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THE METHODOLOGY OF ENERGY PLANNING

ENERGY SERIES No. 7

af Bent Sørensen

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The interactive course of energy planning characterizing highly developed societies poses a number of problems for energy modelling approaches. This work proposes to make the first steps into the field of describing complex consumer behavior under unknown and uncertain external conditions by simulation techniques. As an example, Danish energy consumption is simulated from year 1900 to year 2030, using after 1983 stochastic elements in the energy cost development.

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THE METHODOLOGY OF ENERGY PLANNING

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ABSTRACT

The interactive course of energy planning characterizing highly developed societies poses a number of problems for energy modelling approaches. This work proposes to make the first steps into the field of describing complex consumer behavior under unknown and uncertain external conditions by simulation techniques. As an example, Danish energy consumption is simulated from year 1900 to year 2030, using after 1983 stochastic elements in the energy cost development.

1. INTRODUCTION

Responsability for energy planning is currently in the hands of energy companies (the fuel industries and electric utilities) and government departments, with increasing emphasis on the latter. Interest among concerned citizens and scientists has recently added a new dimension to energy planning, and the need for discussing the methodology behind what is done is becoming increasingly clear.

Through previous work (Sørensen 1979, 1981, 1982a, 1982b, 1982c and 1983; Crossley and Sørensen, 1982), a view has emerged of energy planning as a dynamical process, involving at least the following steps:

1. Formulating the goals of society
2. Translating the goals into energy needs
3. Designing an energy system for meeting the needs
4. Implementing (parts of) the energy system
5. Assessing the system performance and comparing actual to expected goal satisfaction

These steps are to be cycled through in an iterative procedure, without necessarily keeping the order of the steps. Assessment and public debate should take place in all phases, and it may lead to modifications or completely new plans both in the implementation phase and in the pre-implementation phase.

The current planners in government departments and in the energy industry have largely failed to reflect the implications of this scheme. Their picture of societal goals is not generally shared by the public, as the growth debate has revealed(Mishan, 1969; Schumacher 1973). Their way of translating goals into energy needs is not generally accepted by the public, as the energy efficiency debate has revealed (Nørgård, 1979). And their picture of the energy system has met with heavy criticism in society, as the nuclear power debate (Sørensen, 1975; Lovins, 1977) and the debate on decentralized energy systems, e.g. combined heat and power systems (Blegaa et al., 1976, 1977) have revealed.

If the scheme of viewing energy planning as a dynamical process with steps related to the list given above is followed, then existing energy plans, both the governmental and the alternative plans proposed by citizen groups and be scientists, must be reinterpreted. None of them could be regarded as actual plans to be followed over extended periods of time. Rather, they should be seen as elements in the public debate and assessment, mainly serving to spell out some consequences of making one or another choice of goals, of energy sources or of energy system structure, including the weight given to improving efficiency of translating energy inputs into energy supply and of translating energy supply into goal satisfaction.

This paper proposes the use of simulation techniques for the formulation of models on a higher level ("meta-models"), models which can give an idea of the probability spectrum of likely outcomes of the energy planning process based on iteration through the five steps listed above. The modelling of the outcome of public debates could be based on assigning probabilities to the perseverance of different attitudes (introducing the researchers own biases, no doubt), or by using random functions to determine the outcome of such debates. Alternatively, different variations of attitudes with time could be simulated without looking into the probability of each one, but with the purpose of trying out policy measures under such prescribed developments in attitudes. This latter approach could make the planner regain an important role, because it might allow the selection of policies, that would present a least-risk path, that is policies, which would lead to acceptable levels of goal satisfaction under most of the scenarios considered for attitude and public debate outcomes.

Not only attitude changes and the outcome of public assessment give rise to model uncertainties. Also external conditions such as fuel import prices and supply stability introduce such uncertainties. They could therefore be dealt with in the simulation approach by similar techniques: either by scenario simulation or by introducing stochastic elements in the simulation procedure.

The simulation model described in the following must be seen as only a first, extremely simplified, step in the direction of creating a generation of energy models suited for answering some of the questions related to optimal behavior under highly complex planning procedures and greatly uncertain external conditions. It introduces consumer behavior modelling and treats external conditions stochastically, but does not deal with the policy extraction problem.

2. A MODEL OF DANISH ENERGY USE

The behavior of energy users may depend on the cost of supplying energy services, as well as on the amount of energy services considered necessary or desirable for satisfying the goals of particular energy users or of society as a whole. Energy use and investments may also depend on conventions and customs, in short on paradigms related to energy behavior. The intention here is to formulate a model that can simulate consumer behavior under simple assumptions regarding external conditions. The model is intended for simulation of future behavior, but to check the validity of assumptions made, it will be applied to past conditions also.

Verification is based on data for Danish energy use 1900-1983 (Danmarks Statistik 1959, 1967, 1973; Energistyrelsen 1983), data showing considerable structure (situations of war and supply difficulties and also the exceptional growth period in the 1960ies).

Let me first consider the simplest possible model: energy use U (kW/cap.) is determined by the cost of energy C (1980 US cents per kWh) alone,

$$\frac{dU}{U\,dt} = b_1 \left(b_2 - \frac{dC}{C\,dt}\right) \qquad (1)$$

Here b_1 and b_2 are constants. If b_2 were zero it would mean that the relative change in energy use were proportional to the relative cost change, but of opposite sign. By putting $b_2 = .1 y^{-1}$, a behavior is assumed, whereby the customers do not cut energy use before the price rise is more than 10% per year, and increase energy use correspondingly more if prices rise less or fall.

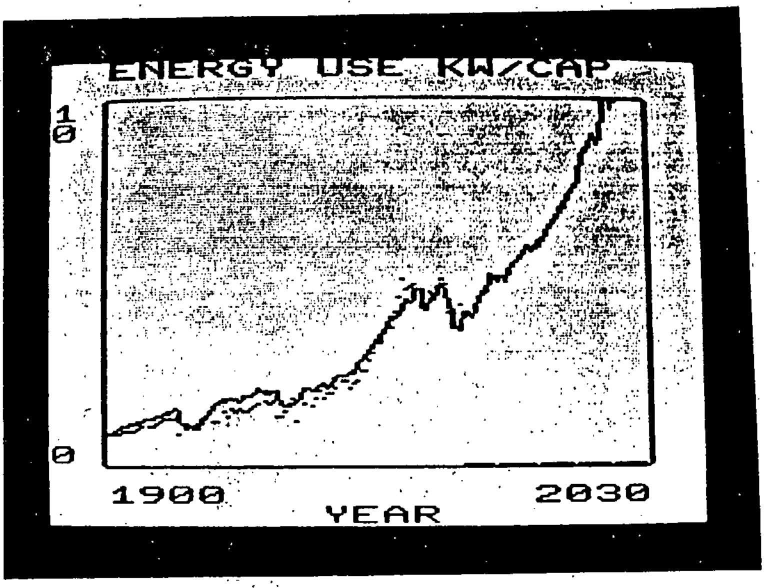

Fig.1. Danish energy use, as calculated with cost-driven simulation model (solid line), compared with data (dots). The model parameters were $b_1 = 0.27$ and $b_2 = 0.1\ y^{-1}$ (time step one year). All scales in this and following figures are linear.

The constant b_1 is what economists call the price elasticity of energy. The positive value of b_2 may be said to represent a growth oriented attitude or a growth paradigm. Fig. 1 shows that this oversimplified model gives a surprisingly good agreement with actual energy use in Denmark 1900-1983, including the war time behavior and recent turmoil in the energy scene. A closer look reveals that the growth rate of energy use before World War I is not well reproduced. If the parameters were adjusted to fit the behavior here, the simulated growth during the 1960ies would fall considerably short of the observed one.

To be discussed are also the energy cost data used to drive the simple simulation model. These were taken as real term import values of all energy used in Denmark, from the same sources as the energy use data. Gross national product deflators were used to translate costs in current Danish Kroners to fixed prices, after 1930 (Danmarks Statistik 1948, 1966, 1976, 1982a and 1982b). Before 1930 deflators for individual years were not available, so 5-10 year averages had to be used (Danmarks Statistik 1954). Values for 1982 and 1983 are as yet estimates. It would have been more consistent to use consumer energy prices to calculate consumer behavior, rather than primary energy prices. However, the consumer costs of different energy types have varied quite differently over time, and it was felt that only in a model treating separately the different energy forms and actually modelling the substitution between energy forms, could meaningful use of consumer prices be made. This is clearly a priority point for the future development of the simulation model considered here. Using equivalent import prices, the effect of substitution, of altered profit structure and of changing taxation is neglected. The energy cost data used can be seen in Fig. 2 (before 1983). They are expressed as effective consumer prices in 1980-US cents per kWh, using a fixed currency exchange rate and a fixed ratio between consumer and primary import prices. Multiplying by the exchange rate 7.5 gives average consumer prices in Danish 1980-øre/kWh (Monopoltilsynet, 1981), while multiplying the prices in 1980-c/kWh by 2.674 gives the import prices in 1975-øre/kWh (the primary data).

In order to simulate future behavior, the energy cost after 1983 was assumed to be given by

$$\frac{dC}{C\ dt} = a_1 \frac{dU}{U\ dt} + a_2 \qquad (2)$$

Here, a_1 is a supply-demand describing factor, telling that prices go up when demand goes up, and down when demand goes down. Such a relationship may describe the current situation, where the production of major energy commodities such as coal and oil is highly controlled and where in the case of oil major producing countries try to keep production fixed. In the beginning of this century, such a relationship would have been quite unrealistic. It is also unlikely that it should remain fifty years into the future. Large energy users will surely try to substitute imported fuels by other energy sources, over which they feel they have more control or assurance of supply (e.g. nuclear or solar energy). I shall therefore assume, that the parameter a_1 declines gradually with time and vanishes in the year 2030:

$$a_1 = 0.0077\ (2030 - t) \qquad \text{(t in calendar years)} \qquad (3)$$

The second parameter, a_2, in (2) is used to model political aspects of energy price-setting. It is made to produce a stochastical sequence of price hikes or declines, with a specified average spacing. The sign of each price jump is taken to be positive if energy use is increasing, and negative if it is declining. However, a second stochastical element is built into the simulation model by assigning a 20% chance that the sign of the price jump will be the opposite of the one indicated by market conditions (as a reflection of the political nature of energy price fixation currently prevailing, with Middle East war outbreak and political revolt being at intervals more important in fixing energy prices than the market conditions). The model value assigned to a_2 may be expressed in the following way:

$$a_2 = (-)^{\mathrm{rnd}(1)}\ \mathrm{rnd}(2)\ (0.2 - 0.3\delta(\tfrac{dU}{dt} < 0))\ \ y^{-1} \qquad (4)$$

where the random function rnd(1) is equal to zero with 80% probability and equal to one with 20% probability, and rnd(2) is an independently generated function with the same properties. The delta-function has the effect of making downward jumps only half as big as upward jumps. It is clear that this represents only a very subjective model of future energy price behavior. However, it generates sequences of energy prices of very different nature and hence serves to illustrate the consumer behavior under widely differing external conditions.

Although (1) may be inserted into (2), the stochastical terms preclude any analytical solution. An example of the simulation results is shown in fig. 1 (energy use) and fig. 2 (cost). Also in runs exhibiting large price increases, energy use continues to go up rapidly. This is due to the presence of the constant $b_2 = 0.1\ \ y^{-1}$ in (1). The maintenance of its implied growth paradigm is unthinkable when the share of energy in the overall budget becomes very high. Therefore it is clear that the model has to be modified in order to deal with the consumer behavior in cases of energy cost above the present level. This is attempted in the next section.

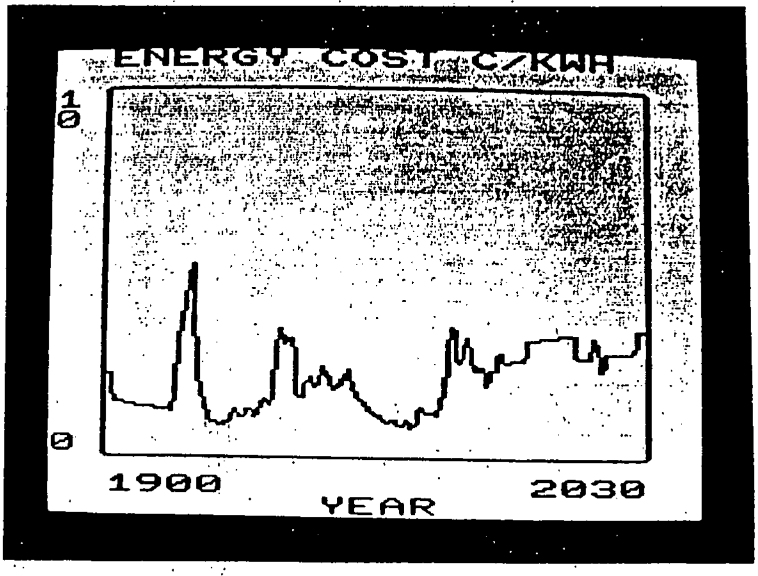

Fig.2. Danish energy cost in 1980 c/kWh. See sect. 2 for details

3. REFINING THE MODEL

Rather than relating energy use to the cost per unit of energy, I shall here explore the consequences of considering energy use as primarily related to the service obtained by using energy, and I shall consider the behavior as driven basically by the cost of providing a given amount of energy service, rather than a given amount of energy. The energy service E is defined as

$$E = \eta U = U/H \tag{5}$$

where η is the efficiency of energy use and H the inverse efficiency. I shall use the same units for energy service as for energy use and use a practical definition of H as the ratio between energy actually consumed and the energy that would have been consumed if the best available technology had been used (Sørensen 1982a). For example, in case of electricity production, the energy service is certainly bounded by the Carnot efficiency, and the best presently available technology can at most deliver slightly above 50% energy service (electric power) per unit of imput energy use. The modelling of the development in time of energy efficiency will be presented below.

Before that the consumer behavior will be discussed. It is assumed that the consumer makes decisions regarding change in energy use on the basis of the average cost per unit of energy service, C', and that this cost is given by a model of the type considered in sect. 2,

$$\frac{dE}{E\,dt} = b_1' \left(b_2' - \frac{dC'}{C'dt}\right) \tag{6}$$

In other words, the primary decision of the consumer is to raise or lower his or her level of energy service, depending on the expense of providing such service. Using the relation between C' and C

$$C' = H\,C \tag{7}$$

(6) may be reexpressed as a relation between energy use U and energy cost C,

$$\frac{dU}{U\,dt} = b_1' \left(b_2' - \frac{dC}{C\,dt} - \frac{dH}{H\,dt}\right) + \frac{dH}{H\,dt} \tag{8}$$

The simplified model indicated that b_2' were connected to the stregth of the growth paradigm, being a measure of the price increase that would be accepted without leading to decreased demand. Two new assumptions will now be made regarding b_2'. One is that it depends on the magnitude of the price changes and on the absolute level of prices (being large if prices are so low that energy costs do not matter much at all in anyone's budget). The other assumption is that a new paradigm with less emphasis on growth has developed during the 1970ies, so that by 1980 some 50% of the Danish population is no longer adhering to the growth paradigm (Mørkeberg, 1982). The numerical values are

$$b'_2 = \begin{cases} 0.04 \text{ if } dC'/C'dt > 0.1 \text{ y}^{-1} \\ 0.10 \text{ if } dC'/C'dt \in [-0.05, 0.1] \text{ y}^{-1} \\ 0.20 \text{ if } dC'/C'dt < -0.05 \text{ y}^{-1} \\ 0.25 \text{ in any case, if } C < 1.1\text{c/kWh} \\ \text{half the above values after 1980} \end{cases} \qquad (9)$$

The parameter b'_1 is used to model the dependence of energy use on the amount of goal satisfaction already achieved. Describing goal satisfaction by a number S between zero and one, the chosen form of b'_1 is

$$b'_1 = 0.5\, S\, (1 - S^2) \qquad (10)$$

The last factor describes the saturation effect: Demand for new activities requiring energy diminishes as the goal satisfaction approaches unity. The second power of S is used to simulate a behavior where the cessation of growth in energy demanding activities does not occur until a very high level of goal satisfaction has been reached. The preceding factor gives a proportionality to S, indicating that the material means for achieving more (energy consuming) goal satisfaction grows with the goal satisfaction already obtained. This term is believed to be important for societies at a very low level of goal satisfaction, where the growth in energy use cannot be expected to show before a certain basis has been established. The constant in front, 0.5, makes the difference between energy use in year 1980 and 1900 come out in correspondance with data, once the entire simulation calculation is performed.

To complete the set of model equations, the goal satisfaction S and inverse energy efficiency H must be derived. S would in a more general model be coupled to the energy service level, but here it will be taken as an externally given function, shown in fig. 3 and based on an evaluation of average goal satisfaction in the Danish society up to 1983 (see Sørensen, 1983), supplemented by an arbitrary guess after 1983. Since goal satisfaction depends

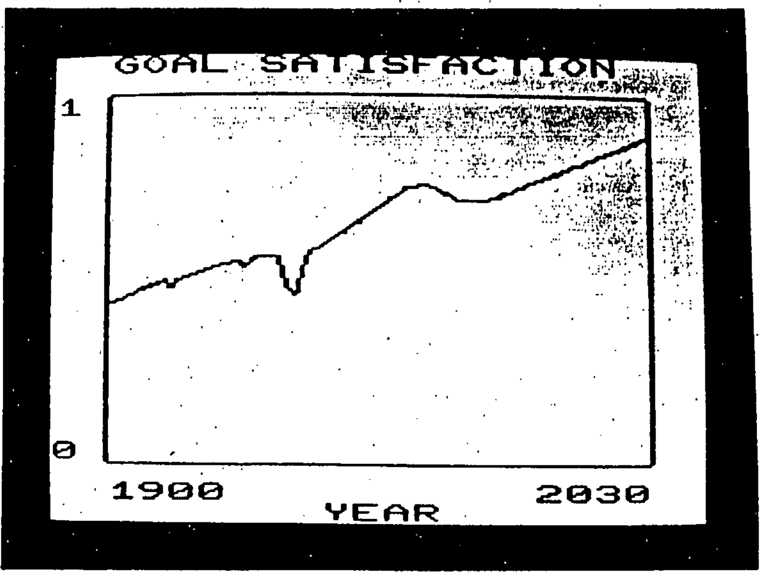

Fig.3. Goal satisfaction S assumed in the simulation model.

on many things other than energy services, it is felt that the introduction of a dynamic model of goal satisfaction within the framework of the present energy model would be unrealistic. The assumed increase in goal satisfaction after year 2000 (reaching 90%) is introduced to study its possible role in saturation of energy use. It should be said that the goals being related to in the data taken from Sørensen (1983) are stationary, i.e. the goals in year 1900 are assumed to be the same as in 1980. A more likely behavior would be one where goals are changed with time and generally become more demanding with time. This would mean that the real goal satisfaction could be higher in the beginning of the period, and it could also mean that the high value of 90% towards the end of the simulation period is unrealistic, considering that new goals may be formulated in the future, and some of them undoubtedly requiring new energy services.

The sub-model for energy efficiency is of the form

$$\frac{dH}{H\,dt} = c_1 + c_2 \frac{H^{opt} - H}{H} \qquad (11)$$

The first term represents smooth technology improvement, tending to improve efficiency with time. A small value is assigned to c_1 ($-0.004 y^{-1}$), for reasons explained below. The second term is supposed to represent consumer behavior, in response to abrupt energy price changes. The idea is that as long as energy prices change smoothly, consumers do not make lump investments in the improvement of energy efficiency (retrofit building insulation, improved industrial production techniques with emphasis on energy optimization, etc.). However, large price hikes or falls induce consumer response, either willingness to invest in efficiency or increased neglect of energy efficiency. The model is

$$c_2 = \begin{cases} 0.08 \text{ if } dC/Cdt > 0.1\ y^{-1} \\ \;\;\,0 \;\;\;\text{ if } dC/Cdt \in [-0.1, 0.1]\ y^{-1} \\ -0.04 \text{ if } dC/Cdt < -0.1\ y^{-1} \\ \text{twice the above values if } t > 1980 \end{cases} \qquad (12)$$

The relapse for declining prices is less strong than the effort to increase efficiency for price increases above 10% per year. The doubling of c_2 after 1980 reflects a paradigm shift towards more emphasis on energy efficiency. It was used only in some of the simulation calculations. The c_2 term is denoted consumer response. However, it also depends on technological progress, since it introduces better technology, which has been developed but which has not been able to penetrate before the consumer awareness caused a demand for more efficient energy techniques. Thus the c_2-term determines when the available best technology will start to become introduced.

Now, it is not indiscriminately possible to improve efficiency, just because there is a ten percent price hike. The economy of the investment must be plausible. This is what the last factor in (11) describes. It depends on the optimal level of (inverse) efficiency, H^{opt}, defined as that level of efficiency, for which the marginal cost of each unit of energy saved equals the actual cost of energy at the time t considered. This function has been studied for different types of energy use by Sørensen (1982c), and it turns out to be possible to summarize all the results (within the uncertainty involved) by a single curve, shown in fig. 4. The last factor in (11) ensures that the investments in energy efficiency are proportional to the separation between the current and the optimal efficiency, and that investments are no longer made, when the optimal point is passed. Fears of future price increases could modify the behavior here.

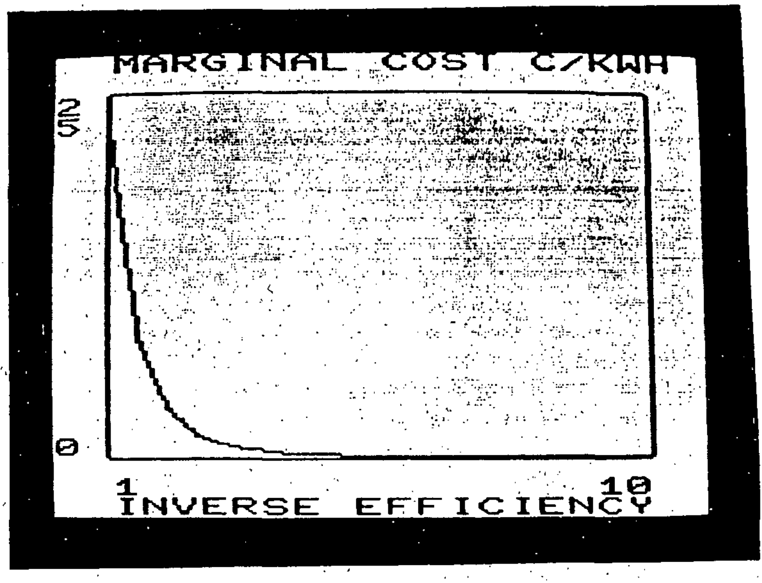

Fig. 4. Marginal investment cost for saving one additional unit of energy, in 1980 US cents per kWh, as function of inverse energy efficiency H (Based on Sørensen, 1982c). A 10 year depreciation time at 4% annual real interest rate has been assumed for the investments.

Some results of simulation calculations with the model described in this section are shown in figs. 5-7. It is seen that the more complex model does give a slightly better agreement with historical energy use data up to year 1983 (the calculation and data are superimposed on fig. 5A and shown separately in fig. 6A and 6B). Now the growth rates are reproduced both in the beginning of the century and during the recent decades. Remaining discrepancies are during the 1930-depression (the main causes of which are outside the present model) and around the end of World War II, where traditional energy supply countries became closed to Denmark, also a trait not included in the model and not strongly reflected in energy prices. After year 1983, the model does as mentioned include some measure of political factors, but not for the historical period where prices are not generated within the model.

The model behind fig. 5 does not include the paradigm shifts indicated by the last lines in (9) and (12). As the particular run predicts large energy price rises, it must be concluded that such price hikes do not in themselves entail curbing of the energy use. It does force the efficiency of energy use up (fig. 5C), but energy use (fig. 5A) still increases despite a more than doubling of energy prices over 30 years (fig. 5B). The growth paradigm built into the parameter b_2' is mainly responsible

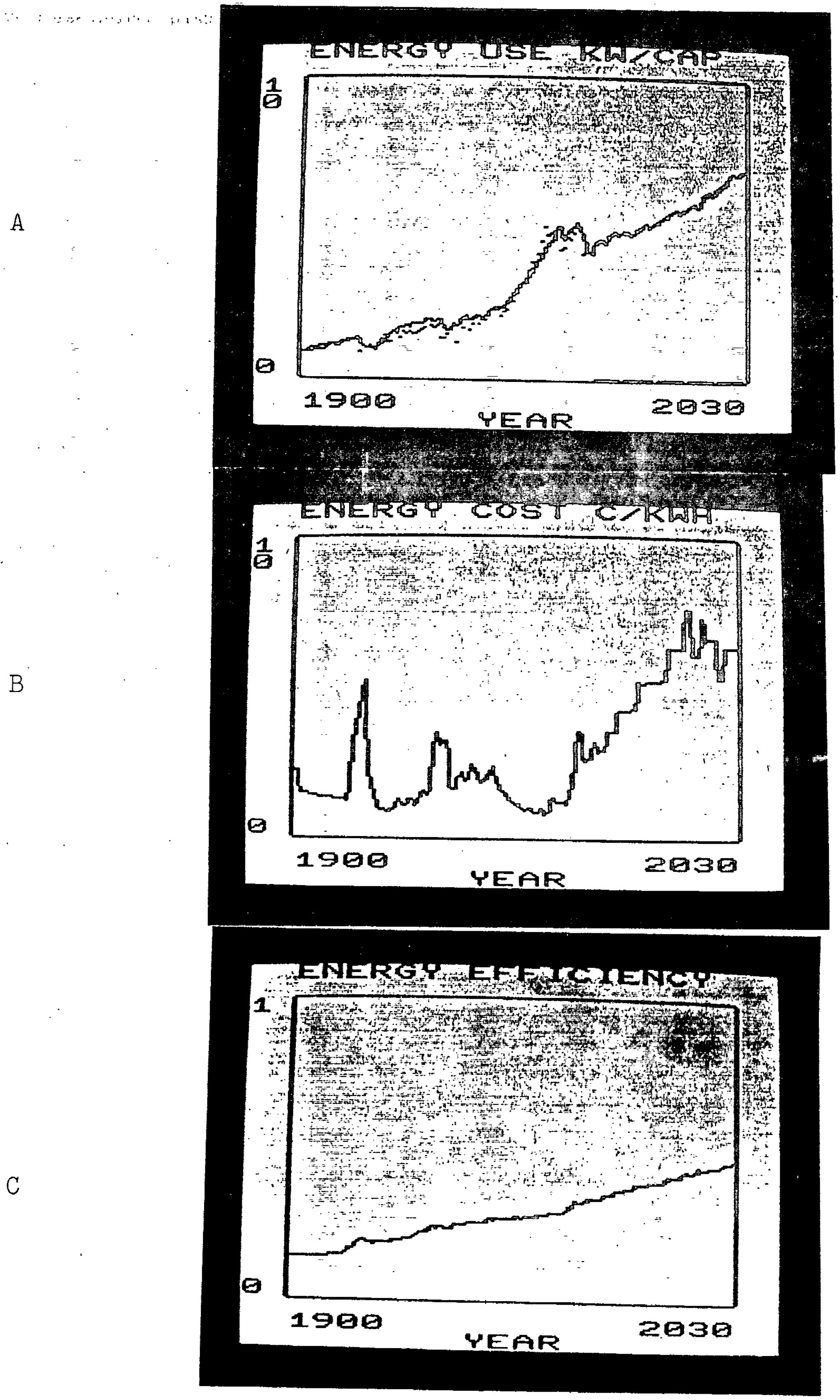

Fig. 5. Danish energy use (A), cost in constant 1980 prices (B) and energy efficiency (C). In A, data points are given as dots. The calculation uses the refined model described in sect. 3, but without any paradigm shifts in year 1980, i.e. unaltered model of growth and energy efficiency throughout.

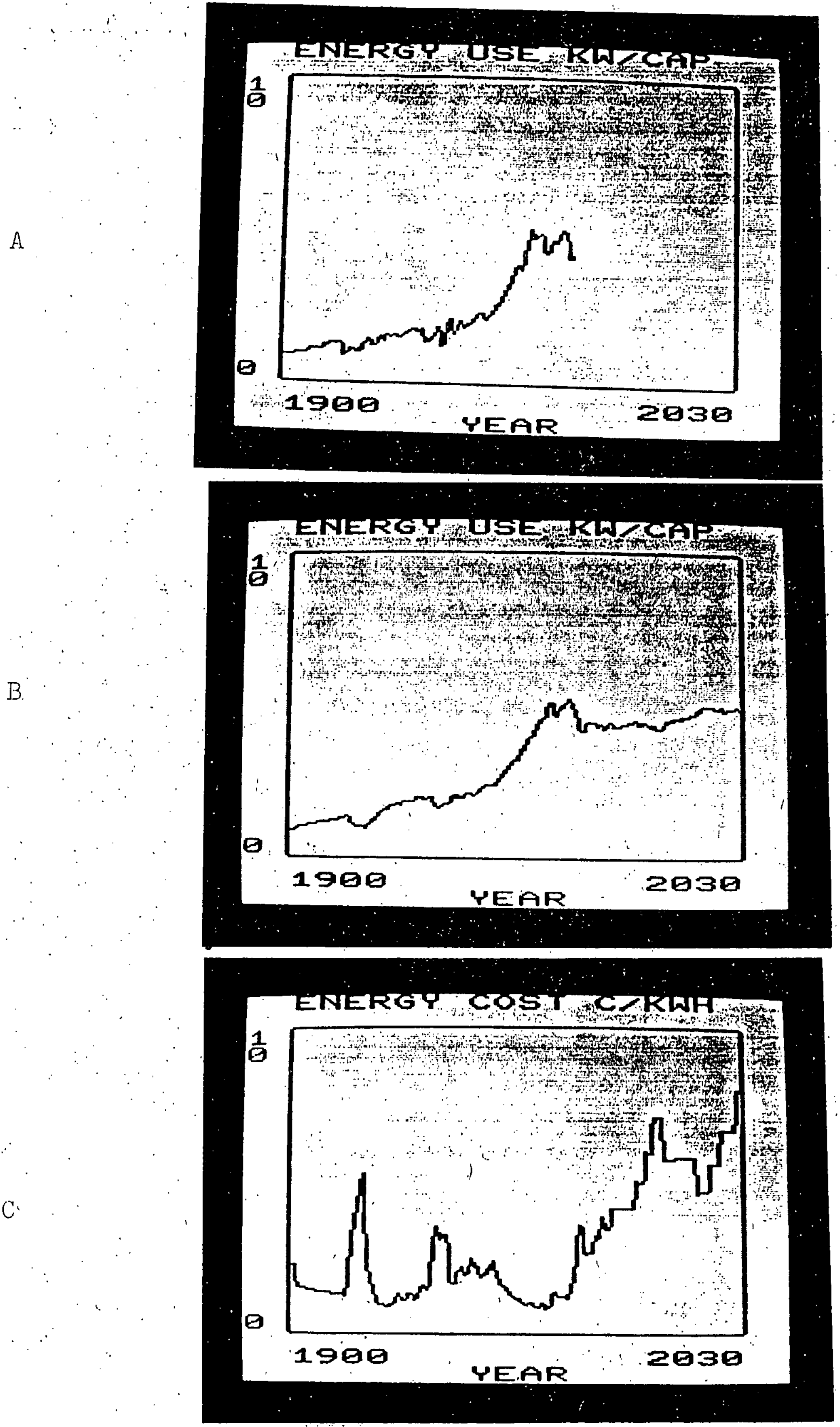

Fig. 6. Actual Danish energy use data (A), calculated energy use (B) and cost in constant 1980 prices (C), using the refined simulation model as in Fig. 5, but now introducing the paradigm shift regarding energy growth from year 1980, as discussed in sect. 3.

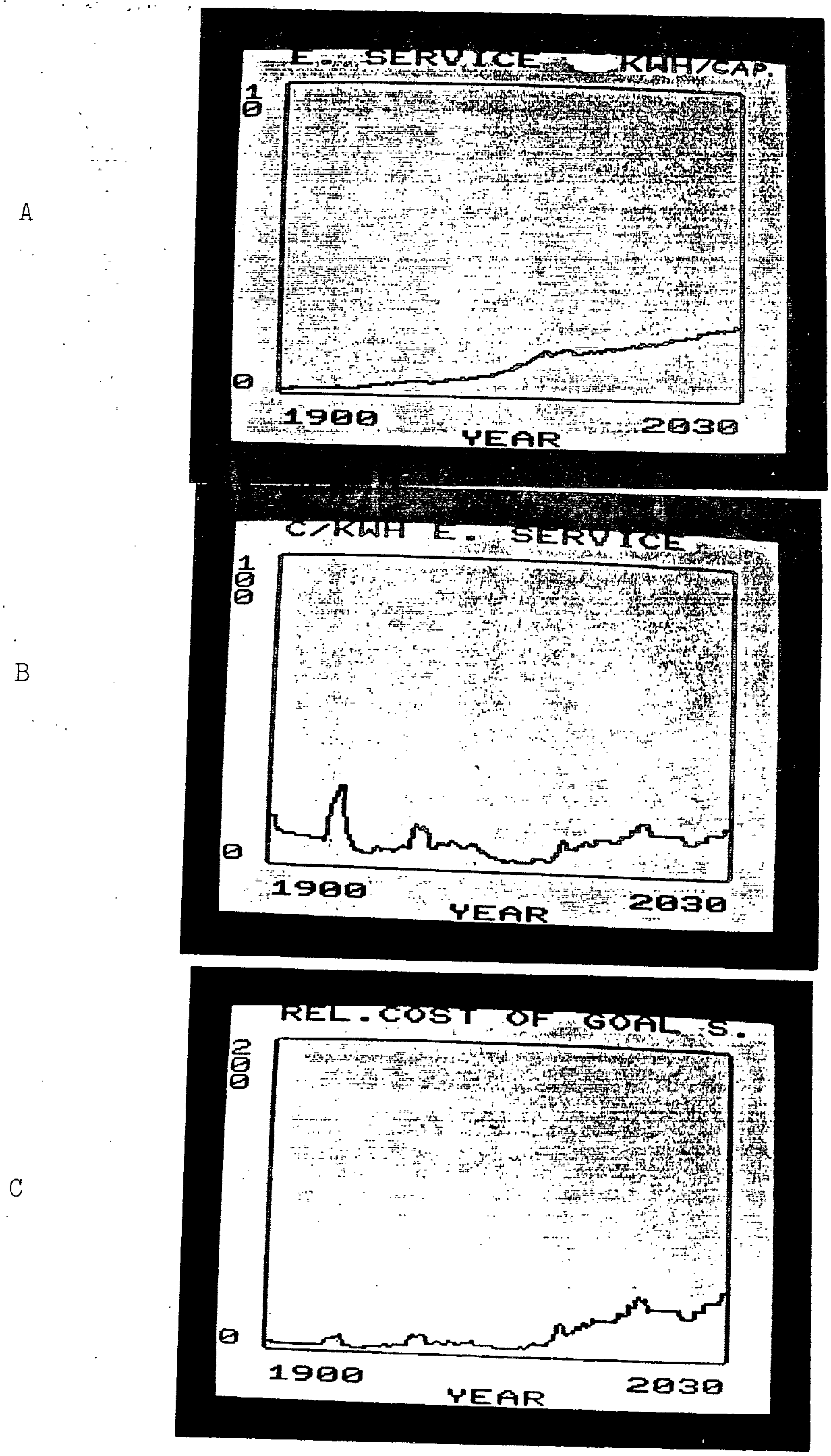

Fig. 7. Calculated development in Danish energy service (in kWh per capita) delivered to the customers (A), the cost of this service in constant prices (B), and the cost per unit of goal satisfaction (C). The simulation run is identical to the one used in fig. 6.

for this.

The simulation calculation used in figs. 6 and 7 includes the paradigm shift regarding growth, expressed through the last line in (9). Again a case of strongly increasing energy prices(fig.6C) has been chosen among the many runs generated by the stochastical model (see (4)). Yet in this case, energy use levels off at approximately the 1983 value (fig. 6B). The efficiency improves to practically the same value as in fig. 5C, because the marginal cost increase for further improvements is so high (see fig. 4), that even the high energy prices do not indicate a very much higher efficiency than the one obtained in year 2030. Still, the small difference between H and H^{opt} in (11) makes the approach to the optimal efficiency rather slow, and if the new paradigm concerning efficiency is introduced (in (12)), then the energy use will decline slightly from the 1983 value rather than staying constant.

Fig. 7A shows that the amount of energy service delivered on average to each Dane increases considerably after 1983, following the stagnation period of nearly ten years. This increase is caused by the effort to increase energy use efficiency, and as indicated in Fig. 7B it leads to roughly constant energy service costs, despite the steep increases in primary energy prices. On the other hand, the saturation in goal satisfaction (at a very high level) assumed (fig. 3), combined with increasing supply of energy services, imply, that the unit cost of goal satisfaction goes up (fig. 7C). This suggests that a reorganization of society with respect to energy (service) use, in such a way that a closer correspondence between energy service and goal satisfaction is established, would make it possible to obtain the same amount of goal satisfaction with less energy input than implied by any of the simulation runs. To model this, a relation between energy service, goal satisfaction and its non-energy determinants should be included in the model.

4. CONCLUDING REMARKS

By running the simulation models of this study a number of times with identical parameters, a number of energy price sequences have been generated and their implications for energy use and efficiency investments studied. Due to the asymmetry in (4), the long-term price trends have been either constant or increasing. The simulation results have indicated, that the entailed energy use is not given in a simple way by the energy cost. In particular, the possibility of paradigm shifts regarding the necessity of energy growth and the rapidity of following price variations by the investments in energy efficiency improvements that would be indicated by a current efficiency level being lower than the optimal one, are key determinants of actual development in energy use. Such paradigm shifts can certainly be influenced by policy measures and by a variety of incentives that could be made by the governmental body responsible for energy planning.

Although working with the simple models of this study has lead to suggestions of further refinement (considering different energy forms separately, varying the structure of the supply system, for example), the main conclusion that I would like to draw is that simulation models should be kept simple, if we are to learn from their results. Many of the complex models used e.g. by international organizations have so many parameters and equations, that the precise mechanism implied by each one of them is very difficult to discern. If the model then has any dynamical behavior of importance, its results will be nearly impossible to understand (and quite probably inappropriate for learning about the real world), and if it does not have any significant dynamic behavior, it is certainly uninteresting as a tool for better understanding the very dynamic world surrounding us. A small model with each dynamic coupling term tried out and understood by the simulation researcher is much more likely to tell something useful for actual energy planning and policy.

The simplicity also allows a broader group of citizens to take part in the discussions of energy simulation models for their society, or even to try out ideas of their own on a computer. It is with this in mind, that the calculations for the present paper have been performed on an inexpensive VIC-20 home computer.

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