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Productive energy in the US economy

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Abstract

In this paper, methods of separation of primary work E_P, which is needed to provide the genuine work of production equipment, from the total amount of primary energy E are proposed. Direct estimates of primary work of production equipment E_P on the base of available data for the US economy for the 20th century are compared with alternative evaluations of the same quantity calculated from time series for consumption of labour and primary energy. The relationship among primary energy E, primary work of production equipment E_P, and genuine work of production equipment P (productive energy) is considered. The results allow one to estimate coefficient of efficiency of primary work of production equipment.

Keywords: Decomposition of primary energy; Energy in production; Production system; Technology

1. Introduction

One of the main questions, which arises at investigating the problems of energy-economy coupling, is a question about existence of a universal measure of cumulative effect of consumption of energy carries on production output. One is looking for a quantity that must be as universal as labour and capital in the conventional theory of production [1,2]. In attempts to answer the question, the scholars [3–6] investigated mechanisms of utilisation of energy in production processes and concluded that exergy, not energy, could be a better characteristic of consumed resources. Exergy, as available energy or potential work, allows one to come closer to description of the essence of production processes. Some investigators [4,5] consider exergy to be such a universal characteristic that allows creating the all-embracing extended exergy analysis [5] including exergy estimation of capital and labour. The others [6,7] are more cautious, they prefer to remain within the conventional theory of production, completing it with a variable, which has the meaning of work of production equipment. Note that, unlike energy or exergy, which are characteristics of the used resources, work is a characteristic of production process itself. This quantity is a universal cumulative characteristic of production processes [6], but another question arises: whether this quantity correlates with production output measured in money units.

In recent paper [7], referring to the mechanism of evaluation of output of the production system and accepting the law of substitution, that is equivalence of labourers' work and work of production equipment, we argued that genuine substitutive work, which does not include quasi-work, that is energy spent for heating, lighting and chemical transformation, ought to be separated as a special quantity in description of production. The specific term *productive energy* was used to dub that part of consumed energy (exergy), which is used to substitute work of labourers with work of production equipment. In economic terms, energy carriers are considered as intermediate products that contribute to value of produced products by adding its cost to the price quite similar to other intermediate products participating in production process. However, the *productive energy* or *substitutive work* P has to be regarded as a value-creating factor which has to be considered in line with the conventional production factors of neo-classical economics—capital K and labour L [7]. In this role, the productive energy can be also considered as capital service provided by

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capital stock equally with labour service. Introduced, in order to take into account technological change [2], the concept of 'capital and labour services' is found [8,9] to be very useful to explain the observed growth of productivity, though nobody did not go so far as to regard labour and capital services as independent production factors.

In this paper, we are going to show that calculated earlier [7] values of productive energy, which are needed to obtain the correct values of output, correspond to estimates of primary substitutive work of production equipment. For this aim, we shall develop methods of estimation of primary productive energy E_P—the amount of energy carries, needed to provide the genuine substitutive work of production equipment P. In other words, we are going to separate the part of primary energy, directed for heating, lighting and chemical transformations E_C, from the total amount of primary energy E, so that

$$E = E_C + E_P. \tag{1}$$

We shall use two methods of estimation of primary productive energy E_P: the first one, considered in Section 2.1, is based on direct separation and estimation that part of primary energy (exergy), which is directed for work (without quasi-work) of production equipment. The second method, considered in Section 2.3, is based on the property of productive energy to substitute labour services in production processes, and, as a consequence of this, we consider that changes of the quantity E_P, as a function of time, anti-correlates with changes of labour. One can assume that changes of the other part E_C correlates with changes of labour, though the correlation cannot be perfect. These properties allow us to develop a method of calculation of that part of primary energy, which is needed to provide the genuine substitute work of production equipment. The calculated values of primary and genuine productive energy are used to evaluate the coefficient of efficiency $\omega = P/E_P$, which is compared with different estimates in Section 3. The conclusion contains a discussion of the problem.

2. Evaluation of primary productive energy

The estimates for consumption of energy careers, or *primary energy* consumption, in the US economy—as it is calculated by official statistics of the US Department of Energy (see also Appendix in the paper [7]), are shown by top solid curve in Fig. 1. The primary energy consumption E is the content of energy in energy carriers as they are taken from the nature: chemical energy embodied in fossil fuels (coal, oil and natural gas) or biomass; the potential energy of water reservoir; the electromagnetic energy of solar radiation; and the energy released in nuclear reactions. Note that primary energy is not used directly but mostly is transformed and converted into fuels and electricity—*final energy*—that can be transported and distributed to the points of final use. The final energy consumption provides energy services at manufacturing, transportation, space heating, cooking and so on, so that, in fact, one has to consider the usage of final energy (exergy) to estimate primary work of production equipment, as it is done by Ayres et al. [6]. However, according to Nakićenović et al. [10], for example, the global average of primary to final efficiency is about 70% in year 1990, while it is higher in developed countries, so that difference between primary and final energy can be disregarded in the first attempts to estimate primary work of production equipment.

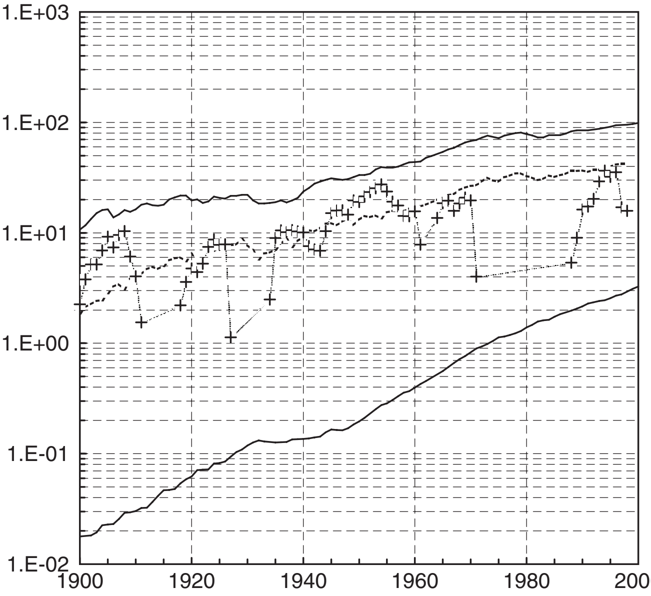

Fig. 1. Consumption of energy in the US economy. The solid lines represent consumption of energy careers (primary energy, top curve) and genuine substitutive work of production equipment (productive energy, bottom curve which can be moved up or down). The dashed line depicts primary energy, needed for production equipment to work, estimated on the base of data (I am grateful to the authors of the paper [6] for opportunity to use their data in a computer-codes form.) of Ayres et al. [6] as the sum of half of the net electricity consumption, consumption of energy by other prime movers and non-fuel consumption of oil products (Section 2.1). Primary productive energy is also calculated (and depicted by cross +) as a part of primary energy, changes of which anti-correlates with changes of labour (Section 2.3). All quantities are estimated in quads (1 quad = 10^{15} Btu ≈ 10^{18} joules), per year.

2.1. Direct estimates of primary work

Primary productive energy E_P can be estimated directly as work of production equipment, which fulfils the same operations as labourers, but with help of external sources of energy. This definition of primary productive energy excludes quasi-work (energy spent for lighting, heating and chemical transformations) from consideration. According to Ayres [11, Table 1], that part of primary energy, which can be considered as primary productive energy (primary work of production equipment: machine drive, transport drive, farming and construction) in the US economy, was about 32% or about 30 quad[1] in 1991. To evaluate time dependence of production energy, we refer to the historical data on consumption of energy (exergy) for different aims in the US economy collected and analysed by Ayres et al. [6]. The quantity, which was estimated in this fundamental study, was work and quasi-work of production equipment in different sectors of the US economy. To exclude quasi-work, we consider three classes of different human's efforts, which can be assumingly substituted in production processes.

1. *Efforts on displacements of substances and bodies* (*including humans own bodies*) were substituted by work of animals, wind and moving steamer engines in the past. Now they are substituted mainly by work of self-moving machines—automobile, trucks, aeroplanes and other mobile equipment. In the US, the self-moving machines are driven mostly by the products of oil, so that estimates of energy used for these purposes in the US economy can be obtained as a sum of energy of consumed distillate fuel oil, jet fuel, and motor gasoline. According to the data of the US Department of Energy (www.eia.doc.gov) the amount was 19.46 quad in year 1998. This is the energy content of fuel; the amount is different from amount of work (service energy) which is moving vehicles.

2. *Efforts on transformation and separation of substances and bodies* are efforts in production of clothes, tools, different appliances and so on—much, if not all, manufacturing. The animal drive, wind drive, water drive and steam engine drive were used to do work instead of humans in the previous centuries. To the middle of the 20th century, the same work is being mainly done by machine with electric drive [6]. According to the US Department of Energy (http://www.eia.doe.gov), motor-driven equipment accounts for about half of electricity in manufacturing sector. Non-industrial motors, driving pumps, compressors, washing machines, vacuum cleaners, and power tools, also account for quite a lot of electricity consumption. Part of electricity consumed by cloth washes and dish washers provide mechanical movement substituting human efforts. So we can account that more than half of consumed site electricity in the US economy, that is about 6 quad in 2000, is taken by motors.

3. *Efforts on sense-based supervision and co-ordination, development of principles of organisation* were considered as essentially human functions up to recent times. While the humans efforts listed above have been successfully substituted by work of other sources of energy from ancient times, the attempts to mechanise the functions of the brain were mainly unsuccessful until the advent of computers (information processors) in the 20th century. Now work of brain is being substituted by information processors driven by electricity. According to Energy Department of the US (http://www.eia.doe.gov), the consumption of electricity by computers and office equipment in commercial sector of the US economy in year 1999 was 0.4 quad. In residential sector, electricity was consumed by computers and electronics in amount 0.75 quad in year 1999. There is no data about consumption of electricity by computers in industrial sector, though one can hardly have any doubt about the presence of appliances of information technology in this sector and sector of transportation. To the sum of the above quantity—0.75 quad—one has to add the amount of electricity consumed by other office and communication equipment in all sectors. In total, one can guess, that the consumption of electricity by computers, electronics and office equipment might be about 1 quad in year 1999. This figure estimates, at least, a scale of phenomenon.

Thus, this consideration allows us to separate primary productive energy—the amount of energy careers needed for work of production equipment, as the sum of half of the net electricity consumption, consumption of energy by other prime movers and non-fuel consumption of oil products evaluated by Ayres et al. [6]. The dashed line in Fig. 1 depicts primary productive consumption of energy (exergy) in the US economy according to this very coarse estimation of the empirical situation. The total consumption of energy directed for substitution at the end of the century counts about 27 quad or about 30% of total primary consumption. This estimate is consistent with the earlier evaluation of Ayres [11].

2.2. Estimates of substitutive work

The genuine substitutive work of production equipment—productive energy—can be estimated as $P = \omega E_{\mathrm{P}}$, if one knows primary productive energy E_{P} and efficiency of use of primary energy sources ω. According to Ayres [11, Table 1], primary work of production equipment (machine drive, transport drive, farming and construction) in the US economy, was about 32% in 1991 with the coefficient of efficiency about 0.01–0.03. These figures, also as above estimates of primary productive energy as 27 quad, allows one to evaluate the amount of genuine substitutive work as 1–2 quad at the end of the century.

The work of production equipment, needed for substitution of labourers' work, can be estimated independently, as shown in the previous paper [7]. The method of evaluation, based on a certain relations between the rates of growth of production factors, allows one to calculate the growth rate of productive energy, if one knows the rates of growth of output, capital and labour consumption. Then, one can restore time dependence of productive energy, if the absolute value of the quantity itself in one of the moments of time is known. The method does not allow to calculate absolute values of productive energy, it was taken, according to the above estimation, to be about 1 quad at the end of the century. The calculated in this way values of productive energy are depicted by the bottom solid curve in Fig. 1.

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[1] It is convenient to measure huge amounts of energy in a special unit *quad* (1 quad = 10^{15} Btu ≈ 10^{18} joules), which is usually used by the US Department of Energy.

These results allows us also to estimate measure of substitution—genuine work of production equipment needed to substitute 1 h of labourer work; the calculated numbers for the US economy are shown in Fig. 2. The measure of substitution is a characteristic of a production process, but it has no universal value: it changes for the chosen economy over time. The measure of substitution is apparently different for different economies. The corresponding primary work of production equipment is much bigger than genuine substitutive work: it counts about 240 MJ/h at the end of the century. The primary and genuine substitutive work can be taken as a measure of labour corresponding to the exergy equivalent of labour introduced and estimated by Sciubba [5]. The above values are average estimates for all sectors of the US economy. However, the measure of substitution can be different in different sectors, and the task of estimation of substitution measure in separate sectors is left. It is apparently especially difficult to estimate substitution in processes of control and organisation; it remains to be "open" problem for the time being.

2.3. Alternative estimates of primary work

The property of productive energy to be a substitute for labour allows us to state that increase in consumption of productive energy corresponds to decrease in consumption of labour and otherwise. To analyse the situation, one has to consider the growth rates of the production factors, which, as was argued earlier [7,12], are connected with investment I, depreciation coefficient μ, and technological characteristics, $\bar{\lambda}$ and $\bar{\varepsilon}$, of production system

$$\frac{\mathrm{d}K}{\mathrm{d}t} = I - \mu K, \quad \frac{\mathrm{d}L}{\mathrm{d}t} = \left(\bar{\lambda}\frac{I}{K} - \mu\right)L, \quad \frac{\mathrm{d}P}{\mathrm{d}t} = \left(\bar{\varepsilon}\frac{I}{K} - \mu\right)P. \tag{2}$$

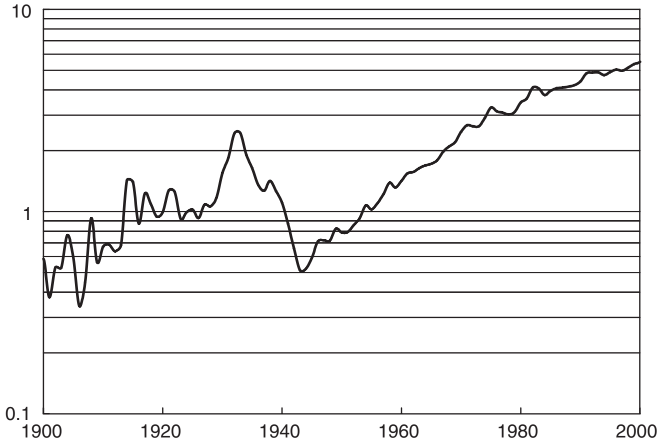

Fig. 2. Measure of substitution in the US economy. Solid curve presents amounts of genuine substitutive work of production equipment (productive energy) needed to substitute one hour of labourer's work, in MJ/hour, for creation of products with equal amount of value.

The first terms on the right side of these relations describe increase in consumption of the production factors due to investment, which is considered a real proponent of development of production and can bring new quality to the production equipment. The dimensionless technological coefficients $\bar{\lambda}$ and $\bar{\varepsilon}$ are general characteristics of production equipment, which denote the required amount of labour and productive energy per unit of introduced equipment (measured in K units), correspondingly. The technological coefficients have apparently to be considered for characterisation of the process of substitution. In virtue of the definition of productive energy as a substitute for labour, one has to define the correlation of the technological coefficients as

$$\mathrm{corr}(\bar{\lambda}, \bar{\varepsilon}) = -1. \tag{3}$$

Additionally, we have to consider changes of primary energy E and its parts E_{C} and E_{P}, the last being primary productive energy. We assume that each quantity is also characterised by its own technological coefficients, so that, in line with Eq. (2), one can write three balance equations more

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \left(\bar{\varepsilon}_{\mathrm{E}}\frac{I}{K} - \mu\right)E, \quad \frac{\mathrm{d}E_{\mathrm{C}}}{\mathrm{d}t} = \left(\bar{\varepsilon}_{\mathrm{C}}\frac{I}{K} - \mu\right)E_{\mathrm{C}},$$
$$\frac{\mathrm{d}E_{\mathrm{P}}}{\mathrm{d}t} = \left(\bar{\varepsilon}_{\mathrm{P}}\frac{I}{K} - \mu\right)E_{\mathrm{P}}. \tag{4}$$

The second terms on the right sides of both Eqs. (2) and (4) reflect decrease in the production factors due to the removal of a part of the production equipment from service. The decrease in amount of production equipment (capital) is characterised by the depreciation coefficient μ, which is assumed also to be a depreciation coefficient of all other quantities. It is valid for the case, when installed technological equipment does not change its quality during time of service, which is assumed for simplicity in the above equations. Note that the balance Eqs. (2) and (4) for the production factors are in fact definitions of technological characteristics of production system and do not involve any assumptions apart of the above one.

One can assume that the quantity $\bar{\varepsilon}$ can be a proxy of the quantity $\bar{\varepsilon}_{\mathrm{P}}$, and the quantity $\bar{\varepsilon}_{\mathrm{C}}$ to be proportional to quantity $\bar{\lambda}$

$$\bar{\varepsilon}_{\mathrm{C}} = \frac{\langle \bar{\varepsilon}_{\mathrm{C}} \rangle}{\langle \bar{\lambda} \rangle}\bar{\lambda}, \quad \bar{\varepsilon}_{\mathrm{P}} = \bar{\varepsilon}, \tag{5}$$

so that some of the correlations[2] of the technological coefficients have to be defined as

$$\mathrm{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{C}}) = 1, \quad \mathrm{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{P}}) = -1, \quad \mathrm{corr}(\bar{\varepsilon}, \bar{\varepsilon}_{\mathrm{P}}) = 1. \tag{6}$$

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[2] The correlation and covariance of two quantities a and b are defined as

$$\mathrm{corr}(a,b) = \frac{\mathrm{cov}(a,b)}{\Delta a\,\Delta b}, \quad (\Delta a)^2 = \frac{1}{n}\sum_{j=1}^{n}(a_j - \langle a \rangle)^2,$$
$$\mathrm{cov}(a,b) = \frac{1}{n}\sum_{j=1}^{n}(a_j - \langle a \rangle)(b_j - \langle b \rangle), \quad \langle a \rangle = \frac{1}{n}\sum_{j=1}^{n} a_j.$$

Note that these relations are the consequences of assumptions (5) and, in contrast to relation (3), have to be considered as approximate ones.

One can see that, due to Eqs. (1) and (4), some of the technological coefficients are connected by the relation

$$\bar{\varepsilon}_{\mathrm{E}} = (1-x)\bar{\varepsilon}_{\mathrm{C}} + x\bar{\varepsilon}_{\mathrm{P}}, \quad x = \frac{E_{\mathrm{P}}}{E}. \tag{7}$$

This equation can be easily obtained, if one sums the last two equations from (4) and compare the result with the first equation from the same set. To find an equation for the ratio x, we consider statistical characteristics of the technological coefficients. Relation (7) is followed by the relations for mean values, covariances and correlations, correspondingly,

$$\langle\bar{\varepsilon}_{\mathrm{E}}\rangle = (1-x)\langle\bar{\varepsilon}_{\mathrm{C}}\rangle + x\langle\bar{\varepsilon}_{\mathrm{P}}\rangle, \tag{8}$$

$$\operatorname{cov}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{E}}) = (1-x)\operatorname{cov}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{C}}) + x\operatorname{cov}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{P}}), \tag{9}$$

$$\begin{aligned}\operatorname{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{E}})\Delta\bar{\varepsilon}_{\mathrm{E}} = {} & (1-x)\operatorname{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{C}})\Delta\bar{\varepsilon}_{\mathrm{C}} \\ & + x\operatorname{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{P}})\Delta\bar{\varepsilon}_{\mathrm{P}}.\end{aligned} \tag{10}$$

The last relation, taking Eqs. (6) into account, can be rewritten as

$$\operatorname{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{E}})\Delta\bar{\varepsilon}_{\mathrm{E}} = (1-x)\Delta\bar{\varepsilon}_{\mathrm{C}} - x\Delta\bar{\varepsilon}_{\mathrm{P}}. \tag{11}$$

One can use relations (5) and (8) to find the deviations of the quantities

$$\Delta\bar{\varepsilon}_{\mathrm{C}} = \frac{\langle\bar{\varepsilon}_{\mathrm{C}}\rangle}{\langle\bar{\lambda}\rangle}\Delta\bar{\lambda}, \quad \Delta\bar{\varepsilon}_{\mathrm{P}} = \Delta\bar{\varepsilon}, \quad \langle\bar{\varepsilon}_{\mathrm{C}}\rangle = \frac{\langle\bar{\varepsilon}_{\mathrm{E}}\rangle - x\langle\bar{\varepsilon}_{\mathrm{P}}\rangle}{1-x}. \tag{12}$$

Eqs. (11) and (12) determine a formula for calculation of the ratio of primary productive energy to total primary energy

$$\frac{E_{\mathrm{P}}}{E} = \frac{\langle\bar{\varepsilon}_{\mathrm{E}}\rangle\Delta\bar{\lambda} - \langle\bar{\lambda}\rangle\operatorname{corr}(\bar{\lambda}, \bar{\varepsilon}_{\mathrm{E}})\Delta\bar{\varepsilon}_{\mathrm{E}}}{\langle\bar{\varepsilon}\rangle\Delta\bar{\lambda} + \langle\bar{\lambda}\rangle\Delta\bar{\varepsilon}}. \tag{13}$$

The formula contains statistical characteristics of the quantities $\bar{\lambda}$, $\bar{\varepsilon}$ and $\bar{\varepsilon}_{\mathrm{E}}$, which can be estimated directly according to Eqs. (2) and (4) on the base of calculated values of productive energy and time series for capital K, labour L, energy E and investment, collected, for example, in the table of Appendix of paper [7]. Absolute values of primary productive energy, obtained by these calculations, are shown in Fig. 1. The results are realistic (close to the direct estimates of this quantity) and show ups and downs of the quantity in contrast to oversimplified direct estimates. The deviations of the calculated values of primary productive energy from empirical ones is quite understandable, taking into account rather arbitrary assumptions, made at empirical estimation of the quantity. For years 1911–1917, 1927–1934, 1962–1963 and 1971–1988, the calculated values are unrealistically small; one can suppose, assumptions (5), which are consequences of assumptions about the rates of depreciation of quality of production equipment, are too coarse in this cases.

3. Efficiency of use of primary productive energy

The estimated in the previous section values of primary productive energy E_{P} are much bigger than the amounts of productive energy P—genuine work of production equipment. The time dependences of primary and genuine productive energy are different, which is connected with both variations of division of primary energy into two parts, E_{C} and E_{P} and changing of efficiency of use of primary energy sources. Both empirical and calculated time dependences show that the gap between productive energy P and primary productive energy E_{P} is decreasing, which can be attributed to improvement in efficiency of use of energy carriers providing primary work of production equipment. A measure of efficiency can be calculated as the ratio

$$\omega = \frac{P}{E_{\mathrm{P}}}. \tag{14}$$

The values of efficiency, found with values of primary productive energy calculated by the method of Section 2.2, are shown in Fig. 3. The calculated values of efficiency correspond to alternative estimates by Ayres [11, Table 1], who found the coefficient of efficiency about 0.01–0.03 at the end of the century. The coefficient of efficiency, due to estimates in separate sectors shown below, are less, but can be considered to be consistent with above. The coefficient of efficiency is increasing in time, according to empirical evidence.

The service delivery efficiency for transportation was analysed by Ayres [11], and the energy delivered to wheels with relation to the fuel energy was estimated as 0.06. The ratio of the useful work (productive energy) to fuel energy is much less; it is close, one can suppose, to the Ayres' technical efficiency [11], which is 0.015 for transportation (much less for farming and construction) in year 1979.

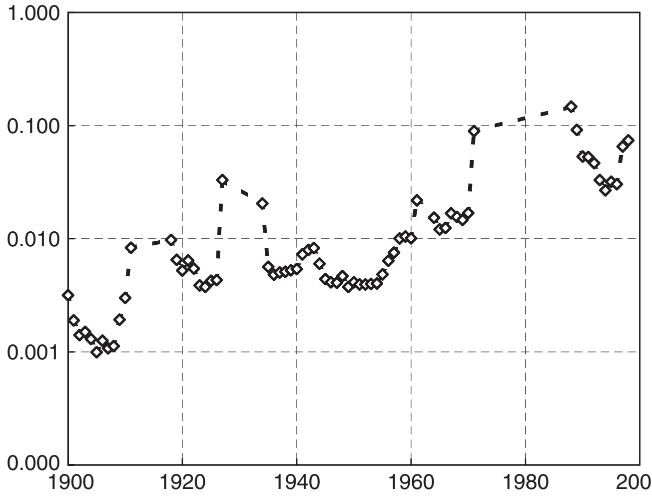

Fig. 3. Efficiency of primary productive energy. The coefficient of efficiency is calculated as the ratio of productive energy P to primary productive energy E_{P} and depicted by diamonds.

According to Ayres et al. [6], efficiency is improving beginning with 1975, so that coefficient of efficiency can be taken as 0.005 in year 1998. It allows one to obtain the contribution of the work of transportation vehicles into the total amount of productive energy as 0.1 quad in year 1998, though the amount of energy carriers needed to provide this work was about 19.46 quad.

In the best cases, electricity in machine drive can be recovered into rotational motion with efficiency up to 0.8–0.9 [11]. However, the result of work of a machine-tool, for example, is a component or detail of another machine, and one has to consider the whole procedure of making a detail: installation, stop–start movements, measurement and so on. It is difficult to get an absolute measure of efficiency in this case, but one can imagine that there is a certain amount of work, which has to be done to obtain the necessary effect. Presumably, it is work of a human who can obtain such effect on his own. Efficiency of machine drive was estimated by Ayres [11] as about 0.002 in years 1960–1970. At manual operation the efficiency is low, but automated control and operation allows increase in efficiency. One can guess that introduction of information processors into production processes can affect the efficiency, which can reach 0.005 to year 2000. It gives an estimate for the contribution to productive energy from machine drive as 0.2–0.3 quad per year 2000.

One cannot directly measure the work produced by devices of information technology to measure the efficiency, but one can see some signs that the useful effect per unit of consumed energy (efficiency) has been increasing. For example, the consumption of electricity by one computer decreased from 299 kWh/yr in 1985 to 213 kWh/yr in 1999 [13,14]. It means that consumption of electricity by a computer was decreasing with the average rate 0.025. Simultaneously, the number of computers and consumption of electricity increase with average rate of growth 0.027 between years 1990 and 1999 as can be calculated from the date of Koomey et al. [13] and Kawamoto et al. [14]. All this means that useful effect from consumption of electricity by computers was growing in the recent time with the growth rate more that 0.052 which is the sum of the rate of growth of consumption of electricity 0.027 and the rate of decreasing of consumption of electricity by one unit 0.025 plus the estimate of improving the unit performance. Similar consideration can be done for all devices of information technologies due to the collection of data of Koomey et al. [13] and Kawamoto et al. [14]. Efficiency of computers is certainly less than unity, but they could be more efficient than many other appliances. It is difficult to judge what part of the resulting amount 1 quad per year can be attributed to productive energy itself, but, perhaps, the estimate of 0.5 quad per year sounds realistically. This huge amount of energy is usefully being spent in the US to produce instructions to humans and apparatuses in the US economy.

4. Conclusion

The paper presents the first attempt of evaluation of primary productive energy that is part of primary energy providing genuine substitutive work of production equipment. The estimates are rather coarse and ought to be rectified, but, by referring to the two methods of evaluation, we can be assured that, at least, they provide the order of magnitude for the quantity. The different estimates of efficiency of the use of primary productive energy are consistent and one can be convinced that productive energy, introduced and formally calculated in the previous paper [7], can be, indeed, considered and evaluated as genuine substitutive work of production equipment. Note, that, in contrast to more general scheme [5], the present approach is restricted to the theory of production itself; it includes neither effects of the environment nor evaluation of the remediation costs. The theory can be expanded, but, one can think, the first, what has to be done, is to understand mechanism of substitution, without any complications, in pure form, which allows us to move further.

The concept of productive energy appears to be necessary for consistent explanation of the phenomenon of economic growth. The theory [7], which has been designed to consider the phenomenon of production of value, can be regarded as a generalisation and extension of the conventional neo-classical approach [1,2], while the roles of production factors are revised. In the conventional, neo-classical theory, capital as variable plays two distinctive roles: capital stock as a measure of production equipment and capital service as a substitute of labour. We ascribe these roles to two different variables and consider the capital stock to be the means of attracting labour and energy services to production, while human work and work of external energy sources are considered as true sources of value. The human work is replaced by work of external energy sources by means of different sophisticated appliances. The properties of the production factors: capital K, labour L, and productive energy P allowed us [7] to specify the production function for output Y in the form of two alternative lines

$$Y = \begin{cases} \xi K, & \xi > 0, \\ Y_0 \dfrac{L}{L_0}\left(\dfrac{L_0}{L}\dfrac{P}{P_0}\right)^{\alpha}, & 0 < \alpha < 1. \end{cases} \tag{15}$$

The productivity of capital stock ξ is an internal characteristic of the production system itself; the quantity is connected with the index α, which can also be interpreted as a technological index. The first line in formula (15) reminds us about Harod–Domar approach, while the function in the second line coincides with Cobb–Douglas production function, in which productive energy P stands in the place of capital stock K.

Relation (15) and following from them relations for marginal productivities of production factors were tested for the US economy; it was shown [7] that one can find such values of both productive energy P and the technological index α that correspond to available empirical data. However, the theory has no arbitrary parameters at all: both productive energy P and the technological index α are variables, which can be estimated in other ways. The index α represents a share of expenses needed for utilisation of capital services in total expenses for production factors and can be evaluated due to estimates of the cost of consumption of production factors [7]. The calculated values of capital services P, which are needed to obtain the correct values of output, correspond to estimates of real substitutive work of production equipment, as was shown in this paper. Within empirical accuracy, the consistency is perfect, so that one can acquire a feeling that productive energy or, in other words, capital service is the only missing production factor in the conventional two-factor theory of economic growth and no other production factors, apart of capital, labour and productive energy, are needed to describe the path of growth quantitatively.

The theory can be used to assess the future output, if one knows the future supply of production factors. Labour and capital are monitoring very thoroughly by special bodies, which allows one to estimate the future quantities. There is also many data for consumption of primary carriers of energy—primary energy E, a part of this amount—primary productive energy plays a special role in production of value. The amount of genuine productive energy or, at least, another measure of substitution has to be known in order to analyse the performance of production system and forecasting the output. These quantities are missing in current statistics, though one can think that data for primary productive energy and productive energy will be included eventually into national statistical accounts. The different estimates of primary productive energy, made in this paper, are consistent, and one can hope that developed methods of estimation of these quantities could be helpful for elaboration the proper methods of monitoring and estimation of primary productive energy and productive energy itself in national economies.

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