ENERGY MODEL OF THE SOCIAL SYSTEM WITH PRODUCTION AND RECYCLING PROCESSES
Ecologic - Energy - Processor - (EEP)

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Abstract

For the survival of the human race and individual societies we need to diminish the system pollution level and the use of our natural resources. Starting from these survival conditions, the paper presents an energy model of a semi self-sustained social system with production and recycling. The model is formulated on the level of energy and an equivalent energy (money) description, and it is solved in an initial linearized approach. Some initial conclusions concerning the type of control and subsystem relation are drawn. However, the problem needs further investigation on the level of system description, formulation and analysis.

1 Introduction

According to many written sources and reports the human race is destroyng its home, the planet earth. The only and urgent solution is to change our way of life, becoming a sustainable society, and human race, (see for example [1]). What does this mean? Generally, it is the demand not to destroy our biosphere any more, and as for human beings and every society to live in harmony with the biosphere. Being more specific, it also means exploiting our resources less, and producing less and less waste. Most of us would like to live at the current level of social and technical evolution. But in order to live we need to **produce** our life support means, and as we know already we must use **recycling and re-use technology** at every possible level of system organization.

Let us consider a part of society which is able to organize itself as a sustainable (sub-) society, or let us say **social model**. In order to live, such a system must produce goods, distribute and use them, and recycle the waste from every subsystem. As is known, our recycling ability or efficiency is less than 100 %, and there are many reasons for this. Hence, our social system and therefore the corresponding model must also have some self-regulating mechanisms for reacting to the intensity of local societal pollution.

The next question we must answer is the level of abstraction and the language of description and analysis of our social system. One of the best approaches is to use energy as such a language, and the equivalent energy (money) as the most general quantity enabling us to make such an analysis. In such a case one can use the concept of the energy processor (EP), developed earlier by the authors, (see, for example, [6]).

The system itself is shown in Fig 1. It consists of four subsystems; for production, distribution/use, recycling and societal feedback on pollution. This feedback depends on the level of pollution - P, which, if it acts, decreases production and increases recycling to the volume of the designed capacity of production and of recycling. The production and recycling subsystem, in essence, may itself possess internal damage and ageing feedbacks. But we already know how it operates and how it influences the life of subsystems, [2], [6]. Hence we can assume for the sake of simplicity that the internal breakdown time of these subsystems is much bigger than the life time of EEP, which we will try to investigate now.

The phaseout of systems followed by recycling are the last working phases within the time dimension of systems engineering [3, 5, 7]. Sustainable environmental protection requires recycling in order to rely on natural resources, to reduce waste products, and to regain material or energy from it. The various steps of recycling, from planning up to material recycling is a reverse production process which needs a mathematical model based on reverse logistics [4] for its design, development, process simulation and evaluation. Part of it is
- reverse distribution
- reuse
- recycling.

Of course, collection, sorting, disassembling etc., are also parts of this process. Model assumptions including a typical network superstructure, the input and output information, will finally lead to a multi-criteria optimization problem with respect to the various costs and subject to various constraints, e.g. with respect to logical variable requirements and capacity constraints. However, optimization of the recycling process is not only a hard task to perform, it is also outside the scope of this paper.

The aim of this paper is to develop a methodology for the model-building of society with production, use and recycling in principle which is based on an energy approach. In a broader sense, costs are also a type of equivalent energy.

2 Analytical Description of the Eco Energy Processor -EEP

As was mentioned in the introduction, the EEP consists of four subsystems, and we will now describe them analytically. Of course, the models are the simplest possible, nonlinear with some indicated linearization, when possible and needed.

2.1 Production Subsystem

This is the most important subsystem in our EEP, delivering all the goods and services needed by society. As Fig. 1 indicates, it receives energy (power) N_i from outside the EEP, equivalent to materials, feeding, control, interaction with the environment, money, etc. The second part of the total input - N_r comes from internal recycling subsystem. Part of this total input $N_i + N_r$ to our subsystem is upgraded as N_u, being the designed product (service) of this subsystem, and part is dissipated outside the subsystem as the power V. Also, a small part of the degraded energy accumulates inside the production subsystem, as well as in any subsystem of the EEP, but we assume here that the lifetime (more exactly the internal breakdown time) of any subsystem is much larger than the anticipated breakdown time of the EEP itself.

The upgraded part of the input energy N_u is controlled externally by the pollution level in the whole system - $P(\theta)$. The pollution P is the accumulated waste in the whole EEP system, and, of course, it depends on the system life time θ. This quantity controls the societal feedback, reacting to the pollution level P in the entire system and, when it acts, it decreases the production level (output) N_u, and increases the recycling level (output) N_r.

Looking at Fig. 1 we can specify the following analytical description of the production subsystem (without subsystem ageing - C):

++ Power balance

$$N_i + N_r = N_u + V, \tag{1}$$

++ Control law[1]

$$N_u = N_{uc} \exp(-\xi P), \ \Rightarrow P = -\frac{1}{\xi} \ln \frac{N_u}{N_{uc}}. \tag{2}$$

This control law can be given in the differential form

$$dN_u = -\xi N_{uc} \exp(-\xi P) dP = -\xi N_u dP, \tag{3}$$

and also lineralized as

$$N_u \simeq N_{uc}(1 - \xi P), \ dN_u \simeq -\xi N_{uc} dP. \tag{4}$$

The exponent ξ of the pollution control subsystem here determines the rate of decrease of production due to the increase in the pollution level. The higher it is, the greater the sensitivity of the production level change to a system pollution P.
As was mentioned, we must not abuse our resources for the secure life of the society. Hence, for this end one may assume that the production subsystem input must be constant $= N_o$, due to the condition of the self-sustainability of our social system. If so, it must be

$$N_i + N_r = const \equiv N_o, \ \ \Rightarrow dN_i + dN_r = 0. \tag{5}$$

We will see how this condition can influence the entire system behaviour, but it flows from the general condition of self-sustainability, or survival, and it may be passed over only in some transient or initial cases.

2.2 Distribution Subsystem

The input to the production subsystem is treated here in three possible ways in series; it is stored for future use as N_{us}, currently used by society - N_{uu}, and part of this, being in use and able to be recycled, is phased out as N_{up}. This is due to physical wear, technology change, economic wear, etc. The second part of this power $N_w = (1 - b)N_u$ goes outside the entire system, as EEP waste, and it does not undergo recycling, as it has no ability to be recycled. We may call this the system lost power N_w. As is seen in this subsystem, there is only one power stream during the product distribution, sequentially delayed, and it can be expressed as below:

$$N_u \Rightarrow N_{us}, \Rightarrow N_{uu}, \Rightarrow N_{up}, N_{up} = bN_u, \ b < 1. \tag{6}$$

Due to the assumptions made on dissipation in the distribution subsystem, it is $b < 1$, $N_{diss} = (1-b)N_u =: N_w$. It follows from (2) for this wasted power, and with Eq. (4) it can be linearized as

$$\begin{aligned} N_w = (1 - b)N_u &= (1 - b)N_{uc} \exp(-\xi P) \\ &\simeq (1 - b)(1 - \xi P)N_{uc}. \end{aligned} \tag{7}$$

We can also treat N_w as the dissipative output from the entire EEP system, not only from the distribution subsystem. In such a case the ageing energy accumulated in containers B and C (see Fig. 1) will be drained outside by this dissipative output N_w.

[1]There may be another form of dependency but this seems to be the simplest one.

2.3 Recycling Subsystem

Input energy to the recycling subsystem consists of two parts here; it is the power corresponding to the phaseout from the distribution subsystem - N_{up}, and the power coming from the secondary recycling as the feedback enforced by the societal reaction to pollution - N_{sr}. Output from the recycling subsystem goes in the form of recycled power - N_r to the production subsystem, and, of course, as the wasted power, not accepted for recycling -N_{na}. This may be due to the lack of direct recycling capacity, or organization of it, or the like. And this power, together with the power dissipated by the production subsystem, is the only source of pollution P of our social system.
Recycled power in this subsystem undergoes control by societal reaction, as the nonlinear relation to the pollution level - P, ranging from zero up to its full capacity - N_{rc}. So for this subsystem one can write:

++ Balance of power

$$N_{up} + N_{sr} = N_{na} + N_r, \tag{8}$$

++ Societal control law

$$N_r = N_{rc}(1 - \exp(-\mu P)), \ \Rightarrow P = -\frac{1}{\mu}\ln(1 - \frac{N_r}{N_{rc}}). \tag{9}$$

Or with some initial social insensitivity zone to pollution P_o described by the Heaviside function H(*),

$$N_r = N_{rc}[1 - \exp -\mu(P - P_o)]H(P - P_o), \ P_o \geq 0.$$

The same control law presented in differential form reads

$$dN_r = \mu N_{rc} dP \exp(-\mu P) = \mu N_{rc}(1 - \frac{N_r}{N_{rc}})dP, \tag{10}$$

and in linearized form

$$N_r \simeq \mu N_{rc} P, \ \Rightarrow dN_r \simeq \mu N_{rc} dP. \tag{11}$$

Here the exponent μ was introduced to measure the rate of growth of the recycling power with respect to the increase in the system pollution level P.

2.4 Societal Reaction to Environmental Pollution

This subsystem consist of a container, where the pollution of all the EEP is accumulated and its level P is measured for the subsequent control of the recycling. There are two inputs here, V and N_{na}, as the waste of the other two subsystems in operation, and also dependent on the pollution level. The control of secondary recycling N_{sr} is introduced and executed if pollution $P > P_o$ crosses the societal reaction level P_o. We can describe the whole subsystem as below:

++ Pollution accumulation

$$P(\theta) = \int_0^\theta N_p d\theta = \int_0^\theta (V + N_{na} - N_{sr}) d\Theta. \tag{12}$$

++ Secondary recycling control law

$$N_{sr} = N_{ss}[1 - \exp\left(-\frac{P - P_o}{P_s}\right)]H(P - P_o), \quad P \geq P_o.$$

When the recycling starts without delay ($P_o = 0$), we can simplify it further to

$$N_{sr} = N_{ss}[1 - \exp\left(-\frac{P}{P_s}\right)], \quad \Rightarrow dN_{sr} = \frac{N_{ss}}{P_s} dP \exp\left(-\frac{P}{P_s}\right) = \frac{N_{ss}}{P_s}\left(1 - \frac{N_{sr}}{N_{ss}}\right) dP. \qquad (13)$$

With linearization performed in the range $P_o \leq P \leq P_s$ we have simply

$$N_{sr} \simeq \frac{N_{ss}}{P_s} P, \quad \Rightarrow dN_{sr} = \frac{N_{ss}}{P_s} dP. \qquad (14)$$

Such is the essence of the operation of the social system with production, recycling and secondary recycling, when societal reaction enforces it.
As is seen, the entire system is strongly nonlinear and has its own internal dynamics introduced by the accumulation of waste P and secondary recycling N_{sr}. We will now analyse the dynamic behaviour of the entire system in an initial approach, assuming that the internal breakdown times of production (C), and recycling (B) subsystems are much greater than the life time of our EEP. We will therefore not include damage evolution and ageing to these subsystems.

3 Simplified Behaviour of the EEP

As seen from Fig. 1, there is one known external stream of the input power N_i, the system's feeding, and the main quantities for the analysis of the system behaviour are: production power N_u with its maximum capacity N_{uc}, and the recycling power N_r with its limit capacity N_{rc}. The other quantities like V, N_{up}, N_{na}, P specify the internal links and conversions of the subsystems. Altogether we have 8 unknown quantities, $N_r, N_u, V, N_{up}, N_r, N_{na}, N_{sr}, P$, so we should use eight equations from the equation set describing the subsystem behaviour Eqs. (1) - (14).
First, let us find what internal relation must be fulfilled during the system operation, independently of the pollution level P. Starting from production control by pollution (2), which if used with recycling control (9), will give

$$N_r = N_{rc}[1 - (\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}}]. \qquad (15)$$

Hence independently of the pollution level P it must be (from the equality of Eqs. (2) and (9))

$$(\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}} + \frac{N_r}{N_{rc}} = 1, \qquad (16)$$

which can be illustrated in Fig. 2.
As can be seen, production diminishes when recycling is in operation, independently of the value of the input power N_i. If we include the condition of constant input to the production processor here (5), as the condition of sustainability, or survival (see (5)), with $N_i + N_r = N_o = const$, we get

$$(\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}} - \frac{N_i}{N_{rc}} = 1 - \frac{N_o}{N_{rc}},$$

When recycling in a system is in full operation it may mean that the input power may be as small as the total efficiency of the EEP system is high. If the natural reycling power capacity is assumed as infinite, as it it was during the early stages of civilisation, $N_{rc} \Rightarrow \infty$, we simply have $(\frac{N_u}{N_{uc}}) = 1$; full production capacity can be utilized only at the start of the system, when the self-recycling of ecosystem is very large or infinite.[2]
¿From this we can reach some design rule of the EEP stating that if:
$N_i + N_r = N_o = const = N_{rc}$ we have $(\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}} = \frac{N_i}{N_{rc}}$,
and the production capacity ratio can be limited only by the recycling capacity ratio.
On the other hand, when we put the pollution level (9) P with P_s the maximally affordable level into the secondary recycling control law (13), it follows

$$N_{sr} = N_{ss}\{1 - (\frac{N_u}{N_{uc}})^{\frac{1}{\xi P_s}}\}, \tag{17}$$

which is illustrated in Fig. 3.
Using the structural relationship just obtained we can calculate the non-accepted power of recycling N_{na}. Starting from (8) and the above equation, we have

$$N_{na} - N_{sr} = bN_u - N_{rc}[1 - (\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}}] \tag{18}$$

$$N_{na} = bN_u + Nss[1 - (\frac{N_u}{Nuc})^{\frac{1}{\xi P_s}}] - N_{rc}[1 - (\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}}].$$

It can thus be expressed by the production power N_u, and some structural and process parameters like: b; $N_{uc}, N_{ss}, \xi, \mu, N_{rc}$. When we analyse it a litle deeper, one can infer as follows:
if the EEP system goes to its full production capacity $\frac{N_u}{N_{uc}} \rightarrow 1$,
then the total phaseout power from the distribution subsystem cannot be recycled totally; as $N_{na} \rightarrow bN_u$ with $b < 1$.
Now we need only to determine the production power N_u for our calculations. Looking for the balance equation of the production subsystem (1), here we require the expression for the dissipated power V. The only way to get it, is from the pollution level P, (12). As can be seen, it is highly nonlinear, but for small values of θ, $0 < \theta < \theta_{systembreakdown}$, so at the start of the whole EEP we can use the MacLaurin expansion of the pollution P with respect to the life time θ in order to obtain

$$P(\theta) = P(0) + \left.\frac{\partial P}{\partial \theta}\right|_{\theta=0} \cdot \theta + ... \simeq (V + N_{na} - N_{sr}) \cdot \theta,\ \theta \ll \theta_e,\ \Rightarrow V = \frac{P}{\theta} - N_{na} + N_{sr}, \tag{19}$$

[2] At the early stages of civilization, for example, burning wood etc., was a waste of energy without recycling at all! Heat and CO_2 output were easily absorbed by the huge environment as the natural recycling power capacity.

where θ_e is pregiven and can be equalized to the system breakdown time, and $P(0) = 0$ is set here for the sake of simplicity.
Putting V into the power balance (1) we have

$$N_u = N_i + N_r - V = N_i + N_r - \frac{P}{\theta} + N_{na} - N_{sr}.$$

Substituting the already calculated expressions for P, Eq. (2), and
$N_{na} - N_{sr} = N_{up} - N_r$, from Eq. (8), we get,

$$N_u = N_i + \frac{1}{\theta\xi} \ln \frac{N_u}{N_{uc}} + N_{up}. \tag{20}$$

This means that with Eq. (6) we have

$$[1 - b]N_u = N_i + \frac{1}{\theta\xi} \ln \frac{N_u}{N_{uc}}. \tag{21}$$

As we see, it is a highly nonlinear equation for calculating N_u, even when $P(\theta)$ has already been linearized (see (19)).
But let us linearize the equation further, substituting the Taylor expansion for the logarithm; $\ln x = x - 1 + ...$, in the last relation, which allows us to obtain

$$\frac{N_u}{N_{uc}} = \frac{1 - \xi\theta N_i}{1 - \xi\theta N_{uc}[1 - b]}. \tag{22}$$

It can be noted from the above equation that, depending on the parameter and process values (ξ, b, N_{uc}, N_i), we can have the growth, the constant value, or the decay of upgraded power in the system. It must also be noted that left hand side of relation (22) must be positive, so the life time values are restricted to

$$0 < \theta < (\xi N_i)^{-1}, \text{ and for the denominator, } 0 < \theta < \{\xi N_{uc}[1 - b]\}^{-1}, \tag{23}$$

with all its consequences.
We also can conclude that followed from the denominator equalized to zero the system breakdown time θ_b is:

$$\theta_b = \{\xi N_{uc}[1 - b]\}^{-1}. \tag{24}$$

Assuming that the system life time we analyze is smaller than this value (θ_b), we can present the life time behaviour of the upgraded power N_u as shown in Fig 4. As we can see from Figure 4 dependent on the parameter value in numerator and denominator we can have increasing or decreasing semi logistic curves, and even a straight line, when both time constants are equal. The behaviour of production power N_u also depends on its initial condition. When the production subsystem starts from its highest capacity $N_u(0) = N_{uc}$ it can only decrease during the system life time, adjusting itself to the recycling capacity. It will be quite visible if we acknowledge the constant input power into our production subsystem as was shown by relation (5), that is

$$N_i + N_r = N_o = const, \quad (dN_i + dN_r = 0).$$

So we can rewrite the equation for the production power as below

$$\frac{N_u}{N_{uc}} = \frac{1 - \xi\theta(N_o - N_r)}{1 - \xi\theta N_{uc}[1 - b]}. \tag{25}$$

In such a case of constant input power N_o, all the behaviour depends on the recycling power N_r and its capacity N_{rc}, (see (16)). We will study this more in detail later.

4 The Nonlinear Case of EEP Dynamics

4.1 Nonlimited Energy Input to the System

The pollution level P which controls the behaviour of EEP cannot be calculated directly, as is seen from integral relation (12), but we can calculate its differential increment as below,

$$\begin{aligned} dP &= \frac{\partial P}{\partial \theta} d\theta + \frac{\partial P}{\partial V} dV + \frac{\partial P}{\partial N_{na}} dN_{na} + \frac{\partial P}{\partial N_{sr}} dN_{sr} \\ &= (V + N_{na} - N_{sr}) d\theta + \theta(dV + dN_{na} - dN_{sr}). \end{aligned} \tag{26}$$

¿From the constitutional Eq. (4) we can also have

$$dP = -\frac{dN_u}{\xi N_u}, \text{ and in the linearized form } dP \simeq -\frac{dN_u}{\xi N_{uc}}. \tag{27}$$

Here we see that the difference is that in the linearized form the current value of N_u is exchanged for the maximum production capacity N_{uc} in the linear case.
Also from the power balance of recycling subsystem (8) we can calculate

$$N_{na} - N_{sr} = N_{up} - N_r, \Rightarrow dN_{na} - dN_{sr} = dN_{up} - dN_r.$$

Using it commonly in (26) we get

$$-\frac{dN_u}{\xi N_u} = (V + N_{up} - N_r) d\theta + \theta(dV + dN_{up} - dN_r). \tag{28}$$

Production balance (1) will give us another substitution

$$V - N_r = N_i - N_u, \Rightarrow dV - dN_r = dN_i - dN_u,$$

which, if used with the distributor/usage subsystem relation $N_{up} = bN_u$, will finally give us:

$$\{1 - \theta[1 - b]\xi N_u\} \frac{dN_u}{d\theta} = \xi N_u \left\{ [-N_i + (1 - b)N_u] - \theta \frac{dN_i}{d\theta} \right\}. \tag{29}$$

As can be seen, the differential equation for the production power N_u is highly nonlinear, in spite of its (disadvantageous) partial linearization (Eq. (14)), possessing linear and quadratic terms, so it may lead to the solution with with some saturation or logistic behaviour. We can also see that the second term in parentheses can grow with system life θ, leading to some type of breakdown behaviour, with the estimated time to breakdown similar to (24)

$$\theta_b = \{[1-b]\xi N_u\}^{-1}. \tag{30}$$

We know from the production subsystem that $0 < N_u < N_{uc}$, and we see that for the zero value of the production power we will have infinitive breakdown time, and from the other side if exchanging N_u for the saturation value N_{uc} as in (27), we will have the same breakdown time as for the linearized case given by relation (24).

4.2 Control of the System Energy Input

As was said in the introduction, the whole idea of recycling is based on three demands:
1. to minimize pollution as much as possible,
2. to minimize the amount of energy (resources) consumption,
3. to keep the production level as high as possible.

The first demand is not self-fulfilling, and it needs proper adjustment between the production and recycling capacities, which can be done easily with the help of the above considerations. The second demand, to diminish the input power of the whole system, can be fulfilled if constant input to the production subsystem is assumed, that means $N_i + N_r = N_o = const.$. In this case recycling will fulfil its role entirely. To do this we will rearrange Eq. (29) with (5) into

$$\{1-\theta[1-b]\xi N_u\}\frac{dN_u}{\xi N_u d\theta} = \left\{N_o - N_r - (1-b)N_u - \theta\frac{dN_r}{d\theta}\right\}. \tag{31}$$

As is seen, the demand for the constant input to production subsystem power, including recycling, forces us to solve the second equation for the recycling power simultaneously, for example in the form of (16), as below

$$(\frac{N_u}{N_{uc}})^{\frac{\mu}{\xi}} + \frac{N_r}{N_{rc}} = 1. \tag{32}$$

We can calculate N_r *and* dN_r from the above side by side, and put them into Eq. (31), or solve them simultaneously in a some way, because they are both highly nonlinear. We can also eliminate from the last equation the recycling power N_r by equation (16), treating it as an internal quantity and by looking only for input power N_i to the whole system.

4.3 The Linearized Dynamics Case

At present, nothing more can be said about this system of nonlinear equations. Hence, let us make a linearization approach. It is enough for the linearized version of production control to start in the form of equation (27), as below

$$dP \simeq -\frac{dN_u}{\xi N_{uc}}.$$

By substituting the above into the expression for the differential increment of pollution (26), the starting point of our transformation, and repeating them all we will finally get

$$\{1-\theta\xi N_{uc}[1-b]\}\frac{1}{\xi N_{uc}}\frac{dN_u}{d\theta}=N_u[1-b]-N_i-\theta\frac{dN_i}{d\theta}. \tag{33}$$

As is seen above, we again have the breakdown time expression, as (30), and (24), i.e.

$$\theta_b=\{\xi N_{uc}[1-b]\}^{-1}.$$

Introducing it into (33) and rearranging it will produce

$$[1-\frac{\theta}{\theta_e}]\frac{dN_u}{\frac{d\theta}{\theta_e}}=N_u-\frac{1}{1-b}(N_i+\theta\frac{dN_i}{d\theta}). \tag{34}$$

We have also obtained a linear differential equation for the production power with the breakdown time behaviour, which we have found already.
Its solution is very simple when we assume that the input power is constant $N_i=N_{io}$.
In such a case and for the initial condition of the production power $N_u(0)=N_{uo}$, we will have

$$N_u(\theta)=\frac{N_{io}}{1-b}+\frac{N_{uo}-\frac{N_{io}}{1-b}}{1-\frac{\theta}{\theta_e}}. \tag{35}$$

In order to investigate a little more what we have obtained in the linearized and stationary input case, let us look for the relation (35) more creatively. We can transform it into the form

$$N_u(\theta)=N_{uo}\frac{1-\frac{\theta}{\theta_e}\frac{N_{io}}{(1-b)N_{uc}}}{1-\frac{\theta}{\theta_e}},\quad \theta_e=[\xi N_{uo}(1-b)]^{-1}. \tag{36}$$

By introducing two new and obvious notations for the dimensionless system life time D, and the coefficient of production and distribution system adjustment γ in the form

$$D=\frac{\theta}{\theta_e},\quad \gamma=\frac{N_{io}}{(1-b)N_{uo}}, \tag{37}$$

we finally have

$$N_u(\theta)=N_{uo}\frac{1-\gamma D}{1-D}. \tag{38}$$

As we can see, the linearized solution of the system production power N_u is very simple: it depends on the dimensionless system life time θ, and the adjustment coefficient γ. All the possible modes of behaviour flowing from (38) are shown in Fig. 5, where one can see three different life curves for; $\gamma=1$ $\gamma<1$, $\gamma>1$, being in agreement with relation (38). The last life curve seen in Fig. 5 was postulated for the nonlinear case, which can also be noted as the case of $\gamma=\gamma(D)$.
The quantity γ (37) here reflects the energy efficiency of the entire system because $N_w=(1-b)N_u$, so the closer b is to unity, the less energy is dissipated outside the EEP, and the higher this part of the γ quotient is. We may infer that in order to keep γ close to unity (see Fig. 5) we may diminish the input power N_{io} as much as needed. In this way we can protect our resources to a greater extent.

5 Conclusion

As shown, it is possible to develop a simple model of energy flow and transformation in a society with production and recycling. The model itself is highly nonlinear, but its static and simplified dynamic analysis has shown that it is workable and can produce some conclusions about the interrelation between the subsystems incorporated and the governing quantities in an EEP system. In particular, we can find what kind of control we should introduce to design such a self-sustaining system. Some conclusions were obtained only for the linearized version of system equations, but it seems that the nonlinear behaviour of a system will also lead to similar results.

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