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Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies

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ABSTRACT

Virtually all goods and services that characterize modern societies' welfare depend on the provision of commercial energy. The core objective of this paper is to identify necessary changes in trends for achieving a transition towards more sustainable energy systems and development paths. The major conclusions of this analysis are (i) a rigorous rethinking process has to take place to identify which level of energy services per capita lead to enhancing human welfare and quality of life; (ii) a significant increase in energy conversion efficiency has to be triggered to finally provide energy services with far less input of energy than today; (iii) a continuous increase in the share of renewable energy sources and other low-emission options has to be brought about; (iv) however, as history has shown this process of technological learning has to be accompanied by proper energy price and regulatory policies. Otherwise, it is very likely that energy conservation gains due to technical efficiency improvements will be outweighed again by increases in energy service demand and, straightforward, energy consumption and CO_2 emissions.

1. Introduction

Virtually all goods and services that characterize modern societies' welfare depend on the provision of commercial energy. Energy is an indispensable factor input for all goods and services and embodied in both. However, what people need and purchase thus is not the commercial energy itself, but rather energy services provided by the energy system that converts energy sources and flows from nature into these services. Some examples are cold beverages, warm dishes, conditioned living spaces, comfortable office rooms, commuting to work or sending an email.[1] Hence, economic welfare depends directly on the availability of (affordable) access to energy services.[2] And, as outlined in more detail in Section 2, all these services are provided by at least two major inputs: energy sources and technology. Yet, with respect to the input of energy to produce these services the availability is limited by scarce resources and environmental constraints. Technology is limited by know-how, by human, physical and natural capital and through institutional constraints.

The core objective of this paper is to identify necessary changes in trends of energy service demand, intensities and efficiency for achieving a transition towards more sustainable energy systems and development paths. The analysis is based on the presentation of some fundamental reflections with respect to energy services. Increasing the efficiency of the provision of energy services—i.e. doing more with less by providing more desired energy services per unit of corresponding primary energy required—is generally the most cost-effective, most environmentally benign and often least well-understood pathway toward more sustainable energy systems (see e.g. Weizsäcker et al., 1997).

Based on these basic reflections, the questions considered in this paper include:

- What are the drivers of the consumption of energy services? (including the analysis of intensities, income, energy price and efficiency)
- How must the development of these drivers be changed to facilitate transitions towards sustainability?

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[1] There are several possible definitions of energy services in various sectors. E.g. in the mobility sector the actual energy service is to reach the shop where I can buy a certain product or to reach my office, etc. In a system of short distances (provided e.g. by corresponding spatial planning and infrastructure) this may be possible with very low-energy input. However, a common and more technical definition of transport energy services are distances travelled. In this paper we will use this definition, keeping in mind that an important additional aspect of efficient mobility is to keep distances as short as possible.

[2] Whether and under which conditions this also holds for human well-being and quality of life will be discussed in Section 3.

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To support our arguments some specific empirical examples will be presented. A more exhaustive empirical treatment of the subject would go beyond the scope of this paper. The major focus will be on end-use conversion of energy, from final energy to services, focusing on private households.

2. The concept of energy services

The basic premise of this analysis is that people do not demand energy per se but energy services like mobility, washing, heating, cooking, cooling and lighting. These services are in general provided by combining different inputs of energy, technology, human and physical capital, and environment (including natural resources). Given the fact that human and physical capital are largely accumulated in the technical efficiency of the technologies used—conversion as well as infrastructure—a general equation for the production of a specific energy service (S) is (see Wirl, 1995)

$$S = f(E, \eta(T)) \tag{1a}$$

where E is the energy input, $\eta(T)$ is the technical efficiency of the technologies; the term "technology" encompasses conversion technologies but also aspects like systems and infrastructure.

If in the short-term sufficient infrastructure is available Eq. (1a) can be written in a simpler way (see Wirl, 1995):

$$S = E\eta(T) \tag{1b}$$

Moreover, short-term and long-term components of service demand exist, see Eq. (1c). Short-term service demand considers consumer behaviour with respect to e.g. setting temperatures in rooms, kilometres driven in leisure time, stand-by operation of TV sets, computers, etc. Long-term service demand takes into account parameters like area of apartments, size of cars, number of light bulbs installed in the living room, etc. In this paper the term "energy service"—if not specified differently—encompasses both short- and long-term components of service demand[3]:

$$S = S_{LR} S_{SR} \tag{1c}$$

S_{SR} is short-term service demand e.g. degree indoor temperature, intensity of light, distance driven; S_{LR} is the long-term service demand e.g. number and size of dwellings, cars, refrigerators, light bulbs.

So far we have described direct energy services, see Fig. 1. Moreover, there is also a broad range of indirect (embodied) energy services, see Fig. 2. It is important to note that in particular indirect (but also direct) energy services comprise energy in an indirect, "non-visible" manner—i.e. by means of embedded (sometimes called embodied) energy. Figs. 1 and 2 depict the flow of energy in a stylised form. It shows that energy is also needed to produce technologies (e.g. machines) and to produce materials. Note, that principally technology in every case also encompasses (cumulated) human capital. Furthermore, the technologies for converting energy into direct energy services are in principle also indirect energy services. Of course, in general, most of the indirect energy services need many more non-energy inputs. However, by this definition we want to stress the fact that there are virtually no goods and services in our economies which can be provided without the input of—mainly commercial—energy. Some examples are depicted in Table 1.

For an assessment of the technical efficiency of energy services the concept of a life-cycle analysis of the whole energy conversion chain has to be applied. Fig. 3 depicts this more sophisticated

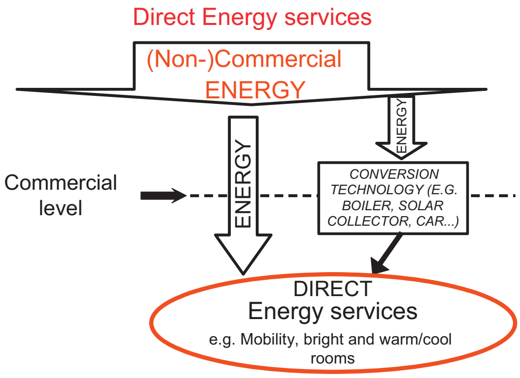

Fig. 1. Demand for direct energy services.

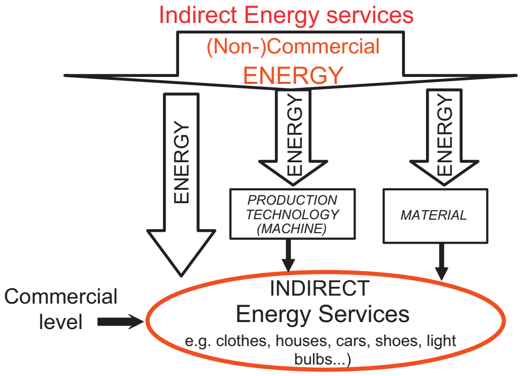

Fig. 2. Demand for indirect energy services.

Table 1
Examples for direct and indirect energy services

Direct energy services	Indirect energy services
• Lighting	• Food
• Heating, cooking, cooling	• Shoes, shirts, clothes
• Washing, ironing	• Communication, exchange of information
• Mobility, transport, etc.	• Buildings
• Drilling, sawing, etc.	• Vehicles
	• Furniture, paper
	• All goods to buy in a super market, etc.

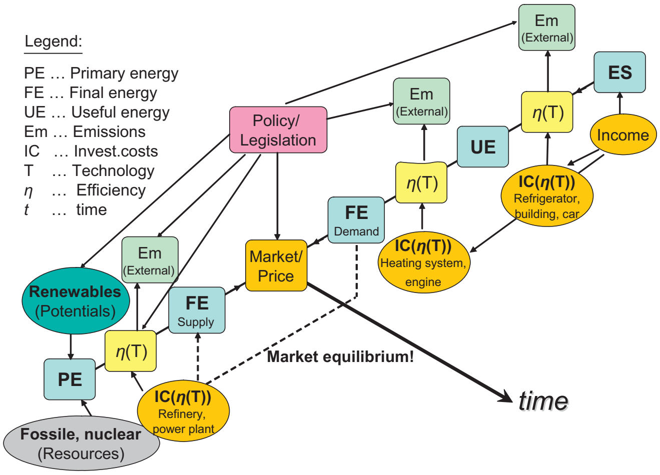

Fig. 3. Impact factors in the energy chain to finally provide energy services.

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[3] For further details on the discussion of long-term and short-term services see Section 6.

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picture of the relevant impact parameters in the energy conversion chain to finally provide energy services. In such an aggregated picture the overall efficiency and the corresponding losses in the whole energy services providing chain has to be taken into account. There are a lot of impact factors on this whole energy service providing chain. These factors encompass the technical efficiencies, investment and O&M costs of technologies, prices in the markets, environmental issues as well as possible political interferences (influencing former mentioned factors) in the whole chain. Moreover, it has to be borne in mind that it is important to understand that and how these energy service providing chains develop and change over time, see Fig. 3.

The level of energy service demand e.g. of a household depends on available income Y, the price of energy service p_s (with $p_s = p_E/\eta$, where p_E is the energy costs) the capital costs CC, and the utility derived from using this service $u(s)$:

$$S = f(p_s, CC, Y, u(s)) \tag{2}$$

The available income Y of a household limits the expenses for direct and indirect energy services:

$$\sum p_{ei}E_i + \sum CC_i + \sum p_{SI_j}S_{I_j} \leqslant Y \tag{3}$$

with p_{sIj} S_{Ij} expenses for indirect energy services; Yearly capital costs CC are calculated from investment cost I and the capital recovery factor α as $CC = \alpha I(\eta)$.

Hence, energy and (accumulated) technology (= technical efficiency) are the major factor inputs for provision of energy services. However, it is often argued (see e.g. Haas and Wirl, 1992) that there exists a tremendous distortion between the amounts of the corresponding inputs: too much energy, too little efficient technologies. E.g. Goldemberg et al. (1987) state that "energy can be used more effectively in providing such services as cooking, lighting, space heating and cooling, refrigeration, and motive power. Decision-makers and consumers have found that energy services can be provided cost-effectively with much less energy than previously thought necessary, and as a result the historical close correlation between the level of energy use and economic well-being has been broken". Hence, of core interest is the aspect of increasing efficiency to reduce the necessary input of energy to provide the same amount of energy service.

3. Energy services, the production of economic values and human well-being

In Section 2 the concept of consuming energy services has been described by means of a bottom-up approach from the consumers' points-of-view. In the following this concept is described from the aggregated point-of-view of a (local, national, or global) economy.

The basic hypothesis is that all economic activities—e.g. expressed as a gross domestic product (GDP)—can be interpreted as the aggregates of the monetary value of all energy goods and services (direct and indirect) created in a society (regardless of whether we consider these goods or services as useful or valuable or not). That is to say, the GDP reflects the sum of the economic values of all energy services produced in a society and that by extension of Eq. (1) to the overall economy virtually all economic values created in an economy depend on an input of (commercial) energy and the corresponding conversion efficiency of the technologies:

$$GDP = \sum_{i=1}^{n} Z_i c(S_{D_i}(E_i, \eta(T_i))) + \sum_{j=1}^{m} Z_j c(S_{I_j}(E_j, \eta(T_j))) \tag{4}$$

where Z is the number of units produced (e.g. dwellings, vehicles, etc.); $C(S)$ is the costs of producing energy services; S_D is the amount of direct energy services consumed (e.g. heat, mobility, electric-specific applications); S_I is the amount of indirect short-term (e.g. clothes, food, shoes, etc.) and indirect long-term energy services (infrastructure, e.g. buildings, streets, railroads, transmission lines, etc.) consumed.

Eq. (4) states that the more services are produced the higher is GDP: Yet, as history proves, see e.g. chapter 7, improvement of efficiency is the core pre-condition for significant increases in the magnitude of energy services produced and straightforward, for an increase of the creation of economic values (e.g. GDP):

$$GDP = f(\eta(T_i)) \tag{5}$$

with $f((\eta(T_i))$ increasing concave.

This equation states that the more efficient goods and services are produced the higher will be the overall quantity of goods and services produced and straightforward, the magnitude of GDP. Moreover, the number of services n, m in Eq. (4), e.g. the bulk of electronic gadgets as well as the market penetration Z, increases with increasing efficiency and declining intensity. This relationship is illustrated in Fig. 12. Decreasing intensity led to increases in saturation of service demand as well as the number of types of services N.

These reflections lead to the following perceptions:

- Every increase in GDP is proportional to an increase in the production of energy services;
- to stabilise energy consumption and growth of GDP an adequate and continuing improvement of efficiency and a shift toward more efficient way of providing services is necessary so as to provide more energy services per unit primary energy;
- energy efficiency cannot be improved infinitely since there are physical boundaries for the efficiency of energy technologies. Thus, infinite GDP growth is not feasible with stabilised or even declining energy consumption. A fundamental technological change can however lead to substantial efficiency leaps, e.g. a shift from working animals to vehicles, from internal combustion engine to fuel cell, etc.

Before judging these perceptions as a pessimistic conclusion, one should have a look on the definition of the GDP indicator: this common definition of GDP is the sum of the economic value of all goods and services produced within an economy. Expenditures for defensive measures (e.g. health costs due to air pollution, repair costs after various types of catastrophes) are valued the same as other economic goods. Moreover, the decline in natural capital, the economic value of non-market transactions, distribution impacts, etc. are not taken into account. There are several approaches of "ecological GDP" measures aiming at considering these aspects.[4] One of them is the index of sustainable economic welfare (ISEW), which has been developed in Cobb (1994). Hochreiter et al. (1994) have carried out a calculation of ISEW for Austria from 1955 to 1992. The results show that from 1955 to 1980 there has been an increase of the ISEW (however, with a lower gradient than the GDP). However, since 1980 the ISEW remained constant in contrary to the GDP which continued to grow. This indicates that since 1980 the depreciation of natural capital, defensive expenditures, etc. compensated additional income effects.[5] If we take ISEW as a value that is more suitable to indicate human well-being and social welfare than GDP, we can

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[4] However, in recent years the focus was more on satellite systems because aggregation of all these different impacts bears a lot of evaluation problems.

[5] We are not aware of any calculation of ISEW for the period since 1990 up to now. However, we see almost no indication that the trend since 1980 (constant ISEW) should have changed dramatically.

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conclude that additional GDP and energy services that have been produced and consumed since 1980 have not brought an increase in human well-being.[6]

On a more basic level an effective meter should be a meaningful indicator for the "quality of life" of people. Besides objective indicators (like ISEW) there are also subjective indicators derived from the answers of people to the question how they enjoy their life as a whole e.g. on a scale from 1 to 10. Empirical investigations demonstrated that happiness increases with GDP up to a certain level where it reaches a plateau. Further income does not significantly increase happiness (Zidansek, 2006). This indicates that there is a clearly decreasing marginal "happiness-utility" of GDP and therefore also of energy services. This is further supported by Zidansek (2006) who showed that "happier" nations on average show lower energy intensities.

Hence, transition to post-materialistic values and strategies[7] represents a path to a sustainable energy system and a higher level of quality of live and happiness simultaneously. This would—in the industrialised countries[8]—definitely imply a lower level of energy consumption, resulting both from higher energy efficiency and lower level of energy services consumed.

Finally, the overall challenge (although we will deal with it further in this paper) would be to analyse the following questions from world-wide society's points-of-view:

- How can limited resources be allocated optimally over time?
- How can the resulting energy be used in an optimal way to produce the maximum output (or in other words: What is the optimal mix of technological and energy input given a certain scarcity of resources, a certain cost of depletion of energy for society?)
- What is the optimal magnitude of energy services to be produced and consumed at a specific location at a certain point-of-time?
- How can the consumption of energy services be allocated fair and "justifiably" among people in the world?

4. Understanding indicators of (global) energy consumption and conversion efficiency

In the foregoing, we have explained now the basic interactions of energy services, energy, GDP and quality of life. Next we look at these issues from an international perspective. First, global energy demand issues are investigated. Fig. 4 depicts the development of global energy demand over the last 150 years and indicates the major technologies that have emerged over this period of time. Fig. 5 shows the aggregated global energy flows in 1994. In total, about 70% of original primary energy inputs provide final energy to the consumer, about 40% the useful energy and drastically less the services themselves. Fig. 6 illustrates the corresponding overall efficiency of energy and exergy of provision of energy and exergy services. Caution is called for in interpreting exergy efficiencies, sometimes denoted as Second Law efficiencies. They represent a ratio of the least available work that could have provided the service divided by actual available work used to provide the service. This means that exergy efficiency illustrates the improvement potential. The overall efficiencies today are in the range of only a few percent. This could be interpreted to mean that improvement potentials are in the order of 10 times or more. Accordingly, the efficiency improvement potential is comparable in its magnitude to oil, gas or uranium reserves. Hence, "NegaWatts"—see Lovins (1978, 1985)—also may represent kind of an energy source.

However, the figures above do not yet explain the relationship between energy and the economic values created. The most important indicator to measure this relationship between energy input and economic output is the indicator "aggregated energy intensity". It is an indicator describing how efficient energy services are provided with respect to the input of primary or final energy. In other words, intensity is to some extent an indicator for (the reverse of) efficiency.

In general, there are different definitions of energy intensities: energy per capita, energy per unit of GDP and in a bottom-up style energy per specific service (e.g. energy per room area heated, energy per kilometres driven, etc.). In the following for the indicator "aggregated energy intensity" the definition of energy in relation to GDP is used as this is the indicator that puts energy in relation to the aggregated monetary value of energy services. The following Figs. 7 and 8 depict that there is a very broad range of energy used (electricity as well as individual passenger transport) to produce one unit of GDP.

Over a long period of time at least until the mid-1980s aggregated energy intensities were decreasing significantly, see also Schipper and Haas (1997). Yet, in recent years, especially after the drop in world oil prices, aggregated energy intensities have stagnated or were even reversed. This suggests that a decrease of energy intensity becomes more and more difficult to achieve the higher the level of GDP (and thus energy services) per capita and the lower the energy prices. This argument supports what we pointed out in Section 3: That an infinite growth of GDP is not compatible with constant or even declining energy consumption. Of special interest in these figures is the example of Hungary as a representative for the development in former communist countries. Since 1990 it showed the steepest decrease in energy intensity.

As the comparison of the country-specific developments indicates, there is still a considerable potential for energy conservation. It can be seen that countries like Japan, Switzerland and The Netherlands show the best performance using only about half of the energy of countries like Sweden, the USA or Hungary.[9] Interpreting Fig. 8 it is important to add that for transport of course other parameters like density of population play a role, which may to some extent explain the high values for Canada and the USA in this depiction. Additionally, as we more and more face a global economy, outsourcing of energy- and labour-intensive industrial production to abroad has also a large impact on the developments at the country level.

5. Technology was the driver but

The most important perception is that technological progress (TP) was the driving force for the increase in energy service demand, economic growth and finally energy consumption. In particular, the "advances in knowledge" and technology are widely recognized as important factors in explaining the

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[6] However, a stronger application of sustainable energy systems could change this trend. Haas and Kranzl (2003) showed that substitution of fossil energy carriers by biomass can have positive impact on the ISEW.

[7] Costanza et al. (2007) suggest that a set of indicators evaluating quality of life should be oriented on basic human needs, which they define as subsistence, security, understanding, freedom, etc. Built, human, social and environmental resources create opportunities for humans to satisfy these needs. In this concept, economic, material and energetic services and goods represent only the capital and thus one of the several possible strategies to satisfy human needs.

[8] Of course, in developing countries, the growth of energy services consumed can lead to a substantial improvement of quality of life.

[9] However, we have to bear in mind that this result does not take into account the import of energy services and goods (especially materials).

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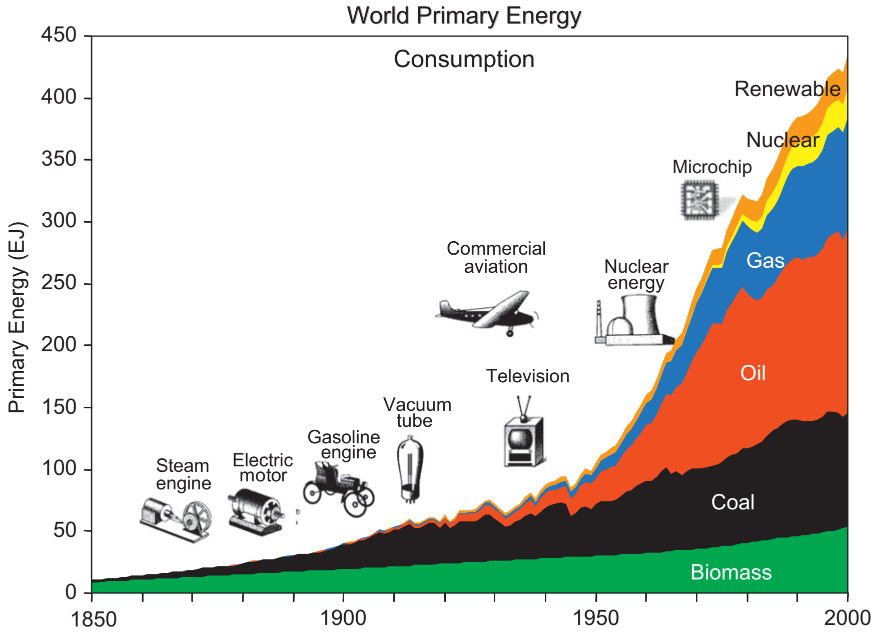

Fig. 4. Total global energy consumption in the period 1850–2000 and corresponding major technological inventions (Nakicenovic and Grübler, 2000).

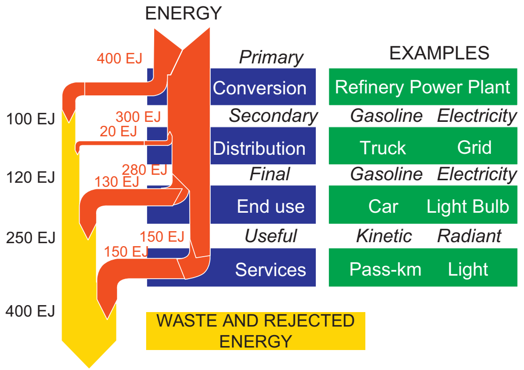

Fig. 5. Total global energy flow (Nakicenovic et al, 1996).

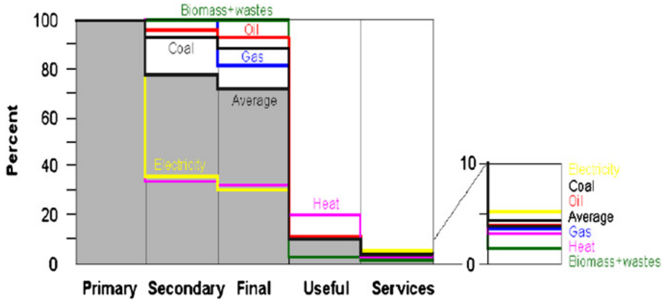

Fig. 6. Global exergy efficiency as percent of primary exergy (Nakicenovic, 1993).

historical record of productivity growth (e.g., see Nakicenovic and Grübler, 2000). For example, in the seminal paper by Solow (1957) technology was estimated to account for 87% of per capita productivity growth (the remainder attributed to increases in capital inputs). In other studies technology is estimated to account for more than one-third of the total GDP growth in the US since 1929 (Denison, 1985) and for between 34% and 63% of GDP growth in the OECD countries over the period 1974–1973 (Barro and Sala-I-Martin, 1995).

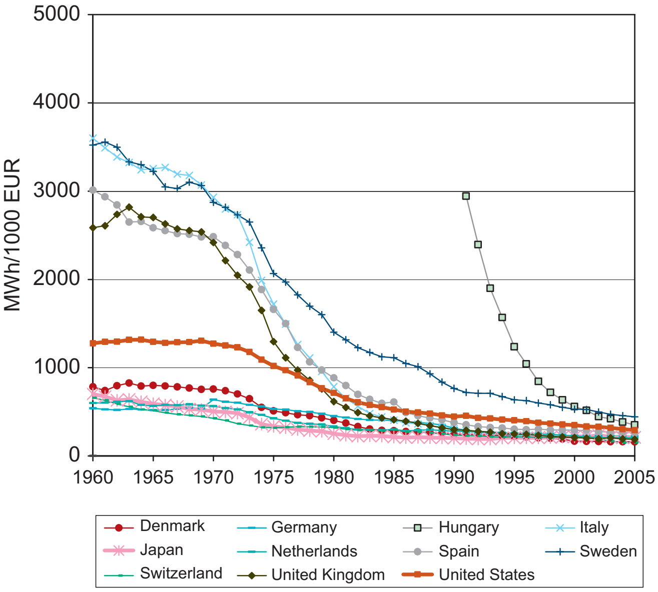

Fig. 7. Energy intensities for electricity for selected OECD countries 1960–2003 (*Source*: IEA Statistics).

TP took place in at least three different dimensions:

- There was a significant increase in the technical efficiency of final conversion technologies, see e.g. Fig. 9.
- The number of new energy conversion technologies for both, the exploration of energy sources and for converting energy into energy services at end-users level—number of electric appliances, central heating systems, light bulbs, fridges, TV sets, computers, electronic entertainment devices, modes of transport—skyrocketed.

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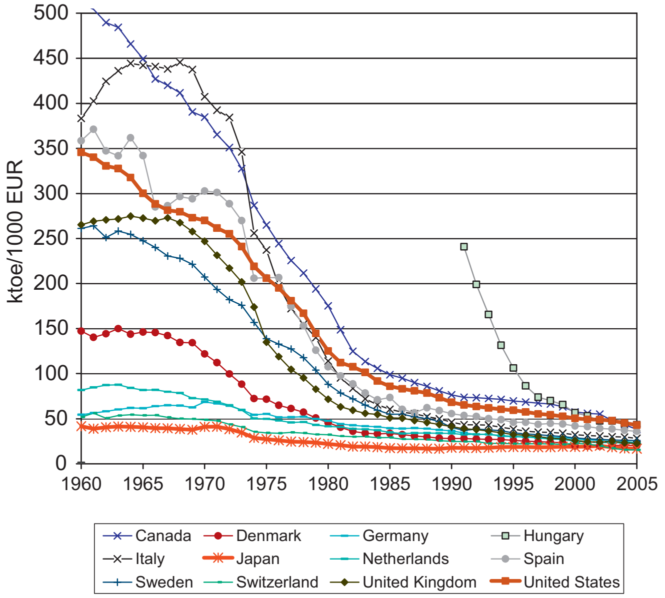

Fig. 8. Energy intensities for transport for selected OECD countries 1960–2003 (*Source*: IEA Statistics).

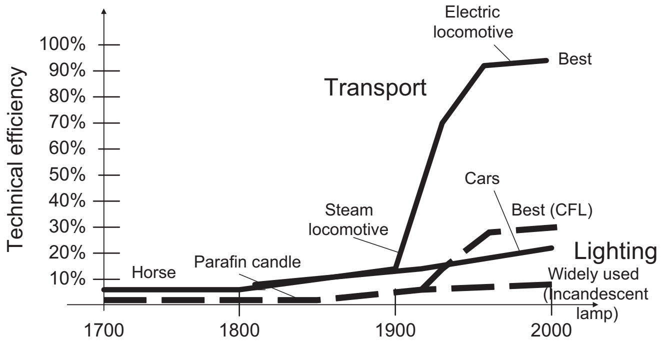

Fig. 9. Historical efficiency improvements of lighting and transport (various sources).

- There was a significant technical improvement of infrastructure technologies, e.g. buildings, railways, street, electric transmission lines.

6. Every increase in end-use efficiency enhances the demand for energy services

However, for every advance in technical efficiency—leading to cheaper energy services—there is commonly an increase in service demand—e.g. larger floor space per unit service, more light per person, more electronics and computers per person, larger vehicles with lower occupancy or rapidly introduction of air conditioning even in more temperate regions like Austria. This is the so-called take-back or rebound effect in economics.

With respect to TP and increase in energy service demand in individual automotive transport the following development is of interest, see Fig. 10: While for specific vehicle categories technical efficiency increased (specific consumption per km driven decreased) overall there was virtually a stagnation (see e.g. IEA, 2004). Hence, this TP was outweighed by an increase in energy service demand due to a switch to larger cars.

Fig. 11 shows the rebound effect for one unit of an appliance or vehicle and the aggregated overall rebound effect for an economy.

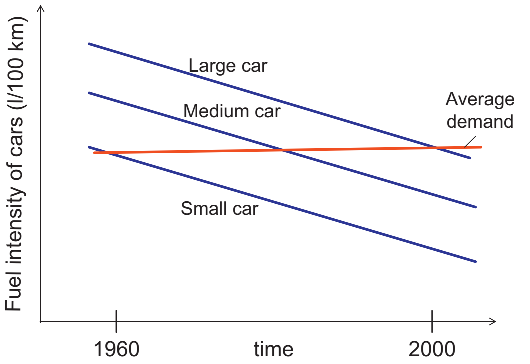

Fig. 10. Technological progress and increase in energy service demand in individual automotive transport.

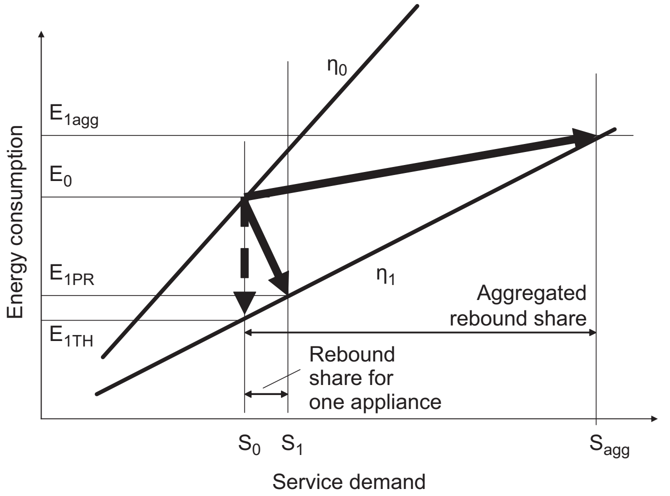

Fig. 11. The rebound effect for one technology and the aggregated rebound effect for an economy.

The rebound share for unit of technology can be explained as follows: If for one technology efficiency is enhanced from η_0 to η_1 a theoretical energy consumption of E_{1TH} is calculated. But due to the fact that technical efficiency improvements lead to cheaper services an increase in service demand from s_0 to s_1 for this appliance is arising—e.g. a higher operation time of an appliance, more lighting points, a larger vehicle—the practical level of energy consumption at η_1 is then E_{1PR}, see Fig. 11.

Fig. 11 also shows how the aggregated rebound effect due to technical efficiency improvements, resulting in cheaper energy services, leads to other corresponding dimensions of changes in Fig. 12. Technical efficiency improvements may lead to an increase in long-term energy service demand, resulting in new and more end-use technologies emerging and a higher saturation of these appliances, and finally an increase in energy demand E_{1agg} due to e.g. purchase of more vehicles.

An example: an inefficient bus in New Delhi is much more effective in providing energy services (mobility in person km) per unit primary energy than an ultra-efficient sport utility vehicle such as the new Toyota Highlander (even the latest hybrid version) say in Los Angeles, see Fig. 11.

In a formal framework this effect can be described as follows. From Eq. (1) energy consumption depending on service demand can be described as

$$E = \frac{S}{\eta} = \frac{S_{LR}S_{SR}}{\eta} \qquad (6)$$

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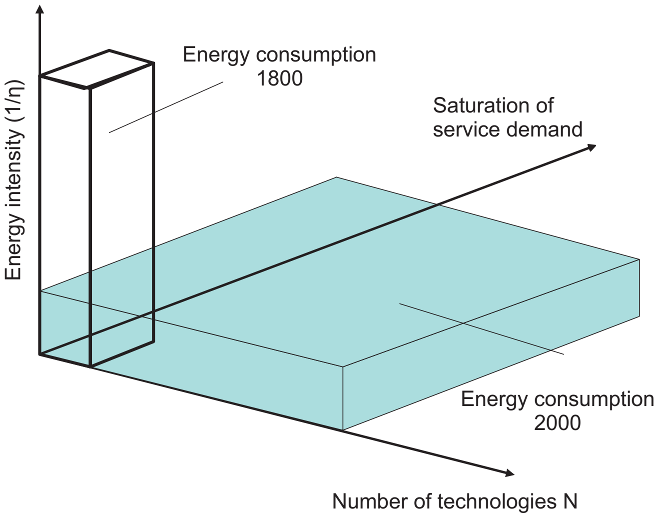

Fig. 12. Stylised description of the three dimensions, which contribute to an increase in energy consumption.

with

$$S_{LR} = Z\pi \tag{7}$$

Z is the number of dwellings, refrigerators, light bulbs, vehicles (long-term quantitative service demand); π is the specific power/quality index e.g. size of dwellings, volume of refrigerators, capacity of light bulbs, capacity of vehicles

$$S_{SR} = d \tag{8}$$

d is the short-term service demand e.g. numbers of hour operated, distance driven per car, degree indoor temperature.

In this context it is important to understand the decomposition of service shares and efficiency. E.g. Howarth and Schipper (1991), Schipper and Haas (1997) and Haas and Schipper (1998) depict the decomposition of energy consumption into structure, intensity and activity components. Note that endogenous efficiency increases were the source of the benefits—more services available—and that growth in π just captures changes in a part of long-term service demand, see example in Fig. 10.

So Eq. (5) can be rewritten for N end-use categories as

$$\sum_{i=1}^{N} E_i = \frac{Z_i d_i \pi_i}{\eta_i} \tag{9}$$

The equivalent to the product of energy consumption of the three dimensions reflected in Eq. (9) is depicted in Fig. 12. Note that (bottom-up) energy intensity ($= 1/\eta(T_i)$)—the inverse of energy efficiency—is used because it allows a better illustration of the amount of overall energy consumed. The resulting amounts of energy consumption in the years 1800 and 2000 are depicted in Fig. 12 in a stylised form.[10]

With respect to saturation of service demand in Fig. 12 it has to be considered that there are three factors influencing overall saturation of demand for a specific service: Z, d and π. While for one or the other component for some end-use category sometimes there may be signs of saturation (e.g. for energy consumption of refrigerators), there is very often still a huge potential for larger, more powerful, second or even third units and, hence, it is hard to really believe in significant saturation effects given affordable costs of these units and low energy prices.

For an appraisal of the prospects of energy conservation it is necessary to identify changes in energy consumption over time. The change in energy consumption from period 0 to period 1 can be described technically as

$$\frac{E_1}{E_2} = \frac{(Z_1/Z_0)(d_1/d_0)(\pi_1/\pi_0)}{\eta_1/\eta_0} \tag{10}$$

Furthermore, from Eq. (2) we know that service demand depends on available income Y, the price of energy service p_s and the capital costs CC. So the change in total number of units Z (e.g. number of dwellings, light bulbs, vehicles, etc.) can be described as

$$Z_1/Z_0 = (GDP_1/GDP_0)^{\beta_Z}((p_{E1}/\eta_1)/(p_{E0}/\eta_0))^{\alpha_Z} \times (CC_1/CC_0)^{\xi_Z} \tag{11}$$

where GDP is the gross domestic product; β_Z is the income elasticity of change in the total number of units (e.g. of dwellings, light bulbs, vehicles, etc.) due to an increase in GDP; α_Z is the price elasticity of change in the total number of units due to a change in energy price or efficiency; ζ_Z is the capital cost elasticity of change in the total number of units due to a change in capital costs (investment costs or interest rate) of units (e.g. of dwellings, light bulbs, vehicles, etc.).

Change in total power/quality index (e.g. capacity of light bulbs, power of cars size of dwellings, etc.):

$$\pi_1/\pi_0 = (GDP_1/GDP_0)^{\beta_\pi}((p_{E1}/\eta_1)/(p_{E0}/\eta_0))^{\alpha_\pi} \times (CC_1/CC_0)^{\xi_\pi} \tag{12}$$

where GDP is the gross domestic product; β_π is the income elasticity of change in total power/quality index due to an increase in GDP; α_π is price elasticity of change in total power/quality index due to a change in energy price or efficiency; ζ_π is the capital cost elasticity of change in total power/quality index due to a change in capital costs (investment costs or interest rate) of units (e.g. of dwellings, light bulbs, vehicles, etc.).

Change in short-term service demand (e.g. numbers of hours operated, distance driven per car, degree indoor temperature, etc.):

$$d_1/d_0 = (GDP_1/GDP_0)^{\beta_\mathrm{d}}((p_{E1}/\eta_1)/(p_{E0}/\eta_0))^{\alpha_\mathrm{d}} \tag{13}$$

β_d is the income elasticity of short-term service demand due to an increase in GDP; α_d is the price elasticity of short-term service demand due to a change in energy price or efficiency and we finally obtain for the change in energy consumption:

$$\frac{E_1}{E_0} = \frac{\eta_0(GDP_1/GDP_0)^{\beta_Z+\beta_\pi+\beta_\mathrm{d}}((p_{E1}\eta_0)/(p_{E0}\eta_1))^{\alpha_Z+\alpha_\pi+\alpha_\mathrm{d}}(CC_1/CC_0)^{\xi_Z+\xi_\pi}}{\eta_1} \tag{14}$$

If we only look at the effect of price and efficiency changes on changes in overall energy consumption we obtain:

$$E_1/E_0 = (\eta_0/\eta_1)^{(1+\alpha_Z+\alpha_\pi+\alpha_\mathrm{d})}(p_{E1}/p_{E0})^{(\alpha_Z+\alpha_\pi+\alpha_\mathrm{d})} \tag{15}$$

The effective share of savings due to efficiency improvements is $(1+\alpha_Z+\alpha_\pi+\alpha_\mathrm{d})$ (assuming that the price elasticities are negative).

An example: efficiency is improved from 0.4 auf 0.8 and hence, theoretically 50% of the initial energy consumption should be saved. The price elasticities are $\alpha_Z = -0.2$; $\alpha_\pi = -0.1$; $+\alpha_\mathrm{d} = -0.4$; Then $(1+\alpha_Z+\alpha_\pi+\alpha_\mathrm{d}) = 0.3$ and the overall savings are only 19%! (Instead of 50%.) Moreover, efficiency improvements might also increase overall GDP growth and also make larger units affordable and hence also influence indirectly the growth of GDP and the switch to larger units of dwellings and cars by increasing the power/quality index π. Then it is easy to imagine that increases in efficiency will in a medium-term effect lead to increases in energy consumption. Hence, conclusions from Eqs. (10) and (11) with

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[10] Correspondingly greenhouse gas emissions increased diluted by the change in fuel mix towards less carbon intensive energy carriers (Nakicenovic, 1999).

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respect to proper corresponding energy policies are the income and the individual power/quality index cannot be influenced by policies. So there are only two remaining approaches: either to increase prices significantly by means of a tax or by complete changes in customers awareness, leading to a paradigm change influencing the elasticities of income, efficiency and individual power and quality of dwellings, light bulbs, cars, refrigerators, etc.

With respect to TP the following changing paradigm is necessary:

- Historical: efficiency improvements lower than increase in service demand (because energy remained cheap while costs for technology improvement increased relatively!).
- Necessary future paradigm change: efficiency must grow more rapid than increase in service demand (due to higher energy prices, regulatory mechanism such fleet average fuel consumption, and changes in consumer behaviour and preferences) OR: Increase in service demand lower than technological growth (due to saturation in service needs and considerable “dematerialization” of affluent societies).
- Identify carefully what the magnitude of the overall rebound could be: There will be applications like heating of buildings, refrigerators where the service is close to saturation it is likely to be low and others where efficiency improvements might lead to significant increases in service demand (see Madlener, 2007).

7. The rebound effect in the historical context

It is since the advent of the Industrial Revolution two centuries ago that the demand for energy services skyrocketed. This increase was accompanied by a soar in energy demand mainly for fossil fuels. It must be borne in mind that the driver for this demand was generally the technological change and not cheap energy per se. Fig. 13 shows the example of the decline in service costs for the end uses lighting and transport; Fig. 14 shows the analogous historical growth of consumption of these services in the UK (Pearson/Fouquet 2003, 2006). Yet the cost of energy did not necessarily decline over this period. Instead, technological change and efficiency improvements have driven down the cost of energy services. In other words, a part of technical efficiency improvements have been translated into lower cost of the services, leading to increasing demand.

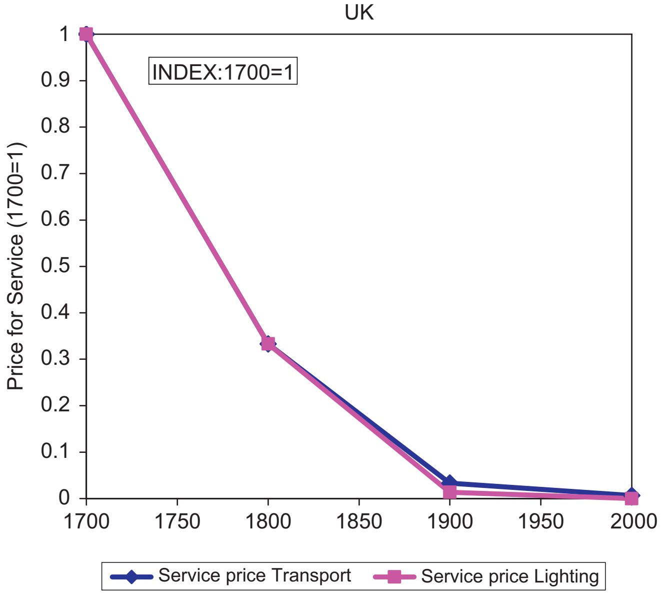

Fig. 13. Development of the price for the services transport and lighting in the UK (*Source*: Fouquet/Pearson, 2003, 2006).

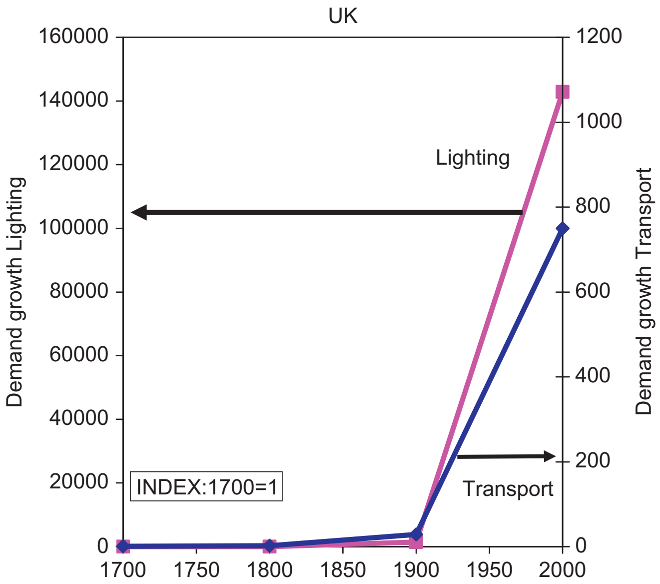

Fig. 14. Development of the demand for lighting and transport in the UK (1700 = 1) (*Source*: Fouquet/Pearson, 2003, 2006).

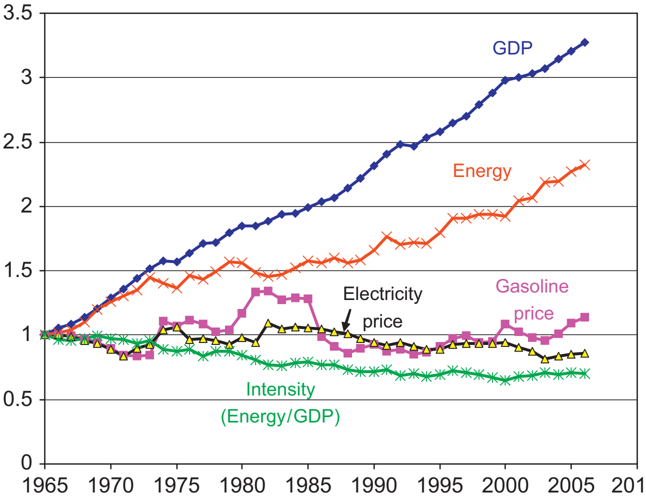

Fig. 15. Development of the major indicators with respect to total energy consumption for Austria (1965–2006), real prices.

Historically, in fact increase in energy consumption outpaced efficiency improvements. At the global level, the energy intensity (primary energy over GDP) declined at about one percent per year during the last two centuries, while primary energy consumption increased by some two percent per year. This means that economic growth of some three percent per year has been offset by aggregate efficiency (and structural change) effects of about one percent per year.

In Fig. 15 the development of the major indicators with respect to total energy demand for Austria (1965–2006) is depicted. While prices for final customers remained almost constant over the last 40 years GDP—and accordingly income—more than tripled. Intensity declined in times of high oil prices and remaining rather constant afterwards. Until 1973 GDP and energy demand grow in lockstep. Obviously, between 1973 and 1985 with high oil prices temporarily decoupling of GDP growth from growth in total

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energy demand took place. This decoupling prevailed for further 5 years after the drop in oil prices. Since about 1990 total energy demand increased continuously again.

8. Interaction between prices and energy intensities

Having analysed the rebound effect in a historical context, next it is of interest to figure out whether prices do also currently matter with respect to energy consumption per economic value. This is in the following done for households' electricity consumption. The relationship between energy prices and aggregated electricity intensities per GDP is depicted in Fig. 16. It can clearly be seen—with a correlation of more than 80%—that the higher the prices are the lower is the aggregated electricity intensity per GDP.

9. Summary and conclusions

Since the beginning of the industrial age some 200 years ago, a rapid increase in economic growth based on equally rapid growth of energy services has taken place. The major driver for this development was TP. It took place in at least three different dimensions:

- New technologies for the exploration of energy sources and especially for the conversion into energy services emerged.
- The conversion efficiency of most technologies was improved considerably.
- Efficiency of infrastructure was increased significantly.

The major effect of TP was that prices for energy services dropped and led to significant increases in energy service demand as well as in energy demand. With respect to the latter an important effect was the switch from renewable mainly to fossil energy sources. This brought about, finally, also the current troubles with respect to greenhouse gas emissions, global warming and the current non-sustainability of the economic and the energy system.

Hence, the current development of the major indicators investigated in this analysis is clearly on a wrong path (see Fig. 17):

- Introduction of carbon-free or low-carbon energy sources is too slow to outweigh the increase in total energy consumption;
- the decrease in energy intensity is too slow to compensate the overall increase in energy service production (= GDP). In this context it is important to note that in the last decades after the drop in oil prices technical efficiency improvements have been more than outweighed to a large extent by increases in short-term and long-term service demand.

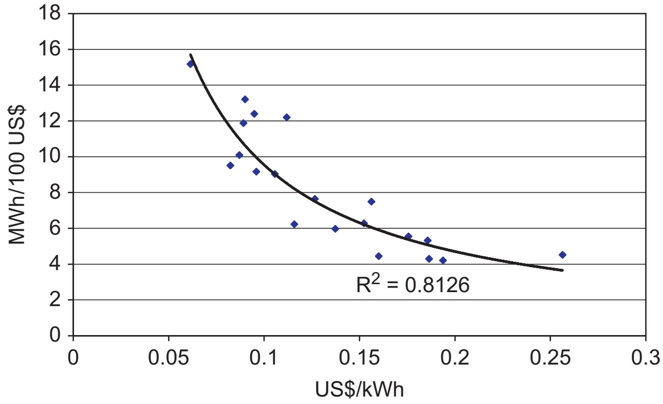

Fig. 16. Electricity consumption per unit of GDP vs electricity prices in selected OECD countries in 2005 (*Source*: IEA data, idea: Verbruggen (2006)).

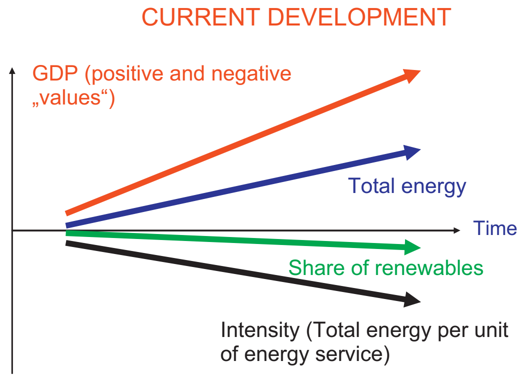

Fig. 17. Current stylised development of major indicators.

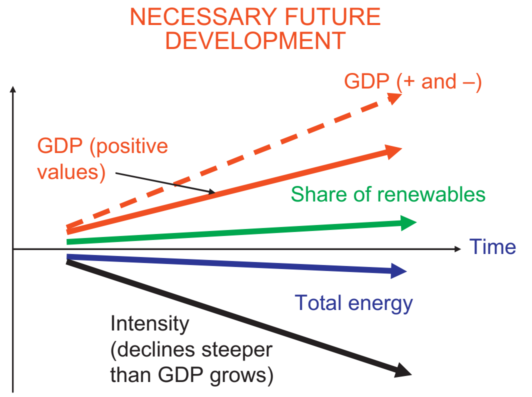

Fig. 18. Necessary developments to head towards sustainability.

Summing up, the major conclusions of this analysis are

1. A rigorous rethinking process has to take place to identify more precisely which GDP per capita values lead to enhancing human welfare and improving the quality of life. Equally, the same question can be posed in terms of energy services per capita: Which levels provide a corresponding positive net value as energy services are coupled with GDP growth (see Fig. 18)? Most important is to reduce the waste of services and adverse energy-related emissions ranging from pollutants to greenhouse gases.
2. Regarding the growth of energy services, we have to distinguish between regions and individuals with a very high level of energy services consumed, where an additional unit of energy service need not bring substantial improvement of quality of life and such regions and individuals with a very low level of energy services consumed (or the two billion people without access), where each additional unit can result in substantial increases in the quality of life.
3. Under this perspective a significant increase in energy conversion efficiency (doing more with less!) has to be triggered to finally provide energy services with far less input of energy than today. More precisely, on a global level an increase of energy efficiency has to be brought about in a way that intensity declines become steeper, allowing for services growth without increasing primary energy requirements (see Fig. 18).

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4. However, as has been shown by history technical efficiency improvements have to be accompanied by proper energy price and regulatory policies. Otherwise, it is very likely that energy conservation gains due to higher efficiencies will be outweighed again by increases in energy service demand and, straightforward, energy consumption.
5. A continuous increase in the share of renewable energy sources and other low-emission options has to be brought about (see Fig. 18).

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