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Energy 31 (2006) 3159–3170

ENERGY

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Methodological aspects of the definition of a 2 kW society

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Abstract

The consumption of primary energy is often used to compare energy systems from a sustainability viewpoint at regional, national or even world level. For such comparisons to be "fair" and meaningful, this implies, however, to define primary energies in a coherent way for all the various possible sources (coal, oil, gas, nuclear, renewables). This paper stems from the acknowledgement that the definitions presently used in the framework of energy policy studies do not really fulfill this requirement, and suggests approaches to correct such a methodological flaw. It is emphasized that exergy is a key concept in this context. The authors' reflections on this matter originated from the recent adoption by the Board of the Swiss Federal Institutes of Technology, soon followed by the Swiss Advisory Committee for Energy Research, of the objective to achieve a "2 kW-society" 2 kW year/(cap year) in Switzerland by 2050. This target, which is about 2.5 times below today's consumption according to official statistics, invites to have a closer look to its concrete meaning. The concept of useful energy is also briefly discussed and linked to the only really pertinent consideration for the end-user in such a context, i.e. the expected services (comfort, transport, …).

Keywords: Exergy; Primary energy; Methodology

1. Introduction

Although its average per-capita energy consumption is presently quoted a little above 5 kW year/year (from governmental statistics, OFEN/BFE [1] and OFS/BFS [2]; see also Fig. 1), Switzerland, via its Swiss advisory committee for energy research, has recently adopted the ambitious objective to decrease this value to 2 kW year/year (present mean world consumption) of primary energy use by 2050. This target originates from an earlier proposal from the Board of the Swiss Federal Institutes of Technology [3] to set the path and stimulate research efforts towards a more sustainable society. The intent underlying such an attractive and challenging target is obviously to strive for a more efficient use of primary resources [4,5], but the nature and diversity of these primary resources are such that an unconsidered use of this concept can lead to quite irrelevant conclusions in some cases. To illustrate this point, it is enough to observe that, for example, an

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doi:10.1016/j.energy.2006.02.011

Nomenclature

E	Exergy (J)
Q	Heat (thermal energy) (J)
T	Absolute temperature (K)
$\underline{\Delta}\tilde{k}^0$	Fuel exergy value (J/mol)
$\tilde{g}$	Gibbs free energy (J/mol)
$\tilde{e}_d$	Exergy of diffusion (J/mol)

Subscripts

0	reference (ambient) state
T	at temperature T
Q	relative to thermal energy
I	reactants
J	products

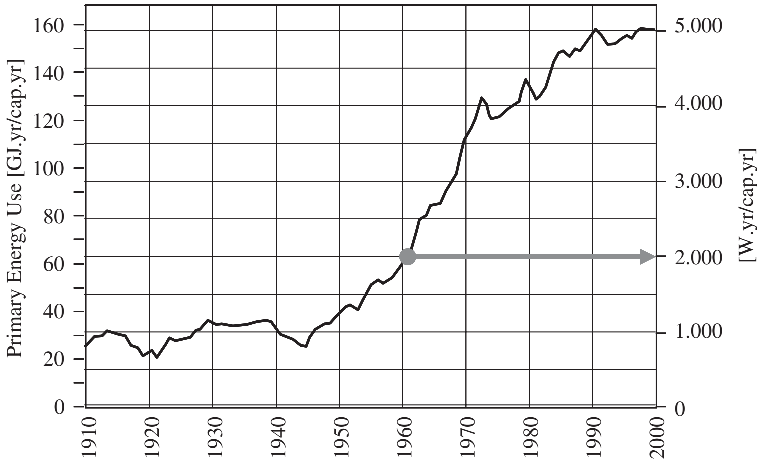

Fig. 1. Swiss primary energy consumption (from Jochem et al. [4]).

increasing use of photovoltaic solar cells would unavoidably degrade the global energy efficiency of the Swiss energy balance if renewable and non-renewable primary energies are indiscriminately accounted for together, because the performances of solar cells in this respect are, and will remain, relatively low. Do we have for all that to limit the development of electro-solar systems, perfectly compatible with the "sustainability" requirements in other respects?!

The above considerations show the importance of correctly and coherently defining the concepts and terminology used in such an energy policy context, following a rigorous scientific approach while keeping also in mind practical considerations. Although it has too often been eluded, this definition problem has very general and important consequences; it is the source of much confusion and has in many cases even masked the substantial progress made these last years in a more rational use of the available energy sources. It is therefore of paramount importance for the concerned authorities to be able to rely on a clear characterization of the definitions and underlying hypotheses used in such a context, what this paper intends to contribute to.

After a brief review of the different forms of energy and chains of transformations the energy can undergo from source to end-use, the following sections will be devoted to a discussion of the questions raised by the suitable definition of primary energy in the cases of different non-renewable and renewable energy sources, respectively. This will be completed by a short reflection on the definition of the concept of useful energy in the same perspective. Finally, we will draw some conclusions about the correct efficiency appraisal of a national/regional energy system and the assessment of the associated losses.

2. Energy forms and transformations

According to the First Law of thermodynamics, energy in itself is neither created nor consumed, but only undergoes transformations converting it from one energy form to another. From an energy accounting viewpoint, it is by comparing the useful energy obtained, or even better the energy service(s) expected by the end-user, to the primary energy consumed to this end that the efficiency of these transformations should be evaluated, knowing that there will inevitably be losses associated with all the steps of the conversion process, either in quantity (e.g. heat energy losses due to thermal insulation imperfections), or in quality (e.g. transformation of chemical energy to thermal energy of finite temperature).

It is by reducing these losses that we could expect to lower the consumption of primary energy—objective of the "2 kW-society" program—while maintaining the end-use services at their present level (or, at least, at a level judged compatible with a satisfactory quality of life). The whole chain of transformations involved in the path from primary energy to useful energy is shown in Fig. 2, together with the respective losses associated with each step of the conversion process.

It is important to emphasize here that the end-user is in fact not interested by the consumption of some useful energy (that is, heat, mechanical power, etc.) as such, but by obtaining a particular service (selected internal room temperature and humidity, transport over a given distance and in a given time, etc.). It is undeniably at the level of the useful energy required to get these services that the most substantial gains could be expected in the framework of the "2 kW-society" program, namely by assuring in all the fields of everyday

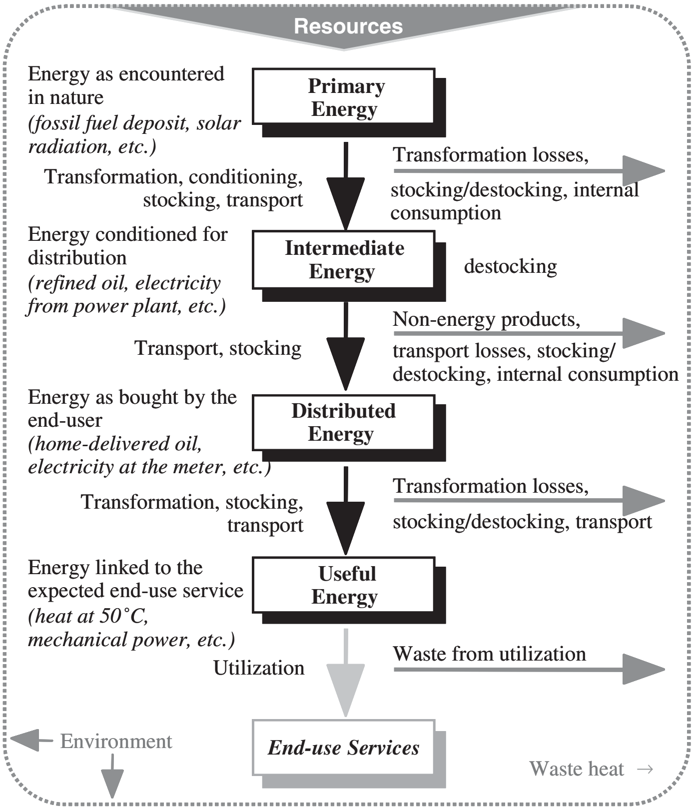

Fig. 2. From primary energy to useful energy and services.

life an equal (or, at least equivalent) quality of services while consuming distinctly less useful energy (energy-saving buildings, vehicles with low specific energy consumption, etc.). The whole energy chain represented in Fig. 2 will therefore have to be analyzed for potentially achievable savings at every steps, starting backwards from the energy services to the primary energy, i.e. the "raw" energy as found in nature, before any transformation or conditioning.

It is to the total annual consumption of such primary energy in Switzerland, also taking into account the imported "gray energy", i.e. the energy used during the manufacturing of imported goods, divided by the number of persons residing in the country, that corresponds the "2 kW-society" objective (according to documents published by its promoters, see Imboden et al. [3]). Unfortunately, it is not as straightforward as it could appear at first sight to give a definition of the primary energy that can coherently be applied to the whole set of energy sources, as shown in the two following sections.

3. Primary energy definitions, the fossil and nuclear cases

Primary energy is usually defined as "*the energy embodied in natural resources that has not undergone any anthropogenic conversion or transformation*" [4]. This satisfactorily defines the *physical form* (e.g. coal, crude oil, natural gas, sunlight, wood, wind, biomass, uranium) of the resource, but does not really specify how to quantify its *energy potential*, as required when the objective is to proceed on this basis towards comparative evaluations. An appropriate definition of a "quantified" primary energy should ideally be independent of the way this energy will then be used, and such that it is possible to unambiguously assess the "energy performance" (that is to say, the efficiency) of any system by dividing the corresponding delivered useful energy by the primary energy used to this end; the difference between these two values representing the transformation losses incurred at the successive steps of the energy chain represented in Fig. 2. The corollary of this is that the ratio of end-use energy to primary energy should take the value of one for any technologically, i.e. here thermodynamically, "perfect" system (see for example Gardel [6] for a general introduction to the question of the definition of primary energy in such a context).

The case of fossil or nuclear fuels ("deposit-type" energy resources, see Wall [7]) seems a priori the less problematic one from this viewpoint. In theory it requires only to be able to attribute a suitable specific "energy potential" to the quantity of raw matter (coal, crude oil, gas, uranium) used as primary source to obtain the expected end-use service. This conversion of physical material quantities in energy terms (e.g. [kg] → [J] or [Nm^3] → [J]) is, however, not straightforward and unambiguously defined in practice. For fossil fuels, this "energy potential" should obviously be related to the chemical energy contained in the raw matter that can be released in the form of heat (combustion) or electricity (direct electro-chemical reaction) when fuel and oxidizer molecules combine. These two conversion modes correspond to oxidation reactions, resulting in "stable" (CO_2 and H_2O), and often in additional "parasitic" (NO_x, CO, etc.), product molecules. Considering or not the latent heat available in the combustion gases results in two different *heating values* (higher and lower) which are unfortunately not always applied in a coherent way among different technology areas. In practice, the lower heating value tends to be preferred when evaluating combustion-based systems, like boilers and internal combustion engines, while the higher heating value tends to be preferred when evaluating fuel cell-based systems; the primary energy associated to a given mass (or volume) of fuel should, however, be an univocal intrinsic property of this material and not depend on the "technical" way this energy will finally be released. Furthermore these First-Law-based heating values do not properly account for the quality of the energy services provided. It is thus highly desirable to base the evaluation of the primary fossil energies on a single indicator and the most suitable one proposed so far to this end is the *fuel exergy* value (see below), as defined for example by Borel–Favrat [8], also called *fuel chemical exergy* [9] or *fuel chemical availability* [10].

The exergy theory results from the simultaneous consideration of both the First and the Second Law of thermodynamics. The concept of exergy moreover successfully links the fields of energy, environment, and sustainable development (see Wall & Gong [11]), which are essential for the definition of a "2 kW-society" program.

Exergy is a thermodynamic potential; it represents the maximum work that can be obtained from a given energy (or fuel mass) quantity, knowing that mechanical energy (and, by extension, electricity) is the energy form of the highest quality and thus the one offering the largest potential of use. As a reminder, mechanical energy or electricity can be used to drive a vehicle as well as to heat a given substance within a large temperature range. On the other hand, a given quantity of heat at a finite temperature can only be transferred to a body at a lower temperature level if no external work is delivered to the system. In the same way, Sadi Carnot [12], showed that only a fraction of the heat energy given to a system can be converted into useful work, fraction that directly depends on the temperatures T of the available heat source and T_0 of the environment. Let us recall here that, in differential form, the exergy δE_q of a given heat quantity δQ_T (thermal energy) at temperature T, is given by

$$\delta E_q = \left(1 - \frac{T_0}{T}\right) \delta Q_T. \tag{1}$$

With the exergy approach, it becomes possible to assign to all the different energy forms (work, heat, chemical energy, etc.) coherent values that take into account the two key energy parameters, quantity and quality.

Whereas the First Law of thermodynamics alone, because it is a conservation law, does not allow us to define any meaningful system efficiency (as stated by Rosen and Scott [13]: "*Earth does not consume energy, neither do we nor does our energy system; rather, we consume exergy*"), the accounting in exergy terms leads to the definition of a "true" efficiency, i.e. end-use exergy given by a system divided by the exergy consumed by this system to produce the expected service. The exergy efficiency is equal to 100% if, and only if, the system is thermodynamically perfect, whereas the usual definition of efficiency in energy terms (First Law) can take any values (<1, $=1$ or >1), according to the system considered. Thus First Law efficiency does not give real useful information on the interest of the considered system from the viewpoint of optimal energy utilization. For example, even a thermodynamically perfect engine converting waste heat into electricity is likely to have an energy efficiency of only a few percents, which does not give any significant information on the thermodynamic quality of the technical system in question.

The exergy efficiency has the additional advantage of providing a suitable way to coherently characterize the quality of advanced energy systems integrating various technologies and delivering multiple services (e.g. cogeneration, simultaneous cooling and heating of water, etc.). Such coherence between very different technological domains and applications is particularly important when the system to be studied is as large as a country, for example, like in the case study considered here.

It can be shown [8,10] that the best suited definition of a fossil fuel primary energy in this context is certainly to consider the *exergy value* of this fuel, given (in molar values) by

$$\underline{\Delta} \tilde{k}^0 = \underline{\Delta} \tilde{g}_f^0 + \sum_j \tilde{e}_{dj}^0 - \sum_i \tilde{e}_{di}^0. \tag{2}$$

In this relation, the first term of the right member is the molar Gibbs free energy, while the last ones represent the molar exergies of diffusion ("chemical exergies") of the reactants and products, respectively, relative to a standard environment [14].

Interestingly, it is not necessary here to distinguish between higher and lower exergy values as the physical state of the water in the combustion gases plays a negligible role on the exergy value.

Let us now consider the case of nuclear energy, which, at first sight, could look quite similar to the one of fossil fuels. After all, the same term, "fuel", is used for both types of primary energy agents. The nuclear "fuel" presents, however, features that are very different from the ones of fossil fuels. First of all, it is made of two components, the fissile part, which is the only one to undergo fissions (at least by "thermal" neutrons), and the fertile part, the most abundant one, which undergoes reactions that partially transform it into new fissile material (conversion/breeding). Secondly, the "fuel" introduced in a nuclear reactor "burns" very slowly (whereas the combustion is almost immediate for fossil fuels) and incompletely (the spent fuel withdrawn from a nuclear reactor after 3–4 years still contains a significant amount of fissile material). Finally, this type of "fuel" must be "pre-processed" (in particular, enriched) before being fed into the reactor as well as reprocessed (in particular to retrieve the remaining fissile material) at the end of the fuel cycle, both operations that require non-negligible energy investments. The nuclear fuel cycle is thus much more complex than the fossil fuels one (see for example Ligou [15]). This makes any attempt to correctly and coherently define primary nuclear energy in the context considered here quite difficult.

Official statistics usually take nuclear energy into account at the primary energy level as the thermal energy "technically" (therefore depending on the technology used, which is not satisfactory for a correct primary energy definition) released in the reactor core. This definition, based on the (partial) analogy existing between fossil and nuclear fuels, does not take into account the important differences mentioned above between these two types of "fuels". In particular, it does not allow to coherently consider the fact that the "energy potential" of a given uranium mass can, for example, easily be multiplied by a factor 50–60, by means of the breeding process converting most of the fertile U-238 atoms in fissile Pu-239 atoms, in a Liquid Metal Fast Breeder Reactor (LMFBR)-type reactor. Based on the above definition, this would lead in the last case to an apparent energy "efficiency" of the order of 1600% (meaningless of course) compared to the fuel utilization performance achieved in a Light Water Reactor (LWR)-type reactor!

The difficulty of selecting a suitable and "universal" primary energy definition when dealing with nuclear fuel is illustrated by the energy and mass flows diagram given in Fig. 3 (LWR case). We have here a situation a little similar to that encountered with the lower and higher heating values of fossil fuels, but far more complex and at a much larger scale.

When it comes to the energy released from nuclear fuels that can be converted into useful work (exergy value), it should be noted that the heat generated by the fission process can a priori be released at a temperature as high as desirable (whereas it is intrinsically limited by the dissociation phenomena for the fossil fuels). However, technological considerations (strength of materials at high temperature) limit in practice the surface temperature of the fuel elements to around 2000 °C [16], that is, the same order of temperatures as the

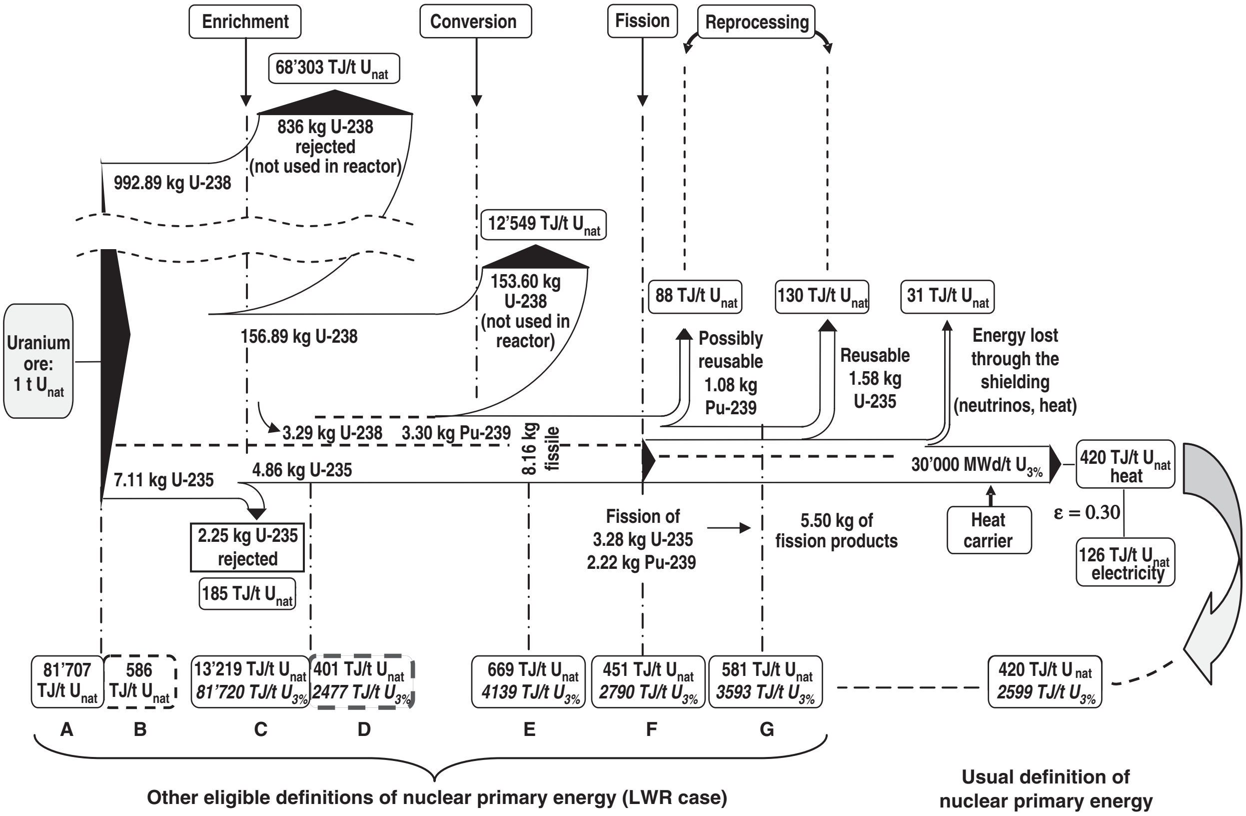

Fig. 3. The problematics of nuclear primary energy definition (schematic representation, not in scale, adapted from Gardel [5]). (A) Complete fission of all the uranium (U-235 and U-238 isotopes) contained in the natural uranium; (B) Complete fission of only the initial fissile material (U-235) contained in the natural uranium; (C) Complete fission of the entire uranium inventory (U-235 and U-238 isotopes) found in core after the enrichment process; (D) Complete fission of only the initial fissile material (U-235) found in core after the enrichment process; (E) Complete fission of the initial fissile material (U-235) found in core after the enrichment process plus the in situ bred Pu-239 (conversion of part of the U-238 core content); (F) Energy released by the effectively achieved fissions in both U-235 and Pu-239 fissile materials; (G) Same as F, but with reprocessing and recovery of the U-235 contained (not the Pu-239) in spent fuel.

ones of combustion gases obtained with fossil fuels. The Carnot coefficient, which allows passing from energy to exergy values for thermal energy, should thus not be very different for nuclear and fossil fuels, respectively.

In their paper on energy and sustainable development, Wall and Gong [11] suggest that nuclear exergy may be written (from the well-known Einstein's formula) as

$$E = \Delta mc^2 - E_{\text{neutrino}}. \tag{3}$$

This is formally correct of course, as it recognizes that nuclear energy Δmc^2, with c, the speed of light in vacuum, is potentially an energy of the highest quality, but that part of it, the one appearing as neutrinos, cannot be converted to work because neutrinos have almost no interactions with our material environment. It remains, however, to precise what is the Δm value to consider in this formula (which is not precised in Wall and Gong's paper). This could be the mass defect corresponding to the sole fission of the effectively used uranium-235 contained in the fuel or, at the other extreme, the one corresponding to the fission of all uranium-235 and uranium-238 atoms initially present in the considered mass of nuclear fuel, as well as all intermediary possibilities mentioned in the energy and mass flows diagram of Fig. 3. Note, however, that the further down the flow (i.e. to the right) we go in this diagram, the more reactor-type-specific (LWR in Fig. 3) are the values given, which is not satisfactory for a suitable definition of nuclear primary energy (or exergy) that, again, should ideally be independent of the ''technical way'' the energy contained in a given mass of fuel will be released. Adopting the most extreme ''energy potential'' would, however, have considerable implications on the way the importance of nuclear energy is presently assessed and considered. Such a rigorous definition of the nuclear primary energy would inevitably lead to very low coefficients of energy utility (low exergy efficiency) for the present reactor technology (which does not favor fuel breeding), multiplying as a result the true amount of primary nuclear energy required to produce one kWh of electricity compared to today's generally accepted values. This, however, actually represents the true upper limit of the energy that could be obtained from such a fuel, moreover with techniques already at our reach today. From a resource management viewpoint at least, why should the limited use of the effective nuclear energy potential observed in today's nuclear installations not be reflected in the primary energy accounting? To take a more familiar analogy, it is as if the energy content of a barrel of crude oil would be identified with the energy delivered by its sole kerosene fraction (yield: ~0.3%) for example, all its other fractions being considered as pure waste!

It is premature to give a definitive conclusion at this stage, but we hope with the above discussion to have at least made clear that nuclear energy, particularly, does not easily lend itself to a ''universal'' (not technology-dependent) definition of primary energy, which makes us strongly believe that further thinking and discussion should now be engaged with recommendations to authors quoting efficiencies for nuclear systems to at least clearly indicate their assumptions.

4. The case of the renewable energies

As shown in Fig. 4, primary energy takes in the case of renewable energies a quite different meaning than in the non-renewable energies case; we are no more dealing with stored energies, originated from the geological times or the origins of our planet (nuclear fuel), but with energies continuously, or at more or less regular intervals, tapped from natural cycles. This necessary distinction to be made in this context between resources originating from deposits or from natural flows has, for example, also been pointed out by Wall and Gong [11].

This difference has direct implications on both the characteristics and utilization modes of what can be considered as primary energy in one and the other cases. To take a classical financial analogy, it can be said that one eats into one's capital (energy stocks) in the case of non-renewable energies use, whereas one lives on interest incomes (energy fluxes) when one relies on renewable energies. Reasons that obviously incite us to curtail the consumption of the primary energy agents in the first case, that is, to conserve limited natural resources and to preserve the quality of the environment (harmful emissions are generally directly proportional to the quantities of primary energy agents consumed), do not apply in the second case. In the latter, any resource that is drawn out from one cycle, insofar as this energy levy remains reasonable, does not reduce the utilization potential of the concerned fluxes in the following cycles. Moreover, only a limited amount of harmful emissions is directly associated with the consumption of most renewable resources; at the

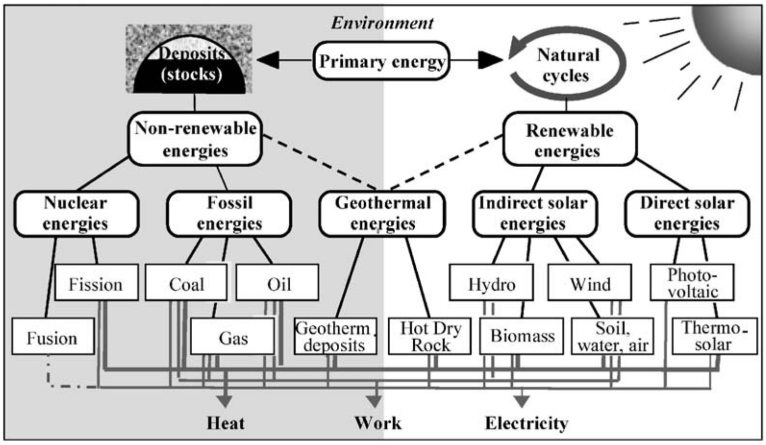

Fig. 4. Renewable and non-renewable primary energies.

most, non-renewable resources consumption and harmful emissions occur during the fabrication and the implementation of the collecting/conversion systems.

On the other hand, what is not used as far as geologically stored resources (deposits), such as fossil or nuclear fuels, are concerned, remains entirely available for future use. Losses occur only when primary energy is released in such a way that part of the original stock is definitively downgraded to a level that prevents any further use.

For renewable energies, on the contrary, all opportunities that are not collected "on the spot" are definitively lost, at least for the current (often annual) cycle. These characteristics bring us to consider here as losses only the part of the renewable energy that the structure of the collecting system itself prevents to recover, as well as the manufacturing and implementation exergy use ("gray exergy").

A direct consequence of the above-mentioned differences between non-renewable and renewable energies is the fact that the units used to quantify the amount of resources available are not the same. In the first case, we are interested in *energy quantities* expressed in [Joules], [kilowatt-hours], [tons of oil equivalent], etc. In the second case, it is to *energy fluxes* that we have to refer to, i.e. to quantities expressed in power units such as [EJ/yr], [GW yr/yr] for example. At the level of primary energies, one typically will make use of [MJ/kg] or [MJ/m^3] in the non-renewable case and, for example, [GJ/m^2 yr] (e.g. solar energy) in the renewable case. The obvious conclusion of this observation is that non-renewable energies and renewable energies should absolutely be accounted for separately in the framework of a program such as the "2 kW-society". These types of energies are not of the same nature and they do not raise the same type of problems. Therefore, there is, in our view, no reason for solar or wind energies for example, to target a consumption reduction similar to that of energy agents such as fossil or nuclear fuels. One paradox of such an undesirable accounting mix, as already mentioned in the introduction, is that an increasing contribution of renewable energies to the country's energy supply will inevitably lead to a degradation of the global energy efficiency for the concerned territorial entity, and thus to an apparent contradiction with the objectives of the "2 kW-society".

This being clarified, it remains nonetheless important to give appropriate definitions of the primary energy for the various types of renewable energies, because this is fundamental to concretely assess, as in the case of the non-renewable energy agents, the "improvement margin" that exists in the utilization of this type of resources and to quantify the progress that could still be made in the concerned technologies.

It should first be noted that most of the renewable energy types result from conversion processes fed by the solar radiation received by the Earth (see Fig. 4) with, in some cases, a more or less pronounced influence of the topography (hydropower, wind energy). Solar radiation is thus *in fine* the true source of practically all the renewable energy resources (the only notable exceptions being the geothermal energy and, partly, the tidal energy). It appears therefore reasonable to consider the quantity of incident solar energy as the appropriate primary energy, at least for the direct uses of the solar radiation (thermo-solar, photovoltaic) and the energy obtained from biomass.

In the last case, this way of defining the primary energy—rather than considering the exergy value of the produced organic fuels, like it is usually done—is justified by the fact that there could be a direct competition for the available surfaces between ''technological'' solar collectors and ''biological'' ones (for example, a given field surface can be covered with photovoltaic cells, … or planted with some particular energy crop; why should the primary energy be defined differently in each of these two situations?!).

If we take for granted that primary energy for these types of renewable energies is given by the amount of available incident solar energy during a given time, it remains to precise what is the available solar power at ground level and what is the reference surface to consider.

The first parameter is usually relatively well defined (at least statistically)—although fluctuating according to seasonal and meteorological conditions—for a given region. As far as the reference surface is concerned, to comply with the general principles defined in the beginning of this paragraph the whole surface made unavailable for other energy uses by the collecting system should be considered rather than the sole active surface of the collectors as it is usually done; the solar radiation that cannot be collected due to the structures of the system itself represents indeed a loss that can be considered an ''imperfection'' of this energy system (a hypothetical ''perfect'' system offering only active collecting surfaces).

Is the above-defined energy actually the ''usable energy'', in the quantitative *and* qualitative sense, defined in Section 3 for the fossil fuels, for example? Solar radiation is obviously an energy of high quality, but it is nevertheless limited in temperature by that of the sun surface, i.e. about 5800 K [13,17]. Assuming that the receptor can be assimilated to a black body, and neglecting the influence of the atmosphere, we can as before define a coefficient of energy utility (Carnot coefficient <1) for the solar energy, which will, however, be closer to one than for the fossil fuels because of the higher temperature of the source (5800 K compared with around 2000 K for the fossil and nuclear energy cases).

In the case of hydropower or wind energy, taking in particular into account the influence of the topography, it is on the contrary probably more appropriate to avoid going back as far as solar radiation when defining the primary energy resource.

The official Swiss statistics take usually the hydraulic primary energy into account as the electric energy produced, divided by an energy efficiency supposed to be close to 80%. This efficiency is primarily based on the electro-mechanical part of the hydropower plants; therefore, only possible future improvements concerning this part of the facilities could reduce the level of the required primary energy, which is obviously not fully satisfactory in the context considered here. To remain coherent with the general principles defined in this paper, it is the potential energy related to the considered energy agent—i.e. a given mass of water available at a given altitude—that should be taken into account, in other words, the weight of this mass of water multiplied by an appropriate head. This immediately raises two questions: what is the water mass to consider, and what is the corresponding head? Classically, the answer to the first question is given by taking into account only the volume of water effectively collected during a fixed time period (often 1 year). However, improved installations could be able to collect larger quantities of water, without losing part of it in the riverbed particularly during peak water falls or ice melting periods. This could imply larger storage basin capacity, a multiplication of such basins or an increased turbining (and sometimes pumping) capacity. The second question can itself be split into two parts. First it is necessary to define the upper level at which the considered mass of water becomes ''physically'' available. This is *not* the level of the water intakes as classically considered, but a higher altitude, because any drop of water is in principle available from the very place it falls on the relief. It is only for practical (and also economical) reasons—necessity of having at least a minimal discharge—that collecting installations are not designed like that; but this constitutes clearly a ''technical'' imperfection of the concerned energy systems that can (at least partially) be improved.

The second part of the question—being a matter of potential energy characterization—is the definition of the reference (lower) level. Again, this is certainly *not* the level at which the water is ''hydraulically'' re-injected into the river, but a lower one, which could be the sea level, or at least some lower topographical point of the considered region (it is always possible, at least theoretically, to complete an existing hydraulic scheme with one or several new hydropower stations situated downstream of the lowest previous water reinjection point on the river). One way of defining the appropriate levels and not go as far as considering the see level downstream of a hydro plant would be to consider the level, from which the balance of the complementary electricity produced (over the life expectancy) versus the gray energy required becomes negative. Such an approach would be similar to the exergetically optimum pinch in extended pinch analyses [18]. In any case all these considerations result in "true" hydraulic primary energy having significantly greater values than the ones generally retained up to now, which in turn will lead to attribute a lower effective efficiency to these installations.

What about wind energy? Wind turbines transform part of the kinetic energy of a blowing mass of air into mechanical energy. Theoretical considerations show that it is not possible to extract all the kinetic energy of the moving air intercepted by such a turbine; *Betz formula* [19] sets the upper limit of the recoverable energy to 16/27 of the intercepted wind kinetic energy. It appears therefore reasonable to consider that this should enter in the definition of the wind primary energy. However, the mass of air involved still remains to be precised. This mass is obviously greater than the sole mass of air passing through the wind turbine (as defined by its cross section) during a given time lapse, because the presence of the wind turbine itself prevents further use of the wind flow in its immediate vicinity. This "technical" constraint should be taken into account in the definition of the wind primary energy (by allowing for some appropriate multiplication factor).

On the other hand, the coefficient of energy utility will here be equal to one, as in the case of the hydraulic energy, both being mechanical energies (i.e. of the highest quality).

5. The definition of useful energy

Primary energy is not the only concept that should be more closely analyzed in the framework considered in this paper, although it is here the main focus because it constitutes by definition *the* reference for the "2 kW-society" program. As already mentioned above, the same kind of definition problem arises regarding the concept of useful energy (as a matter of fact, this applies the same way to all the energy stages of the chain described in Fig. 2). As pointed out above, the common end-user is finally interested by appropriate *services* and not by energy consumption for itself. The question is therefore here to estimate the minimum energy theoretically required to achieve the expected service(s).

For the transport of loads (vehicles, hoisting apparatus, etc.), the useful energy is evidently given by the cumulated variation of kinetic and potential energies, both being potentially recoverable (e.g. hybrid car), plus the friction energy (on air, water, soil, rail, bearings). If kinetic and potential energies were indeed recovered, the energy actually required to move a vehicle from one place to another would become extremely low in theory and would correspond to the sole friction energy (usually small for most transport systems at low to moderate speed).

What about space heating? Is the useful energy the heat given by the fuel to the heating system, or the heat available in the convectors? In fact, only the latter is determinant to actually warm the occupants and their surroundings; the rest is lost, in particular through insulation flaws of the considered room. However, it is more and more demonstrated that highly insulated buildings with heat reclaim air renewal can significantly reduce the heating requirements in cold climates. Moreover, as in the case of the primary energy, the accounting of useful heat should take into account its temperature level, and thus be measured in exergy—rather than energy—units [13].

From these few examples, we can conclude that the useful energy required to obtain a given service should therefore be best defined as some "technical" exergy indicator based on the estimation of the "best possible practice" according to the present state of knowledge in technology and science. This would of course not fully avoid some degree of arbitrariness (related, in particular, to evolution in time of the best possible practice), but would nevertheless provide a more coherent assessment tool.

As for the question of the primary energy definition, all this would obviously deserve a more extensive study and thorough discussion, but this goes beyond the objectives assigned to the present paper, which is more to raise what we believe to be some pertinent, and largely eluded up to now, questions regarding classically used definitions in the energy policy framework and suggest lines of thinking towards possible solutions, than providing definitive answers.

6. Conclusions

What really matters in the framework of an ambitious program such as the "2 kW-society" is to find a way to minimize the energy (or, better said, exergy) losses occurring at all stages of the energy chain from primary energy to useful energy and services (see Fig. 2), the sum of the various losses being equal to the difference between the primary energy (exergy) and the useful energy (exergy) for the considered system.

Based on the official Swiss national statistics, these energy losses add up to a little more than 50% of the total primary energy defined the usual way for the whole country. We have, however, shown above that the primary energy is often underestimated (nuclear energy, hydropower, solar energy, etc.) and the useful energy, on the contrary largely overestimated relatively to given expected services (heating, transport uses, etc.). The energy actually lost—and thus possible gains in global efficiency with improved technologies—is therefore in fact significantly higher than the one suggested by these statistics. Energy losses occurring between the primary and useful levels are even bigger if calculations are (as should be) made in exergy (usable energy) terms.

When establishing a target based on primary energy use (e.g. “2 kW”), a clear differentiation should be made between non-renewable and renewable primary energies. On the one hand imposing limits of use of the former is clearly commendable from a sustainability viewpoint but, as shown in this paper, must be based on more coherent definitions than the ones used today. On the other hand the interest of a better definition of renewable primary energies is essentially to facilitate a more pertinent assessment of technology progresses made in this field (there are no “environmental” reasons to impose here the same limits as in the former case).

The struggle against exergy losses and waste, and more generally the quest for a more efficient and rational use of the available energy resources, constitute effectively the foundations of the kind of resolute policy of primary energy consumption reduction that the “2 kW-society” program intends to promote. This supposes however for the decision-makers to have at disposal suitable analysis tools to be able to correctly estimate and value the true energy performances of the system of interest. In this context, the aim of the present paper was precisely to better specify basic concepts, identify problems and required thinking, and propose some preliminary guidelines to help answering them.

References

[1] OFEN/BFE (Office fédéral de l’énergie/Bundesamt für Energie). Swiss Global Energy Statistics 2003. BBL, Vertrieb Publikationen, CH-3003 Bern, Switzerland [in German/French]. See also: 〈http://www.energie-schweiz.ch/imperia/md/content/statistikperspektiven/gesamtenergie/10.pdf〉.

[2] OFS/BFS (Office Fédéral de la Statistique/Bundesamt für Statistik). Statistik des jährlichen Bevölkerungsstandes 2004. Population. Section Démographie et migration, Espace de l’Europe 10, CH-2010 Neuchâtel, Switzerland [in German/French]. See also: 〈http://www.bfs.admin.ch/bfs/portal/de/index/themen/bevoelkerung/uebersicht/blank/analysen__berichte/result.ContentPar.0018.DownloadFile.tmp/bfs%20aktuell%20espop%202004%20prov.pdf〉.

[3] Imboden D, Voegelin CR. Die 2000 Watt-Gesellschaft—Der Mondflug des 21. Jahrhunderts, ETH Bulletin 2000; (276) 24–7 [in German].

[4] Jochem E, et al., editors. Steps towards a sustainable development. A White Book for R&D of energy-efficient technologies. Novatlantis, ETHZ, EPFL, Paul Scherrer Institut, EMPA, WSL, EAWAG, March 2004. See also: 〈http://www.novatlantis.ch/frames_e.html〉.

[5] Marechal F, Favrat D, Jochem E. Energy in the perspective of the sustainable development: the 2000 W society challenge. Resour, Conserv Recy 2005;14:245–62.

[6] Gardel A. Energy, economy and prospective. Oxford: Pergamon Press; 1981 [chapter 2, part 1].

[7] Wall G. Exergy—a useful concept within resource accounting. Institute of Theoretical Physics, Göteborg, Report No. 77-42, 1977. See also: 〈http://www.exergy.se/ftp/paper1.pdf〉.

[8] Borel L, Favrat D. Thermodynamique et énergétique. Lausanne: Presses Polytechniques Romandes; 2005 [in French].

[9] Kotas TJ. The exergy method of thermal plant analysis. New York: Krieger; 1995.

[10] Moran MJ, Shapiro HN. Fundamentals of engineering thermodynamics. New York: Wiley; 1993.

[11] Wall G, Gong M. On exergy and sustainable development—Part 1; Conditions and concepts. Exergy Int J 2001;1(3):128–45.

[12] Carnot S. Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance, 1824 [in French].

[13] Rosen MA, Scott DS. Entropy production and exergy destruction: Part I— hierarchy of Earth’s major constituencies. Int J Hydrogen Energy 2003;28:1307–13.

[14] Rivero R, Garfias M. Standard chemical exergy updated. In: Monroy L, Tsatsaronis G, editors. ECOS 2004. Guanajuarto, Mexico; 2004. p. 773–86.

[15] Ligou J. Elements of nuclear engineering. Chur, Switzerland: Harwood Academic Publishers; 1986 [chapter 3].

[16] Marshall W. Nuclear power technology. Oxford: Clarendon Press; 1983. p. 29.

[17] Bejan A. Advanced engineering thermodynamics, 2nd ed. New York: Wiley; 1997.

[18] Staine F, Favrat D. Energy integration of industrial processes based on the pinch analysis method extended to include exergy factors. J Appl Thermal Eng 1996;16:497–507.

[19] Betz A. Wind-Energie und ihre Ausnutzung durch Windmühlen, Bandenhoeck & Ruprect, Göttingen 1926, facsimile edition by Ökobuch Verlag, Staufen, 1994 [in German].