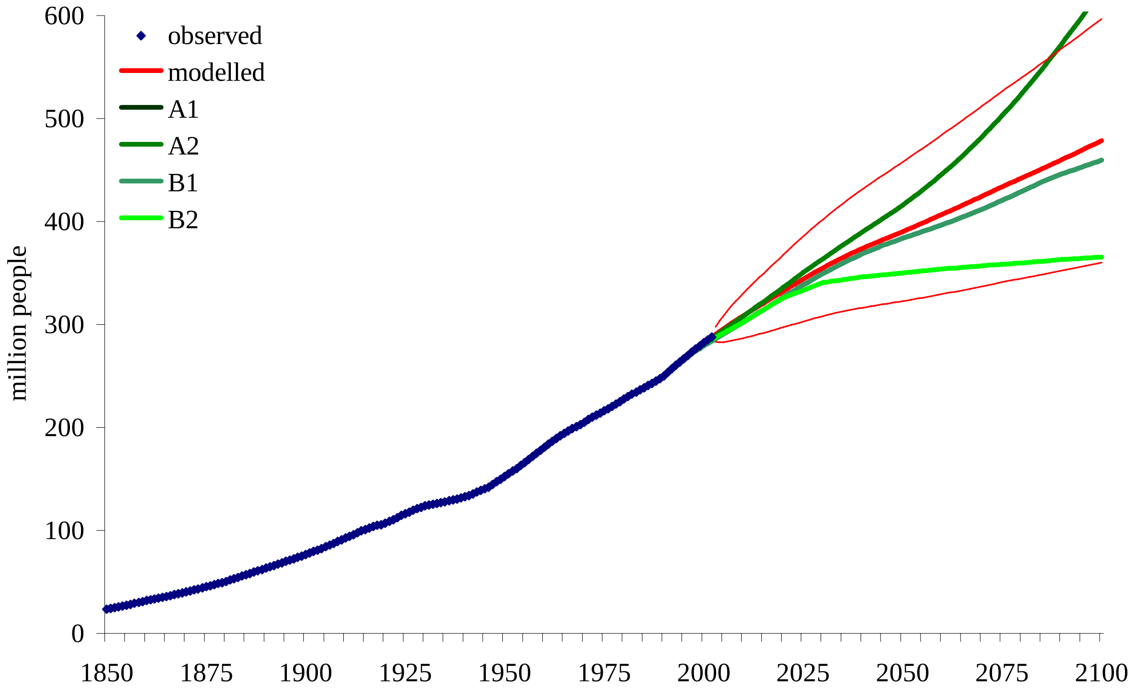


Figure 3. Number of people in the USA as observed and as projected; note that the A1 and B1 scenarios coincide.

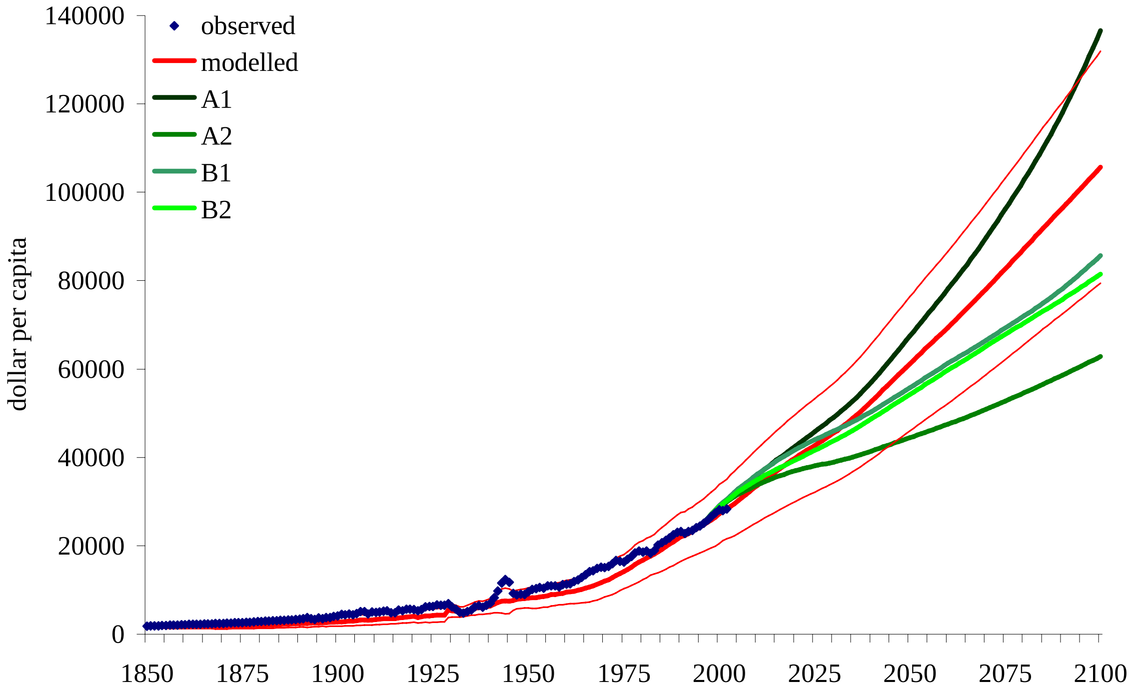


Figure 4. Per capita income as observed and as projected.

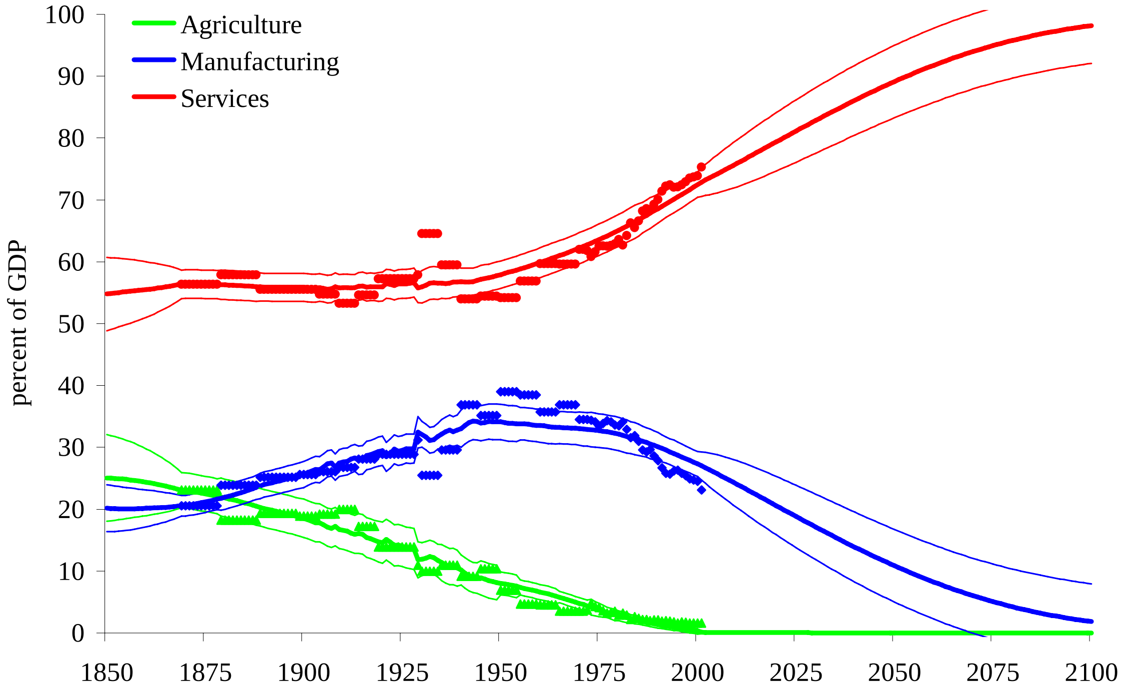


Figure 5. The composition of economic production, as observed and as predicted.

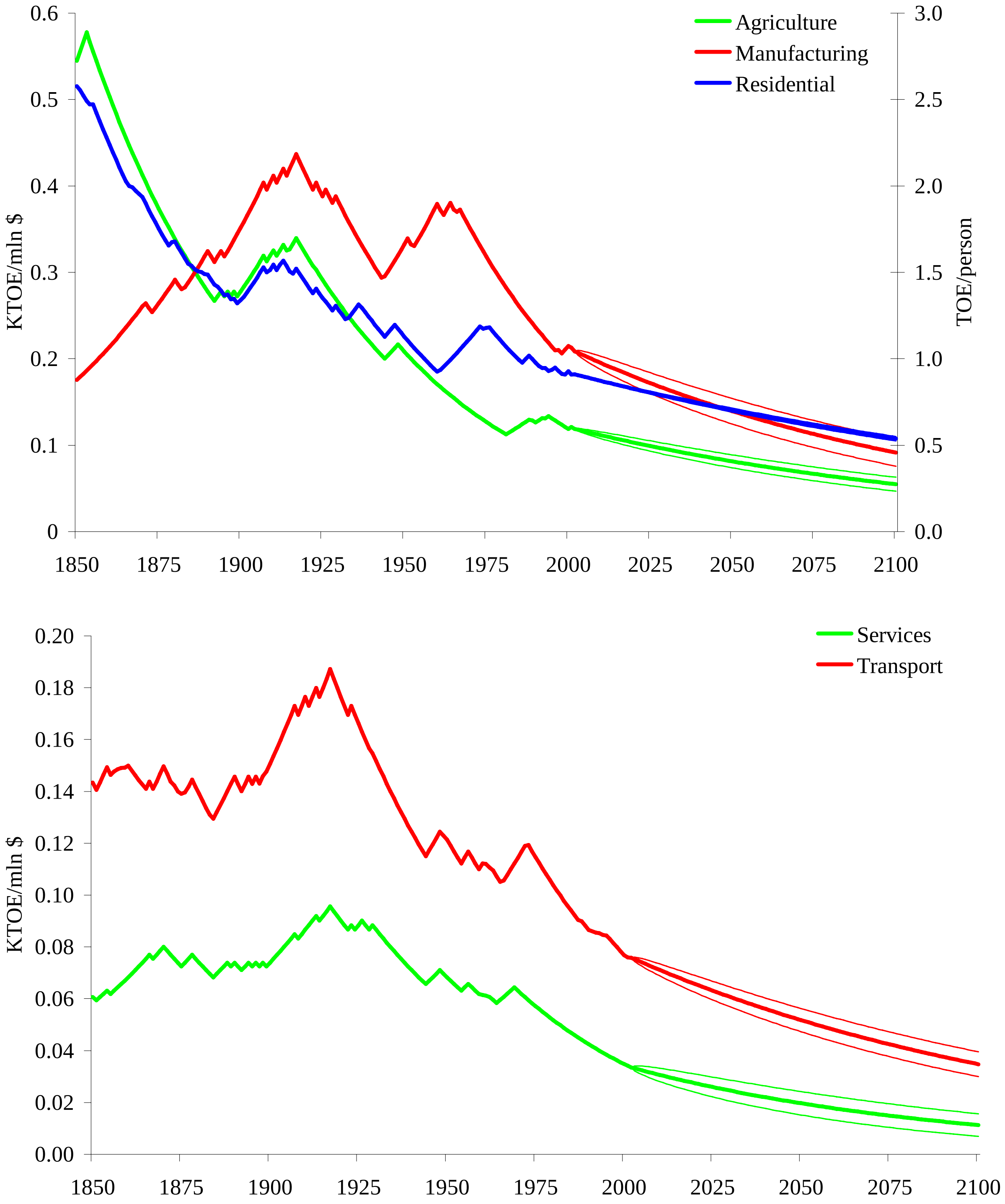


Figure 6. Energy intensities as observed and as projected for agriculture, manufacturing and residential (top panel) and for services and transport (bottom panel).

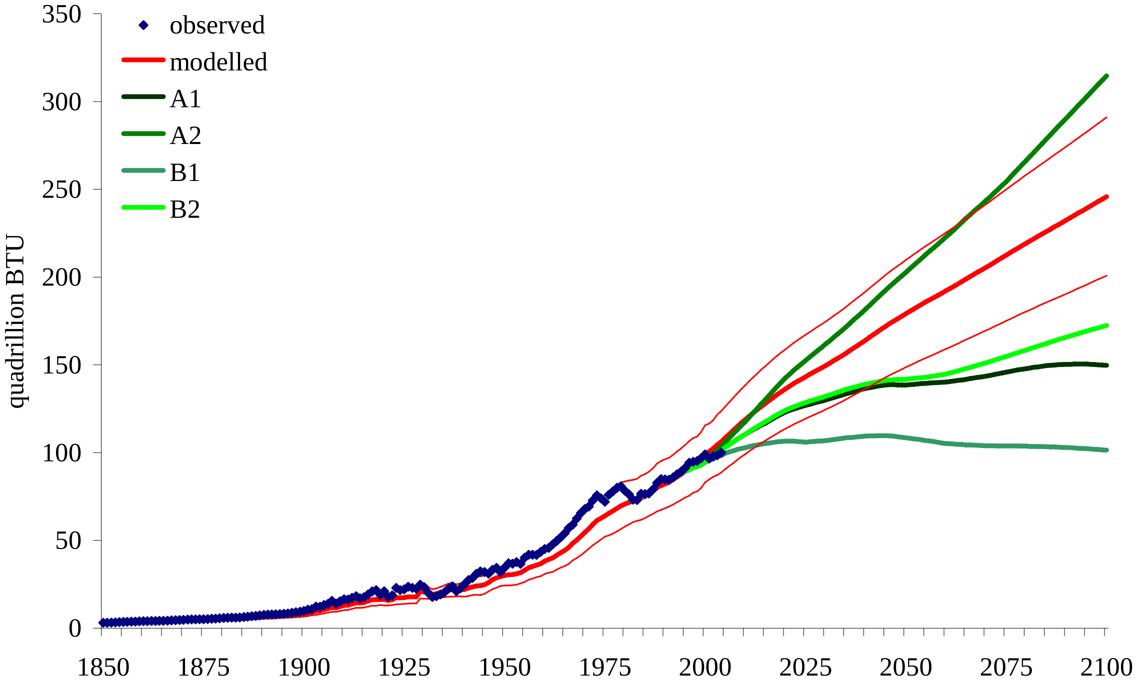
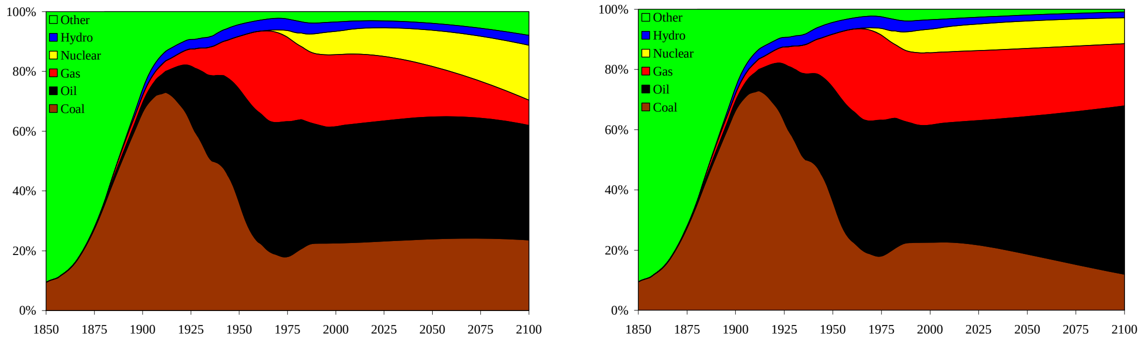
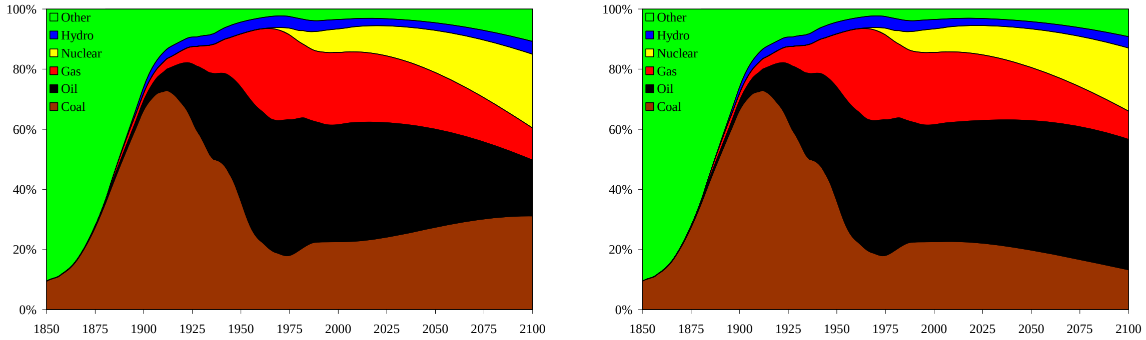


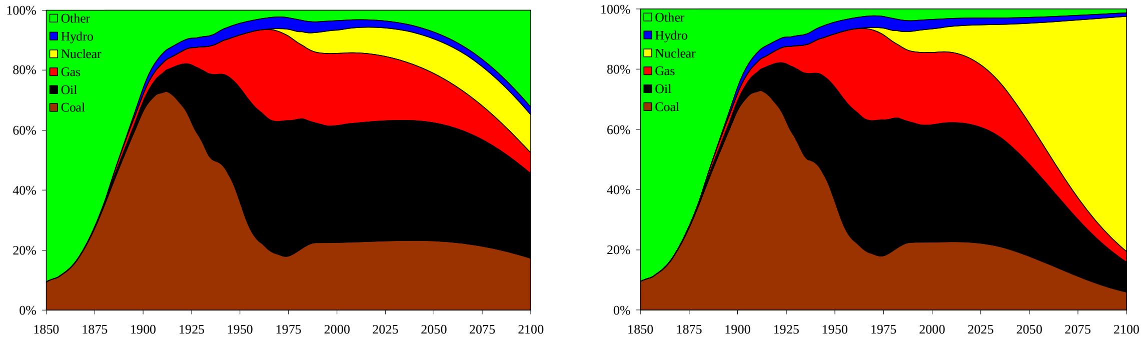
Figure 7. Primary energy use, as observed and as projected.


Base case

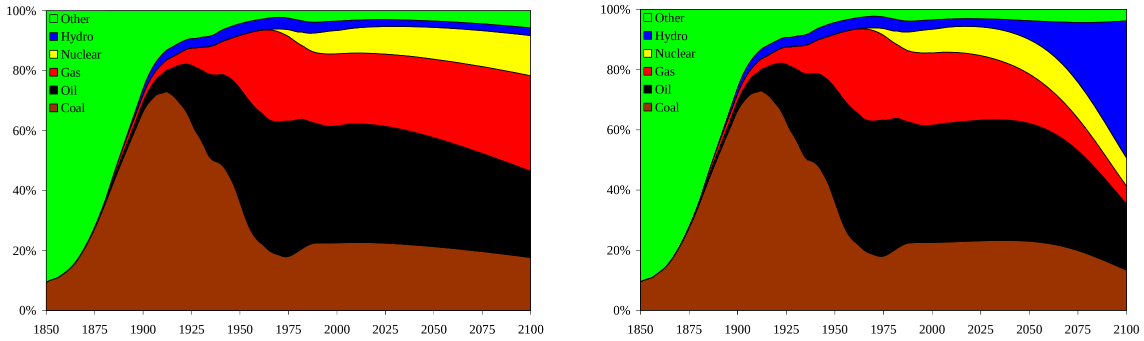
Extrapolation


Expensive oil

Expensive coal


Cheap renewables

Cheap nuclear power


Cheap natural gas

Cheap hydropower

Figure 8. Primary energy use, by source, as modelled; share in total.

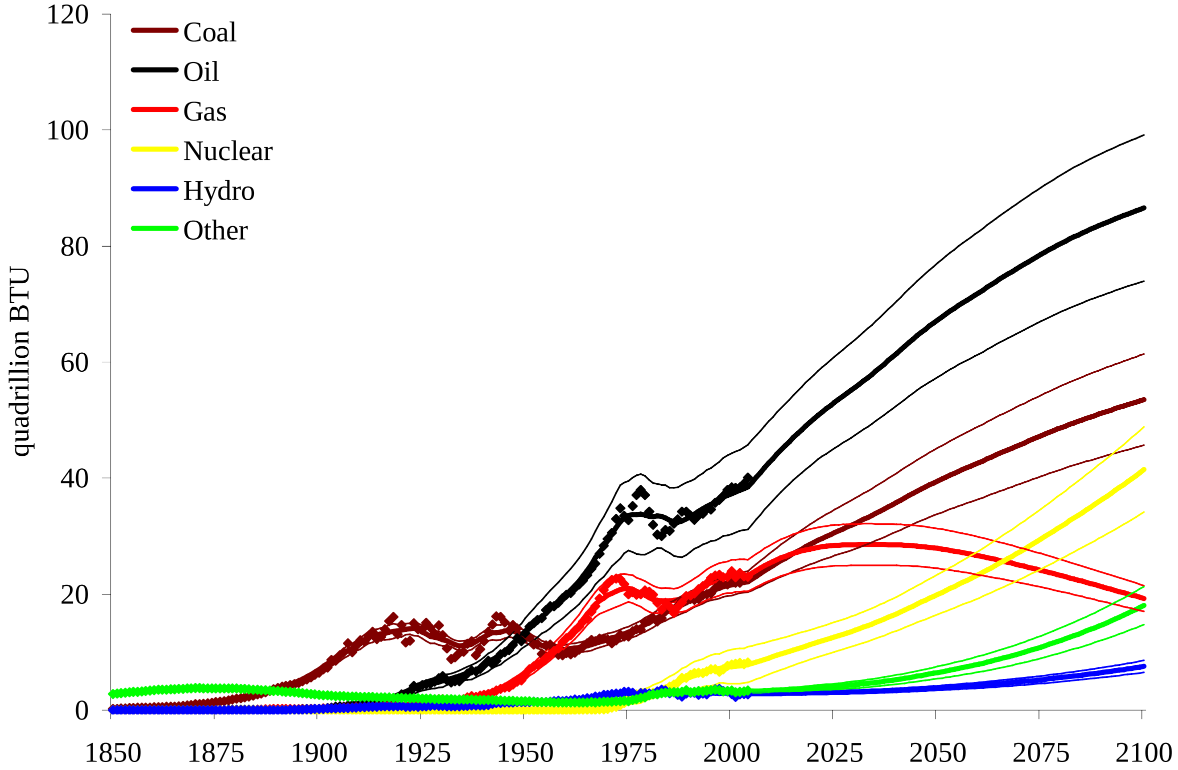


Figure 9. Primary energy use, by source, as modelled; absolute amounts.

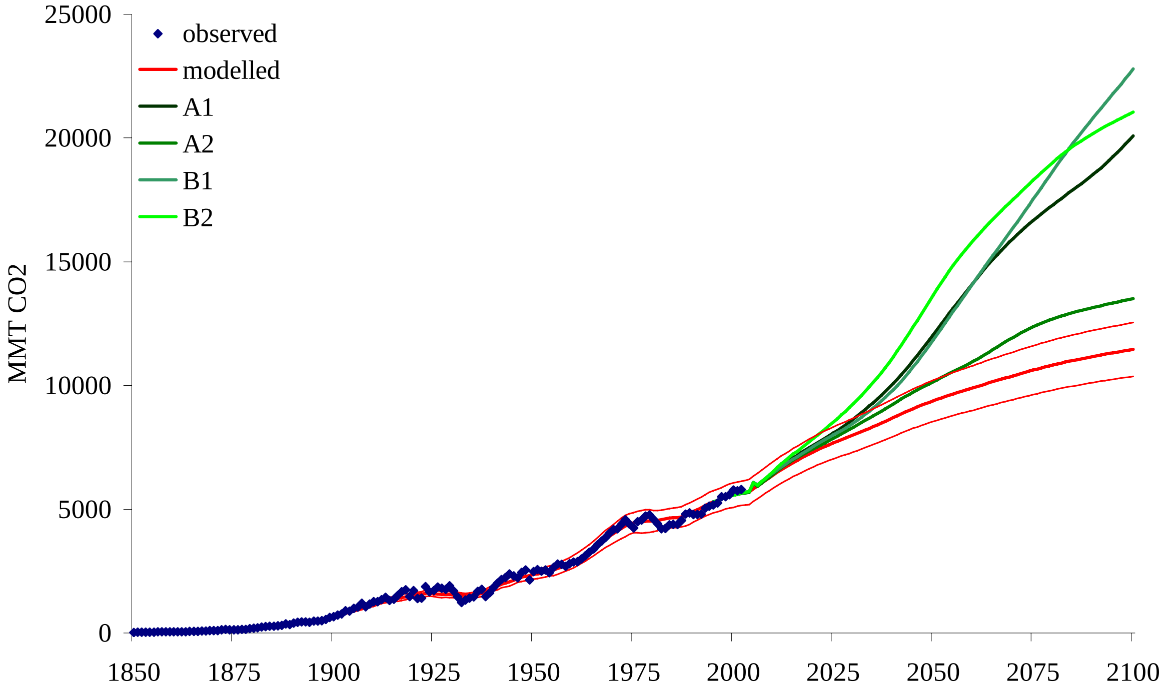


Figure 10. Carbon dioxide emissions as observed and as projected; note that all scenarios are based on the same primary energy use.

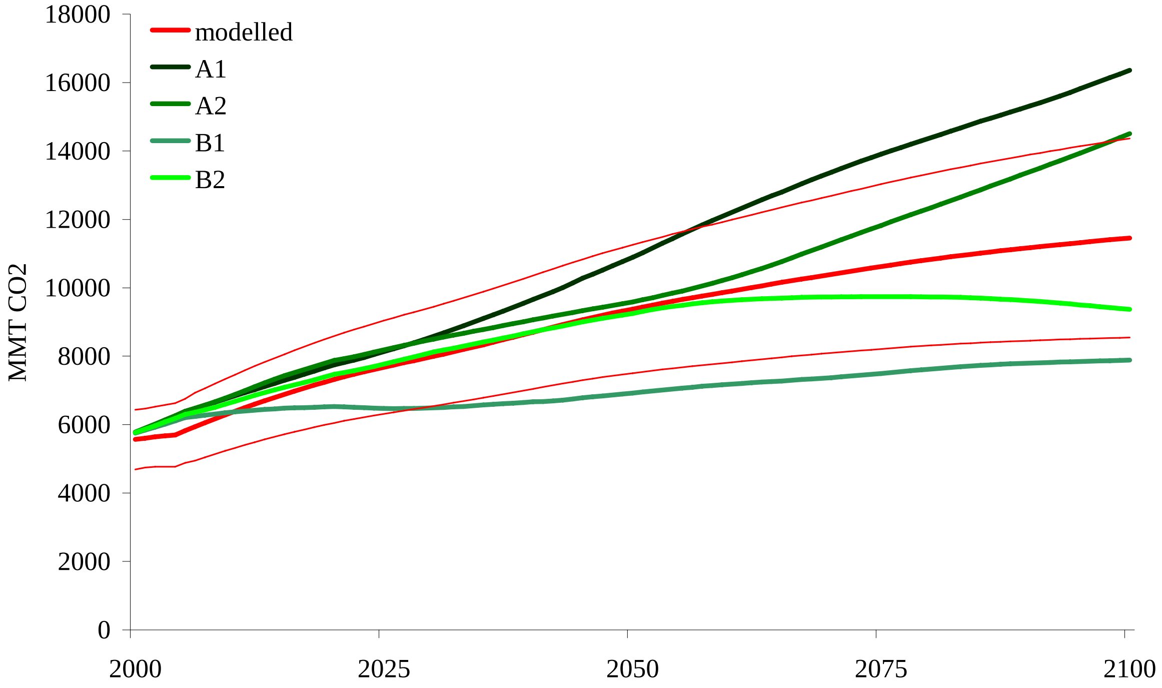


Figure 11. Carbon dioxide emissions, as projected, according to our baseline scenario and four IPCC scenarios.

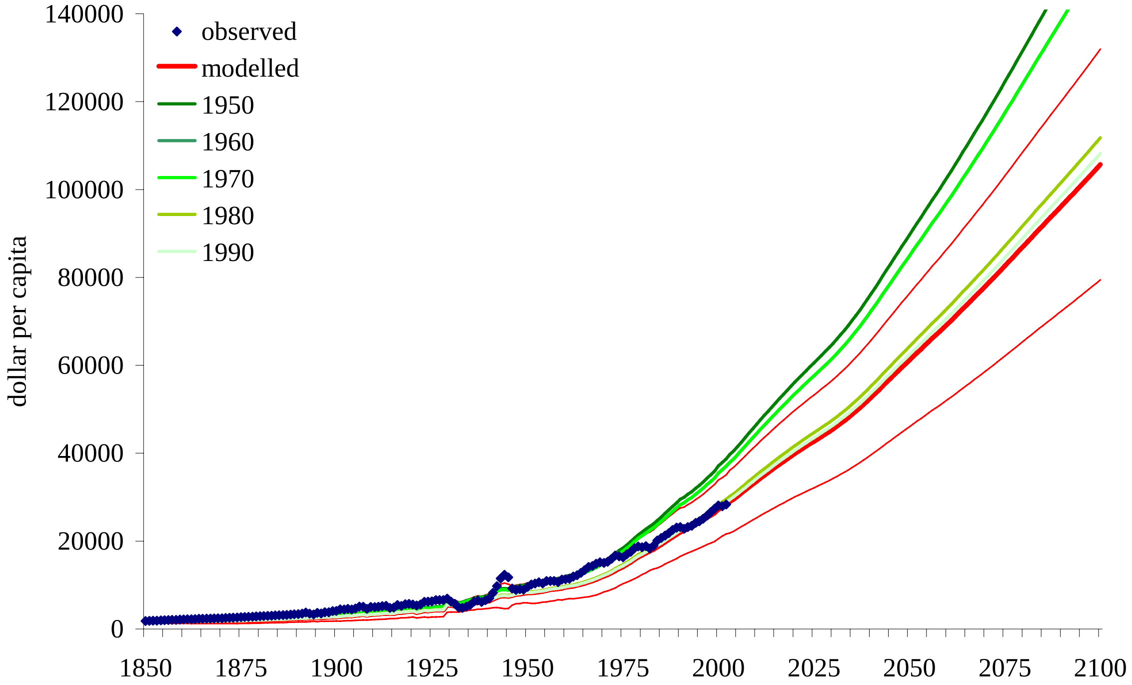


Figure 12. Sensitivity analysis, economic growth; the model was calibrated for the period from 1850 to the year in the legend. For “modelled”, the calibration period extended up to 2000; this projection include the 67% confidence interval.

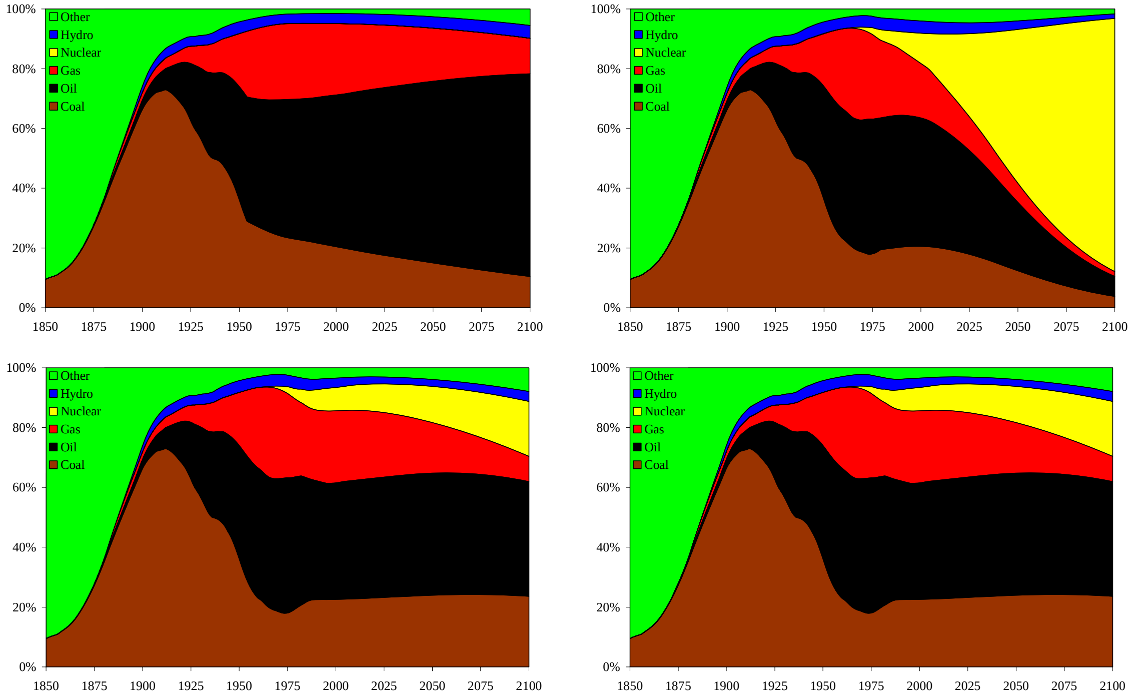


Figure 13. Primary energy use, by source.

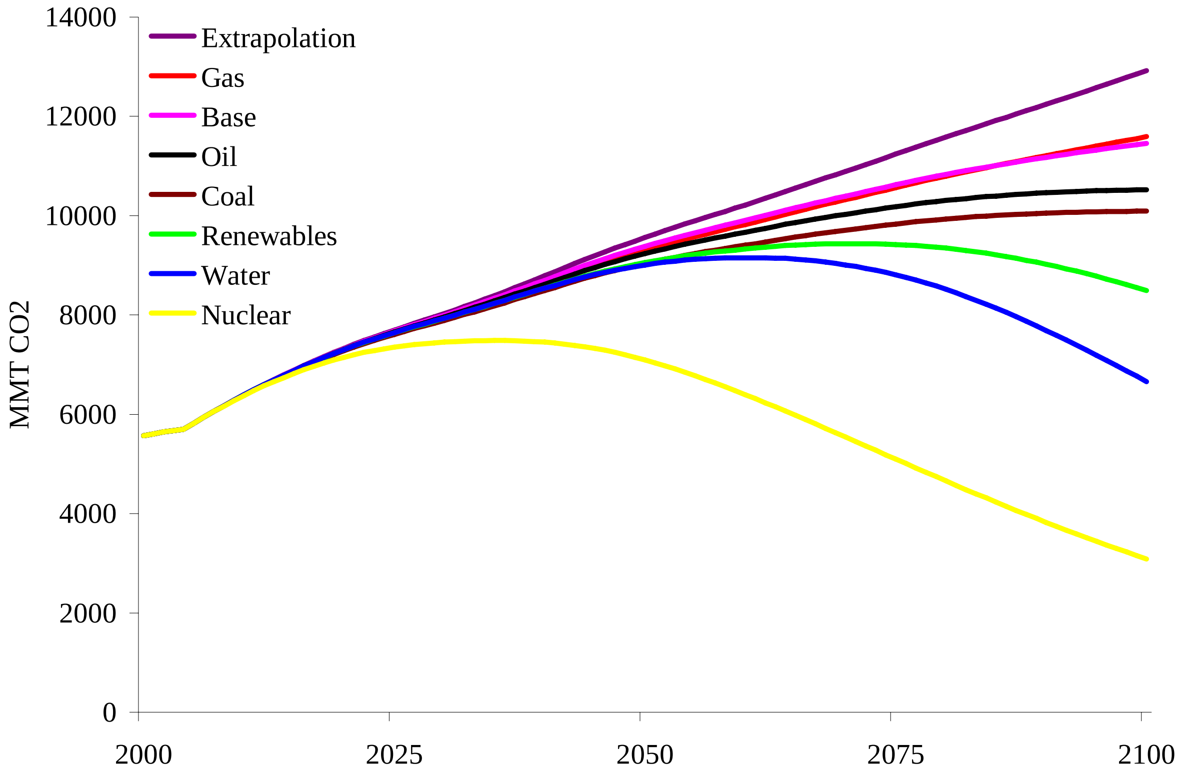


Figure 14. Carbon dioxide emissions, as projected, according to our baseline scenario and seven sensitivity analyses.

Appendix: The Kongsamut, Rebelo and Xie (KRX) model

Below, we show three versions of the same model. The first version is identical to the one in Kongsamut *et al.* (2002), but with an error corrected (in relative employment). The second version is more general, but more specific than the second model in Kongsamut *et al.* (1997), the working paper version of the 2002 article. The third version is more general still, and coincides with the third model in Kongsamut *et al.* (1997). However, the solution proposed here is much more straightforward than in Kongsamut *et al.* (1997), which is unnecessarily complicated.

Mathematically, the model consists of a set of conservation equations and differential equations. From first principles, all conservation equations are known, but only some of the differential equations. The model is solved by finding the missing differential equations. This is relatively straightforward in the simple version of the model. That solution inspires a proposal for a solution of the intermediate version, which in turn suggests a solution for the general model. In the paper, we use the general model; see Equations (5)-(7).

The basic model

Labour and capital are the only two factors of production. The economy has three sectors: agriculture, manufacturing and services. Production is given by

(A1) $A(t) = B_A F(\varphi_A(t)K(t), \vartheta_A(t)L(t))$

(A2) $M(t) = B_M F(\varphi_M(t)K(t), \vartheta_A(t)L(t)) - I(t) - \delta K(t)$

(A3) $S(t) = B_S F(\varphi_S(t)K(t), \vartheta_S(t)L(t))$

with

(A4) $\varphi_A(t) + \varphi_M(t) + \varphi_S(t) = 1$

(A5) $\vartheta_A(t) + \vartheta_M(t) + \vartheta_S(t) = 1$

(A6) $\dot{L}(t) = gL(t)$

(A7) $\dot{K}(t) = \delta K(t) + I(t)$

If we assume perfect capital and labour mobility and constant returns to scale, then production efficiency implies

(A8) $\frac{\varphi_A}{\vartheta_A} = \frac{\varphi_M}{\vartheta_M} = \frac{\varphi_S}{\vartheta_S} = 1$

If we normalise the price of manufactured goods to unity, product-mix efficiency implies that the price of agricultural produce and services equals

(A9) $P_A = \frac{B_M}{B_A}; P_S = \frac{B_M}{B_S}; \frac{P_A}{P_S} = \frac{B_S}{B_A}$

Consumers maximise

(A10) $U = \int_0^\infty \frac{\left[\left(A(t) - \overline{A}\right)^\kappa M(t)^\lambda \left(S(t) + \underline{S}\right)^{1-\kappa-\lambda}\right]^{1-\varepsilon} - 1}{1-\varepsilon} e^{-\rho t} \mathrm{d}t$

$\bar{A}$ is the subsistence level of agriculture, while $\underline{S}$ is the amount of services produced in the household.

Equation (A10) is maximised under the budget constraint

$$\text{(A11)}\quad \begin{aligned} &P_A A(t) + M(t) + P_S S(t) + I(t) + \delta K(t) = \\ &P_A B_A F(\varphi_A K(t), \vartheta_A L(t)) + B_M F(\varphi_M K(t), \vartheta_M L(t)) + P_S B_S F(\varphi_S K(t), \vartheta_S L(t)) = \\ &B_M F(L(t), K(t)) = B_M F(1, k(t)) L(t); k(t) := \frac{K(t)}{L(t)} \end{aligned}$$

The final steps follow from (A9) and the assumed constant returns to scale.

The static first-order conditions of (A10) and (A11) yield

$$\text{(A12)}\quad \frac{P_A\left(A(t)-\bar{A}\right)}{\kappa} = \frac{M(t)}{\lambda}; \frac{P_S\left(S(t)-\underline{S}\right)}{1-\kappa-\lambda} = \frac{M(t)}{\lambda}$$

which determine the movement of the consumption of agriculture and services relative to manufacturing, as relative prices are constant by (A9).

The interest rate *r* follows from

$$\text{(A13)}\quad r(t) = B_M \frac{\partial F(k(t),1)}{\partial k(t)} - \delta$$

Manufacturing follows Euler's equation

$$\text{(A14)}\quad \frac{\dot{M}(t)}{M(t)} = \frac{r(t)-\rho}{\lambda}$$

Along the generalised balanced growth path, the interest rate is constant: $r(t)=r$. This in turn implies that $k(t)$ is constant – see (A13) – that is, capital and labour grow at the same rate *g*. Constant returns to scale and Equation (A2) imply that $M+\partial K+I$ grow at the same rate as well; in fact $\partial K+I$ is net investment, which grows at *g*, so that *M* grows at *g* as well. So, the right-hand-side of budget constraint (A11) grows at rate *g* and some elements of the left-hand-side grow at *g* as well. This implies that $P_A A+P_S S$ has to grow at rate *g* too. Equations (A9) and (A12) imply that $A-\bar{A}$ and $S+\underline{S}$ grow at rate *g*. These two conditions can only be simultaneously met if $\bar{A}B_S=\underline{S}B_{A.}$; combined with (A9):

$$\text{(A15)}\quad \begin{aligned} &\bar{A}B_S = \underline{S}B_A \;\Leftrightarrow\; P_A\bar{A} = P_S\underline{S} \;\Rightarrow \\ &P_A A + P_S S = P_A A + P_S S - P_A\bar{A} + P_S\underline{S} = P_A(A-\bar{A}) + P_S(S+\underline{S}) \end{aligned}$$

The right-hand-side of (15) grows at rate *g*, and so does the left-hand-side. With this parameter restriction, budget constraint (A11) holds.

If $A-\bar{A}$ and $S+\underline{S}$ grow at rate *g*, then

$$\text{(A16)}\quad \frac{\dot{A}(t)}{A(t)} = g\frac{A(t)-\bar{A}(t)}{A(t)}; \frac{\dot{S}(t)}{S(t)} = g\frac{S(t)+\underline{S}(t)}{S(t)}$$

Equations (A1-A3) imply

$$\frac{\dot{\varphi}_A(t)}{\varphi_A(t)}+\frac{\dot{K}(t)}{K(t)}=\frac{\dot{\varphi}_A(t)}{\varphi_A(t)}+g=\frac{\dot{\vartheta}_A(t)}{\vartheta_A(t)}+\frac{\dot{L}(t)}{L(t)}=\frac{\dot{A}(t)}{A(t)}=g\frac{A(t)}{A(t)}-g\frac{\overline{A}(t)}{A(t)}\Rightarrow$$

$$\begin{aligned}&\frac{\dot{\varphi}_A(t)}{\varphi_A(t)}=\frac{\dot{\vartheta}_A(t)}{\vartheta_A(t)}=-g\frac{\overline{A}}{A}\\&\frac{\dot{\varphi}_M(t)}{\varphi_M(t)}=\frac{\dot{\vartheta}_M(t)}{\vartheta_M(t)}=0\\&\frac{\dot{\varphi}_S(t)}{\varphi_S(t)}=\frac{\dot{\vartheta}_S(t)}{\vartheta_S(t)}=g\frac{\underline{S}}{S}\end{aligned}\tag{A17}$$

Note that (A17) deviates from the result by Kongsamut *et al.* (2002).

Different production functions

Equation (A17) is rather restrictive; it implies that the relative movement of labour, capital and production in the three sectors is not only of the same sign, but also of the same magnitude. That is, if 10% of workers shifts from agriculture to services, then 10% of invested capital, production and consumption shifts too. This result follows from Equation (A8), and goes back to the fact that the production functions in (A1)-(A3) are proportional. In reality, one would expect that manufacturing is more capital-intensive, and services more labour-intensive, so that economic modernisation is characterised by a shift of workers to services, and a shift of capital to manufacturing.

Let us assume that the production functions (A1-A3) are Cobb-Douglas with different parameters for the three sectors:

$$A(t)=B_A\left[\varphi_A(t)K(t)\right]^{\alpha}\left[\vartheta_A(t)L(t)\right]^{1-\alpha}\tag{A1'}$$

$$M(t)=B_M\left[\varphi_M(t)K(t)\right]^{\mu}\left[\vartheta_M(t)L(t)\right]^{1-\mu}-I(t)-\delta K(t)\tag{A2'}$$

$$S(t)=B_S\left[\varphi_S(t)K(t)\right]^{\sigma}\left[\vartheta_S(t)L(t)\right]^{1-\sigma}\tag{A3'}$$

Then, (A8) is replaced by

$$\frac{1-\alpha}{\alpha}\frac{\varphi_A}{\vartheta_A}=\frac{1-\mu}{\mu}\frac{\varphi_M}{\vartheta_M}=\frac{1-\sigma}{\sigma}\frac{\varphi_S}{\vartheta_S}\tag{A8'}$$

Whereas (A8) implies that the distribution of labour is the same as the distribution of capital, (A8') allows the two to deviate.

Instead of (A9), we have

$$P_A=\frac{B_M}{B_A}\frac{\mu\left(\varphi_M K\right)^{\mu-1}\left(\vartheta_M L\right)^{1-\mu}}{\alpha\left(\varphi_A K\right)^{\alpha-1}\left(\vartheta_A L\right)^{1-\alpha}};P_S=\frac{B_M}{B_S}\frac{\mu\left(\varphi_M K\right)^{\mu-1}\left(\vartheta_M L\right)^{1-\mu}}{\sigma\left(\varphi_S K\right)^{\sigma-1}\left(\vartheta_S L\right)^{1-\sigma}}\tag{A9'}$$

which reduces to (A9) if $\alpha=\mu=\sigma$; note that (A8) holds then as well.

The budget constraint (A11) does not change, although it cannot be simplified to manufacturing production only. Therefore, Equation (A12) still holds, although in this case both relative prices and relative production may shift.

Equations (A13) and (A14) are unchanged, so a constant real interest rate *r* implies that *k* has to be constant, and both *K* and *L* grow at rate *g*. In fact, *M* and $\partial K+I$ grow at *g* too. This implies that

$$\text{(A18)} \quad \begin{aligned} \dot{P}_A &= \frac{\partial}{\partial t} \frac{B_M \mu \varphi_M{}^{\mu-1} \vartheta_M{}^{1-\mu}}{B_A \alpha \varphi_A{}^{\alpha-1} \vartheta_A{}^{1-\alpha}} K^{\mu-\alpha} L^{\alpha-\mu} = \\ & C\left[(\mu-\alpha) L^{\alpha-\mu} K^{\mu-\alpha-1} gK + (\alpha-\mu) K^{\mu-\alpha} L^{\alpha-\mu-1} gL\right] = 0 \end{aligned}$$

The same holds for the change in the price of services. Therefore, the parameter condition for the generalised balanced growth path changes from $\bar{A}B_S=\underline{S}B_A$ to

$$\text{(A19)} \quad \bar{A} B_S \sigma \left(\varphi_S K\right)^{\sigma-1} \left(\vartheta_S L\right)^{1-\sigma} = \underline{S} B_A \alpha \left(\varphi_A K\right)^{\alpha-1} \left(\vartheta_A L\right)^{1-\alpha}$$

Although (A19) has time-dependent variables, their joint growth rate is zero.

Therefore, (A16) still holds, and so does (A17). The model has become more complicated, but its dynamic behaviour has not changed.

Biased technological change

Let us further complicate the model and explicitly introduce labour-augmenting technological change. The production functions are:

$$\text{(A1'')} \quad A(t) = B_A \left[\varphi_A(t) K(t)\right]^{\alpha} \left[\vartheta_A(t) H_A(t) L(t)\right]^{1-\alpha}$$

$$\text{(A2'')} \quad M(t) = B_M \left[\varphi_M(t) K(t)\right]^{\mu} \left[\vartheta_M(t) H_M L(t)\right]^{1-\mu} - I(t) - \delta K(t)$$

$$\text{(A3'')} \quad S(t) = B_S \left[\varphi_S(t) K(t)\right]^{\sigma} \left[\vartheta_S(t) H_S(t) L(t)\right]^{1-\sigma}$$

with

$$\text{(A4)} \quad \varphi_A(t) + \varphi_M(t) + \varphi_S(t) = 1$$

$$\text{(A5)} \quad \vartheta_A(t) + \vartheta_M(t) + \vartheta_S(t) = 1$$

$$\text{(A6)} \quad \dot{L}(t) = gL(t)$$

$$\text{(A7)} \quad \dot{K}(t) = \delta K(t) + I(t)$$

$$\text{(A20)} \quad \dot{H}_A(t) = g_A H_A(t); \dot{H}_M(t) = g_M H_M(t); \dot{H}_S(t) = g_S H_S(t)$$

Note that if $g_A=g_M=g_S$, we might as well have added it to *g*, and set $H(t)=1$.

Statically, nothing has changed. Equations (A8’), (A9’), (A11), and (A12) still hold.

Dynamically, things do change; $k(t)$ is redefined as $k(t):=K(t)/L(t)/H(t)$. Then, Equations (A13) and (A14) hold. However, if the interest rate is constant, capital in manufacturing now grows as the rate of *effective* labour, that is $g+g_M$. Then,

$$\begin{aligned}
&\dot{P}_A = \frac{\partial}{\partial t}\frac{B_M \mu {\varphi_M}^{\mu-1} {\vartheta_M}^{1-\mu}}{B_A \alpha {\varphi_A}^{\alpha-1} {\vartheta_A}^{1-\alpha}} K^{\mu-\alpha} L^{\alpha-\mu} H_M^{1-\mu} H_A^{\alpha-1} = \\
\text{(A18')}\quad & C\begin{bmatrix} (\mu-\alpha)L^{\alpha-\mu}H_M^{1-\mu}H_A^{\alpha-1}K^{\mu-\alpha-1}(g+g_M)K + (\alpha-\mu)K^{\mu-\alpha}H_M^{1-\mu}H_A^{\alpha-1}L^{\alpha-\mu-1}gL + \\ (1-\mu)K^{\mu-\alpha}L^{\alpha-\mu}H_A^{\alpha-1}H_M^{-\mu}g_M H_M + (\alpha-1)K^{\mu-\alpha}L^{\alpha-\mu}H_M^{1-\mu}H_A^{\alpha}g_A H_A \end{bmatrix} \Leftrightarrow \\
&\dot{P}_A = P_A(1-\alpha)(g_M - g_A) \\
&\dot{P}_S = P_S(1-\sigma)(g_M - g_S)
\end{aligned}$$

Note that for agricultural prices to fall, we need that technological progress is *faster* in agriculture than it is in manufacturing. Kongsamut *et al.* (1997) show empirical support for this.

If the savings and depreciation rates are constant, both effective labour and capital grow at $g+g_M$, and the relative shares of labour and capital in manufacturing is constant, then

$$\text{(A21)}\quad \frac{\dot{\varphi}_M}{\varphi_M} = \frac{\dot{\vartheta}_M}{\vartheta_M} = 0$$

Equation (A12) still holds, so

$$\text{(A22)}\quad \frac{\dot{P}_A A + P_A \dot{A} - \dot{P}_A \overline{A}}{P_A(A-\overline{A})} = \frac{\dot{P}_S S + P_S \dot{S} + \dot{P}_S \underline{S}}{P_S(S+\underline{S})} = g + g_M$$

which implies

$$\begin{aligned}
&\frac{\dot{A}}{A} = \frac{A-\overline{A}}{A}\left(\frac{\dot{P}_A}{P_A} + g + g_M\right) = \frac{A-\overline{A}}{A}\left((1-\alpha)(g_M-g_A) + g + g_M\right) \\
\text{(A23)}\quad & \\
&\frac{\dot{S}}{S} = \frac{S+\underline{S}}{S}\left((1-\sigma)(g_M-g_S) + g + g_M\right)
\end{aligned}$$

Note that (A23) and (A16) differ by a constant only. If all elements on the left hand side of budget constraint (A11) expand at the same rate $g+g_M$, we again have the restriction

$$\begin{aligned}
&P_A\overline{A} = P_S\underline{S} \Leftrightarrow (1-\alpha)(g_M-g_A) = (1-\sigma)(g_M-g_S) \Leftrightarrow \\
\text{(A23)}\quad & \\
&g_S = g_M\frac{\alpha-\sigma}{1-\sigma} + g_A\frac{\alpha-1}{1-\sigma}
\end{aligned}$$

In addition, (19) holds.

$$\begin{aligned}
&\frac{\dot{\varphi}_A}{\varphi_A} = \frac{\dot{\vartheta}_A}{\vartheta_A} = \frac{A-\overline{A}}{A}(1-\alpha)(g_M-g_A) - (g+g_M)\frac{\overline{A}}{A} \\
\text{(A24)}\quad & \\
&\frac{\dot{\varphi}_S}{\varphi_S} = \frac{\dot{\vartheta}_S}{\vartheta_S} = \frac{S+\underline{S}}{S}(1-\sigma)(g_M-g_S) - (g+g_M)\frac{\underline{S}}{S}
\end{aligned}$$

which reduces to (A17) if $g_A=g_M=g_S$. Equation (A24) is qualitatively different from (A17). However, capital and labour still move in tandem.

Equation (A23) corresponds to Equations (5) and (7). The model is initialised by setting the starting values equal to the first observations.

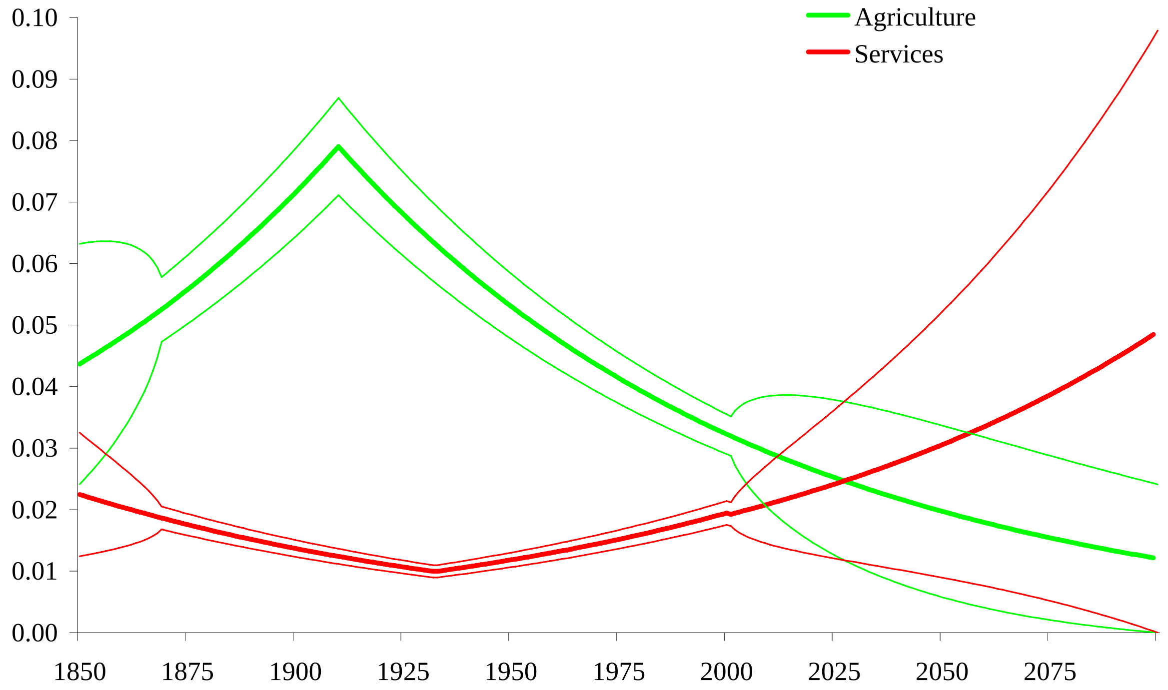


Figure A1. Adjustment factors for agriculture and services; see Equations (5), (7) and (A24).

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