Long-term diffusion factors of technological development - an evolutionary model and case study

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Long-term diffusion factors of technological development - an evolutionary model and case study[*]

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Abstract

In the first part of this article, a short description of the most popular models of two competing technologies (the Fisher-Pry model and its modifications proposed by Blackman, Floyd, Sharif and Kabir) and the multi technological substitution models of Peterka and Marchetti-Nakićenović are presented. In the second section, we describe an evolutionary model of diffusion processes based on biological analogy, together with the method of its parameters' identification using real data on technologies development. In the final sections the applications of that model to describe the real diffusion processes (namely, primary energy sources in the world energy consumption and the raw steel production in the United States) are presented. The feasibility of using the model to predict future shares of given technologies and to build alternative scenarios of future evolution of structure of the market is suggested.

Key words: diffusion, substitution, evolution, simulation.

Introduction

The word *diffuse* was derived at the end of the fourteenth century from the Latin *diffundere*, which means to spread over. In science, the term *diffusion* refers to the phenomenon of the spread in space or the acceptance in a social environment, over time, of some specific item or pattern. The spatial diffusion is mainly the object of interest of sociologists and development planners. Diffusion in human-social environment interests researchers of market development and planners of technological development at the firm, regional, and national levels. Integration of those two approaches is possible and, in fact, has been done. However, it leads to relatively sophisticated models that are interesting from a theoretical point of view, but at the current stage of development they are without much practical use. In this study we focus on the time pattern of technological diffusion.

Taking into account all the problems of reaching relevant data on technological development, we assume that the only available data are on current market shares of competing technologies. Our aim is to develop a relatively simple and easy to handle model of technological substitution

(diffusion). Ryan and Gross (1943), early investigators of diffusion, noted two important features of that process: the very wide range of rates at which different innovations spread and the general S-shaped (or the logistic-type pattern) diffusion of the most innovations. Those two features have now become the key stylized facts of the diffusion process. But it is necessary to add that the S-shaped pattern of diffusion is recorded only in the case of two competing technologies, the "new" and the "old". At any moment, more than two technologies compete so we have multi technological diffusion (or sometime called substitution) processes. In such multi-technological substitution the diffusion of a single technology has a form of the bell-shaped curve. Broadly speaking, the bell-shaped curve consists of an initial, introductory phase when the diffusion rate is not very high, followed by a phase of relatively quick diffusion. The third phase may be called the matured phase in which the market share of the technology reaches maximum value. In the fourth phase, the market share of that technology declines, caused by emergence of new, better technology (typically the new technology emerges in the second phase of quick diffusion of the old technology).

Most time diffusion models deal only with two competing technologies. To our knowledge the only practical models of multi-technological substitution are those proposed by Peterka (Peterka, Fleck, 1978) and Marchetti, Nakićenović (1979). In the first part of the article we present the most popular models of the two competing technologies and comment on the models of Peterka and Marchetti and Nakićenović. In the second section, we present our model, and in the final sections, we present the applications of that model to describe the real diffusion processes.

Review of the basic models

Most approaches aiming to describe diffusion of innovation are based on analogy to dissemination of information or to epidemic processes (diffusion of disease through contagion). This approaches lead to description of diffusion as the well-known logistic pattern. The assumptions under which the logistic model is obtained are:

1. The number N of individuals (firms, products, services, etc.) in the total population is constant and the nature of these individuals does not change.
2. The disease (information, innovation) is disseminated when contact by two individuals occurs; the frequency c of contact in the unit of time between any two individuals is the same for all pairs of individuals and constant over time.
3. The probability p that the disease (information, innovation) will be transmitted during the contact of affected and unaffected individuals is constant over time and is the same for all relevant pairs.
4. Disease (information, innovation) cannot be lost once acquired.

Let $N_a(t)$ be a number of affected individuals at time t, from the second assumption we get that the number of contacts between affected and unaffected individuals in the period from t to $t + \Delta t$ is equal to $c\, N_a(t)\, (N - N_a(t))\Delta t$. Applying the two last assumptions, the number of new affected individuals in the Δt period is equal to

$$\Delta N(t) \;=\; c\, p\, N_a(t)(N - N_a(t))\Delta t \tag{1}$$

Let $f(t)$ denote the fraction $N_a(t)/N$ affected individuals in the total population. Replacing $\Delta x / \Delta t$

by dx/dt we obtain the following well-known logistic differential equation

$$\frac{df}{dt} = bf(1-f) \qquad \text{where} \quad b = apN \tag{2}$$

with the logistic function as its solution

$$f(t) = \frac{1}{1+\exp(-a-bt)} \tag{3}$$

where a is a constant of integration which value is given by initial fraction $f(0)$.

For the purpose of estimation of parameters a and b, the above equation is frequently rewritten in the following form:

$$\ln\left(\frac{f(t)}{1-f(t)}\right) = a+bt \tag{4}$$

The above presented model is known also as the Fisher-Pry (1971) model. The modification of that model was proposed by Blackman (Blackman 1973, see also Linstone, Sahal, 1976). Blackman assumes that there exists an upper limit F of the market share by the new technology. Therefore, the solution of the market share in that model is equal to

$$ln\left(\frac{f(t)}{1-f(t)}\right) = a+bFt \tag{5}$$

For F=1, the Blackman model turns to be the Fisher-Pry model.

Floyd (Bright J.R. (ed.), 1968, see also Linstone, Sahal, 1976) proposed another modification of the Fisher-Pry model by adding to the Fisher-Pry solution the second, analogous term but with the limit F and without the natural logarithm. The form of that model is the following:

$$ln\left(\frac{f(t)}{1-f(t)}\right) + \frac{F}{F-f(t)} = a+bt \tag{6}$$

The Fisher -Pry and the Blackman models give overestimations of the forecast and the Floyd gives underestimations of the forecast. Sharif and Kabir (1976) proposed a generalized version of the model for technological substitution. They suggest that the linear combination of the Blackman's and Floyd's models can give correct results. This leads to the following generalized model:

$$ln\left(\frac{f(t)}{1-f(t)}\right) + \frac{\sigma F}{F-f(t)} = a+bt \tag{7}$$

The Sharif-Kabir model can be rewritten in the differential equation form

$$\frac{df}{dt} = \frac{bf(F-f)}{F(F-f(1-\sigma))} f(1-f) \tag{8}$$

For $\sigma=1$ we have Floyd's model, and for $\sigma=1$ Blackman's model; for $\sigma=0$ and F=1 we have the Fisher-Pry model.

All the above models deal with two competing technologies only. Marchetti and Nakićenović (1979) and Peterka (Peterka, Fleck, 1978) proposed the models of multi technology substitution. The Marchetti-Nakićenović model is an extension of the Fisher-Pry model to multi technological substitution. The model is based on the assumption that each technology passes three distinct

phases, as measured by its market share f_i: logistic growth, nonlogistic saturation, and finally logistic decline. This assumption is accompanied by two other important ones, namely: (1) when more than two technologies compete, one technology is in its nonlogistic, saturation phase (defined as residual after calculation of the logistic growth-decline trajectories of other technologies); and (2) the technology that enters the saturation phase (which is due to the increase of newer competitors) is the oldest of the growing technologies. Thus the market share f_i of the growing (declining) technology i is defined by

$$y_i(t) = \log\left(\frac{f_i(t)}{1 - f_i(t)}\right) = a_i + b_i t. \tag{9}$$

The 'residual' market share of the saturating technology j is given by

$$f_j(t) = 1 - \sum_{i \neq j} f_i(t). \tag{10}$$

The saturation phase is modeled by a parabolic function that fits the linear growth and decline phases modeled by the logistic substitution curves. To complete the model, the point where the nonlogistic transition trajectory ends and the logistic decline phase for technology j begins ought to be determined. The end of the saturation phase and the beginning of the logistic decline phase is defined as the point where the curvature of $y_i(t)$ relative to its slope reaches its minimum value

$$\frac{y_i''(t)}{y_i'(t)} = \text{minimum}. \tag{11}$$

When the minimum condition is satisfied at time t_{j+1}, then technology $j+1$ may in turn enter the saturation phase. The logistic decline trajectory of technology j is determined by

$$\begin{aligned} b_j &= y_j''(t_{j+1}) \\ a_j &= y_j(t_{j+1}) - b_j t_{j+1} \end{aligned} \tag{12}$$

The model of Marchetti and Nakićenović was developed at the end of the 1970s, almost at the same time Peterka proposed his model of multivariate competition. Peterka starts from considerations of the capital α_i needed to increase the production of a commodity i by a unit (and is called specific investment), next taking into account specific production cost c_i of the commodity i and the market price for the commodities. Applying the rational balance equations related to investment and capital, Peterka delivers his basic difference equation describing competition of n commodities

$$\frac{\mathrm{d}f_i}{\mathrm{d}t} = \frac{1}{\alpha} f_i \left(\sum_{j=1}^{n} c_j f_j - c_i \right) \tag{13}$$

where f_i is the market share of the commodity (technology) i, α is specific investment, being the same for all technologies, but Peterka considers also the case of competition under different specific investment.

The above equation is very similar to the Eigen's replicator equation (Eigen, 1971) of evolution of self-replicating macromolecules. They were derived by Peterka independently of Eigen. It is interesting to note that considerations of the two unrelated phenomena, evolution of biological macromolecules and technologies competition, lead to almost identical differential equations.

The solution of the above equations is equal to:

$$f_i(t) = \frac{1}{1 + \sum_{j \neq i} \dfrac{f_j(0)}{f_i(0)} \, e^{-c_{ji}(t-t_o)}}$$

(14)

where

$$c_{ij} = \frac{c_i - c_j}{\alpha}$$

It is possible to estimate parameters of the Peterka's model from historical data and use this model, e.g., to predict future development of technologies' shares. In fact Peterka proposes such an approach (Peterka, Fleck, 1978, section 6), but it seems to us to be too sophisticated to be useful in real cases. What we need is a relatively simple model with easy identification of the model's parameters to handle with real multi technology substitution processes. It happened that in the 1970s we were also engaged in similar research related to simulation of evolution of asexual biological populations (Galar, Kwaśnicka, Kwaśnicki, 1980; Kwaśnicka, Kwaśnicki, 1976; Kwaśnicki, 1979; Kwaśnicka 1979). The way of developing the model is presented in the next section; our replication equations, although slightly different in form and method of delivery, are also very similar to the replicator equations of Eigen. We use discrete time, and it seems that this form of equations is useful to describe the substitution-diffusion processes and is convenient to identify the unknown model's parameters.

Evolutionary model

Let us assume that each of n given technologies is characterized at any moment t by a single index describing its quality of performance; let us call this index the competitiveness $c_i(t)$ of technology i (in biological interpretation this index is called fitness). In general, competitiveness is a function of time t and depends on the technical characteristics of a given technology and its price (related to the cost of using or applying that technology). The competitiveness is greater when the technical characteristics are better and the price is smaller. In general, the external environment in which the technologies evolve is not stable and influence the relative values of all competitiveness $c_i(t)$. This general notion of competitiveness is applied in our model of industrial development presented in (Kwaśnicka, Kwaśnicki, 1992, Kwaśnicki, 1994). For the purpose of the article it is convenient to assume that for given period of time competitiveness is constant and not influenced by any external factor. If we denote by $N_i(t)$ a measure of the extent of using technology i at time t (it can be a number of products of specified technology sold on the market at time t or any relevant measure of using technology as, e.g., a sum of all traveling distances of all passengers using specific type of transport [so the measure would be passenger-kilometers] in the case of considering competition process of different means of passenger transport – roads, air, sea, etc.). We assume discrete time, and make the assumption that the extent of using technology i in the next moment (t+1) is proportional to the extent of using that technology in the previous moment (previous period) $N_i(t)$ and technology competitiveness c_i,

$$N_i(t+1) = A N_i(t) c_i$$

(15)

If we assume that total demand for services of all technologies is equal to $N(t)$, so from the condition that $\sum_{i=1}^{n} N_i(t+1) = N(t+1)$ we calculate the parameter A

$$A = \frac{N(t+1)}{\sum\limits_{i=1}^{n} N_i(t)\, c_i} \tag{16}$$

A fraction $f_i(t)$ of the technology i in the total extent of using all technologies at time t is defined as the ratio $f_i(t) = N_i(t)/N(t)$. Applying equation (16) and rearranging equation (15) the formula for technology i share is

$$f_i(t+1) = f_i(t)\, \frac{c_i}{\overline{c}(t)} \tag{17}$$

where $\overline{c}(t)$ is the average competitiveness within the whole set of used technologies, and is equal to

$$\overline{c}(t) = \sum\limits_{i=1}^{n} f_i(t)\, c_i(t) \tag{18}$$

So it is seen that using the replicator equation (17) we are able to describe the evolution of the structure of applied technologies (i.e., the diffusion process) without reference to the specific evolution of the market for the whole set of those technologies. The prediction of structure evolution is separated from the prediction of the market size. We are interested in the evolution of technologies structure as measured by the shares $f_i(t)$. To describe the evolution of the set of technologies, we ought to know the values of their competitiveness c_i and the initial share $f_i(t_0)$. In principle, it is possible to calculate the competitiveness c_i on the basis of technical characteristics of technology i and the unit price of that technology (or product price), but in reality it is a difficult task and the only practical solution is to estimate (identify) those values on the basis of collected records of technologies development as it was observed in the past.

Identification problem

It is reasonable to assume that we are able to collect data about changes of technologies shares during the limited period of time, let us say since t_1 to t_2. How to identify competitiveness c_i (assuming that they are constant parameters) and the initial share $f_i(t_0)$ on the basis of collected data of technologies shares during the period (t_1, t_2)? Let us note that the model behaves in exactly the same way if we multiply each competitiveness by a constant parameter r and assume that new values of competitiveness are equal to $c_i^* = rc_i$, so it is seen that the values of technologies competitiveness are the relative values. Therefore, it is necessary to assume one value of any chosen technology as a base value of competitiveness. Let us assume that the base technology is denoted by k and the base value of competitiveness is equal to c_k.

It is difficult to identify values of competitiveness directly using the replicator equations. But it is possible to rewrite the equations in such a way that we will be able to use well-known method of parameters identification of linear systems. If we divide replicator equation for technology i by the replicator equation of the base technology k we obtain the following equation

$$\frac{f_i(t+1)}{f_k(t+1)} = \frac{f_i(t)}{f_k(t)}\, \frac{c_i}{c_k} \tag{19}$$

The solution of that difference equation is equal to

$$\frac{f_i(t)}{f_k(t)} = \frac{f_i(t_0)}{f_k(t_0)} \left(\frac{c_i}{c_k}\right)^{t-t_0} \qquad \text{for} \qquad t \geq t_0 \qquad\qquad (20)$$

In the logarithmic form the equation may be rewritten in the easy to identify linear expression

$$\ln\left(\frac{f_i(t)}{f_k(t)}\right) = \ln\left(\frac{f_i(t_0)}{f_k(t_0)}\right) + (t-t_0)\ln\left(\frac{c_i}{c_k}\right) \qquad \text{for} \qquad t \geq t_0$$

Let us use the following notation $y_i(t)=\ln(f_i(t)/f_k(t))$, $a_i=\ln(c_i/c_k)$ and $b_i=\ln(f_i(t_0)/f_k(t_0))$. Therefore, the above equation can be rewritten in the following form:

$$y_i(t) = b_i + a_i(t-t_0) \qquad \text{for} \qquad t \geq t_0$$

Values of $y_i(t)$ for all t belonging to the period (t_1, t_2) can be calculated on the basis of the record values of shares $f_i(t)$; therefore, values of all parameters a_i and b_i for all $i \neq k$ can be identified applying the well-known method of identification of parameters of linear equations. The usual identification criterion is the least squares fit

$$Q_i = \sum_{t=t_1}^{t_2} (y_i(t) - a_i u(t) - b_i)^2$$

where $u(t)=t-t_0$, $t_0=t_1 - 1$, and we use that notation to indicate that the identification of both parameters a_i and b_i is possible even in the case of incomplete records, i.e., in the case of missing data for some moments within the period t_1 to t_2. For the above criterion of the least squares fit, the optimal values of both parameters are equal to

$$a_i = \frac{\displaystyle\sum_{t=t_1}^{t_2} y_i(t)u(t) - \frac{1}{m}\sum_{t=t_1}^{t_2} y_i(t)\sum_{t=t_1}^{t_2} u(t)}{\displaystyle\sum_{t=t_1}^{t_2} (u(t))^2 - \frac{1}{m}\left(\sum_{t=t_1}^{t_2} u(t)\right)^2}$$

$$b_i = \frac{\displaystyle\left(\sum_{t=t_1}^{t_2} u(t)\right)^2 \sum_{t=t_1}^{t_2} y_i(t) - \sum_{t=t_1}^{t_2} u(t)\sum_{t=t_1}^{t_2} y_i(t)u(t)}{\displaystyle m\sum_{t=t_1}^{t_2} (u(t))^2 - \left(\sum_{t=t_1}^{t_2} u(t)\right)^2}$$

where m is a number of moments for which the data on technologies shares are available, if we have data for all moments in the period t_1 to t_2 then $m= t_2 - t_1 +1$.

An advantage of the proposed approach is that the identification of the parameters a_i and b_i for each technology may be done separately. Once we have values of a_i and b_i for all technologies, we are able to calculate the values of competitiveness c_i and the initial shares $f_i(t_0)$. For the base technology, the competitiveness is equal to the assumed value c_k, from the definition of a_i we are able to calculate competitiveness c_i

$$c_i = c_k e^{a_i}$$

From the definition of b_i we have that $f_i(t_0) = f_k(t_0)e^{b_i}$ and from the condition that the sum of all shares is equal to 1 we are able to calculate all initial shares – namely, the initial share of the base technology is equal to

$$f_k(t_0) \;=\; \frac{1}{1 + \sum\limits_{j \neq k} e^{b_j}},$$

and for all other technologies

$$f_i(t_0) \;=\; \frac{e^{b_i}}{1 + \sum\limits_{j \neq k} e^{b_j}}.$$

This way we are able to identify all indices of competitiveness and initial shares for all technologies in such a way that the model, as described by equation (17), fits the best with the collected records on the past histories of those technologies.

The model can be used for different purposes, e.g., knowing the values of competitiveness c_i and knowing some details about the i technology, as expected profitability, size of investment, technical characteristics, price, etc.; we can estimate the influences of those characteristics on the basis of the values of the competitiveness of technology i. In this study, we show how it is possible to use the model to predict future shares of given technologies and to build alternative scenarios of future evolution of those technologies. The competitiveness in our model is assumed to be constant during the given period of time. Naturally it is not true for long periods, but it is a good approximation for relatively short periods. By choosing such short periods of time for different stages of given technology development, we are able to use our model to show differences in relative advantages of given technologies, as it was observed in different past periods.

The best way to deal with prediction and scenario generation problems is to show properties of that model using real examples. The model was applied to different kinds of phenomena, and the results are very promising. Due to the limited space, we present only two examples – primary energy sources in world energy consumption and raw steel production in the United States. We have chosen these two examples due to different modes of dynamics observed in both cases. It was possible to collect records on evolution of primary energy sources and the steel production technologies for a relatively long period, around 130 years, since the middle of the nineteenth century. As history shows, the dynamics of primary sources substitution (diffusion) is much slower than it is in the case of the different technologies of steel production. The competitiveness of different primary sources of energy varies naturally in the course of time, but it may be said that the indices of competitiveness were relatively stable during long periods. This is not the case in the diffusion of steel production technologies. Due to fervent research and development, the relative competitiveness of different methods of steel production varied significantly reversing the trend observed in past periods.

Both examples, as well as many other cases not presented here (e.g., the U.S. length of transport infrastructures [canals, rail, roads, airways], music shipments [records, CDs, cassettes], domestic freight transport in Japan [road, rail, water, air], transport of coal in underground mines of the former U.S.S.R. [manual, locomotives, conveyors]), show the possibility of using the model for quite different types of systems.

Primary energy sources

We have made numerous experiments in which real data from periods of the far past were used to identify the model's parameters, and next the simulation results for the years after the

specific identification period were compared to the real development. We call this kind of experiment retroprognosis. Experiments of this kind allow us to investigate the competence of the model to predict future market structure. The results of two retroprognoses are shown in Figures 1 and 2. The market shares of the main primary energy sources of the world energy consumption since 1860 were collected by Nebojsa Nakićenović and Arnulf Grübler (updated from Marchetti, Nakićenović, 1979).

In the period before 1862, only two primary energy sources existed – namely wood and coal – and in that period coal was substituting for wood. In 1862, the first data on using oil as an energy source are available, so in the first experiment the period 1862 to 1882 is used for identification of the model's parameters. The identification of diffusion models' parameters is especially sensitive in the period just after introducing the new technology, when the shares of new technology are small and may fluctuate. The share of wood at the beginning of the identification period was around 70%, and coal was around 30%. Oil was introduced in 1862 with the initial share equal to 0.15% and during that 20-year period, its share increased to 0.8%. Identification based on the real data of the period 1862 to 1882 (the period marked in Figure 1 by two vertical dotted lines) indicates that the competitiveness of wood is smaller and the competitiveness of oil is greater than that of coal; exact relative values are coal 1.0, wood 0.958, and oil 1.057. The other known sources of energy, namely gas and nuclear, were not present in that period and therefore are not involved in the experiment. The first practical use of gas was reported in 1885 and that of nuclear in 1961.

Assuming the constancy of the three identified indices of competitiveness, the prediction of shares of these three sources for the next 100 years was made (the solid line in the Figure 1). The real values of shares are marked by the dotted lines. As shown, the prognosis is really good for the next 50 years (for coal and wood even longer). Deviations became larger after 1930. The main cause of these deviations (especially visible in the case of oil) is, initiated in 1885, diffusion of gas. Interestingly, the prognosis is relatively good in the period since 1885, in spite of relatively quick diffusion of gas as the energy source.

In the second retroprognosis experiment, we assume the period 1920 to 1940 as the identification base. Now, the four technologies are involved in the experiment. The indices of competitiveness of wood, coal, oil, and gas are 0.978, 1.00, 1.042, 1.061, respectively. The values of competitiveness of oil and wood with respect to coal are slightly different than those in the previous experiment (for oil slightly smaller and for wood greater), but still oil is a better source than coal, and wood worse than coal. Gas became the best source of energy. As before, the retroprognosis (for next 50 years) was done (see Figure 2). The model's development fits relatively well to real data up to the beginning of 1970. The deviations from the real shares are mainly due to the oil crisis at the beginning of 1970s. The emergence of nuclear energy was not essential for development of other sources' shares. Significant deviations in the case of coal and oil in the end of 1930s and in the beginning of 1940s are caused by the pre-war and the war conditions, but as it is seen in Figure 2, after that period the course of changes of those two sources came back to their trend values. The identification period also encompasses the world economic crisis at the end of 1920s and the beginning of 1930s. The prediction for the next 30 years seems to be surprisingly good despite including data from the world crisis for identification and involvement of the world war at the beginning of the prediction period.

These two retroprognosis experiments show that in the case of primary energy sources, assumption of constancy of competitiveness gives satisfactory results in the perspectives of decades but is not valid for periods longer than 50 years.[1] In general, competitiveness is influenced by discoveries of new supplies of relevant sources but also by industrial (e.g.,

emergences of new industries, changes of industry structure) and social development. To investigate to what extent the constancy of competitiveness is observed, the following experiment was devised. For a given year t, the indices of competitiveness of relevant technologies are identified on the basis of the data of the preceding 10 years (i.e., the identification period is equal to (t-10, t)). We change t from 1870 to 1990 (i.e., we change the identification from the beginning to the end of the period for which we have real data). Through this, we obtain a kind of moving averages of all competitiveness. The results are presented in Figure 3. During the experiment, coal is assumed to be the base technology and its competitiveness is equal to 1.0.

It is seen that in the perspective of more than 100 years the relative values of competitiveness of all technologies are far from being constant, but in shorter periods the assumption of competitiveness constancy seems to be justified. Wood was almost continuously the worst source of energy, besides a short period in the 1930s and a longer period from the middle of the 1950s to the middle of the 1970s (when coal was the worst source of energy). For both oil and gas, the competitiveness of these two sources, just at the beginning of their diffusion (i.e., in the end of 1860s for oil and the 1890s for gas), was worse than coal, but their use was relatively quickly improved and their competitiveness boosted over that of coal. Gas was a worse source of energy than oil, from its introduction in 1885 up to the end of the 1930s (beside very short periods at the beginning of the twentieth century). Since the beginning of 1930s, gas was the best source of energy. The fluctuations (not very significant) of gas competitiveness almost parallel the fluctuations of oil competitiveness.

The oil crisis is a singular period in the history of world primary energy consumption. It is marked by an increase of wood competitiveness (what may be caused by diminishing use of energy in the most industrialized countries and constant use of energy in the less developed countries). As seen in Figure 1, the share of wood as the source of energy diminished steadily since the middle of the nineteenth century, but since the 1950s its share is almost constant, and in real terms increased in that period from 144 GW per year to 618 GW per year in 1990. This may be caused by the specific evolution of energy sources in underdeveloped countries, but also by some movements in developed countries (e.g., the idea of energetic forests in Sweden). Wood, coal, and gas were almost equivalent sources of energy in 1970s (with the competitiveness equal to 1.0), the competitiveness of oil dropped below one, and in 1985 (identified on the basis of the period 1975 to 1985) was around 0.97 (it seems that it reflects the shift in the structure of energy used in the most industrialized part of the world). In the 1980s, as seen in Figure 3, we observe the reverse tendency to return to the relative values of competitiveness observed before the oil crisis – with gas being better than oil, and oil better than coal.

We have mentioned nothing about nuclear energy – it seems to be a special case. Introducing nuclear energy is significantly different from oil and gas (does it reflect the much more significant engagement of governments in introducing nuclear energy than in introducing oil and gas?). Nuclear energy was introduced in 1961 with the initial share equal to 0.04%. In the next 30 years, its share increased very quickly to more than 6% in 1990. The competitiveness of nuclear energy has been enormously high since entering. Maximum competitiveness of oil was equal to 1.15 (around 1880); at the beginning of the diffusion of nuclear energy its competitiveness was equal to 1.36, and dropped very quickly in the next decades – in the end of 1980s its competitiveness was 1.10. It seems that since the beginning, practical applications of nuclear energy were artificially forced, and in the course of its development, more natural application was reached. This is not the place to discuss the details, but it seems that in future nuclear energy will remain the best source of energy, but its advantage over gas and oil will be of the order of a few percent – not tens of percent. As we see from this experiment and the two

previous ones, the values of competitiveness are far from being constant in the long-term perspective, but their general relationship, in terms of being better or worse, is relatively stable even in the perspective of 50 or more years.

Naturally the main aim of using this kind of modeling of diffusion processes is to apply it to forecast future development of the structure of primary sources of energy. The simplest way to make a prediction is to identify the model's parameters on the basis of the latest period and apply them to simulate future development of the model. Identification based on the period 1960 to 1990 gives the following values of competitiveness: wood 1.0186, coal 1.000, oil 1.0179, gas 1.0296, and nuclear 1.2031. The results of such a straightforward experiment are presented in Figure 4. If the current trend continued, nuclear energy would have been the major source of energy within next 10 to 15 years, and around 2030 almost 100% of used energy would flow from nuclear sources. It seems to be a very improbable course of development.

Taking into account observed trends of changes of all indices of competitiveness, it seems justified to assume that competitiveness of nuclear energy will still decline in the near future, and that oil and gas competitiveness will increase, gas competitiveness being greater than oil. Let us assume that the competitiveness of nuclear energy proportionally decline from 1.3 in 1960 to 1.1 in 1990 (see Figure 3), that is $c_i = 1.3-0.00666$ (t -1960), in the 1990s the decline is slightly slower and in the year 2000 will be equal to 1.05, that is $c_i = 1.1-0.005$ (t -1990), and since that year it will remain constant and equal to 1.05. Similarly, oil competitiveness will increase from 1.0179 in 1990 to 1.023 in 2000, and gas competitiveness will increase from 1.0296 to 1.035 in 2000. The competitiveness of wood and coal will be constant during the whole period and equal to their identified values. Let us also assume that a hypothetical, new source of energy will be introduced in 2025 with 1% initial share, and its competitiveness will equal to 1.07. The results of that scenario of development are presented in Figure 5. The development is significantly different from that of the straightforward prediction. The share of gas will increase in the next 50 to 60 years, reaching its maximum share (33.9%) around the year 2055 and after that year will slowly decrease (e.g., in 2070 the share will be 32.9%). The share of oil will slowly decrease. Around the year 2030, its share will be almost the same as the share of gas (around 32%); in 2050, the share of oil will be 27%. The share of coal will drop significantly from around 30% in the beginning of 1990s to 5.1% in 2050. The share of wood will remain almost constant at the level of 3%. The share of nuclear energy will grow steadily, although not so quickly as in the past, reaching 28.5% in 2050. Fraction of the new hypothetical source of energy will increase from its initial 1% in 2025 to 2.5% in 2050, and the noticeable impact of that new source will be visible 40 to 50 years after its first practical application, as was the case with oil, gas, and nuclear energy. It may be expected that around the year 2050, shares of three basic sources of primary energy (oil, gas, and nuclear) will be almost the same, around 30%.

To investigate the sensitivity of that scenario on patterns of future changes of competitiveness, a scenario was created in which only the competitiveness of nuclear energy will vary accordingly to the abovementioned pattern and all other competitiveness is constant and equal to their identified values (wood 1.0186, coal 1.000, oil 1.0179, gas 1.0296). So in that scenario, the competitiveness of oil is slightly smaller than the competitiveness of wood. The results of that scenario are presented in Figure 6. Compared to the previous scenario, the share of nuclear energy increases to 35% in 2050; the share of oil is slightly smaller (24% in 2050). Gas reaches its maximum share earlier, namely around the year of 2040 and is also smaller, equal to 31%. The share of coal is slightly greater – in the year 2050 its share is equal to 7%. So we see that the general mode of development in both scenarios is very similar, the differences are of the order of 2% to 5%. The main difference is that in the former scenario, gas has the maximum share of

around 34%, and nuclear is second with a share of 28.5%; in the second scenario, the nuclear energy has the maximum share equal to 35% and gas is second with a share of 31%.

Marchetti and Nakićenović (1979) present a scenario of primary energy substitution development to the year 2050. They base their prediction on long-term trends. To be very close to their scenario conditions, we assume that the identification period in our approach is much longer than was assumed in former experiments; namely, we use the period 1900 to 1990 to identify the model's parameters. Average, long-term competitiveness equals: wood 0.9919, coal 1.000, oil 1.0444, gas 1.0533. Nuclear energy was introduced in 1961, so it was not possible to identify its competitiveness. To create similar future development of nuclear energy and a new source of energy (solfus), as in the scenario of Marchetti and Nakićenović, we assume that nuclear energy was introduced in 1965 with 1% initial share (and competitiveness 1.086) and the new source will be introduced in 2025 with 1% initial share (and competitiveness equal to 1.12). The results of such created scenario are presented in Figure 7. The future share of coal is very similar to that of Marchetti and Nakićenović – share of coal in the year 2050 is equal to 1.2% but shares of oil and gas are significantly different. According to our long-term identification scenario, oil will still be the dominant source of energy in the next decades, with maximum share equal to 48% in the year 2005. After that time, the share of oil will decline to 33% in 2050. Share of gas in the next three decades will grow slightly quicker than the share of oil and will reach a maximum of 35% in 2030 and 31.5% in 2050.

The main difference between our long trend identification scenario and that of Marchetti and Nakićenović (1979) is in the course of development of oil and gas shares. Maximum share of oil in the Marchetti and Nakićenović scenario is slightly smaller (around 40%) and occurs 10 years earlier (in the middle of 1990s). According to Marchetti and Nakićenović the maximum share of gas will be reached also around 2030, but its value is twice greater (over 70%) than in our scenario.

U.S. raw steel production

Our second example has its internal dynamic significantly different from that of world primary energy consumption. The dynamics of shares changes of different sources of energy were relatively slow and stable. This is not the case in raw steel production. The changes are caused not only by exogenous changes of environment (related industries, social processes), as it was mainly in the case of the energy consumption, but also, in some periods very significantly, by endogenous factors (mainly innovation). The records collected by Grübler and Nakićenović (updated by Grübler (1990a and b) from Nakićenović, 1987) cover more than 120 years. Modern steelmaking dates from 1856 when Henry Bessemer discovered his process. Before that invention, steel was produced mainly in puddling furnaces and by crucible process. These methods of steel production were not very efficient, involved heavy manual labour and exposure of workers to high temperatures. The scale of production was not very impressive. It was possible to produce metal in batches of not more than a few hundred kilograms each. The real shares of the five basic steel production methods – crucible, Bessemer, open-hearth, electric, and oxygen – at the end of the nineteenth and twentieth centuries are presented in Figure 8 (dotted lines).

Industrial development in the first half of the nineteenth century created, and in some way forced, the demand for large tonnage of wrought iron and steel. This general economic development seems to be the main stimulus to invent new methods of the mass production of steel. William Kelly of Kentucky was probably the first person who worked on a pneumatic

means for producing steel from liquid impure iron by blowing a blast of cold air up through the molten mass. His first trials were done in 1846. Henry Bessemer was makng efforts along the same lines in England. These efforts ended in 1856 by patenting the Bessemer process. First applications of processes proposed by Bessemer and Kelly were not very promising. First of all, the process could not be used to make good steel from common English and American liquid crude iron. Fortunately, it was soon discovered that the addition of manganese to the blown metal from the converter makes the steel ingots dense enough and easily workable by rolling and forging without cracking. In the Bessemer process, air is blown through tuyeres (pipes) at the bottom of an acid-lined converter into a bath of molten pig iron. Most iron ores are contaminated by phosphorus and sulphur. The converter's acid lining in the Bessemer process does not help to remove these impurities from the steel. The other problem in the Bessemer process is caused by air blowing. The natural nitrogen component of air yielded steel with an undesirable nitrogen content. But in spite of these disadvantages, the Bessemer process proved to be much better than the traditional methods.

The first commercial production of Bessemer steel in the United States was in Wyandotte, Michigan, in 1864, but our data on Bessemer production in the U.S. starts after 1868, with a relatively high initial share equal to 33.3%. As seen in Figure 8, the Bessemer process very quickly superseded the traditional crucible process; in 1874, the share of the Bessemer process was more than 86%, whereas the share of the crucible dropped to almost 16%. We intentionally mention the year 1874, because since that year, data on the third steel production process are available, namely, the so-called open-hearth process. The introductory share of open-hearth was equal to 4.2% but dropped to 2.3% in the next year.

The Bessemer process has its disadvantages. Searches for new methods of steel production in the middle of the nineteenth century preceeded in various directions. In 1856, the same year in which Bessemer got his patent, two German-born scientists who also lived in England, William and Friedrich Siemens, invented a regenerative system for preheating the air supplied to a furnace. This idea produced flames of very high temperature. Siemens proposed a chamber filled with open brickwork which was heated for a time by the hot gases from a furnace. Next the air supply for combustion is heated by passing it through this chamber. Naturally, the chamber is alternately heated and cooled in cycles; to allow a kind of continuous heating of the air supply, a furnace is equipped with two regenerator chambers. In 1858, the Siemens brothers received a patent for the use of regenerators with a shallow-hearthed furnace for melting and refining steel. Applying the Siemens' idea, Pierre Martin (in France in 1862) built a furnace that was fired by gas (he improved it in 1864); the furnace was equipped by a set of two Siemens regenerator chambers at each end of the furnace; one heated air, and the other heated the fuel gas. The idea was useful; it was possible to operate with a flame sufficiently hot to melt steel scrap. The furnace became known as the Siemens-Martin furnace or, more commonly, the open-hearth furnace. This idea of the regenerative system was also applied to the crucible process. Crucible process competitiveness slightly increased and its share was not dropping so quickly since 1880s.

In 1868 the first commercial open-hearth operation was started in Trenton, New Jersey. The Bessemer and open-hearth processes produced steel in batches, or heats, much greater than the crucible process. Their sizes ranged from one or two tons at the initial phase of development to 15 tons or more. Introduction of the open-hearth process initiated competition among the three technologies, but the two newest ones played the most important role. Each of these three methods had its own advantages but also drawbacks. The open-hearth, where fuel oil or gas blows on the surface of the ore bath and heats the pig iron in a furnace, produces steel of excellent quality; however, it is slow and costly to install and operate. And it is the main reason

that the substitution of open-hearth for Bessemer was not so spectacular as substitution of the Bessemer for crucible in the end of 1860s and the beginning of 1870s. Competitiveness of the Bessemer process just after its introduction was more than 40% greater than the competitiveness of the crucible; in the analogous period just after introducing the open-hearth process, its competitiveness was only 10% higher than that of Bessemer. It seems that in the introductory period, in spite of some technological advantages of open-hearth steel, the economic factors (expressed, e.g., in terms of production costs) played an important role.

As in the previous example of the primary sources of energy consumption, retroprognosis experiments were done with the steel production diffusion process (Figure 8). The first 10 years just after introducing the open-hearth process were used for identification. The relative competitiveness of crucible, Bessemer, and open-hearth during that period is equal to 0.88, 1.00, and 1.11. Using those values of competitiveness indices, the prediction for the next 100 years was done. As seen in Figure 8, the quality of that prediction is relatively good for the next 50 to 60 years; significant deviations occur in the 1930s and later on due to the improvement of electric furnaces. The crucible process was steadily superseded, and its share at the beginning of the twentieth century was no greater than 1%. The Bessemer process reached the 80% share 10 years after its introduction. The same level of the share of the open-hearth was reached 30 years after its introduction.

From a practical point of view, in the end of the nineteenth and beginning of the twentieth centuries only two processes competed. Although both processes were significantly improved during that period, their relative indices of competitiveness were almost constant, and this is the main reason for the accuracy of the retroprognosis during that time. In 1876, Sidney G. Thomas and Percy Gilchrist invented a modification of the Bessemer process by which satisfactory steel could be made from high phosphorous iron. In the Thomas process, as it was called later on, instead of silica, a lining of lime was used. It solved the problem of phosphorous and sulphur removal but not that of high nitrogen content. The process permitted operation with a slag high in lime that could absorb phosphorus from the metal. Very shortly after this inventory, open-hearth furnaces were also built with their hearths lined with lime or magnesia instead of silica. As we have mentioned, parallel improvements of an open-hearth furnace were made. For example, in the open-hearth process, progress was directed toward building the aggregates of constantly bigger capacity. The smelting process was intensified through the application of mazut and oxygen, and further improvements were made by diminishing the amount of refractory material used. The use of gas as a fuel in the open-hearth was an important step in the development of fuel for steelmaking. This permitted all of the combustion to occur over the charge, a condition that could not be achieved with the combustion of solid fuel in a grate. A similar effect was achieved between 1880 and 1900, using heavy oils atomized with steam or air under pressure to form a long, nonturbulent flame over the hearth.

The next technology that emerged in the steel production is connected to the possibility of generating electric power. The first attempts to use an electric arc as the source of heat were made by William Siemens in 1878, who is credited with having first used electric power to make steel. The generators of electricity at that time were not very efficient, so the progress of using electricity to make steel was not impressive. The first commercial electric furnace used for the production of steel was build by P.-L.-T. Héroult in France in 1899. In fact, his design was the forerunner of all modern high-powered arc furnaces. The first commercial installation in the United States was in 1904. In that installation, the furnace was enlarged to the capacity of almost four tons per charge. The most commonly used electric furnace for steelmaking uses an arc struck between graphite electrodes and the metal charge as the source of heat for the system. The

electric-arc furnace is well suited to the production of high-quality special and alloy steels. Up to the moment of emergence of the electric furnace, special kinds of steel were produced by the crucible process. The electric process replaced the crucible, so the latter disappeared by the end of 1930. Electric furnaces have numerous advantages in steelmaking over the classical method, e.g., absence of contamination of the steel with elements present in most fuels (mainly sulfur); flexibility of the system, which permits special slags to be made and removed easily; very high temperature obtainable and its excellent control. During the electric process much less loss of expensive alloying elements occurs, so it significantly diminishes production costs.

The first available data on the electric method of steel production in the United States relates to 1909 – relatively small initial share equal to 0.08% was recorded in that year. In the next 15 years the share of electric steel was no greater than 0.5% and fluctuated steadily. It is impossible to evaluate the competitiveness of that technology on the basis of the data from that period. Electric furnaces were used in that period for special production. The electric-arc furnace, then relatively expensive to operate, became the principal method for producing alloy, specialty steels by 1920. The technology reached a kind of matured level in the mid 1920s, and since that time it is possible to make retrospective predictions. One of the retroprognoses is presented in Figure 9.The identification period is 1920 to1935 and on the basis of this 10 year period, the following indices of competitiveness are identified: Bessemer 0.939, open-hearth 1.000, electric 1.059. The forecast for the next 25 years is relatively good. But since 1960, the deviations are significant, especially in the open-hearth process. This deviation is caused mainly by the emergence of the new, in some way radical, technology of steelmaking in the 1950s – namely the oxygen process.

Henry Bessemer mentioned the possible use of oxygen for steelmaking in his fundamental British patent of 1856. At that time, this was not possible for practical use. The fractionation of air to produce pure oxygen was developed in 1889, but even after working out that technology, oxygen remained too costly for many years to be used as a primary oxidant in the manufacture of iron and steel. It was necessary to wait another few decades to work out a large-scale production of pure oxygen; the Linde-Fraenkl process was available in 1928. The first practical step was done before the World War II; in 1925, oxygen was added to the air blast of the Bessemer convertor. This idea spread and become common practice in Europe after 1945. The nitrogen content of the steel produced was still big problem; to reduce its content nitrogen-free blasts of oxygen and steam or oxygen and carbon dioxide were used (as suggested by T. Haglund in 1943).

A very promising idea of blowing pure oxygen into a bath of molten pig iron was proposed by professor Schwarz of the Technical University at Aachen, but it involved deep penetration and was not developed commercially. In 1952, the German steel firm, Mannesmann A.G., licenced the Schwarz patent but never used it in industrial practice. Similarly, English engineer John Miles proposed in 1946 a method of blowing a fluid containing from 65% to 98% of oxygen, preferably at an angle, from the top of the converter into the bath. Inventors also blew oxygen into the converter from below, in the hope that this would remove excess nitrogen from the steel. These experiments were done in 1940s, but the idea turned out to be unsuccessful because the heat from the pure oxygen blowing caused refractory damage.

The real breakthrough was provided by Swiss Robert Durrer at the end of the 1940s. He had advocated the use of pure oxygen in steel refining long before. In 1929, he performed small-scale experiments with oxygen in steel refining and smelting. The Germans, during World War II, adopted some of his ideas. In 1943, Durrer returned to Switzerland as the member of the management board of the largest Swiss steel firm, von Roll A.G. He and his assistant Hellbruegge from Germany began small-scale tests in the spring of 1948 using a 2.5-ton

converter which Durrer purchased in the United States. They continued their experiments in the next year and proved Durrer's ideas of blowing oxygen from above the converter into the molten pig iron bath below. They also encountered refractory damage and high phosphorous content in the steel, but their results indicated that Durrer's idea contained something new and important. Theodor Eduard Suess, manager of the VOEST, a government-owned Austrian steel firm, contacted Durrer at that time. Austria has had similar problems to Switzerland with making steel from its low grade ores. The Bessemer process was not suitable for the Austrian ores of high manganese content. Austria faced the problem of rebuilding its steel industry, highly damaged after the war. In April 1949, Austrian firms agreed to undertake a joint project on the use of pure oxygen in steelmaking. Suess with his collaborators organized the experiments at VOEST's Linz plant. They started experiments with provisional equipment of a 2-ton converter in order to meet some problems Durrer had predicted for the process. They followed Durrer's instructions to blow vertically from above into the bath but their first results were less satisfactory than those of Durrer. As it frequently happens, an accident occurred that led them to new data, indicating that process can be successfully modified. Simultaneously, Roesner and Kuehnelt of another Austrian firm Alpine conducted a series of tests, using 5- and 10-ton converters. A jet of pure oxygen was blown through a lance vertically from the top of a converter into the molten pig iron below. The jet was regulated in the distance from the bath and in pressure so as to avoid a deep penetration; this avoided refractory damage and allowed refining a phosphorous residue in the steel.

Very shortly after making pilot plant construction, both firms decided to open full-scale production. Commercial production was launched at VOEST in 1952 and at Alpine the following year. The revolutionary conception of the steelmaking process was developed into full-scale industrial production in 3 years. The oxygen process reduces both capital and labour requirements. The first commercial oxygen furnaces installed at Linz and Donawitz had a capacity of 39 tons, but successive installations became larger. Furnaces with capacities more than 275 tons per heat have been in operation in Italy, the United States, and Germany since 1964. The basic oxygen furnace produces carbon steel at least the equivalent in quality to basic open-hearth steel. The first oxygen converter was installed in the United States 3 years after launching commercial production in Austria. McLouth Steel Corp., then a small U.S. steel producer, purchased the know-how and engineering services essential for operating the oxygen process. The largest American steel firms were the last to adopt new techniques.

The speed of the oxygen process diffusion is so exceptional that it may be compared with the speed of diffusion of a few other radical innovations the twentieth century, e.g., computers and telecommunications technology. After the initial period of relatively slow diffusion, use of the oxygen process started to accelerate around 1961. Twenty years after its first implementation, the share of the oxygen steelmaking process reached 50% of the world steel production. The first available data on the industrial production of steel by the oxygen process in the United States are from 1955. The initial share of the oxygen process was 0.26%, but 10 years later in 1965, the share was more than 17%, and in the 1970s the majority of U.S. steel was produced by that process (in 1975 it was 61.5%). The first 10 years just after introduction of the oxygen process were used for the competitiveness identification; the values of these indices for Bessemer, open-hearth, electric, and oxygen are 0.854, 1.000, 1.063, and 1.542, respectively. The unnatural value of the oxygen competitiveness is clearly visible. We used those values to make retroprognosis for the next 20 years. The results are presented in Figure 10, and they are a very good example of how cautious we ought to be in making predictions using the straightforward approach. The prediction is really bad in the case of oxygen and open-hearth processes – the relative good fit of prediction is only for the next 3 years – but the most embarrassingly bad prediction is for the

electric process – its predicted share deviates from real data just in the first year of prediction. The reason for that ought to be searched in overestimation of the advantages of the oxygen process in the first years just after its introduction, but it seems that the main reason ought to be searched in the innovation process, mainly in the electric process.

From its nature, the emergence of any innovation is unpredictable as to what can be related (Kwaśnicki, Kwaśnicka, 1992, Kwaśnicki 1994) to the specific mechanisms of development of evolutionary processes, which lead to recrudescence and fulguration, by which we understand the impossibility of prediction of emergence of new systemic properties, radical innovation, etc.[2] If the search process is vigorous, we really do not know what is just around the corner. Results of the search for improvements of the electric process in the 1950s and 1960s were not so spectacular as in the case of the oxygen process, but due to a specific socioeconomic development of the 1960s, long-lasting research produced results in the end of the 1960s.

For several hundred years, metallurgists have argued the relative merits of the indirect and the direct processes for producing steel. The complicated processing sequence and the enormous capital investment for the facilities are the characteristic bad side of the classical processes. The indirect process consists of several stages, starting from producing a crude, relative impure iron in the blast furnace and then refining it in the liquid form in one of the traditional steelmaking processes. Contrary to the indirect method, in the direct process relatively pure iron ore is reduced to the solid-metallic state by hydrogen, carbon, and carbon monoxide. The solid metal is then melted, alloyed, and cast into ingots or strand-cast bars and slabs for subsequent processing into finished products. Interest in direct methods revived between 1965 and 1970 for a number of reasons. First of all relatively large supplies of high-quality ores suitable for direct processing have become available commercially.

The modern high-powered electric-arc furnace is well suited to economical melting of solid reduced ore. Direct processing is suited to small-scale production of steel in the range of 500 to 2,000 tons a day away from the large-scale production centers. Around 1970, one of the biggest steel companies rejected the idea of mini-steelworks, claiming this idea as a temporal fashion, which will pass off within a few years. (In spite of its name, mini-steelwork is not a small unit; its optimal size equals around one-tenth to one-sixth of traditional steelwork.) Mini-steelwork is an effective way of steel production. High temperature once achieved at the beginning of the process is not reduced in the following stages of production. It allows also for effective combination of using ore and scrap metal. Traditional, integrated steelwork requires a great amount of labour; mini-steelwork is suitable for automatization. It is possible to concentrate the production on one kind of final product, e.g., sheets, beams, bars. In effect, the unit costs of production of the modern electric process are a half of the analogous costs of the traditional methods.

The steelmaking processes was the subject of a vigorous innovation process, and it is not surprising that the competitiveness of different steelmaking methods is far from constant, especially in the long-term perspective. As before, in the case of primary sources of energy consumption, we made an experiment with moving the identification period. For given year *t*, identification of relevant competitiveness was made on the basis of the last 10 years. The results are presented in Figure 11. The open-hearth process was assumed as the base technology, and its competitiveness is equal to one. The Bessemer and crucible processes were worse (in terms of their competitiveness). Astonishingly, in spite of continuous improvements of the Bessemer and open-hearth processes during almost 100 years of their common history, their relative indices of competitiveness were almost stable. It seems that the drop of the competitiveness of the crucible process in 1920 is related to the emergence of the electric process in that period. The electric

process relatively quickly replaced the crucible process in making special steels. The substitution of the electric process for crucible started at the end of 1910 with a very high value of competitiveness of electric process and ended in the next decade. It is interesting to observe a strong correlation of the competitiveness of electric and crucible processes in 1920s; their relative values were almost stable during that period, e.g., in 1919 the relative advantage of the electric process over the crucible is 37%, 36% in 1925, and 31% in 1929, i.e., the last year of the crucible process. In the end of the 1930s the competitiveness of the electric process was almost equal to the open-hearth competitiveness, but since that time a substitution of electric process for the open-hearth can be noticed.

Improvements of the electric process were done at the end of the 1930s and the beginning of the 1940s. Maximum advantage of the electric process over the open-hearth was equal to 16% in the middle of the 1940s. In the next 15 years, the competitiveness of the electric process dropped to the small value of 1.05, i.e., slightly greater than that of the open-hearth. These low values of electric process competitiveness were accompanied with the emergence of the oxygen process. The competitiveness of the oxygen process was very high at the initial period just after its introduction (in 1965 it was equal to 1.54). From that perspective, there were no prospects for the electric process. But since the end of 1950s, two opposed trends can be noticed – significant reduction of oxygen process competitiveness (which dropped to 1.10 20 years later in 1985) and significant improvement of the electric process (1.03 in 1960, in 1965 increased only to 1.06, but in 1975 it was 1.22). In the middle of 1970, the competitiveness of the electric process became greater than that of oxygen. In the 1970s, the expansion of the oxygen process was stopped, and its share was kept almost at the same level of 55% to 60%. In that period, substitution of the electric process for the open-hearth occurred. The share of open-hearth diminished to the 7% in 1985, and at that time, the share of electric process increased to almost 33%.

It is very difficult to predict the future changes of competitiveness of the two best steelmaking technologies. It seems that the electric technology will have advantages over the oxygen process but not very significant. In the 1980s, the competitiveness indices of electric and oxygen processes reached their stable level, around 1.18 and 1.13, respectively. We have no data on steel production in the last 10 years, but judging from the collected records up to 1986, the process of substitution of electric process for oxygen ought to be present at the end of 1980s and the beginning of the 1990s. We have made straightforward prediction of the future structure of steel production. The last available data from the period 1970 to 1986 were used to identify the competitiveness of open-hearth, oxygen, and electric, which are equal to 1.00, 1.132, and 1.183, respectively. The prediction of the shares for the next 30 years is presented in Figure 12. It may be expected that open-hearth will disappear within the next 10 to 20 years (in 2010, the expected share is equal to 0.17%). From the perspective of the 1970s and the beginning of 1980s the shares of electric and oxygen processes ought to be almost equal (around 49%) in 1998 or 1999, and after that time, the electric process is expected to dominate the production of steel. Probably the oxygen process will be improved (but to what extent and what will be the response of the electric process is very difficult to say), or maybe some other process will emerge in the beginning of the next century. To what extent it will change the shares of the electric and oxygen process, we can only speculate. It seems that the relative values of competitiveness for electric and oxygen processes will remain at the actual level, so we may expect that in 2020 almost 70% of steel will be produced by the electric process and 30% by the oxygen process.

Our straightforward prediction corresponds with the prediction made by Nakićenović (1987) and Grübler (1990a and b). The differences between the two predictions are not significant. Nakićenović also predicts that the electric process will dominate U.S. steel manufacture and in

2000 will reach 57% (in our prognosis, it is 51%). The oxygen process will decline in the end of the twentieth century and in 2000 will be equal to 42% (our prognosis is 48%). The open-hearth process will be not used in 2000, its share will be very close to zero (in our prediction, around 1%). Also, the moment of almost equal partition of the market between electric and oxygen processes is very close in both predictions – in Nakićenović-Grübler in 1995, in our prediction in 1998.

Conclusions

The model of substitution-diffusion processes is a simplified version of the evolutionary model of industrial dynamics (Kwaśnicki, Kwaśnicka 1992, Kwaśnicki, 1994) and continuation of our former attempts to describe diffusion processes in our article on "Technological Substitution Forecasting with a Model Based on Biological Analogy" (Kwaśnicka, Galar, Kwaśnicki, 1983). It was shown in this study how it is possible to use the model to predict future shares of given technologies and to build alternative scenarios of future evolution of a market structure. The proposed approach to describe diffusion-substitution processes seems to be very flexible: it allows dealing with many technologies; data required to make predictions or build scenarios of development are relatively easy to collect (shares of different technologies as observed in the past); the identification procedure allows observation of dynamic changes of indices of competitiveness of all technologies involved (see Figures 3 and 11; moving identification period).

Two examples presented in this study (primary energy substitution and steel manufacture) were chosen because of different dynamics features of both processes. As history shows, the dynamics of primary sources substitution (diffusion) is much slower than it is in the case of different technologies of steel production. The competitiveness of different primary sources of energy varies naturally in the course of time, but it may be said that the indices of competitiveness were relatively stable for long periods. This is not the case in the diffusion of steel production technologies. Due to a fervent research and development process, the relative competitiveness of different methods of steel production varied significantly, reversing the trend observed in past periods. As the results of simulation and scenario generation show, in both cases the model can be successfully applied to describe both processes.

The proposed approach was used to describe and predict future development of many other processes (e.g., the U.S. length of transport infrastructures, music records shipments, domestic freight transport in Japan, transport of coal in underground mines of the former U.S.S.R.), and the obtained results are very promising.

Besides prediction and scenario generation, it is possible to use the model to estimate influences of technologies characteristics (e.g., expected profitability, size of investment, technical characteristics, price) on the values of indices of competitiveness $c_i(t)$ (values of which can be identified through using moving identification period approach) of different technologies – in a similar fashion as was done by Mansfield (1961) in a case of an innovation-specific rate of diffusion as the parameter of the logistic function.

Notes

1. The coincidence of our empirical results of the limited 50-year period of prediction with well-known phenomenon of long waves (or Kondratieff cycles) is intriguing and requires further investigation.

2. This is a general problem of the prediction abilities of social scientists, and economists in particular. Many researchers complain that the ability to predict future changes of social processes is not as accurate as for natural processes, which are the subject of research of physicists, astronomers, cosmologists, etc. The reasons for this inability are not only due to limited knowledge of mechanisms of socioeconomic development and impossibility to formulate similar, strong laws of socioeconomic development as formulated by physicists. In our opinion, the main reason of bad prediction abilities of economic processes (and all evolutionary processes in general) is the essential unpredictability of the emergence of innovations (new genotypes in the case of biological evolution). It may be said, with a half smile, that the situation of physicists would have been very similar in their prediction abilities to, for example, economists if randomly from time to time God sneezed and abruptly changed the state of the natural process being predicted (e.g., changed the position of a planet whose trajectory is the subject of a prediction).

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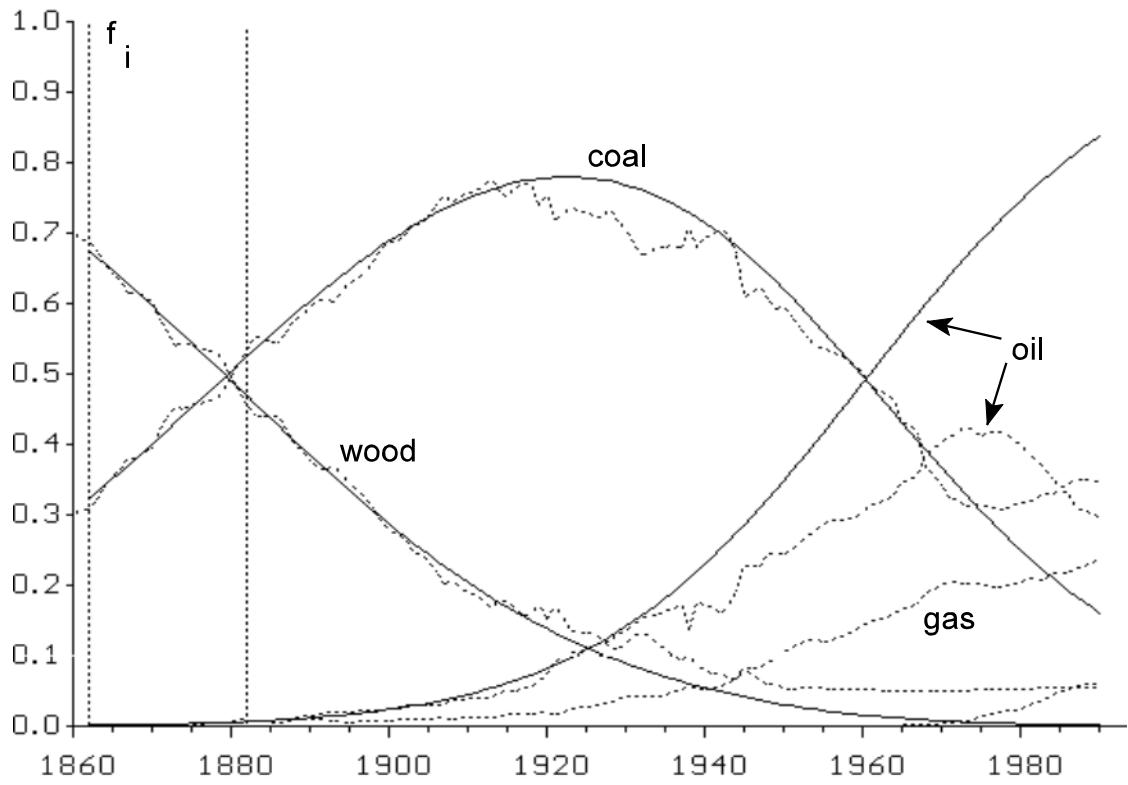
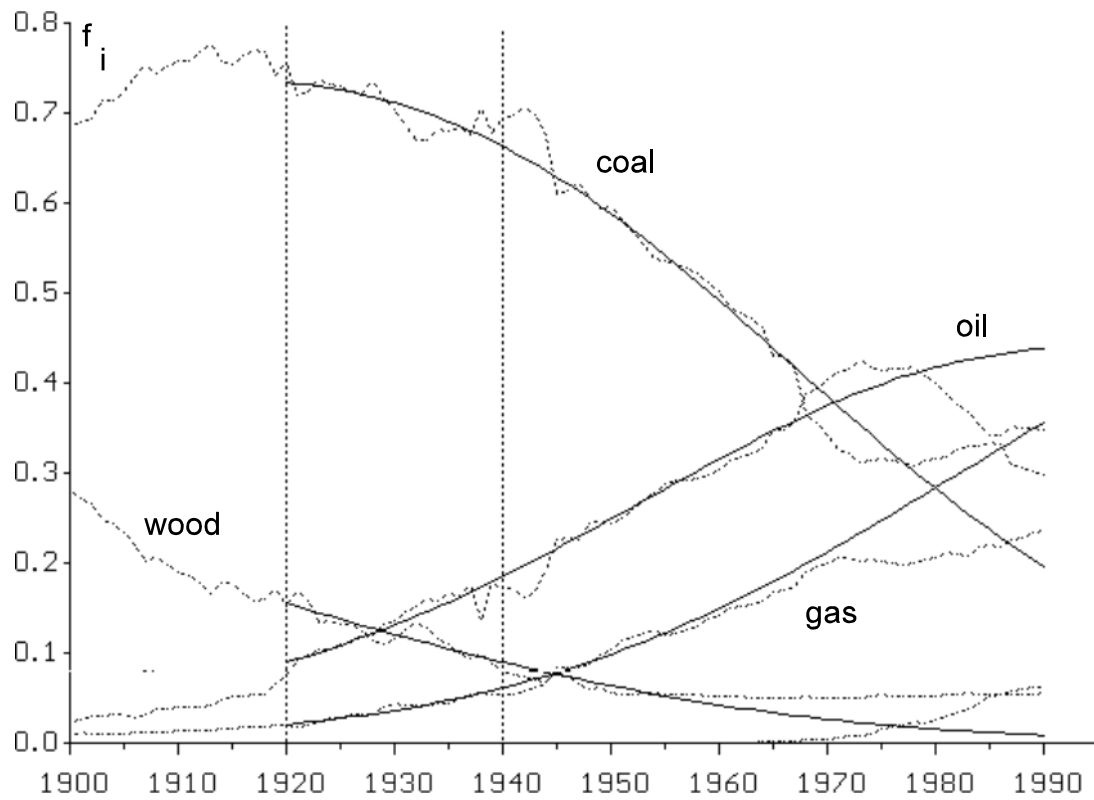**Figure 1**. Retroprognosis of energy structure - identification period 1862-1882.

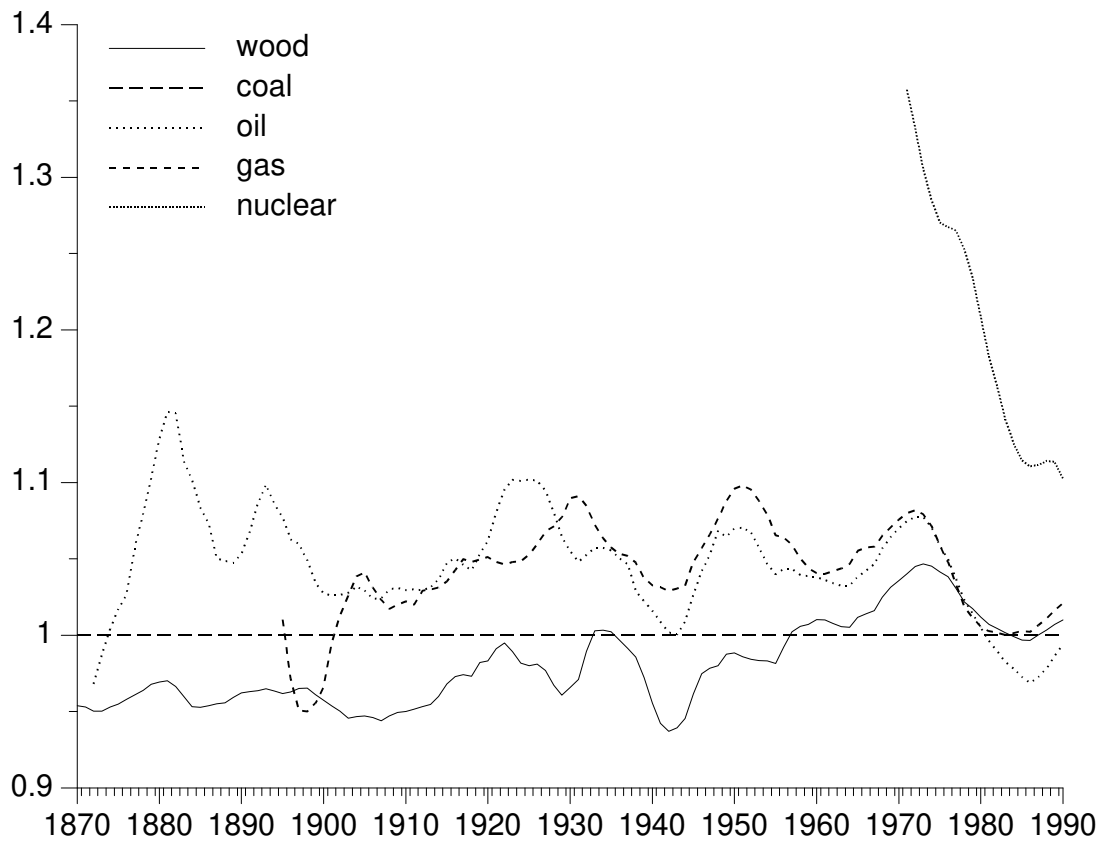**Figure 2**. Retroprognosis of energy structure - identification period 1920-1940

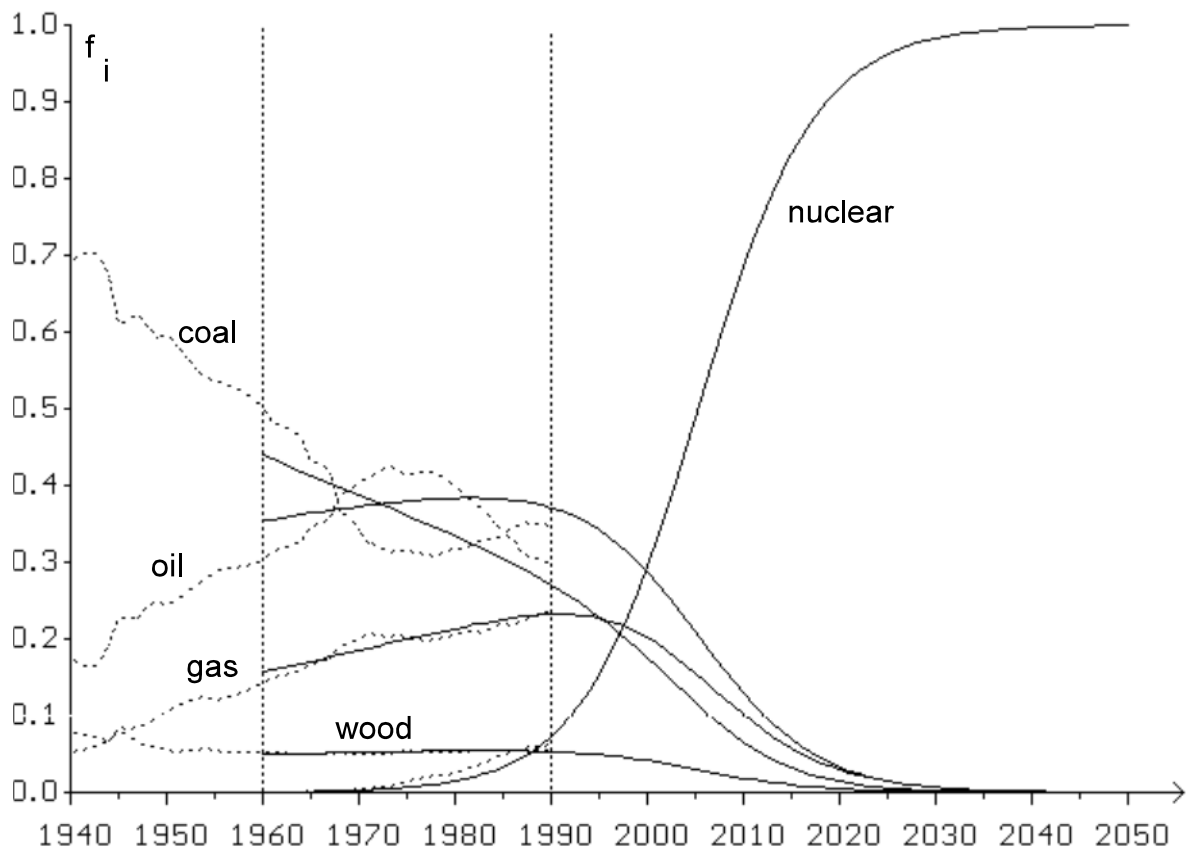**Figure 3**. Relative competitiveness of different sources of energy (the coal competitiveness equal to 1)

Figure 4. Straightforward prognosis of energy structure - identification period 1960-1990
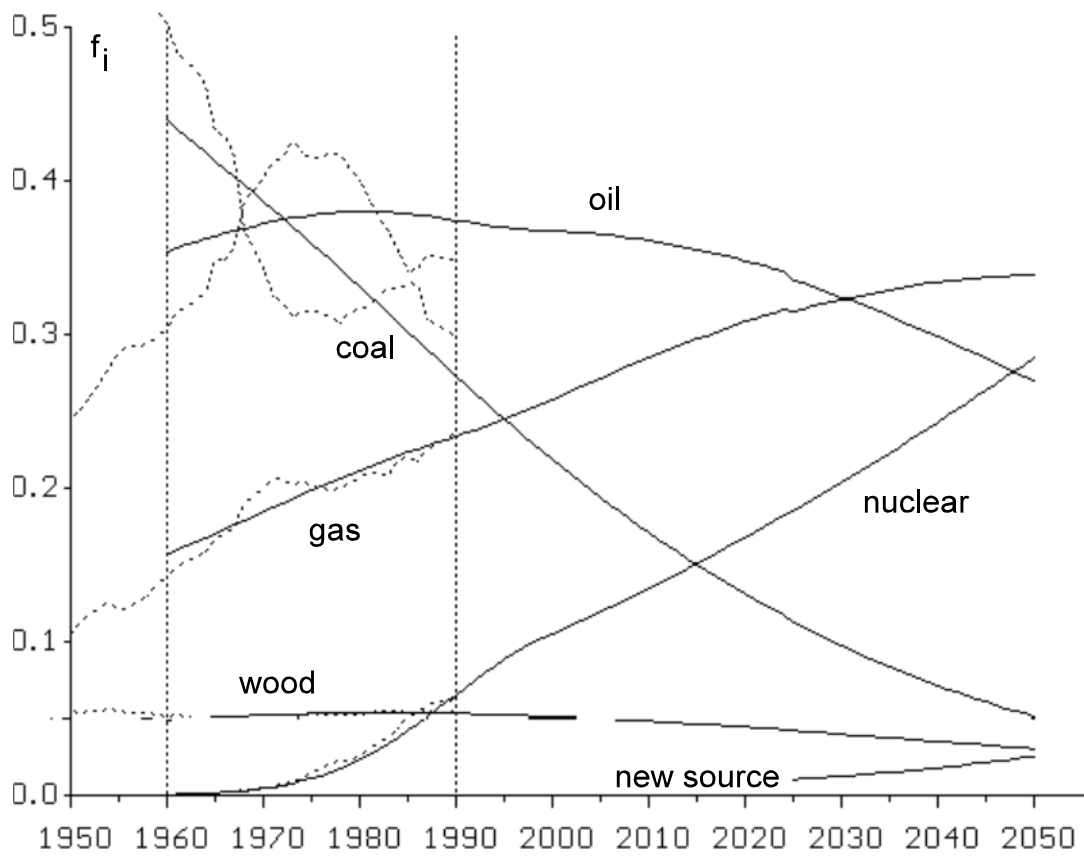
Figure 5. The first scenario of energy structure development - oil, gas and nuclear energy competitiveness variable
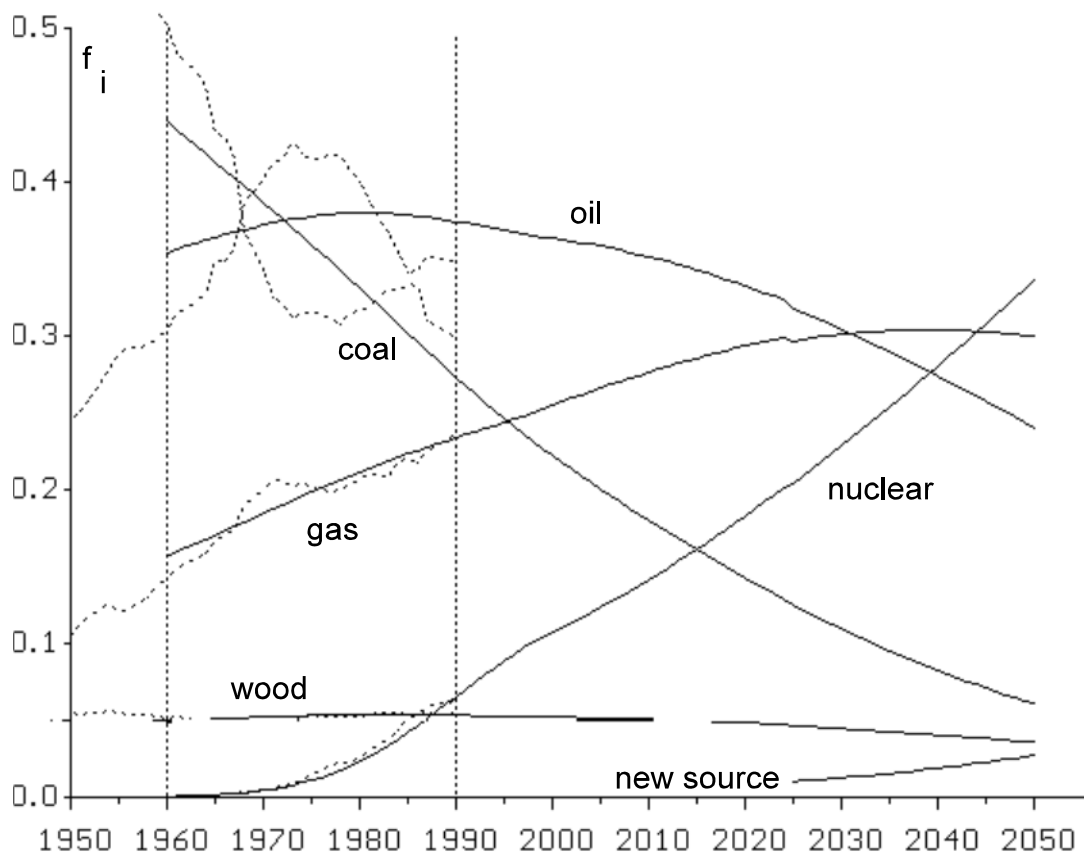
Figure 6. The second scenario of energy structure development - identification period 1960-1990; nuclear competitiveness variable.
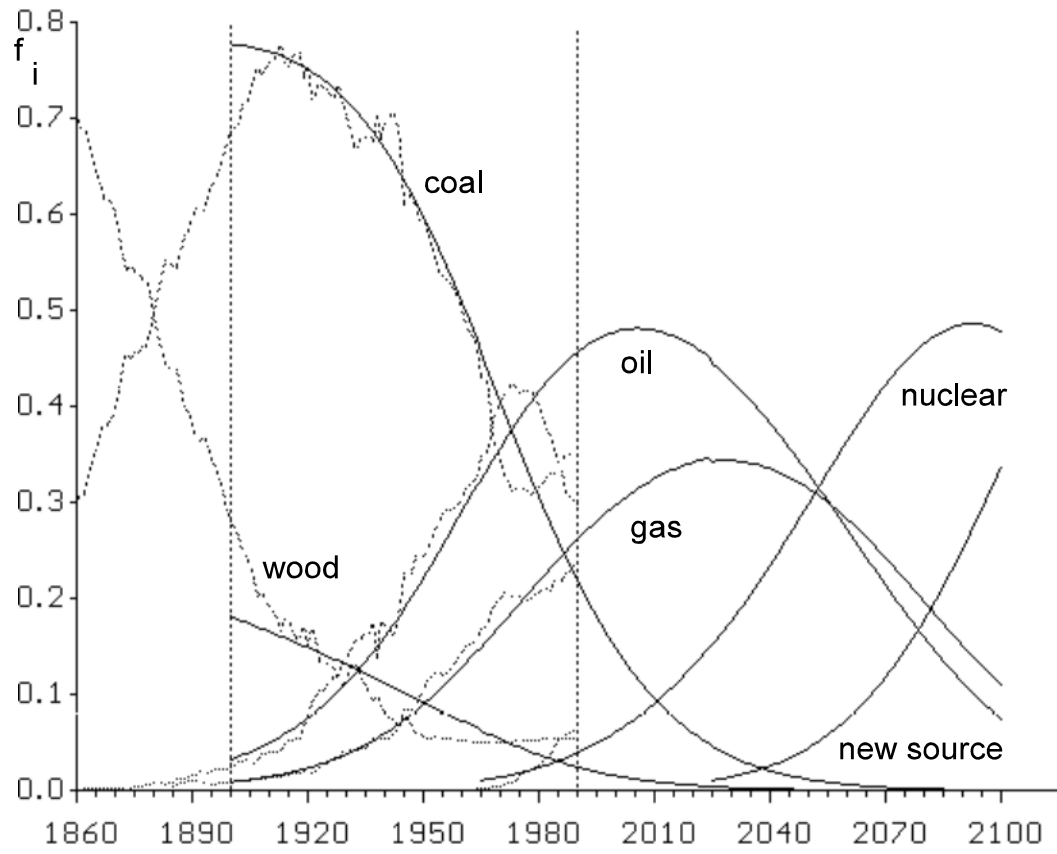
Figure 7. The long term scenario of energy structure development
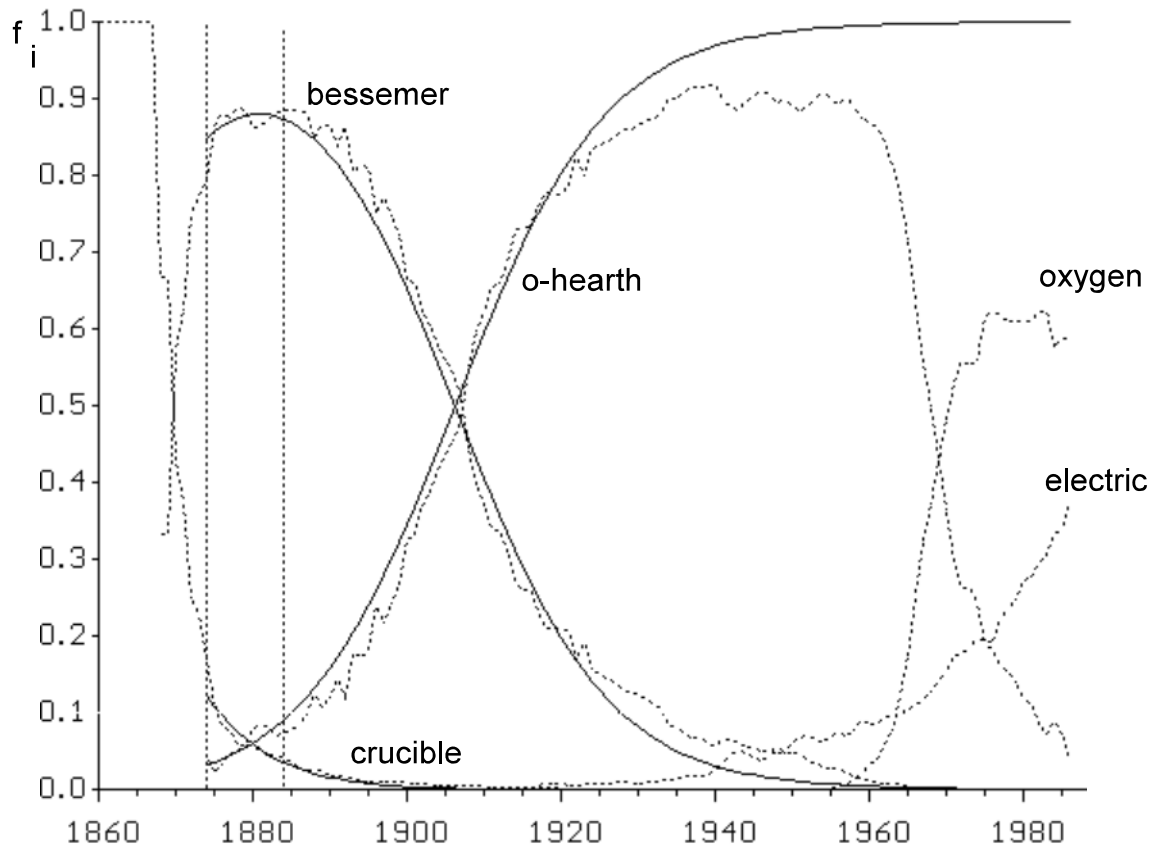
Figure 8. Structure of raw steel production in USA - retroprognosis, identification period 1874-1884
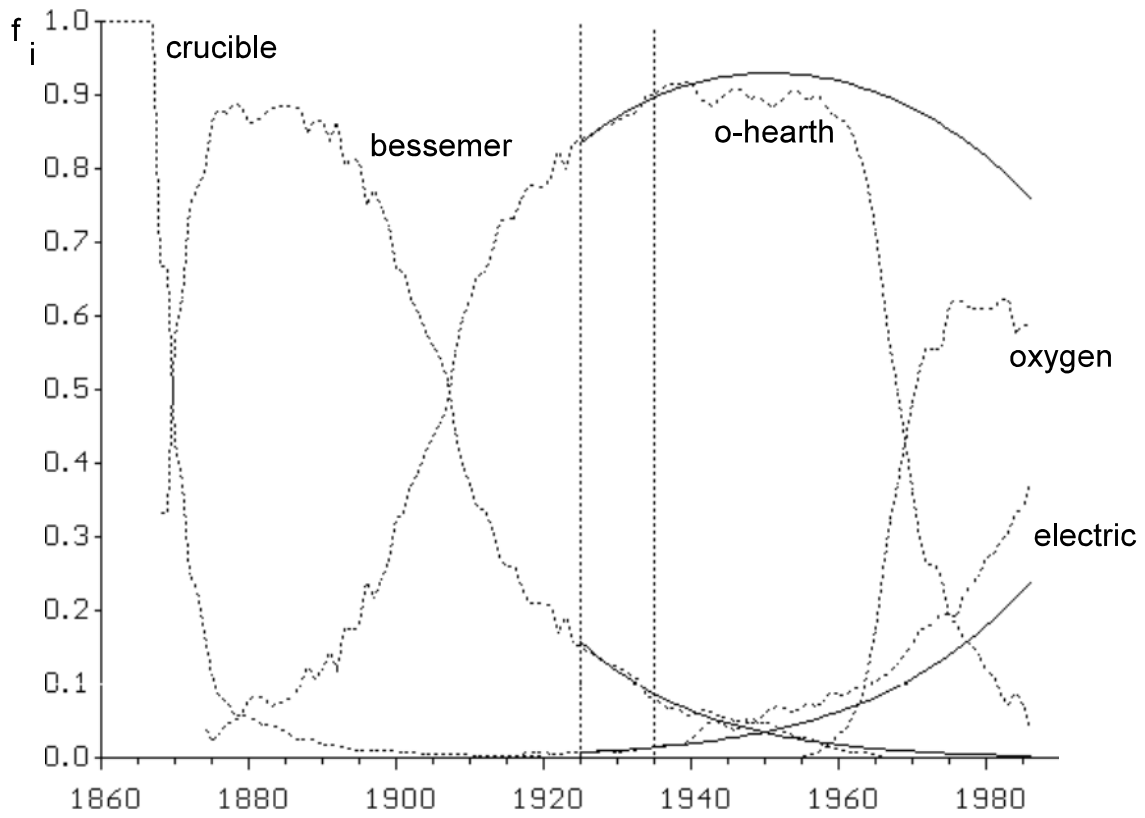
Figure 9. Structure of raw steel production in USA - retroprognosis, identification period 1925-1935
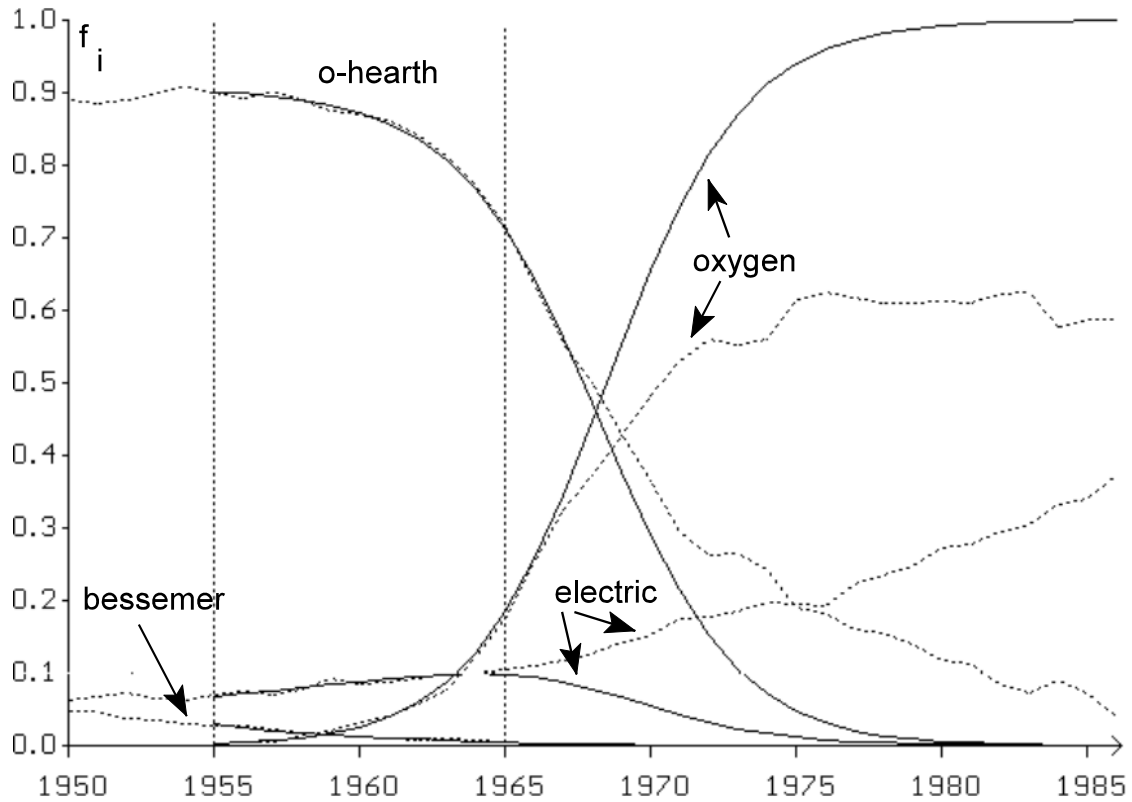

Figure 10. Structure of raw steel production in USA - retroprognosis, identification period 1955-1965
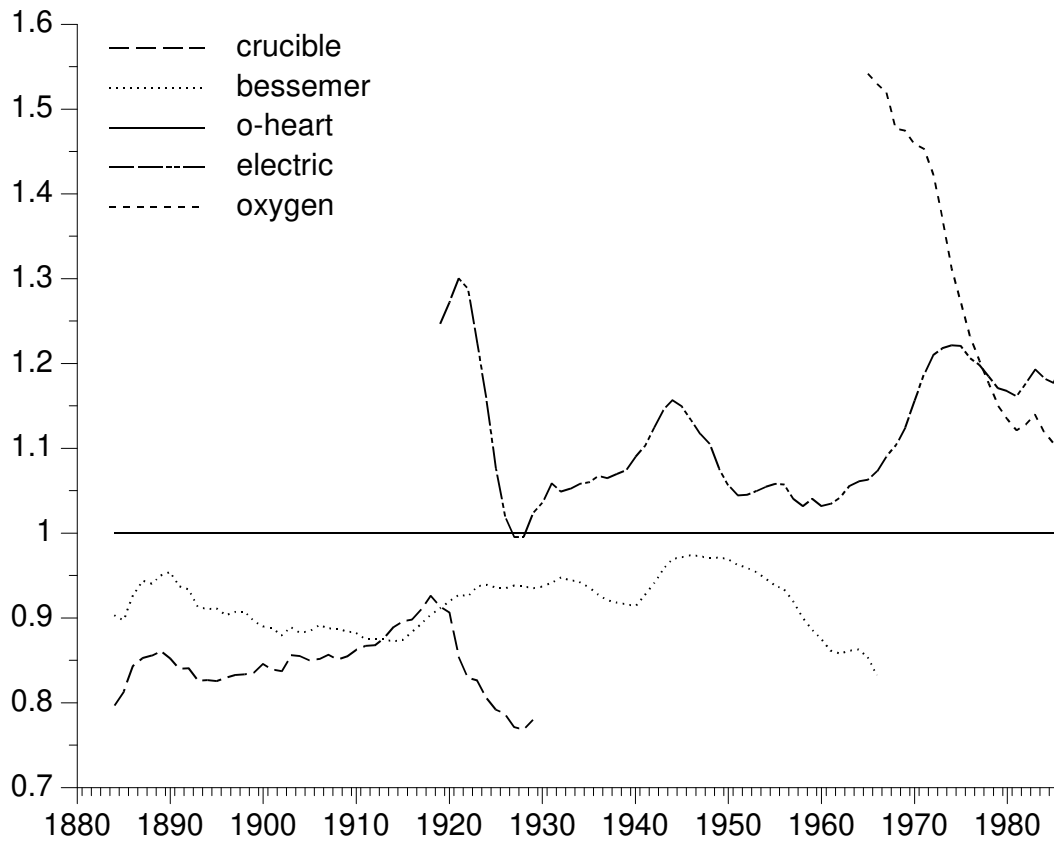
Figure 11. USA raw steel production; relative values of competitiveness
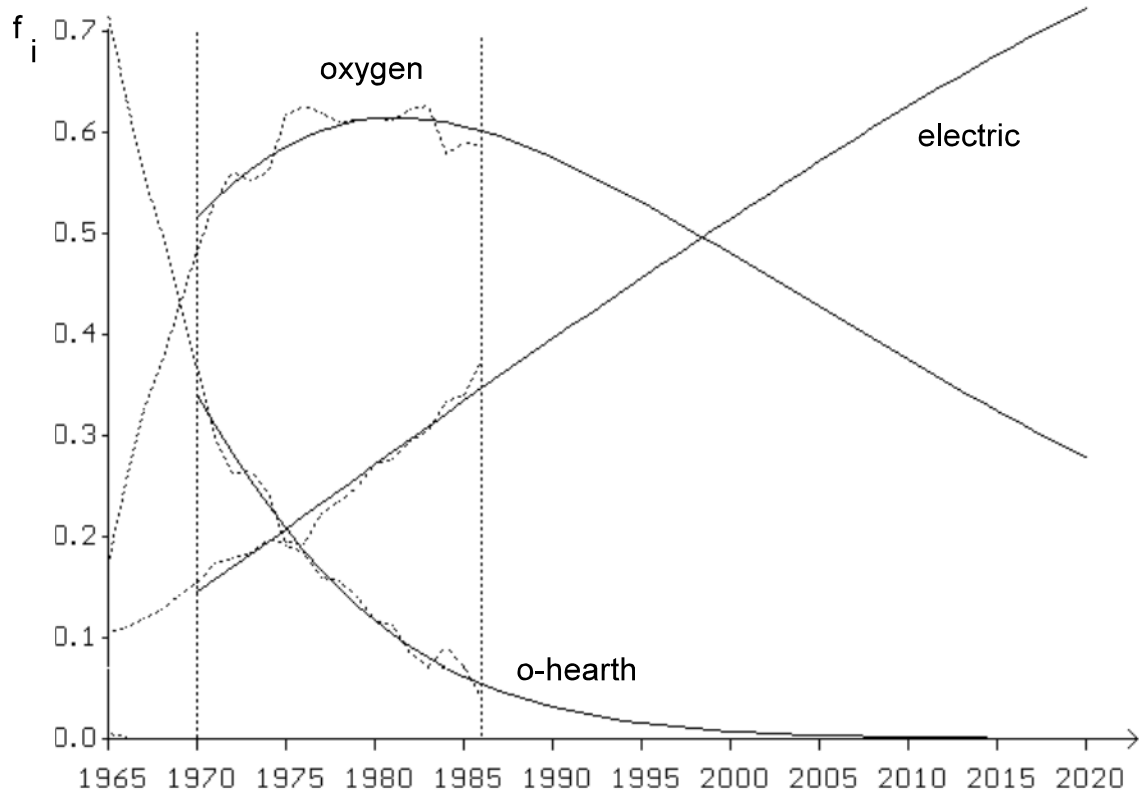

Figure 12. Structure of raw steel production in USA - prognosis, identification period 1970-1986