AN EVOLUTIONARY ANALYSIS OF WORLD ENERGY CONSUMPTION AND WORLD POPULATION

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PREFACE

This paper is a product of network activities coordinated by the System and Decision Sciences Program at IIASA. It also gained much from collaboration with other IIASA projects, in particular the Energy Development, Economy and Investments Program and the Population - Aging and Changing Lifestyles Program.

Together with the National Academy of Sciences of the GDR (Departments of Cybernetics and Mathematics), IIASA is working on an ecological approach to applied systems analysis based on the Volterra equations. In this paper, the evolution of world energy consumption and world population are analyzed using this approach. The results should be viewed as complementary to those obtained using different methods by other research projects at IIASA.

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ABSTRACT

The evolution of large-scale systems is described by a model based on the assumption of hyperbolic growth and saturation processes. It is shown that this Hyper-Logistic Evolution Model (HLEM) successfully describes the development of world population and global primary energy consumption over the past century; the model is also used to provide projections of world population and primary energy consumption up to the year 2100.

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1. INTRODUCTION

Ever since the invention of the crystal ball, men have tried to foresee what will happen to them in the future.

The development of high-speed computing machines in the mid-sixties encouraged attempts to project the present behavior of large-scale systems into the future using complex mathematical models. This work culminated in the construction of many large computerized simulation models [1,2,3] designed to aid in long-term planning.

Most of the programs and methods currently in use require the system being studied to be decomposed into a number of "basic" subsystems. Among these subsystems are some with intrinsic growth characteristics which drive the evolution of the whole system, e.g., the population subsystem. Very often the development of these individual subsystems follows an exponential growth law, with external conditions having a multiplier-like influence on the growth rates. The behavior of the total system is then simulated by linking the subsystems via transfer functions, taking into account the relationships between subsystems.

When applying this method to a given system in practice, the user has to decide how to decompose the system and which subsystems are sufficiently basic to be described by a simple exponential law. In addition, the number of unknown parameters increases as the number of subsystems rises, and this soon leads to complex multidimensional problems.

Another approach is based on the assumption that the investigated system develops as a whole and that the external perturbations are not very strong. Here the interrelationships between the subsystems are such that they fulfill a certain uniform law of evolution for the entire system. Generally this approach drastically reduces the dimension of the problem, making decomposition unnecessary. However, there is still the question of finding an evolution law appropriate to the system studied and yet sufficiently simple. One tentative step in this direction has been taken in ref. 4, where the long-term development of world population is described by a hyperbolic law.

The approach adopted in this paper is based on the second of the two strategies outlined above. We assume that the evolution of large-scale systems may be described by a combination of hyperbolic growth laws and hyperbolic saturation functions, the latter reflecting the idea that the system cannot grow *ad infinitum* - at some point saturation effects must take over. The validity of this assumption is demonstrated empirically, and a systems-theoretical justification is also given. Our Hyper-Logistic Evolution Model (HLEM) is described in Section 2, and in Section 3 the model parameters are evaluated by fitting model curves to observed data for world primary energy consumption [5] and world population [6]. Using this model, world primary energy consumption and world population are projected to the year 2100 and compared with results obtained from IIASA studies [5,6] in Section 4. The conclusions of the study are summarized in Section 5.

2. THE HYPER-LOGISTIC EVOLUTION MODEL

The model is based on the assumption that the systems to be modeled have a hierarchical structure and that evolution is a smooth deterministic process which can be described by differential equations. The basic structure is assumed to be a chain of rate-coupled systems with exponential growth functions, similar to enzyme reaction chains or food chains. The general form of such a process can be written as follows [7,8]:

$$\frac{dx_i^N}{dt} = K_i x_i^N x_{i+1}^N - L_i x_i^N x_{i-1}^N - a_i x_1^N \quad (i=0,1,\ldots,N) \quad (1)$$

where i and N are indices of hierarchical level and chain length, respectively, x is a state variable, t is time, and K, L and a_i are parameters. Neglecting the death rate $a_i x_i^N$ and the feedback term $L_i x_i^N x_{i-1}^N$ from the previous hierarchical level (as in refs. 7 and 8) leads to a structure in which the growth of each level is governed only by its own state and by the state of the level above it:

$$\frac{dx_i^N}{dt} = K_i x_i^N x_{i+1}^N \qquad (i = 0,1,\ldots,N) \quad . \quad (2)$$

This is the simplest rate-coupled chain structure, which we call an exponential tower. For convenience, all initial values are set to $x_i(t_0) = 1$. With a constant input x_N^N, a chain with N = 1 thus exhibits exponential growth with a constant rate K_0, while for N = 2 we have the following growth law:

$$x_0^2 = \exp\left\{\frac{K_0}{K_1 x_2^2}\left[\exp\left(K_1 x_2^2 (t-t_0)\right) - 1\right]\right\} \quad . \quad (3)$$

It is difficult to integrate equation (2) for N > 2. However, it can be shown [9] that as the chain length $N (N \gg 1)$ increases, system (2) converges to a system with hyperbolic $(b_0 > 0)$ or parabolic $(b_0 < 0)$ growth, assuming that the higher K_i $(i = 1,2,\ldots,N)$ are finite and equal to a positive constant a:

$$x_0^N \approx \frac{K}{(t_p - at)^{b_0}} \qquad (N \gg 1) \quad . \quad (4)$$

Here t_p/a denotes the value of t at the pole of the hyperbola.

Using the substitution $b_0 = 1/(k-1)$, equation (4) can be reformulated as a differential equation:

$$\frac{dx_0^N}{dt} \approx \tilde{A}\left(\frac{x_0^N}{\tilde{x}}\right)^k \qquad (N \gg 1) \qquad (4')$$

where the normalizing factor $\tilde{x}$ is introduced to obtain reasonable units for parameter $\tilde{A}$.

Thus a hierarchically organized rate-coupled chain of exponentially growing systems with equal rate constants in the higher levels exhibits hyperbolic or parabolic growth, and this kind of behavior has actually been found in a great number of real systems [10]. We therefore suggest that hyperbolic or parabolic growth is a fundamental characteristic of such large-scale hierarchical systems.

The equations given above do not include any growth-limiting processes. However, reasonably pure hyperbolic or parabolic growth processes can only be observed far from saturation. To take into account saturation processes with a saturation limit B we have to incorporate a second chain of length M in our model:

$$\frac{dx_0^M}{dt} \approx \hat{A}\left(\frac{B-x_0^M}{\tilde{x}}\right)^\ell \quad . \qquad (5)$$

To obtain the combined equation we simply multiply equations (4') and (5) together, which ensures that coupling between the processes is small [9], and then take the limits $M,N \rightarrow \infty$:

$$\frac{dx}{dt} = A\left(\frac{x}{\tilde{x}}\right)^k \left(\frac{B-x}{\tilde{x}}\right)^\ell \quad . \qquad (6)$$

Here k and ℓ express the strength of the interlevel interactions affecting the driving and saturation processes, respectively. In general, the stronger these interactions, the more complex is the system, so that the exponents k and ℓ give a rough measure of the complexity of the corresponding processes. Since there is no link between levels in the case of exponential growth, we use k-1 and ℓ-1 as measures of interlevel interaction. It should perhaps be pointed out that for $k=\ell=1$ eqn. (6) yields the wellknown logistic growth law (corresponding to chain lengths M=N=1), whereas for $k,\ell > 1$ it leads to hyperbolic growth and saturation functions. For this reason we describe eqn. (6) as a Hyper-Logistic Growth Law.

Because of the high convergence velocity of systems (2) [9], the condition $M,N \to \infty$ can be relaxed.* Thus, eqn. (6) should also provide a satisfactory description of systems with only a few hierarchical levels. This equation describes the transition from one stationary level (x=0) to the next (x=B) as a process with very smooth dynamics - there are no sudden changes in growth rates, rates of change, etc. This is a very desirable property from the point of view of economic systems. The growth dynamics of the model are internally consistent, which in real economic systems corresponds to a high potential for self-regulation, thus making such "soft" transitions possible.

3. EVALUATION OF MODEL PARAMETERS

Before the model can be used to explain historical data or predict future developments, it is necessary first to ensure that the assumptions made in Section 2 are satisfied, and then to evaluate the model parameters. We use world primary energy consumption and world population as state variables in the following discussion.

Figures 1 and 2 present observed data on world primary energy consumption and world population growth and also give the corresponding model curves. Except for the period between the years 1914 and 1949 in Figure 1, the data show a smooth regular growth pattern with no sign of saturation. The irregular pattern between 1914 and 1949 is probably due to the effects of World War I, the Depression, World War II, and post-war depression. However, we assume that these events only slow down the evolutionary process without changing its structural parameters, e.g., the exponents. Thus, eqn. (6) with A = A(t) can be used to describe the pattern of evolution over this period. We assume that all parameters remain constant except that parameter A is reduced by a constant factor $0 \leq \varepsilon \leq 1$ between 1914 and 1949. This is equivalent to a

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*The relative approximation accuracy of eqn. (2) can easily be calculated. Taking the hyperbola $x=1/(1-t)$ and a three-level tower (N=3), we obtain a relative accuracy of about 0.01 for the point t=0.5. An additional level would increase the accuracy by a factor of ten.

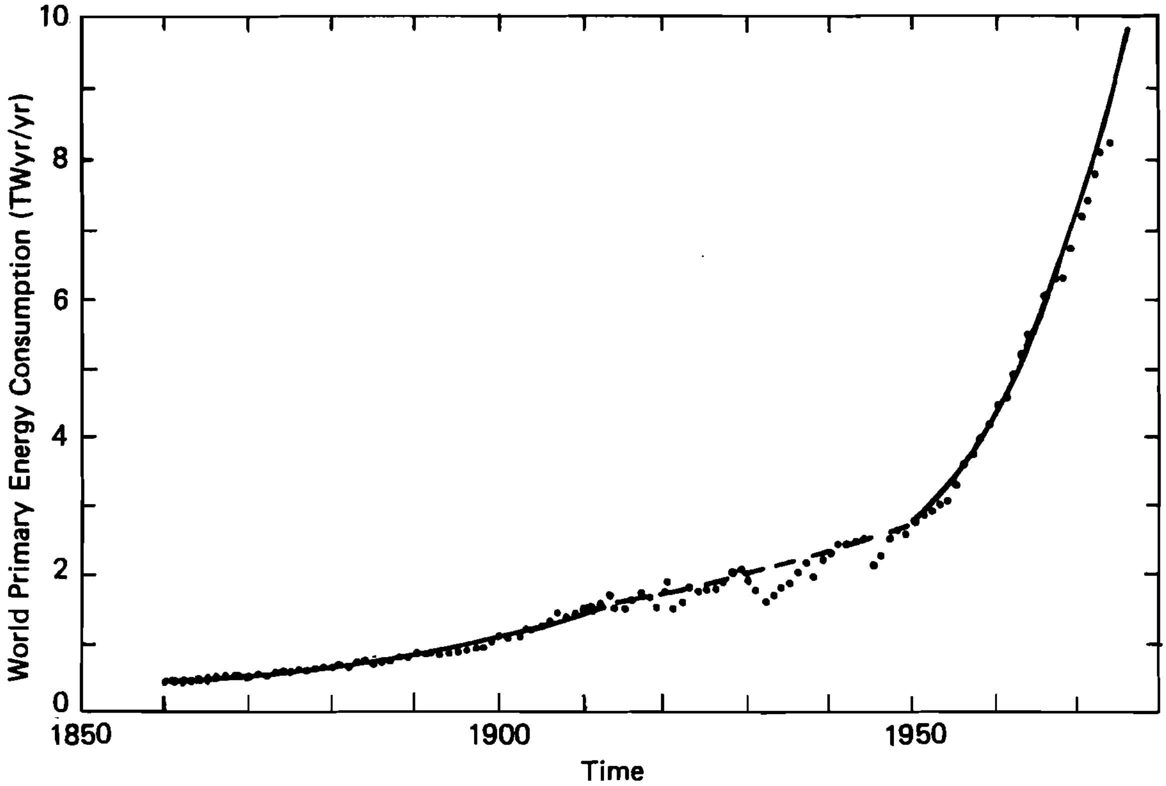

Figure 1. World primary energy consumption. The solid line represents the HLEM fit with ℓ = k and t_M = 1972, the dashed curve shows the behavior of the model in the unfitted region 1914-1949, and the individual dots represent observed data.

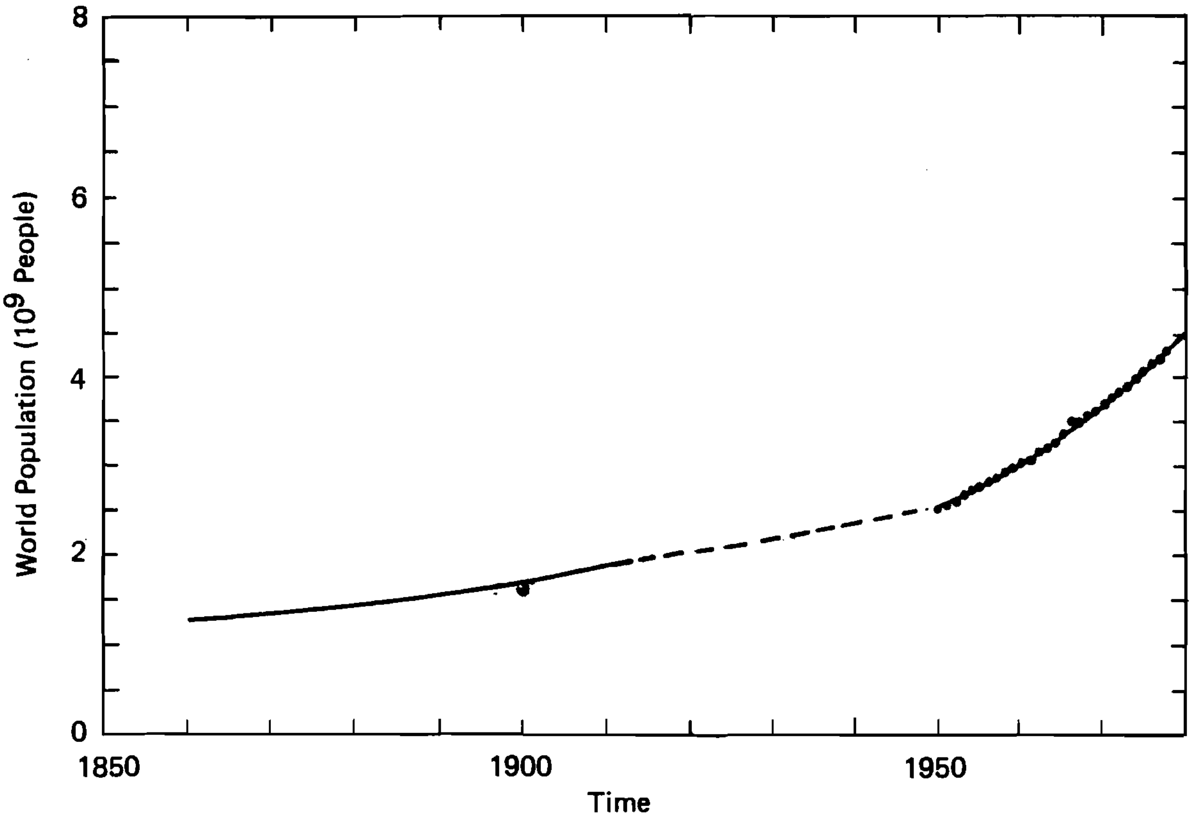

Figure 2. World population. The solid line represents the HLEM fit with ℓ = k and t_M = 1975, the dashed curve shows the behavior of the model in the unfitted region 1914-1949, and the individual dots represent observed data.

definite delay in the evolutionary process. There is no information on the saturation function in either of these data sets so that our parameter identification problem appears to be underdetermined. However, we can obtain some idea about the saturation process from other sources. For example, we know that the maximum rate of population increase has now been reached [6], and that the maximum rate of increase in energy consumption is probably already behind us. Knowing the time t_M when the maximum growth rate $\frac{dx}{xdt}\big|_{t=t_M}$ occurs, we may express the saturation level B in terms of parameters k and ℓ and the value of the state variable x at time t_M:

$$B = x_M \frac{k + \ell - 1}{k - 1} \quad . \tag{7}$$

We assume that the strength of the interactions in driving and saturation processes are equal, i.e., $k = \ell$. Thus, we still have to evaluate

- the time-scale factor A
- the delay factor ε
- the measure of interaction k
- the value x_M of x corresponding to the maximum growth rate.

In order to identify the values of these parameters, eqn. (6) must first be integrated. In general, an analytic integration of eqn. (6) is impossible if the exponents have real values. We therefore used a fourth-order Runge-Kutta-Merson method [11]* to perform a numerical integration. We excluded the data between 1914 and 1949** and adjusted the integrals by minimization of the χ^2-distance with the help of the program system MINUIT [12]. Since we had no information on the uncertainty of the data we minimized the χ^2-function with an assumed error of 10% and then renormalized the χ^2_{min}-value in such a way that an error σ in the data would correspond to an error of one standard deviation in the parameters. Using this method we obtained deviations of $\sigma = 3\%$ and $\sigma = 1\%$ for energy and population data, respectively.

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*The results are not significantly different if higher-order algorithms are used.

**Parameter values do not change (within the error limits) if we alter the boundaries of this period by a few years.

In order to estimate how the errors δ_{HLEM} of our model curves depend on the errors $\delta\alpha$ of the fitted parameters α we used a numerical approximation of the Gaussian error propagation law [12]:

$$\delta_{HLEM}(t) = \left\{ \sum_{\alpha_i} [x(t,\alpha_i+\delta\alpha_i) - x(t,\alpha_i)]^2 \right\}^{1/2} \tag{8}$$

where $x(t,\alpha_i+\delta\alpha_i)$ denotes the model output obtained at time t with parameter values $(\alpha_i+\delta\alpha_i)$ and $\alpha_j (i \neq j)$.

Table 1 presents the parameter values obtained by fitting the model to world primary energy consumption data, under three different assumptions as to when the maximum growth rate occurred (t_M = 1970, 1972, 1974). The fits show that the period before 1914 is governed by a Hyper-Logistic Evolution Law with essentially the same parameters as the post-war period. Within the error bounds, parameters ε and k are the same for different values of t_M. The value of the interaction factor $k \approx 1.5$ shows that the HLEM curves should be quite different from logistic curves, the driving function taking the form of a hyperbola. As an additional check a hyperbola (4) was fitted to the data under the assumptions made above. This resulted in a value for b of about 2.3, corresponding to $k \approx 1.4$. Comparing the significance value σ = 4% ($\chi^2_{10\%}$/NDF = 13/76)* of the hyperbola fit with corresponding values for the HLEM fits, it is clear that the assumption of a hyperbolic saturation process improves the fit.

From the delay factor ε we can conclude that the evolution of the energy system was retarded by about 21±1 years due to the two world wars and several economic depressions. Again this was checked by fitting a hyperbola, which suggested a delay of 19±1 years.

Unlike k and ε, which remain constant as t_M increases, the parameter x_M clearly increases with t_M, since we start our integration procedure at time t_M with value x_M. Equation (7) shows that for fixed values of k the saturation level B depends only on x_M and therefore increases with increasing t_M (see Table 1).

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*NDF stands for normalized distribution function.

Table 1. Values of parameters A, ε, k, and x_M obtained by fitting world primary energy consumption data under different assumptions for t_M. The calculated values of the saturation level B are also given.

Parameter	t_M = 1970	t_M = 1972	t_M = 1974
A($\times 10^2$TWyr/yr)	$1.704^{+0.007}_{-0.2}$	$1.501^{+0.006}_{-0.2}$	$1.312^{+0.006}_{-0.2}$
ε	$0.38^{+0.01}_{-0.05}$	$0.39^{+0.02}_{-0.05}$	$0.40^{+0.02}_{-0.05}$
k	$1.55^{+0.01}_{-0.04}$	$1.53^{+0.01}_{-0.04}$	$1.51^{+0.01}_{-0.04}$
x_M(TWyr/yr)	$7.11^{+0.06}_{-0.2}$	$7.89^{+0.08}_{-0.3}$	$8.79^{+0.11}_{-0.4}$
B(TWyr/yr)	27 ± 1	31 ± 1	35 ± 2
$\chi^2_{10\%}$/NDF	7.3/76	7.7/76	8.1/76

Table 2. Values of parameters A, ε, k, and x_M obtained by fitting world population data. The calculated value of the saturation level B is also given.

Parameter	t_M = 1975
A(people)	4×10^9
ε	$0.5^{+0.04}_{-0.03}$
k	3.1 ± 0.3
x_M(people)	$(4.0 \pm 0.1) \times 10^9$
B(people)	1×10^{10}
$\chi^2_{10\%}$/NDF	0.7/29

The choice of the t_M value therefore has a strong influence on x_M and B values, although the goodness of fit is not affected due to the complete decoupling of driving and saturation processes in (6) and the lack of information on the latter. A similar result may be obtained by varying ℓ according to $\ell = \eta k$ where $0.5 \leq \eta \leq 2$. In this case only the saturation level B will be influenced, all other parameters remaining unchanged. Thus, with the present data it is impossible to check hypotheses concerning the value of t_M and the strength of interactions in the saturation process.

As an example, Figure 1 shows the integral obtained with $t_M = 1972$. The solid line represents the model output in the fitted region while the dashed line between 1914 and 1949 was obtained by assuming a reduced speed of evolution.* The HLEM curve reproduces the shape of the data in the fitted region quite accurately, although in the unfitted interval between 1914 and 1949 there are large deviations from the observed data. It is interesting to note that, with the exception of a few points, our model gives values for primary energy consumption which are higher than the actual data. This implies that the real deceleration is stronger than ε. However, after an event such as a war there seems to be an upsurge which temporarily increases the velocity to values greater than normal. The depression of the data relative to the delayed model curve is plausible and can be explained by the fact that during crises a certain part of the existing system is put out of action and hence does not contribute to the output of the system. When the crisis is over these reserves are reactivated and used to bring the evolution rate back to normal relatively quickly. Nevertheless, this cannot bring back what has already been lost. The most recent data show a level of energy consumption considerably lower than that suggested by our model, reflecting the so-called energy crisis in the seventies. According to our model, this behavior should not represent the start of an entirely new trend but rather the effects of a tempo-

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*The discontinuous change of shape at t = 1913, 1950 is due to the assumption of an unsteady change in the rate of evolution at these points. This can be smoothed by using a continuous transition.

rary depression; there are already hints of a recovery. We therefore argue that the current energy crisis is only an interruption in the normal long-term behavior of the system as projected by our model.

The results obtained by fitting the model to world population data are given in Table 2 and Figure 2. The relative lack of historical data means that the parameter errors are larger than in the earlier case, but even within these larger parameter errors the fit shows a large deviation from a logistic growth law ($k \sim 3$). The value of the delay factor $\varepsilon \sim 0.5$ corresponds to a loss of about 17 years of evolution, which is comparable with the delay obtained for world primary energy consumption. However, a comparison of values of k in Tables 1 and 2 shows that population is a more complex system with more internal interactions than the energy system. Since smaller systems are in general less complex than larger ones [9], and the energy system can be seen as a component of the world population system, this result is not surprising. The HLEM curve shown in Figure 2 again increases smoothly with increasing time and provides a good description of the data.

4. PROJECTION OF WORLD ENERGY CONSUMPTION AND WORLD POPULATION UP TO THE YEAR 2100

There are several ways of making long-term projections of the evolution of large-scale systems. For example, predictions can be made by estimating the increase in per capita consumption together with population growth in an appropriate scenario, or by estimating local energy densities and making certain assumptions about urbanization [5]. Another quite different approach is to assume that observed dynamics of growth propagate according to a particular evolution model.

In Section 3 we have shown that, despite the simplicity of our model, it provides a good description of historical data. We will now use our model to make predictions, under the following assumptions about growth dynamics:

- The long-term growth dynamic is a process of transition from one stationary level to another
- In the absence of external disturbances, the transition follows a Hyper-Logistic Evolution law
- Driving and saturation processes have the same degree of complexity and level of internal interactions ($\ell = k$)
- An estimate of the time t_M at which the maximum growth rate occurs is obtained by analyzing historical data

It is also assumed that the present trend of evolution will continue undisturbed in the future.

Figure 3(a) presents a projection of world primary energy consumption up to the year 2100 for three different values of t_M; the corresponding error ranges (see eqn. (8)) are given in Figure 3(b).* The values obtained by an IIASA study [5] and those from the Global 2000 Report [13] are also included for comparison.

After a slightly braked rise between 1970 and 2000, the saturation process predominates, resulting in a very weak increase towards the saturation level from about 2020 onwards. The height of this saturation level rises strongly as the value of t_M increases, in accordance with eqn. (7). The point of inflection of the curves, i.e., the point at which driving and saturation processes are of equal strength, lies between 1984 and 1988, depending on the t_M value. Around 1990 the HLEM curves separate (the error bars no longer overlap), and one can try to decide which of our assumptions for the t_M value is the best and therefore which value of energy consumption may be expected in the steady state. A comparison with the IIASA energy scenarios [5] shows that for the year 2000 the energy consumption predicted by our model is more than 20% higher than that suggested by the IIASA "high" scenario, while all our projections for 2030 lie

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*Our assumption about the saturation level reduces the error ranges as time increases and therefore these ranges should not be viewed as measures of uncertainty in the traditional sense.

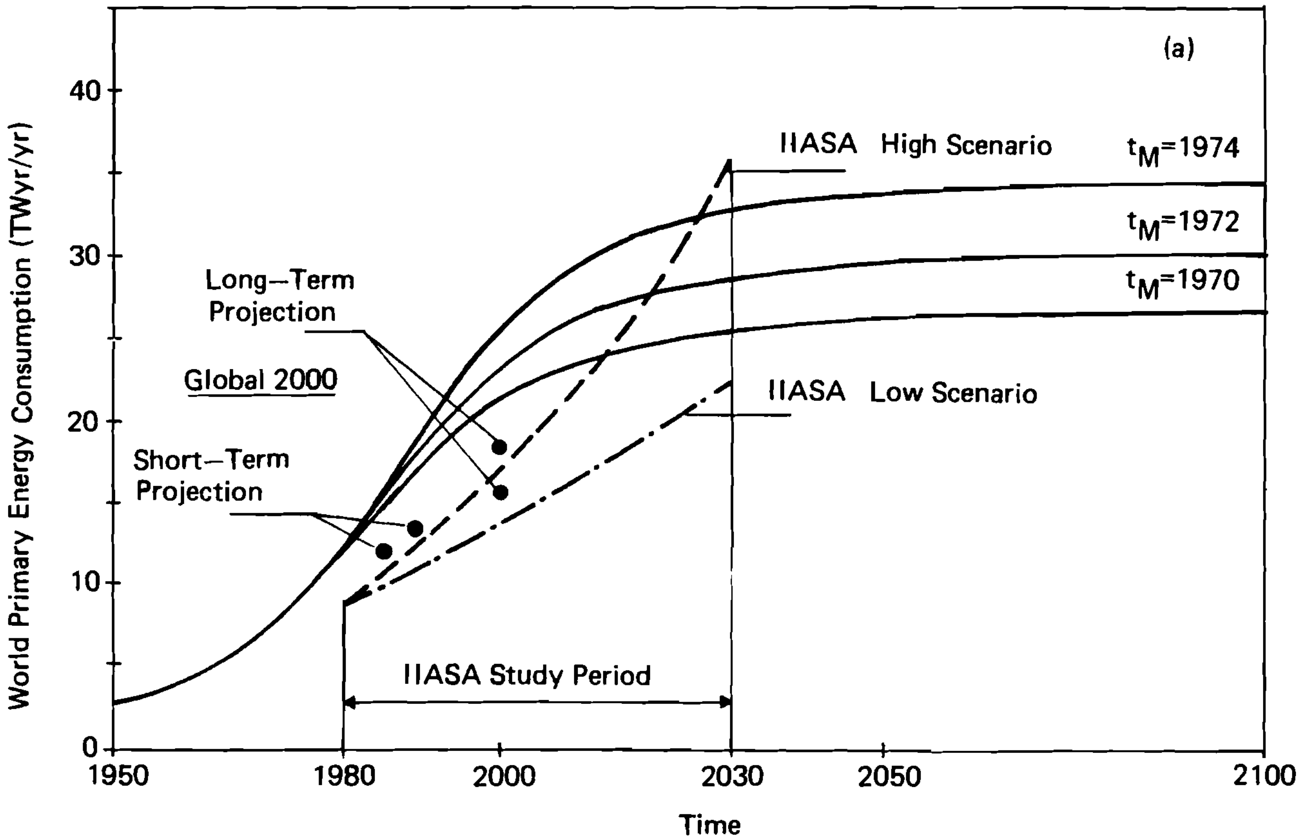
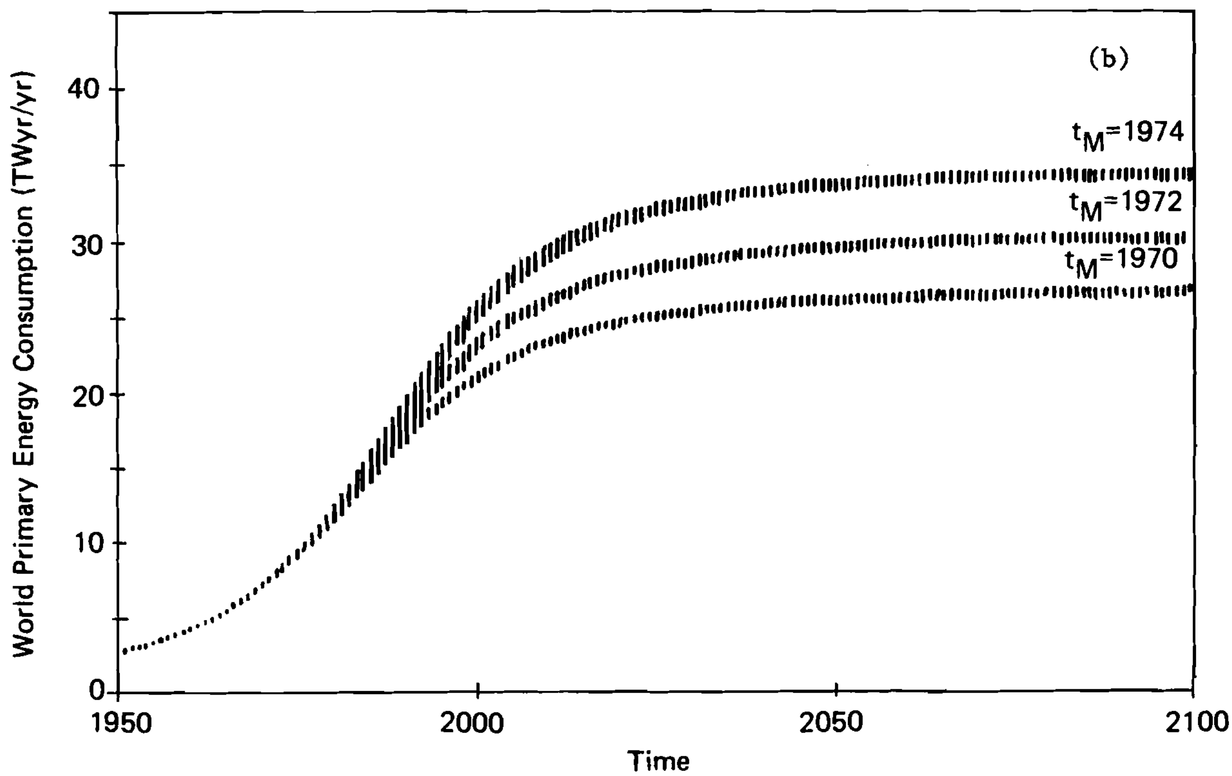


Figure 3.(a) Projection of world primary energy consumption up to the year 2100 under the assumption $\ell = k$ and with t_M = 1970, 1972, and 1974; the IIASA high and low scenarios and the Global 2000 projections [13] are also shown.

(b) Error ranges corresponding to the HLEM projections given in (a).



between the "high" and "low" IIASA scenarios. However, the growth rates predicted by HLEM behave more steadily than the IIASA predictions. This is shown in Table 3, which gives the growth rates corresponding to the various projections. As we go further into the future, the growth rates calculated by our model steadily decrease, reaching a value of about 0.04%/year for the period 2060-2100. Between 1975 and 2000 the IIASA scenarios suggest lower growth rates than does HLEM, although for the next period the IIASA predictions are more than twice as high as our values.

Figure 4(a) shows the projection of world population up to the year 2100; the corresponding error bars are given in Fig. 4(b). It can be seen that there are only small differences between the HLEM projections and the IIASA estimates [5,6]: up to the year 2000 our predictions are slightly higher than IIASA's and then this situation reverses. Having projected world primary energy consumption and world population, it is now easy to calculate future per capita primary energy consumption. The results are presented in Figure 5. After rising to a maximum of between 3.3 kW per capita and 4.2 kW per capita around the year 2010, the curves decrease smoothly to the plateau values. From the results given in Tables 1 and 2 we calculate that these values lie between 2.7 kW per capita and 3.5 kW per capita. This points to the need to increase the efficiency of energy use if we are to guarantee increasing standards of living. Since HLEM and the IIASA study predicted nearly the same population values, the discrepancies between the two sets of projections must be due to different predictions of primary energy consumption. This is also reflected in the growth rates given in Table 4: after the year 2000 the HLEM growth rates decrease very smoothly, with values of between -0.1%/year and 0.2%/year for the period 2000-2030 compared with a range of 0.8%/year to 1.6%/year for the IIASA scenarios.

In summary, HLEM predicts that world primary energy consumption and world population will undergo a very smooth transition to saturation during the next 50 years. This differs in several respects from the IIASA projections. The actual level at which saturation occurs depends strongly on the value of t_M (the time

Table 3. Annual growth rates (as percentages) of world primary energy consumption calculated from historical data and projected using HLEM. The corresponding values for two IIASA projections are given for comparison.

Basis of	Historical	Projection				
projection	1950-1973	1950-1975	1975-2000	2000-2030	2030-2060	2060-2100
HLEM						
t_M = 1970		4.98 $\pm$ 0.09	3.38 $\pm$ 0.10	0.63 $\pm$ 0.06	0.12 $\pm$ 0.04	0.04 $\pm$ 0.04
t_M = 1972		4.99 $\pm$ 0.10	3.75 $\pm$ 0.12	0.73 $\pm$ 0.08	0.13 $\pm$ 0.04	0.04 $\pm$ 0.03
t_M = 1974	4.80	5.00 $\pm$ 0.10	4.11 $\pm$ 0.15	0.84 $\pm$ 0.10	0.14 $\pm$ 0.04	0.04 $\pm$ 0.03
IIASA						
High scenario		-	2.92	2.53	-	-
Low scenario		-	2.04	1.68	-	-

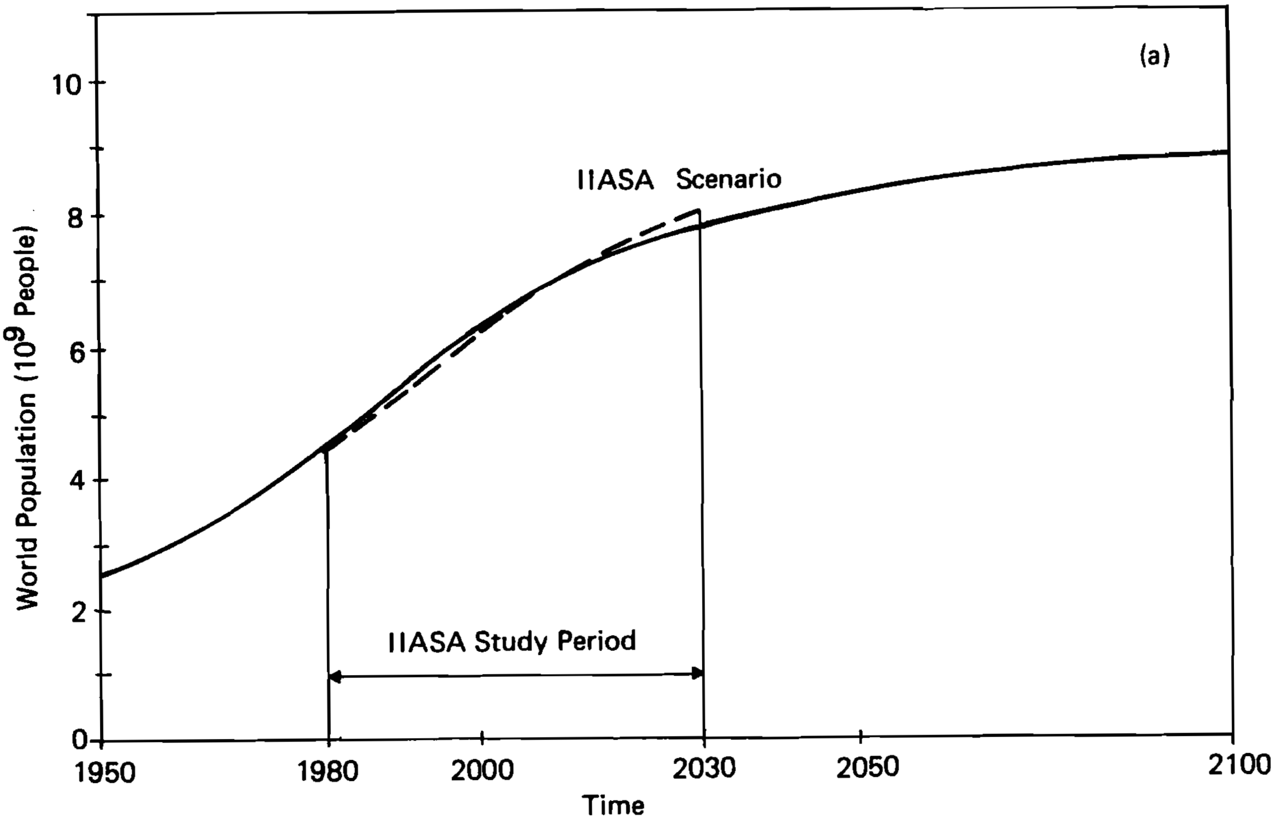
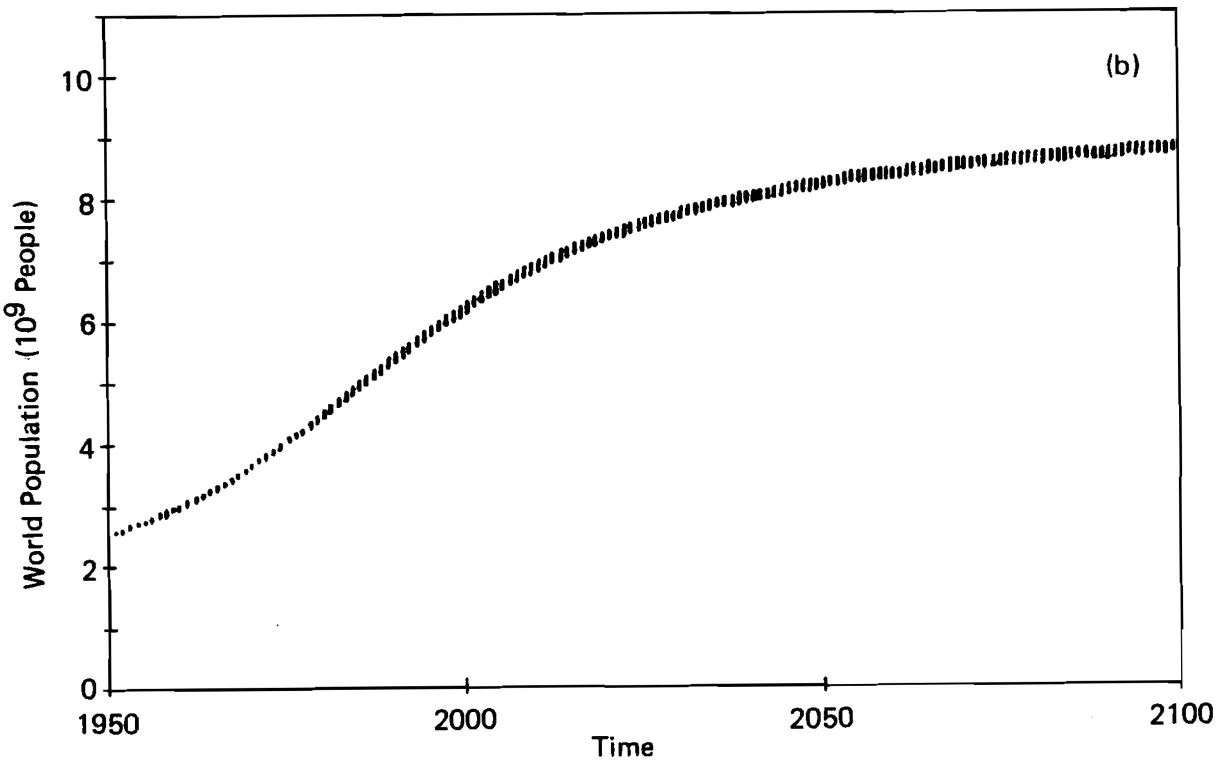


Figure 4.(a) Projection of world population up to the year 2100 under the assumptions $\ell = k$ and $t_M = 1975$. The dashed line represents IIASA projections.

(b) Error ranges corresponding to the projections given in (a).



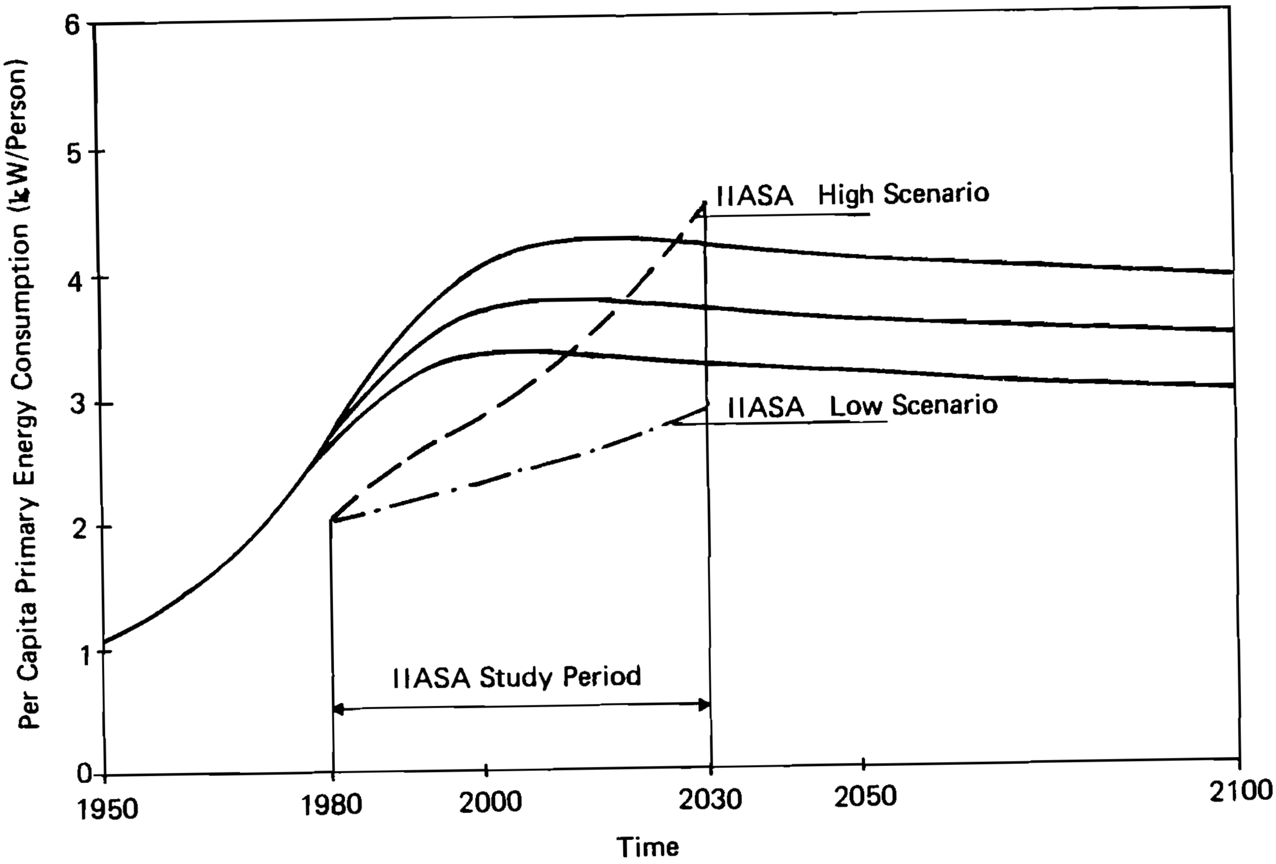


Figure 5. Projection of per capita primary energy consumption up to the year 2100. The IIASA predictions are shown for comparison.

Table 4. Annual growth rates (as percentages) of world per capita primary energy consumption calculated from historical data and projected using HLEM. The corresponding values for two IIASA projections are given for comparison.

Basis of	Historical	Projection				
projection	1950-1973	1950-1975	1975-2000	2000-2030	2030-2060	2060-2100
HLEM						
t_M = 1970		3.06 $\pm$ 0.09	1.58 $\pm$ 0.010	-0.09 $\pm$ 0.06	-0.14 $\pm$ 0.04	-0.08 $\pm$ 0.04
t_M = 1972		3.07 $\pm$ 0.10	1.94 $\pm$ 0.12	0.004 $\pm$ 0.08	-0.13 $\pm$ 0.04	-0.08 $\pm$ 0.03
t_M = 1974	2.80	3.07 $\pm$ 0.10	2.30 $\pm$ 0.15	0.11 $\pm$ 0.10	-0.12 $\pm$ 0.04	-0.08 $\pm$ 0.03
IIASA						
High scenario		-	1.15	1.63	-	-
Low scenario		-	0.29	0.76	-	-

corresponding to the maximum relative growth rate) - our model thus implies that the future development of the human race will depend on whether or not the maximum growth rates have already been reached.

5. SUMMARY

This paper describes an attempt to construct an evolutionary model for large-scale systems. Hyperbolic driving and saturation processes are taken as the basis for a Hyper-Logistic Evolution Model (HLEM); the parameters of this model have been fixed by fitting curves to world primary energy consumption and world population data. Making the assumption of a slowdown in the first half of the 20th century due to economic depressions and wars, it was possible to achieve close agreement between the model and the data. From the value of the slowdown factor we estimate that the evolution of both population and energy systems has been delayed by about 20 years. World primary energy consumption and population were then projected up to the year 2100, assuming that the maxima of the corresponding growth rates lie between 1970 and 1975. The HLEM curves show a smooth transition to saturation levels of between 27 TWyr/yr and 35 TWyr/yr (for energy consumption) and of 10^{10} people (for population). The resulting per capita world primary energy consumption shows a maximum around the year 2010 and then decreases to plateau values of between 2.7 and 3.5 kW per capita. Comparison with the IIASA energy scenarios reveals near-term discrepancies, although the predictions for 2030 are in good agreement.

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