Energy intensities, EROIs, and energy payback times of electricity generating power plants

D. Weißbach[a,b], G. Ruprecht[a], A. Huke[a,c], K. Czerski[a,b], S. Gottlieb[a], A. Hussein[a,d]

[a]*Institut für Festkörper-Kernphysik gGmbH, Leistikowstraße 2, 14050 Berlin, Germany*
[b]*Instytut Fizyki, Wydział Matematyczno-Fizyczny, Uniwersytet Szczeciński, ul. Wielkopolska 15, 70-451, Szczecin, Poland*
[c]*Institut für Optik und Atomare Physik, Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*
[d]*Department of Physics, University of Northern British Columbia, 3333 University Way, Prince George, BC, Canada. V6P 3S6*

Abstract

The Energy Returned on Invested, EROI, has been evaluated for typical power plants representing wind energy, photovoltaics, solar thermal, hydro, natural gas, biogas, coal and nuclear power. The strict exergy concept with no "primary energy weighting", updated material databases, and updated technical procedures make it possible to directly compare the overall efficiency of those power plants on a uniform mathematical and physical basis. Pump storage systems, needed for solar and wind energy, have been included in the EROI so that the efficiency can be compared with an "unbuffered" scenario. The results show that nuclear, hydro, coal, and natural gas power systems (in this order) are one order of magnitude more effective than photovoltaics and wind power.

Keywords:

ERoEI, EROI, energy return on invested, energy intensity, energy payback time, life cycle assessment

2000 MSC: 7.020, 7.050, 8.080, 21.070, 22

1. Introduction

The economic efficiency and wealth of a society strongly depends on the best choice of energy supply techniques which involves many parameters of quite different significance. The "Energy returned on invested", EROI (often also called ERoEI), is the most important parameter as it describes the overall life-cycle efficiency of a power supply technique, independent from temporary economical fluctuations or politically motivated influence distorting the perception of the real proportions. The EROI answers the simple question "How much useful energy do we obtain for a certain effort to make this energy available" (the terms "effort", "useful", and available will be specified below).

The independence from economical fluctuations is lost when input and output energies are weighted by qualitiy factors, essentially representing the different energy production costs. To distinguish this "energy

money returned on invested" from the EROI, it will be called *EMROI* here (see sec. 2.5). Although the EMROI is not the EROI it is often called this way which entails a lot of obfuscation of the EROI comparison. In particular the so-called "renewable" energies have often been treated in a confusing manner by weighting their output by a factor of 3 (motivated by the "primary energy") but comparing it with the unweighted output of other energies like nuclear. Only a strict *exergy* concept leads to independent and comparable results as described in sec. 3. The "primary energy" misconception and the exergy concept was also discussed in detail by Ayres et al. [1], and resulting conflicts even on the level of top-ranking statistical institutions have been recently pointed to by Giampietro et al. [2]. In this work, based on several LCA studies, EROIs will be calculated by using a strictly consistent physical definition thus making the energy producing techniques comparable to each other. Energy input with the highest quality difference, i.e. thermal energy and electricity, are listed *separately* (given in percentage electrical of the total energy input), so the factor of interest, either the EROI or the EMROI can easlily be determined and compared.

Here, an overview of EROIs and EMROIs for wind, photovoltaics, solar thermal, hydro, natural gas, biogas, coal and nuclear power is presented. It is the most extensive overview so far based on a careful evaluation of available Life Cycle Assessments (LCA). Only those studies could be taken into account that sufficiently keyed down the numbers to allow for a calculation of the correct EROI. EROIs and EMROIs including storage systems are also provided as they are unavoidable when turning the power supply from fossil fuels to "renewables". The most effective system, the water pump storage, already reduces the EROI remarkably. However, for a mixed scenario including conventional back-up power plants which has not been investigated here, the change might be more moderate.

Regarding the "renewables" it should be noted that energy and matter are never consumed or generated or even "renewed" but always just converted. A coal-fired plant does not "consume" coal but converts it to ashes and CO_2 while converting the chemical binding energy to heat and electricity. There is always a flow of materials (fuel, materials for construction, maintenance) driven by the "invested" energy with the result of making the "returned" energy available. The same is true for photovoltaics (PV) for building the cells, the plant, the converter, etc. Neither the energy nor the materials are renewed here, the only difference is that the actual energy source, the sun, is not controlled by the power plant, a fact that is irrelevant for the EROI.

Besides the physical limit there is also an economic one given by the society's Gross Domestic Product (GDP). This leads to an economic "threshold", as discussed in the sec. 6 and in the conclusions.

2. Mathematical description

The primary quantity thoroughly used here is the EROI. When used in formulas it will be abbreviated with R. Energy intensity and energy payback time are derived by simple relations as shown in the following.

2.1. EROI

The EROI of a power plant, R, is the ratio of the usable energy E_R the plant returns during its lifetime to all the invested energy E_I needed to make this energy usable,

$$R := \frac{E_R}{E_I}. \tag{1}$$

The *energy intensity* is simply the inverse of the EROI, therefore it will be denoted as R^{-1}. It describes the "effort" needed to "generate" a certain energy output.

E_I is also called the *cumulated energy demand* or the *embodied energy*. The greatest part of LCA studies is devoted to a precise evaluation of E_I, based on material databases. It has a fixed part E_{fix} for construction and deconstruction, and a part that increases with time t, $P_I t$ (e.g. maintenance and fuel provisioning, if required). P_I has the unit of a power and describes the energy demand per time. Therefore, the cumulated energy demand after a time t is

$$E_I(t) = E_{fix} + P_I t. \tag{2}$$

The energy output is the product of the average power P times the elapsed time t, $E_R(t) = P t$. For the EROI, energy output $E_R = E_R(T)$ and input $E_I = E_I(T)$ *after the plant's lifetime T* are compared, therefore

$$R = \frac{P T}{E_{fix} + P_I T}. \tag{3}$$

2.2. Energy payback time

The energy payback time T_a, also called the energetic amortization time, is the time after which the returned energy equals the energy invested, $E_R(T_a) = E_I(T_a)$, which leads to

$$T_a = \frac{E_{fix}}{P - P_I}. \tag{4}$$

It should be noted that E_I contains E_{fix}, e.g. some energy demand like the one for decommission that occurs *after* T_a. The plant's lifetime plays no role for the payback time, so no statement for the energy efficiency can be made.

2.3. Approximation for small P_I

If the energy demand for maintenance and fuel provisioning during the plant's lifetime is small compared with the fixed energy demand, $P_I T \ll E_{fix}$, and small compared with the energy output, $P_I \ll P$, the EROI is simply $R \approx P T/E_{fix}$, and the energy payback time is $T_a \approx E_{fix}/P$. They are both related to each other by

$$R \approx \frac{T}{T_\mathrm{a}}. \tag{5}$$

This approximation holds for most power plants. An exception are gas-fired power plants where the energy demand is dominated by P_I. The results presented here are not based on those approximations but other publications sometimes use it without the awareness that it is an approximation.

2.4. Net energy

Sometimes, the energy *difference* between output and input energy is used, called the *net energy* $E_\mathrm{net} = E_\mathrm{R} - E_\mathrm{I}$. Since E_net depends on the power plant size it does not describe the technique but rather the gain of a specific power plant. Either E_I or E_R is needed as an additional number, E_net alone makes no sense. The relation to the EROI is simply

$$E_\mathrm{net} = E_\mathrm{I}\,(R - 1) = E_\mathrm{R}\,(1 - R^{-1}). \tag{6}$$

2.5. EMROI – Energy money returned on invested

The economy runs on energy of different qualities, essentially thermal energy and electricity. In the current economy, the production cost ratio w of electricity to thermal energy is $w \approx 3$, corresponding to the reciprocal of 33% for the efficiency of thermal power plants, as well as for the cost ratio of electricity and primary energy. If the input energy E_I is composed of thermal energy E_th and electricity E_el (as given as percentage in the tables in sec. 7), the *energy money returned on invested*, hereon called *EMROI*, R_em, can be calculated by

$$R_\mathrm{em} = \frac{w E_\mathrm{R}}{E_\mathrm{th} + w E_\mathrm{el}}. \tag{7}$$

The EMROI describes only the money return for energy, excluding the labour costs. It is therefore neither a pure economic factor, nor a pure energetic factor. Unfortunately, many LCA studies calculate the EMROI but label it "EROI" which is the source of much confusion.

3. Exergy and primary energy

Exergy is the central concept in the utilization of energy. This utilization is bound to a physical process which transforms primary energy to exergy defined as the usable work inside a system with borders to (most frequently) the surrounding [1]. The maximal attainable exergy is then the difference between the energetic potentials inside and outside the system. These may be multiple potentials with respect to the four fundamental forces not just thermodynamical ones. On the other hand, *anergy* is the part of the primary energy in the physical transformation process that is bound to non-directed stochastic particle

4

movement (entropy). The link between the primary energy and the produced exergy is the efficiency of the physical process which performs the transformation. Pure exergy can be transformed by consecutive physical processes into any other form of energy. However, while the total energy as a sum of exergy and anergy is conserved, exergy is destroyed in every non-reversal process. So, only exergy is generated and destroyed. The definition of exergy based on potential differences, physical processes and its efficiencies, and system borders is versatile and can be used for any physical transformation process, not just thermodynamical or chemical ones in case of material flows.

The utilized physical process provides the theoretical limit for the exergy generation. Its actual technical implementation remains below this limit due to anergy generating subprocesses like friction which are accounted for in the technical efficiency factor of the utilized technical process. Thus the efficiency factor of the technical process joins the primary energy with the generated exergy and the inevitably remaining waste anergy.

In the case of power plants many technical processes are involved which are categorized as construction, decommissioning, maintenance and fuel supply. For example, construction materials are involved from the mine to the finished component. The required exergy for steel production is primarily determined by the difference of the enthalpies of the metal oxides and the steel. Secondarily, the exergy expense for the ore extraction and concentration, and the steel machining has to be added. Similarly the exergy for the fuel supply, etc should be added as well. All these technical processes are characterized by their efficiencies which determines the expended primary energy in its different forms.

Ideally, E_{I} and E_{R} should be both exergies, not energies. For the input E_{I}, the actually *utilized* exergy should be used. So far, Daviddson [3] made an exergetic analysis of a wind turbine and calculated the exergy taken from the system (Earth) and "flowing" through the society for the input, but this reflects not the work *done* by the society which stands for the physical economy. Cleveland [4] [5] highlighted different views of describing energy flows inside the system, including the physical approach using the exergy method, but inconsequently, changed to the economist's perspective using top-down calculations to obtain the physical parameter EROI. Indeed, available data from LCA studies and databases provide the *expended* primary energy sometimes divided into electric and thermal energy. As such with respect to the utilized exergy and the obligatory system borders, both parts of the primary energy, electrical and thermal, are composed of exergy and anergy. The link to the utilized exergy is given by the efficiencies of the technical processes. If they are known, exergy and primary energy are interchangeable. Thus E_{I} is pragmatically the expended energy. Being still physically inconsequent, it is larger than the expended exergy, based on a lack of process information which should be evaluated to obtain the exergy input [1]. Whenever possible, the electrical and thermal energy have been kept separately but for the final calculation of E_{I} those numbers have been added *with no weighting*, which is mandatory due to the system borders which co-defines the utilized exergies.

Weighting electricity is a critical point as a few LCA studies and guidelines [6] apply it also to the output

5

E_R. The weighting factor is usually 2-3, corresponding to an alleged average efficiency of thermal power plants of 30%-40% when burning fuel to produce electricity. This procedure is not considered sensible here as it makes assumptions about the origin of the exergy and the efficiency it has been produced with. This would change the meaning of the EROI which now becomes a replacement factor rather than an energy multiplication factor. E_R is the exergy output, not the primary energy of a hypothetical power plant needed to produce the same exergy. If the input energy is weighted as well, the result is the EMROI R_{em} as described in section 2.5. R is a physical property inherent to the power plant technique while R_{em} depends on the surrounding economy.

It is evident that the actual task is the evaluation of the input energy E_I, involving all production steps down to the raw material extraction or recycling, contrary to E_R which is easy to determine. This "bottom-up" method should be preferred but some authors [7] applied also a "top-down" method, for instance, by using the overall electricity bill of a solar cell production facility.

4. Usable energy, storage, and over-capacities

Power systems provide exergy (electricity), but they must do it when this exergy is required, the second quality factor of usability. For the energy output, although the term "available" is easy to implement by defining the connection point to the network (as done here) or to the consumer, the term "usable" is more complicated. It implies that the consumer has an actual need for the energy at the moment it is available. It also means the opposite, that energy is available when the consumer needs it. There are only three possibilities to make the energy output fit the demand.

- Ignoring output peaks and installing multiple times of the necessary capacity as a backup to overcome weak output periods.

- Installing storage capacities to store the peaks, with reduced over-capacity plant installations (short: buffering).

- Adapting the demand to the output at all times.

The third point is obviously not acceptable, because one becomes dependent on random natural events (wind and PV solar energy). A developed and wealthy economy needs predictably produced energy every time, especially the industry needs a reliable base-load-ready output to produce high quality goods economically. So only the first two points are acceptable, whereof the second one is the economically most promising. Some energy generation techniques need more buffering (wind energy, photovoltaics), some less (solar CSP in deserts, hydro power) and the fuel based ones almost no buffering (the fuel is already the storage). Technologically, this can only be solved by storage systems and over-capacities which are therefore inside the

system borders, "replacing" the flexible usage of mined fuel by fuel-based techniques. In opposite to that, the IEA advises to consider the backup outside the system borders without any scientific justification [6].

If E_{SS} is the total energy demand for a storage system, T_{SS} its lifetime, and S its capacity, the mean energy demand rate per capacity is

$$q := \frac{E_{\mathrm{SS}}}{T_{\mathrm{SS}} \, S}. \tag{8}$$

q is the rate energy has to be invested to operate a park of storage systems, including replacement of old storage plants with new ones after their lifetime, normalized to its capacity. A power plant generating unstable electricity can now "rent" a fraction of the storage system park in order to stabilize its supply. The needed capacity depends on the desired buffer time t_{s}. Assuming that the power plant wants to maintain its mean power output P, the required storage capacity is $P \cdot t_{\mathrm{s}}$. The additional energy demand E_{S} the power plant has to "pay" to "rent" this storage capacity over its entire lifetime T is then

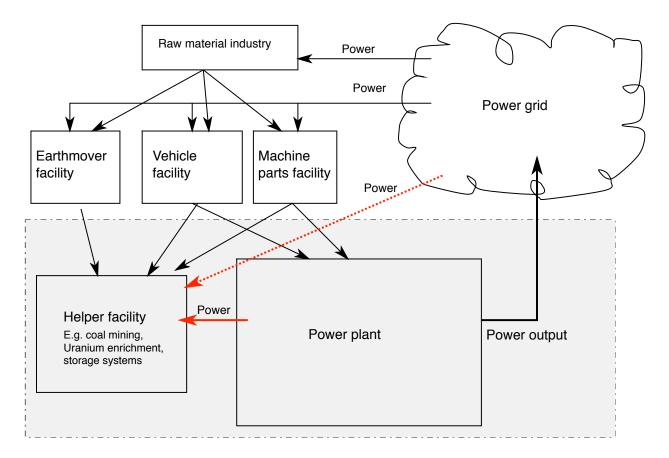$$E_{\mathrm{S}} = q \, P \, t_{\mathrm{s}} \, T. \tag{9}$$

Storage for long periods can become a very cost-intense and even impossible business. The economically better solution is the installation of additional power which is called "over-capacity". This is shown in an Australian optimal-cost balance scenario for photovoltaics [8]. It is just a factor f_{o} the original energy demand E_{I} has to be multiplied with. Therefore, the energy demand $E_{\mathrm{I,S}}$ for a power plant including storage as well as over-capacities is

$$E_{\mathrm{I,S}} = f_{\mathrm{o}} \, E_{\mathrm{I}} + E_{\mathrm{S}}. \tag{10}$$

The EROI reduces correspondingly. It should be noted that reserve capacities, e.g. due to maintainance or predictable peak demands, are not included which additionally might be considered for all energy techniques but is typically never included in any study. In other words, the assumed overcapacity assumptions are only applied to natural volatilities.

No direct LCA studies could be found for storage systems but pump storage systems are very similar to hydro electricity plants with storage capabilities. Alternative storage techniques like hydrogen electrolysis and gas storage are much more uneconomic anyway. Here, the Australian Benmore station [7] with an energy demand E_{SS} of 24,000 TJ has been selected and slightly scaled up (30,000 TJ) in order to fit the planned German Atdorf pump storage system with a projected lifetime of $T_{\mathrm{SS}} =100$ years. The material and working demands are similar, strongly dominated by the dam's energy input. Atdorf's storage capacity is about $S = 52$ TJ, so that q can be calculated as described above. It should, however, be kept in mind that if no favorable topology is available the necessary geo-engineering [9] (pp. 46) elevates the energy investment substantially.

For solar photovoltaics and wind energy, a storage time of $t_s = 10$ d (full-load days) has been assumed which is the average between the optimal German (30 d, 30% overcapacity) and the very optimistic (6 d, 30% overcapacity) European scenario [9] (pp. 135, 136) assuming a partially multinational used power grid. For concentrating solar power (CSP) in the desert, $t_s = 2$ d is sufficient thanks to the very short times without sunlight in the Sahara. The over-capacity factors due to seasonal fluctuations are $f_o = 2$ for solar photovoltaics (Germany), 1.5 for wind energy and CSP and 1.4 for hydro power, for all other techniques 1 (no over-capacities).

In order to have a picture of the effect of including storage systems both, the buffered EROIs (EMROIs) as well as the EROIs (EMROIs) resulting from the unrealistic assumption that all electricity is usable are presented.

5. Other methodological problems

Figure 1: System borders for a typical power plant. It makes a difference if electricity for a helper facility like a coal mine is taken from the grid (dashed line) or from the power plant.

The problems, related to the the exergy/energy definition, in evaluating the EROI have already been mentioned above (sec. 3). Another problem arises from the system border definition as shown in Fig. 1: It

makes a great difference if some energy demand needed to operate the plant is added to E_I or subtracted from E_R, so advised by a guideline for photovoltaics from the IEA [6]. For instance, a nuclear power plant needs electricity for operating its own pumps. This energy is taken from its own output leading to a slight reduction of E_R, barely changing the EROI. However, the electricity for operating centrifuges for Uranium enrichment is added to E_I which reduces the EROI remarkably. The reason for the different treatment is that the pump operation happens *on site* while the enrichment process is decoupled from the actual power plant. This is the "investor's view" who must buy the nuclear fuel while the pump operation is up to his own. If there were a nuclear power plant with integrated enrichment facility it could be treated the other way. In general the "investor's view" justifies to account all energy that must be applied in advance as "investment" while energy that must be applied inside the production process as reduced return. See also the discussion of the Forsmark power plant analysis at the end of sec. 7.7.

Another problem is that a few authors use recycled material with a fraction (often 100%) other than available on the market, thus reducing the energy demand remarkably. This has been corrected in this paper. It is conceivable that a manufacturer advertises his product, e.g. a wind turbine, to have a very high EROI by using mainly recycled materials. This, however, is a non-representative distortion of the usual mix of recycled and new material favoring this particular product and can not be accepted in a balanced evaluation. Some LCA studies subtract the energy inventory of material amounts that are recycled, which is not correct, and is not so done here. The recycled material's energy demand (including the demand of the recycling process) has to be considered in the construction energy demand, when it is used.

In general, it is necessary to define useful parameters due to comparison reasons, for example the full-load hours for wind and solar in that way, that there are enough locations to create a complete supply for the demanding society. In Germany, the EROI for wind turbines located directly at the coast (more than 3000 full-load hours) is relatively high but the respective land area is by far too sparse to supply the society, in opposite maybe to Denmark. For the same reason, it is obligatory to use the same material inventories. Furthermore, the "usability" quality of the gained energy has to be the same for all techniques, so volatility effects of the "renewable" energies have to be compensated by buffering, see section 4, and this additional demand has to be applied to the respective techniques. All these conditions have to be taken into account when comparing the results of this work with other papers. As stated in chapter 3, the addition of input energies without weighting is not physically consistent, but reflects the exergy approach better than using primary energy equivalents only. The fraction of the technically used exergy of a process is often indeterminate, so this difficulty is unavoidable. This, of course, penetrates the comparability of the techniques. Thus, the inputs are given in thermal and electrical fractions to make the calculations transparent.

It should also be noted that many LCA studies, databases and guidelines [6] focus too much on CO_2 emission rather than cumulated energy demand. This is owed to the popular CO_2 climate discussion and

the upcoming CO_2 certificate trading but makes a reliable estimation of the cumulated energy demand very difficult. Sometimes it was necessary to perform a backward calculation from CO_2 emission values to energy demand. It would be very desirable if those databases would again put more attention on the energy demand. Current techniques don't care on CO_2 elimination, since the impact is not exactly known, so the respective additional demand has not been considered in this work.

In opposite to this, scarcity and environmental (and safety) standards are in fact part of the EROI, as they all lead to a higher energy demand and therefore to a lower EROI. Thus, in the calculations here it is considered that all power plant LCAs process steps are according to respective common standards and that mining and extraction of needed resources is based on the concentrations raw materials are currently available. Scarcity in the future will be reflected in lower concentrations of raw materials that have to be extracted, leading to a higher energy demand. As soon as the EROI for a fossil plant falls below the economic limit, the corresponding fossil fuel can be regarded as "exhausted" (though, there might be still a demand to use them for mobile applications, if no other solution is available). However, as long as all fossil and nuclear resources are available on the same level of concentration at least for the lifetime of the plant, the EROIs remain correct. This is currently the case all power plants.

6. Economical Aspects

Since the "investor's view" has been used whenever possible there should be a simple relation to the economy. In fact, the EMROI R_{em} as defined in sec. 2.5, is supposed to describe the the economic relation better, even though it depends not only on the kind of the power plant but also on the surrounding market. R_{em} is used by many authors as "EROI", but in fact it is somwhere in the middle of the physical EROI and the actual cost ratio as it still ignores human labour costs. Energetically, human labour is negligible but financially, it dominates and represents the welfare of the society or of the sub-society working in this energy sector. For the returned energy E_R, the money to energy ratio is simply given by the usual market price. For the invested energy E_I, however, the ratio is much larger since it contains all the surplus of the value-added chain. Therefore, an EROI threshold can be roughly estimated by the ratio of the GDP to the unweighted final energy consumption while an EMROI threshold can be estimated by the *weighted* final energy consumption (which is not the primary energy consumption). For the U.S., for instance, the GDP was $15 trillion in 2011 while the unweighted end energy consumption was about 20 trillion kWh, resulting in an "energy value" of some 70 cent/kWh (Germany $\sim$135 cent/kWh). The average electricity price, however, is 10 cent/kWh [10], (Germany $\sim$18 cent/kWh) so there is a factor of 7 higher money to energy ratio on the input side. The same calculation for the weighted final energy consumption (the electricity demand was multiplied by a factor of about 3) results in a ratio of about 16 for both countries, assuming average primary energy costs of 5 cent/kWh and 3.5 cent/kWh for Germany and the USA, respectively. A similar ratio can

be seen for other countries which leads to the conclusion that the thresholds are 7 and 16 for the EROI and the EMROI, respectively, assuming OECD-like energy consuming technology. For lower-developed countries thresholds might be smaller, thus making also "simple" energies like biomass economic.

Of course, the cost structure for different power plants is quite different. For construction and maintenance of a nuclear power plant there are a lot of non-energetic costs, dominated by prolonged licensing procedures and highly-qualified personnel costs that can not be "outsourced", contrary to solar cell production which profits from cheap manpower for manufacturing, e.g. in China. Besides ethical complications the monetary ratio can fluctuate anyway due to changing safety policies, international trading agreements and politically motivated subsidies. In summary, one has to consider both the EROI and the technical grade of energy-consuming infrastructure (non-technical issues are ignored for simplicity here) to assess the society's prosperity.

7. EROI values of different electrical power generating systems

Using the formulas mentioned above and the correspondingly corrected data from several studies, the EROIs for the most commonly used energy techniques are obtained, each calculated for an unbuffered and buffered scenario. The results are shown below and in Fig. 3, for details regarding the inventories and buffering efforts, see the spreadsheet attached or the constantly updated spreadsheet accessible from the Web [11]. The power plant's lifetime should be carefully considered since the EROI scales directly with it. It is dominated by the lifetime of the most energy-intense parts. Whereas wind- and solar-based techniques have estimated lifetimes from 20 to 30 years (limited to turbine-rotor or silicon degradation), fossil-fueled power plants can reach 35 (CCGT, 260,000 full-load hours including life extension), 50 (e.g. coal power in the U.S.) and even more than 60 years (new and refurbished nuclear plants). Lifetimes for refurbished steam turbines often exceed 50 years [12]. These longer lifetimes are often ignored in LCA studies. Hydro power has a lifetime of more than 100 years, which is discussed in the respective section 7.5. On the other hand, no statistically relevant experience exists for the lifetime of solar cells. Aging test procedures are still being developed [13] [14] with the goal of a 25-30 years lifetime guarantee but remarkably shorter lifetimes for very southern countries like Tunisia with 1,700 full-load hours per year have been reported, too [15].

The given EROIs have uncertainties due to material inventory and maintenance assumptions, which cannot be determined in detail here because LCA database material was not available. These errors affect all techniques roughly equal, so the EROI's relative error is assumed to be about 10%.

7.1. Gas-fired power plants (CCGT)

The dominating part of E_I is the extraction and refining of natural gas. These numbers are given in [16], with the flaw that the primary energy of lost and flared gas has been included. Since this is clearly not part of

the energy demand, only exploration, transport and refining has been considered here. The energy demand in [16] has also not been separated in thermal energy and electricity, so the energies had to be taken as given, even if they are probably smaller. The energy demand for building, maintaining and decommissioning E_{fix} has been taken from [17], corrected by using updated material energy inventory data given in the attached table [11]. Furthermore, there is a production surcharge of probably up to 50% mentioned which is not included in the calculations here because it was not given numerically. This surcharge, however, as well as the lifetime, has no great influence on the EROI since for CCGT $E_{\text{fix}} \ll P_i T$ holds, see sec. 2.3.

Producing natural gas from maize growing, so-called biogas, is energetically expensive due to the large electricity needs for the fermentation plants, followed by the agriculture's energy demand because of fertilizers and machines, see [18]. As for natural gas, losses and flares are not included in E_I.

The results are shown in Tab. 1.

Net output [MW]	820
Load per year [h]	7500
Operational life time [a]	35
E_I, building [TJ]	470 (11% electrical)
E_I, decommissioning [TJ]	30
E_I, maintenance [TJ]	255 (14% electrical)
E_I, natural gas provisioning [TJ]	26100
EROI	**28**
E_I, biogas provisioning [TJ]	201,000 (60% electrical)
EROI	**3.5**

Table 1: EROI for gas-fired power plants. Key figures taken from [17]. The energy payback times for natural gas and biogas are 9 and 12 days, respectively.

For natural gas, this can be compared with the work of Cleveland [19] [5] and Hall [20]. They used mineral industry's energy and monetary data and top-down calculations in a mix, which makes a comparison to the results in this work difficult. Referring to the methods here, their works are irrelevant for this paper's motivation. Their EROIs are roughly 50% lower, probably due to the top-down part. The mining data, which cannot be found, is probably based on older extraction techniques, resulting in a higher energy demand.

Keoleian [21] made another analysis based on willow biomass. The respective EROI of ~13 (even 20 when adjusted to the same GuD conditions used here) is significantly higher than that for maize (3.5) but willow need much longer growing time (during this time there is nearly no energy input necessary) after planting and fertilizing, increasing the land consumption per kWh by a factor of 10 (0.5 m^{2}years/kWh).

This corresponds to a supply system with garbage or natural wood, which won't satisfy the demand of countries with a dense population. Thus, this analysis does not qualify for a comparison.

7.2. Solar photovoltaics (PV)

So far, only Silicon (Si) based PV technologies are applicable on a large scale, so only those have been evaluated here. CIGS- or CdTe-based cells are no option since there is not even a fraction of the needed Indium or Tellurium available in the Earth crust and organic cells are still far from technical applications.

In the past, the energy demand for producing Si-based solar cells was dominated by the crystallization processes. As described in [22], for highly pure Si from semiconductor fabs' "scrap" (off-spec Si) many evaluations overestimated the EROI because the energy demand for the crystallization process done by that factory was not included. If included, the EROI becomes underestimated, because solar cells do not need such high-quality Si. The production of solar cells for the high demand today needs its own factory infrastructure, because such amounts of off-spec-Si are not available. It is therefore necessary to analyze the manufacturing chain of a solar module factory to get the energy demands as done by [23].

Manufacturing the cells is dominated by electrical energy use (arc-melted, cleaned and casted Si, composing modules), while producing the factory and the solar plant installation components is almost completely thermal energy use (material energy inventories), each about half of the whole E_I for construction. The demand for Si cleaning (30% of the whole E_I) can be reduced by 75% using the mono-silane method.

Amorphous solar cells need far less amounts of Si, reducing the energy demand for the Si-based steps, but the installation demand remains unaffected. Furthermore, these modules have a lower operation lifetime and efficiency.

The numbers in Tab. 2 (data taken from Scholten et al. [23]) are calculated for $1m^2$ poly-crystalline modules, for which 1.6 kg metallurgical grade Si [23] is used (embodied energy is 11 to 14 kWh/kg).

The efficiency of poly-Si here is 14.4%, for the modules 13.2% because of frame cover effects, respectively [23]. There are commercial ones with higher efficiencies, but their energy demand is unknown. Dirt layers and the conversion efficiency of the inverters [24] give an additional, so-called performance factor of 75%, resulting in an overall efficiency of 9.9%. Assuming 25 years lifetime and 1,000 peak-hours (South Germany), this gives 8353 MJ electrical energy produced.

Now, the EROI for Germany (see Tab. 3) for poly-Si photovoltaics can be directly calculated from the numbers mentioned above. Mono-crystalline techniques have a 25% higher efficiency, but the energy demand will be roughly doubled. Amorphous PV products have a much less energy demand (at least the production plant, frame and installation), but their lifetime and efficiency is reduced to about 50% of polycrystalline PV, so their EROI is smaller.

Assuming the German market mix of roughly 1/3 mono-Si and 2/3 poly-Si PV modules [25], a weighted EROI of 3.3 (unbuffered) can be calculated, not considering synergetic effects by the chip industry for

Manufacturing step	Embodied energy [MJ]	thereof electrical [%]
Production metallurgical grade silicon	72	100
Purifying (Siemens process)	850	65
Wafer production	190	70
Cell production	180	75
Module production (frame)	480	80
Sub-total	**1772**	**67**
The embodied energy of the production plant and for the module installation is taken from [22]. For an open-field plant, a frame made of steel is used, which is not necessary for a roof installation.		
PV module production plant	150	70
Installation roof / field	180 / 250	40
Total roof / field	**2102 / 2172**	**67 / 64**

Table 2: Solar photovoltaics production line's energy demand [23]

	Poly-Si roof / field	Amorphous roof / field
Embodied energy [MJ]	2102 / 2172	880 / 950
Lifetime energy production [MJ]	8353	2000
EROI	**4.0 / 3.8**	**2.3 / 2.1**
EROI, buffered	**2.3 / 2.3**	**1.6 / 1.5**

Table 3: EROIs for solar photovoltaics with 1,000 peak hours per year (Germany) using the energy inputs from Tab. 2. The energy payback times are in the range from 6 years (unbuffered) to 16 years (buffered).

mono-Si as described above. For locations in south Europe, the EROIs are about 1.7 times higher due to the higher solar irradiation, but a higher irradiation also speeds up the aging. The resulting EROIs for a roof installtion and an open field installation are shown in Tab. 3.

Results from Battisti et al. [26], Ito et al. [27], Meijer et al. [28] and another paper from Alsema [29] are all in good agreement but less detailed. The energy per installed peak power ranges from 34 MJ/W$_p$ to 53 MJ/W$_p$, at 1000 to about 2000 peak-hours, resulting in the EROI range from about 3 (where the inverters are not included [28]) to about 4 (with remarkable 1700 full-load hours), assuming 25 years lifetime. These values correspond very well to this work's results based on the very detailed database provided by Scholten at al. [23], though all authors calculated the armortization time using the output as the primary energy equivalent. One should also consider that all works did not take buffering into account.

7.3. Solar thermal power (CSP)

Only one work [30] has been found that provides values for invested energy and materials for different CSP technologies in a sufficient manner. The study which is part of a report from the German Centre for Aerospace (Deutsches Zentrum für Luft- und Raumfahrt) is a life cycle assessment for a hypothetical plant called "Sokrates". Three different techniques were analyzed: Parabolic through with phenyl (SEGS) or steam (DSG) as coolant and a steam-cooled Fresnel power plant, whose plane mirrors are roughly arranged to big parabolic mirrors. Plane mirrors are easier to manufacture and maintain, but have a lower concentration capability compared to parabolic mirrors, reducing the plant's efficiency. Extremely high temperatures will reduce heat transportation, which also reduces the efficiency.

To achieve the high solar concentration, relatively big parts (mirrors) are necessary which are only usable in big plants. Therefore, due to economical aspects small or even individual plants are never considered. It should further be mentioned that, contrary to photovoltaics, the output of a CSP plant is not a linear function of the solar radiation intensity, so that only a deployment in sunbelt regions is in an economical scope. For regions with lower solar radiation like Germany this means additional power transportation energy demands and energy losses.

The results shown in Tab. 4 are only for SEGS and Fresnel type technique, DSG is not tested yet. The location was assumed to be Ain Beni Mathar (Marocco, 34.17°N, 2.12°W) with a solar radiation constant of 2340 kWh/m^2. The plant size is scaled to an annual output of 145 GWh (525 TJ), or 15,660 TJ over its adopted 30 year life time.

	Parabolic through SEGS (phenyl coolant)	Fresnel (steam coolant)
Aperture [m^2]	470000	700000
Net efficiency [%]	13.2	9
Embodied energy (construction) [TJ]	555	870
Embodied energy (maintenance) [TJ]	192	60
Embodied energy (total) [TJ]	**747**	**930**
EROI	**21**	**17**
EROI, buffered	**9.6**	**8.2**

Table 4: EROIs and key figures of DLR's CSP plant concept based on numbers from [30]. The energy payback times are in the range from 1 year (unbuffered) to 3.5 years (buffered).

The higher demand for maintaining SEGS is caused by coolant losses due to the dominant phenyl energy inventory. The energy demand does not include the efforts for daily energy storage to provide electricity in the night hours, which is not possible with steam coolant as used by SEGS. The estimations for mirror replacements are very optimistic, doubling this rate will reduce the EROI by 20%, so the given values are the upper limit. Another significant reduction of roughly 30% (buffered) occurs when connecting this CSP plant to the European grid instead of using the output nearby the plant due to the very large copper demand.

It should be mentioned that the authors of the report [30] subtracted the phenyl maintaining demand from the output rather than adding it to the demand which can only be done if the used phenyls are directly produced by the CSP plant, on its site (see sec. 5) . This is not possible with the described CSP plant and would lead to wrong EROIs, making it infinite if all energy inputs are subtracted. Further corrections due to material inventory corrections lead to EROIs given in Tab. 4.

7.4. Wind energy

Wind turbines are installed on-shore, partly at the coast, and off-shore (sea), several 10 kilometers away from the coast. Off-shore wind parks have a higher yield which is roughly balanced by higher expenses for fundament, long cable, grid connecting and transformer. No thorough LCA studies for off-shore plants could be found. For on-shore plants, the Enercon E-66 (1.5 MW) has been chosen as a reference turbine for the modern multi-megawatt class typically used in Germany, although there are newer types of turbines, since there exist very detailed studies about the E-66 from Pick [31] and Geuder [32]. The latter calculated an additional maintaining energy demand of 1.3% (not including the generator).

Due to weather conditions and high loading of important construction parts (blades, rotor,...) the expected lifetime is often assumed to be only 20 years. In this paper, 2,000 full-load hours have been assumed, justified by several places in Germany [33] [34]: Bavaria 1,000, Schleswig-Holstein 2,200, and at very rare mountain and coastal positions 2,700 full-load hours with the E-66. This assumption is obliging because the high-load places are too rare for a large-scale supply with electricity generated from wind energy. So the lifetime output can be calculated to 216 TJ and the EROI can be determined using the energy demands in Tab. 5.

An output reduction due to additional offline periods for maintaining when the wind is blowing is ignored in this calculation. The difference between the construction demands mentioned above is caused by using lower energy inventories for steel. There are no known detailed LCA studies concerning offshore-wind energy converters.

Because of the strong dependence of the wind power from the wind velocity ($P \sim v^3$) the calculation above is only viable for places like Schleswig-Holstein. Other places, e.g. in Brandenburg and Lower Saxony, have mostly profiles with lower wind velocities [34], decreasing the output and therefore the EROI significantly. Higher/larger wind turbines with larger generators have a higher load and installed capacity but also have

16

Installed capacity	1.5 MW
Full-load hours	2000 (flat land in Northern Schleswig-Holstein)
Lifetime	20 years
Lifetime output	216 TJ
Energy demand for construction	12.9 TJ, thereof 8% electrical (Geuder [32] 13.6 TJ)
Energy demand for maintenance	0.3 TJ (0% electrical)
Decommissioning	unknown, probably negligible
Corrected EROI	**16**
Corrected EROI, buffered	**4**

Table 5: Modified energy input and resulting EROI for the E-66 wind turbine based on [32]. The energy payback times are in the range from slightly above 1 year (unbuffered) to 5 years (buffered).

higher construction energy demands due to static issues (wind forces), dampened only by a more intensive usage of energy-cheap concrete. Regarding to this, the EROI can achieve values of up to 25 for wind turbines located on the assumed place mentioned above.

In comparison to that, Lenzen [35] presented many EROIs on an electrical output basis from several studies though they calculated the amortization time by using the primary energy equivalent of the electrical output. In general, they are similar (10 to 25) to the results here. Most papers Lenzens evaluation is based on investigated very small plants which are not suitable for a large-scale energy supply due to land consumption, or are based on top-down analyses. Four works are picked out here because they looked at wind turbines with a similar peak power or which calculated very high EROIs: Kuemmel [36], Gürzenich [37], Krohn [38] and Roth [39]. Kuemmel selected an elevated load compared to this work, the material inventories for glass fibre and copper are remarkably low and some energy-intensive materials (electric sheets, lacquers) are missing. Taking this into account, the EROI will lower from 50 to 20 at the same location used in this paper – this is in roughly good agreement to the results here. Gürzenich placed the E-66 turbine already analyzed by Hagedorn and later by Geuder [32] at a very special onshore location in India with an extremely high load of 4000 peak hours, double as high as used here. This, of course, results in a EROI twice as high, so one can see how important it is to set equal conditions for all techniques to make them comparable. Krohn made a top-down calculation and also used a coastal offshore location (Denmark) where the turbine gains high loads, resulting in an EROI of 33, twice as large as the results here. Remarkably, Lenzen cited an EROI of 45 for a 300 kW turbine from Roth [39] but in Roths paper, only an EROI of 10 is determined. The selection of the location depends on the area which has to be supplied by the wind turbines and must represent the load possibilities reachable there, so, for comparison reasons, it is not suitable here to select arbitrary locations. One should also consider that all works did not take buffering into account.

17

7.5. Hydro power

Only run-of-river hydro power is discussed, using the master thesis of Fernando [7]. That work assumes 200 years lifetime due to assumptions of the operator, but a production time of 100 years is much more reasonable as used for calculations presented in Tab. 6. This is far more realistic, because the lifetime is limited by the dam's concrete structure, whose material is permanently attacked by erosion and corrosion. If the dam can not safely bare the reservoir anymore, it must be closed. Also the sedimentation of the reservoir limits the economical use of the plant. There is no existing plant known with a higher lifetime. The lifetime of modern generators often reach 50 years [40], limited by the sedimental erosion of the blades.

Hydro energy can only be used in a limited way due to topological issues. Nevertheless, it can provide a significant part of the whole supply and therefore it is analyzed here.

Installed capacity	90 MW
Lifetime	100 a
Location	Waitaki River, New Zealand
Full-load hours	3000 (predictable)
Energy demand construction	1800 TJ
Energy demand maintenance	75 TJ (100 TJ for an assumed turbine replacement not included here)
Decommissioning	60 TJ
EROI	**50**
EROI, buffered	**35**

Table 6: EROI of run-of-river hydro power plant, New Zealand, based on numbers from [7]. The energy payback times are in the range from 2 years (unbuffered) to 3 years (buffered).

Detailed bottom-up life cycle studies are rare. The work mentioned above [7] is partly a top-down analysis based on a conversion of monetary costs into energy demands. This is definitely not a physical method and the reason why electrical energy costs are not available here. Furthermore, the strong dependence of the EROI on geological aspects makes it difficult to apply this result to other hydro power plants. Nevertheless, it is obvious that smaller (sub-MW) plants have a lower EROI, and (very) large plants (e.g. Itaipu) a higher one (probably over 100). Again, the dam's lifetime has a dominant influence on the EROI, so the values in Tab. 6 may be conservative.

Another work is done by L. Gagnon [41], who mentioned an EROI of up to 267. It is not possible to find out how this number is calculated, neither is it based on any references. For very large hydro power plants with an elevated load, it is conceivable to obtain an EROI of 100, but Gagnon's results lacks any reasoning.

7.6. Coal-fired power plants

The energy demand is dominated by the coal extraction. Only the LCA study from the U.S. department of energy [42] provides sufficient bottom-up information about the extraction, though only for *open pit mining*. For one megaton (Mt) coal extracted the following is needed.

- 2,340 tons of steel for the equipment exclusively used for extraction,

- 14.3 GWh electricity, and

- 269 m^3 liquid fuels and oil.

The energy inventory of steel has to be corrected and is equivalent to 35 TJ. The inventory for the fuels is assumed to be 36 GJ/m^3, resulting in 10 TJ here. The electricity amount must not be converted into its primary energy equivalent and therefore corresponds to 50 TJ, leading to a sum of 100 MJ/t, thereof 60% electrical.

Because there are no official numbers for *underground mining*, the CO_2 emission ratios between open pit mining and underground mining of 2.5 mentioned in the report [43] has been used for scaling, resulting in 250 MJ/t.

There is another LCA study [44] based on the Ecoinvent database. The inputs there are only given as primary energy equivalent inputs, and the corresponding raw data are not available. The obtained results fit very well to the results here, considering that no primary energy equivalent of the electricity input has been used in this paper. Energy inputs for transportation and logistics have been also calculated there, for Germany a few 100 kJ per kg coal, resulting in an additional relative input increase of about 20% for hard coal.

Because of the low heating value of brown coal (10.5 GJ/t) compared to hard coal (29.5 GJ/t), the relative extraction and transportation energy costs are higher. This is the reason why hard coal is often shipped to the plant while brown coal is often extracted nearby the power plant. Therefore, the electricity needed for mining the brown coal is usually delivered from the power plant, see section 5. A brown-coal-fired power plant has a larger fuel throughput, affecting the construction energy costs to be higher. Transportation energy expenses for hard coal could not found. They depend on transportation means and distance and therefore can reduce its EROI by 10% to 20%, assuming energy demands for other goods' large scale transportation.

A comprehensive evaluation of materials and energies for coal power plants, particularly including maintenance, has been provided by Hoffmeyer et al. [45]. Electricity is separately listed there for all expenses, therefore easily fitting into the evaluation here. The energy demand for coal extraction, however, is completely missing there which is the reason it had to be completed from [42]. For the output, it is assumed that all energy generation techniques operate at maximum load technically possible, so the full-load hours

have to be increased. Furthermore, the energy inventories for steel, copper, aluminum, operating materials (using the electricity amount instead of its primary energy equivalent) and the lifetime had to be corrected.

The results for hard and brown coal are shown in Tab. 7.

	Hard coal (underground mining)	Brown coal (open pit mining)
Installed capacity (net)	509 MW	929 MW
Full-load hours	7,500	7,500
lifetime	50 a	50 a
Annual hard coal usage	1.16 Mt	5.85 Mt
Construction energy demand	1,970 TJ (9% electrical)	4,600 TJ (12% electrical)
Decommissioning energy demand	91 TJ	170 TJ
Maintenance and operation energy demand	7,400 TJ	7,050 TJ
Coal extraction energy demand	14,500 TJ (60% electrical)	29,250 TJ (60% electrical)
Sum energy demands over lifetime	23,960 TJ (37% electrical)	40,170 TJ (45% electrical)
EROI	**29**	**31**

Table 7: EROIs of typical open pit brown coal and underground-mining hard coal power plants based on [42] and [45]. Transportation of mined hard coal is ignored, and the electricity for brown coal mining is assumed to be provided by the corresponding plant, building one unit. The energy payback time is about 2 months.

These results can be compared to the "balloon graph" values presented in a blog [46], based on the methods of Hall [20]. There, an "EROI" (actually an EMROI) of 65 in average is given, though it is merely the ratio of the combustion heat of the coal and the top-down calculated primary energy to get it to the power plant. If one includes the construction and maintenance demands of the plant mentioned in this work, and takes only the electricity output into account, this lowers to about 22. Accounting the energy input without weighting, results in an EROI of about 30 – a good agreement to the value presented in table 7. Though the values are obviously interchangable, the method used in this paper fits the physical approach better since the exergy influence is higher.

7.7. Nuclear power

The overall energy demand is dominated by the Uranium extraction and enrichment. In the future it will be dominated only by the extraction because the enrichment process has been changed from diffusion to gas centrifuge technique (well over 80% centrifuge today) while the extraction demands are rising for decades due to lower ore concentrations.

The publication by Hoffmeyer et al. [45], used already for coal power plants, turned out to be a good basis for a nuclear power EROI evaluation as well. It describes, however, too low energy consumptions for Uranium extraction, and the inventories for working chemicals used for that are missing. Here, the mass flows as described in the essay by Leeuwen [47] has been used but the old inventory data mentioned there had to be replaced with modern ones (see attached spreadsheet [11]). The other assumptions from Leeuwen have been ignored because they are based on old facts and arbitrary extrapolations which have proven wrong today. The inventory for the most important chemical for extraction, Sulfur, is taken from a paper of the chemical industry [48]. One gets roughly the same overall mining demands using the corrected values published by Rössing [49].

The full-load hours from [45] had to be corrected to 8,000, proven by the experience of the U.S. nuclear industry whose plants achieved a mean utilization rate of about 90% over the last decade [50], although they are several decades old. Furthermore, permissions are given to run nuclear power plants for 50 years in Russia, and even for 60 years in the USA [51]. A lifetime extension up to 80 years will be investigated, including pressure vessel modifications [52]. The containment and concrete construction tends to last even longer, so a mean of 60 years is a more realistic lifetime. Again, material inventories are corrected, as well as test run electricity demands are no longer taken as its primary energy equivalent. There is also a tendency to shutdown the remaining diffusion enrichment plants and to implement laser enrichment techniques. This leads to the values given in Tab. 8.

Installed capacity (net)	1,340 MW
Full-load hours	8,000
Lifetime	60 a
Output	**2,315,000 TJ**
Construction energy demand	4,050 TJ, thereof 35% electrical
Decommissioning energy demand	1,150 TJ, thereof 40% electrical
Maintenance energy demand	6,900 TJ, thereof 68% electrical
Fuel related energy demand	18,800 TJ (9,650 TJ), thereof 68% (40%) electrical
Sum energy demand	**30,900 TJ (21,750 TJ), thereof 60% (50%) electrical**
EROI	**75 (105)**

Table 8: EROIs and key figures [45] of the reference nuclear power plant (100% centrifuge enrichment in brackets). The energy payback time is about 2 months.

Since top-down analyses, so done by Tyner [53] and Hall [20], with their great monetary influence in the nuclear industry due to licensing and administration makes the EROI extremely unphysical, these

become very unsuitable for comparison here. The paper of Fleay [54] which is based on Leeuwen's [47] data overestimated the important mining needs by a factor of more than 10 due to approximations of energy demands of old mining techniques to very low ore concentrations, which have been proven wrong. Assuming Leeuwen's numbers, the energy costs for extracting uranium would be three times as high as the market price and the Rössing Mines would consume more energy than the country it is located in. Furthermore, the energy-intense diffusion enrichment was taken into account, which is almost completely replaced by gas centrifuge plants today. This leads, of course, to EROI values that are by a factor of 20 lower than the ones in this work.

A good agreement can be seen when comparing the results to a detailed analysis made by the Melbourne University [55] based on data from the electricity provider Vattenfall. It should be critisized that the enrichment energy demands are substracted from the output instead of adding it to the input, see also sec. 5 which leads to a high EROI of 93. There, it was argued that the enrichment is done by nuclear power in Tricastin (France), but this happens outside the analyzed plant, Forsmark, so it should be treated as an (external) input. Then, the EROI lowers to 53. On the other hand, the Melbourne analysis assumes a lifetime of only 40 years. This is a typical licensing time but not the lifetime which is much longer, see explanations above. Extending the physical lifetime to 60 years, leads to an EROI of 80 which is in good agreement to the results in table 8.

8. Comparison with other results

There are not many EROI evaluations comparing fossil, nuclear and "renewable energies, and almost all determine the EMROI, mistakenly calling it "EROI". For comparison reasons, Fig. 2 shows the results for the weighted economical calculation, i.e. the EMROIs for all techniques determined in this paper with a weighting factor of 3 (see sec. 2.5) and a threshold of 16 (see sec. 6). The corresponding EROIs are presented in the conclusion, Fig. 3.

A book by Hall, Cleveland and Kaufmann from 1986 [20] presents one of the first most extensive collections. However, the mathematical procedure was not quite consistent, as the weighting was applied for the input for all power plants while the output energy was weighted only for fossil fuels and "renewable" energies but not for nuclear energy. For nuclear energy, the power plant was included in the energy demand but for fossil fuels not, just mining costs and shipment. Additionally, the nuclear enrichment process was based on the barely used but extremely energy-intense diffusion process. Furthermore, all EMROIs there are merely cost-based top-down calculations which include all the human labor costs. This moves the results further away from R and R_{em} towards a pure cost ratio excluding the power plant and there is no relation to the EROI anymore.

A widespread collection of numbers called "EROI" can be found in blog entries assigned to Hall on the

website "The Oil Drum", managed by the "Institute for the Study of Energy and Our Future", cumulated in a so-called "balloon graph" [46] which shows the "EROI" (actually more the EMROI) versus the (U.S. domestic) primary energy contribution. They refer to Hall's book for fossil fuels and therefore suffer from the same flaws. For fossil fuels the process chain ends when the fuel is delivered to the power plant, completely disregarding the power plant itself and therefore reducing the energy demand remarkably. Again, the energy output for fossil fuels as well as for "renewables" has been weighted by 2-3, but for nuclear energy no weighting was applied, strongly disadvantaging the latter.

To give an example, Hall's result for the EMROI for coal is pretty large, around 65, contrary to the results here for coal (sec. 7.6) of only 49. However, when only the mining is included, the EMROI climbs to 61 in fair agreement with Halls result, though it does not describes neither the EROI, nor the EMROI anymore (see sec. 7.6). For natural gas, there are no reproducible data at all, just a statement that the EROI should be 10:1. Another extreme example is hydro power which is based in the blog on a publication by L. Gagnon [41], see sec. 7.5. But there, numbers are just presented with no reference at all, nor any literature, nor any calculation, nor any database. The numbers for "EROIs" are just stated, they are incredibly high (267), and are cited by the blog author as probably not "quality corrected" which would make them even "three times as high", i.e. 800. Such extreme values with no rationale of their origin can not be accepted.

In the recently published EROI evaluation by Raugei et al. [56] it is mentioned that the EROI gives no information about the fossil fuel range which justifies *"upgrading"* the output to its primary energy equivalent (in fact they provide both, the electrical EROI and the "primary" EROI). It is not apparent how this possibly solves the "scope of inventory" problem, if there is any. The scope of the primary energy source must be higher than the respective plant's lifetime which is clearly fulfilled for all techniques, but it must be analyzed separately and there is no way to include it in the EROI. The electrical EROIs for photovoltaics presented by Raugei et al. [56], however, are similar to the result presented here when taking their 1,700 full-load hours for photovoltaics into account. The EMROIs from his numbers for coal, which are based on the Ecoinvent database 2011, can be calculated to an intervall of 39 to 77 which well covers the EMROI of 49 determined here. This agreement might be still a random coincidence as a wrong lifetime of 30 years was assumed there and the mining demands seem extremely high compared with the power plant energy demands. The Ecoinvent database is not sufficiently transparent to clarify those details.

9. Conclusions

Only a uniform mathematical procedure based on the exergy concept makes it possible to compare all power generating systems. The results are shown in Fig. 3. All EROIs are above the physical limit of 1 which means they all "produce" more energy than they "consume". Not all of them are above the economical limit of 7, though (see section 6).

Solar PV in Germany even with the more effective roof installation and even when not taking the needed buffering (storage and over-capacities) into account has an EROI far below the economic limit. Wind energy seems to be above the economic limit but falls below when combined even with the most effective pump storage and even when installed at the German coast. Biogas-fired plants, even though they need no buffering, have the problem of enormous fuel provisioning effort which brings them clearly below the economic limit with no potential of improvements in reach. Solar CSP is the most hopeful option among the new solar/wind technologies, in particular because of the smaller influence of the buffering. However, pump storage is often not available in regions with high solar irradiation. Choosing less effective storage techniques like molten salt thermal storage and the connection to the European grid probably brings the EROI again far below the economic limit. It is also important to keep in mind that small units are much more ineffective, as is an installation in sun-poor regions owed to the non-linearity, see sec. 7.3.

Criticism is in order for other EROI evaluations that suffered from an unbalanced and partially unacceptable procedure. The most common flaws are

- *Tweaking the lifetime.* Absurd low lifetimes are assumed for fossil and nuclear plants, and unrealistic high ones for "regenerative" plants.

- *"Upgrading" the output.* The output energy is multiplied by 3 for reasons of "primary energy equivalent", i.e. the EMROI is calculated, but compared with the EROI of conventional plants.

- *Counting all output,* even if not needed, i.e. ignoring the need for buffering. This has been resolved in this paper.

Other flaws are outdated material databases or workflows, as in Leeuwen et al. [47].

It is finally noted that the EROI, even though it is the most important parameter, is neither fixed nor the only parameter to assess a power technology. EROIs slowly change with time, in particular for fossil fuels when stockpiles become harder to access but also when processes are improved as it happened with the steel production and the Uranium enrichment. Other parameters like land consumption, the "death toll", the impact on nature, and the scope of the stockpiles as mentioned above have to be taken into account separately.

References

[1] Ayres RU, Leslie WA, Martins K. Exergy, waste accounting, and life-cycle analysis. Energy 1998;23:355-63.

[2] Giampietro M, Sorman AH. Are energy statistics useful for making energy scenarios?. Energy 2012;37:7-12.

[3] Davidsson S. Life Cycle Exergy Analysis of Wind Energy Systems. Examen work Uppsala University 2011.

[4] Cleveland CJ. Energy quality and energy surplus in the extraction of fossil fuels in the U.S.. Ecological Economics 1992;6:139-62.

[5] Cleveland CJ. Net energy obtained from extracting oil and gas in the United States. Energy 2005;30:769-82.

[6]   Fthenakis V, Frischknecht R, Raugei M, Kim HC, Alsema E, Held M et al.. Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity. IEA PVPS Task 12, Subtask 20, LCA Report IEA-PVPS T12-03:2011.

[7]   Fernando ATD. Embodied Energy Analysis of New Zealand Power Generation Systems. Master Thesis 2010.

[8]   Lang P. Solar Power Realities Supply-Demand Characteristics – Storage and Capital Costs. On bravenewclimate.com by Barry Brook 2009. Visited 2013/01/04.

[9]   Popp M. Speicherbedarf bei einer Stromversorgung mit erneuerbaren Energien. Berlin: Springer;2010.

[10] Electric Power Annual 2010, chap. 7.4. U.S. Energy Information Administration 2011. Visited 2013/01/04.

[11] Google+ table this work is based on.

[12] Leyzerovich AS. Steam Turbines for Modern Fossil-FuelPower Plants. ISBN 0-88173-549-3 (electronic), ISBN 1-4200-6102-X (paper) 2007; pp. 455.

[13] Lütke D, Kuehnlein HH, Verbunt H, Irsen S. Accelerated Ageing Tests of Solar Cells. G.I.T. Imaging & Microscopy 2009;1:42-3.

[14] Ton D, Tillerson J, McMahon T, Quintana M, Zweibel K. Accelerated Aging Tests in Photovoltaics – Summary Report. U.S. Department of Energy 2007.

[15] Rabii AB, Jraidi M, Bouazzi AS. Investigation of the Degradation in Field-aged Photovoltaic Modules. 3rd World Conference on Photovoltaic Energy Conversion May 18, 2003, Osaka, Japan 2003;2:2004-6.

[16] Meier PJ. Life cycle assessment of electricity generation systems and applications for climate change policy analysis. Fusion Technology Institute, Wisconsin 2002.

[17] Parthey F. Lebenszyklusanalyse und Bestimmung von Einflussfaktoren zur nachhaltigen Produktgestaltung von GuD-Kraftwerken. Fakultät für Umweltwissenschaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus 2009.

[18] Hundt B. Energie- und Klimaeffizienz von Biogasanlagen mit Biogasaufbereitung und -einspeisung unter Nutzung von Silomais – Untersuchungen am Beispiel der Biogasanlage der HSE AG in Darmstadt-Wixhausen. Schriftenreihe zur Bodenkunde, Landeskultur und Landschaftsökologie der Justus-Liebig-Universität Gießen 2010;55.

[19] Cleveland CJ, Costanza R, Hall CAS, Kaufmann RK. Energy and the US economy: A biophysical perspective. Science 1984;225:890-7.

[20] Hall CAS, Cleveland CJ, Kaufmann R. Energy and Resource Quality: The Ecology of the Economic Process. New York:John Wiley & Sons;1986.

[21] Keoleian GA, Volk TA. Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance. Critical Reviews in Plant Sciences 2005;24:385-406.

[22] Alsema EA, Frankl O, Kato K. Energy pay-back time of photovoltaic energy systems: present status and prospects. 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna 1998.

[23] de Wild-Scholten MJ, Alsema EA. Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production: status 2005/2006. Updated March 2007, Energy Research Centre of the Netherlands 2007. Visited 2013/01/04.

[24] Mayer D, Wald L, Poissant Y, Pelland S. Performance Prediction of Grid-Connected Photovoltaic Systems Using Remote Sensing. Report IEA-PVPS T2-07:2008, IEA 2008. Visited 2013/01/04.

[25] Hering G. Das Jahr des Tigers. Photon Europe 2011;April:64. Visited 2013/01/04.

[26] Battisti R, Corrado A. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy 2005;30:952-67.

[27] Ito, M, Kato K, Komoto K, Kichimi T, Kurokawa K. A Comparative Study on Cost and Life-cycle Analysis for 100MW Very Large-scale PV (VLS-PV) Systems in Deserts Using m-Si, a-Si, CdTe, and CIS Modules. Progress in Photovoltaics: Research and Applications 2008;16:17-30.

[28] Meijer A, Huijbregts MAJ, Schermer JJ, Reijnders L. Life-cycle assessment of photovoltaic modules: comparison of mc-Si,

InGaP and InGaP/mc-Si solar modules. Progress in Photovoltaics: Research and Applications 2003;11:275-87.

[29] Alsema, EA. Energy Pay-back Time and CO2 Emissions of PV Systems. Progress in Photovoltaics: Research and Applications 2000;8:17-25.

[30] Viebahn P. Solarthermische Kraftwerkstechnologie für den Schutz des Erdklimas – SOKRATES-Projekt. Report, Deutsches Zentrum für Luft- und Raumfahrt Stuttgart 2004. Visited 2013/01/04.

[31] Pick E, Wagner H-J, Bunk O. Kumulierter Energieaufwand von Windkraftanlagen. BWK, Band 50, 11/12 1998;50:52.

[32] Geuder M. Energetische Bewertung von Windkraftanlagen. Master Thesis, FH Würzburg 2004.

[33] Otto A. Faktensammlung zur Windenergie 2007. University of Düsseldorf 2007. Visited 2013/01/04.

[34] Wind profile maps on the DWD homepage, to find at (German language only) "Klima und Umwelt" – "Klimagutachten" – "Windenergie" – "Windkarten", Germany, 80 meters above ground 2004. Visited 2013/01/04.

[35] Lenzen M, Munksgaard J. Energy and CO2 life-cycle analyses of wind turbinesreview and applications. Renewable Energy 2002;26:339-62.

[36] Kuemmel B, Srensen B. Life-cycle analysis of the total Danish energy system. Tekst Nr 334. Roskilde (Denmark): IMFUFA, Roskilde Universitetscenter, 1997.

[37] Gürzenich D, Mathur J, Bansal NK, Wagner H-J. Cumulative energy demand for selected renewable energy technologies. The International Journal of Life Cycle Assessment 1999;4:143-9.

[38] Krohn S. THE ENERGY BALANCE OF MODERN WIND TURBINES. WIND POWER Note NO. 16, DECEMBER 1997. Visited 2013/01/04.

[39] Roth E. Energetischer Vergleich von Kraftwerken. Brennstoff-Wärme-Kraft 1994;46(1-2):28-32.

[40] Sumereder C. Statistical Lifetime of Hydro Generators and Failure Analysis. IEEE Transactions on Dielectrics and Electrical Insulation 2008;15/3:678-85.

[41] Gagnon L, Belanger C, Uchiyama Y. Life-cycle assessment of electricity generation options: The status of research in year 2001. Energy Policy 2002;30:1267-1278.

[42] Spath PL, Mann MK, Kerr DR. Life Cycle Assessment of Coal-fired Power Production. Report of the National Renewable Energy Laboratory, U.S. Department of Energy 1999. Visited 2013/01/04.

[43] Life Cycle Assessment of GHG Emissions from LNG and Coal Fired Generation Scenarios: Assumptions and Results. PACE for Center for Liquefied Natural Gas 2009. Visited 2013/01/04.

[44] Dones R, Bauer A, Röder R. ecoinvent report No. 6-VI: Kohle. Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen, Ökobilanzen für die Schweiz 2007;6-VI. Paul Scherrer Institut 2007.

[45] Hoffmeyer M, Köhler D, Schwaiger K, Fleißner T. Ganzheitliche energetische Bilanzierung der Energiebereitstellung (GaBiE). Forschungsstelle für Energiewirtschaft, Gesellschaft für praktische Energiekunde e.V., München 1996. Visited 2013/01/04.

[46] Hagens N. EROI on the Web part 2 of 6, (Provisional Results Summary, Imported Oil, Natural Gas). The Oil Drum 2008. Visited 2013/01/04.

[47] Storm van Leeuwen JW. Nuclear power – the energy balance. Part D, Ceedata Consultancy 2007;D. Visited 2013/01/04.

[48] Postlethwaite D, Schul W, Stalmans M. A life-cycle inventory for the production of sulphur and caustic soda in Europe. Tenside, surfactants, detergents 1995;32/5:412-18.

[49] Environmental impacts of uranium mining, website of the Rössing mining company, Rössing Uranium Limited 2012. Visited 2013/01/04.

[50] Nuclear Power Plant Operations, 1957-2010. From Annual Energy Review 2010, Energy Information Administration 2011. Visited 2013/01/04.

[51] Fact Sheet on Reactor License Renewal. Website of the United States Nuclear Regulatory Commission 2012. Visited

2013/01/04.

[52] Workshop on Life Beyond 60 EPRI/DOE/CENG Demonstration Plant Project: EPRI Perspective. Electric Power Research Institute 2011. Visited 2013/01/04.

[53] Tyner Sr G, Costanza R, Fowler RG. The Net-energy yield of nuclear power. Energy 1988;13:73-81.

[54] Fleay BJ. Nuclear Power Energy Inputs and Life Cycle Net Energy Yields. 2006. Visited 2013/01/04.

[55] The Benefits of Nuclear Power, University of Melbourne, 2010. Visited 2013/01/04.

[56] Raugei M, Fullana-i-Palmer P, Fthenakis V. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. Energy Policy 2012;45:576-82.
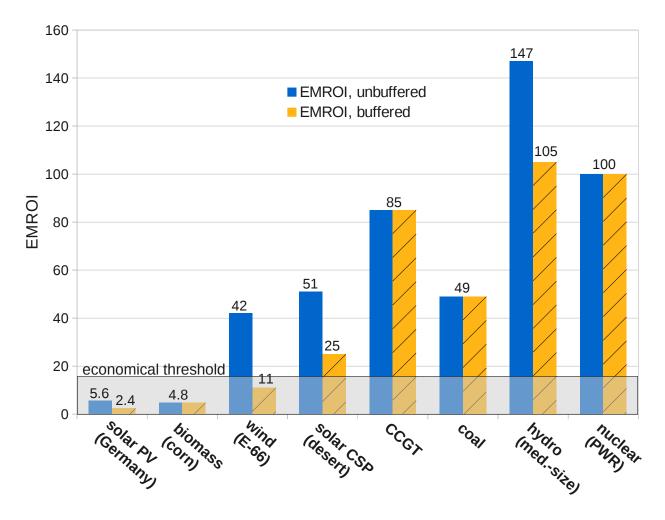
Figure 2: (Color online.) EMROIs of all energy techniques with economic "threshold" based on the current production cost ratio electricity/thermal energy of $w = 3$. The weighting factor w is expected to decrease with time, approaching 1 or even lower, which makes the EMROI identical to the EROI as shown in Fig. 3.

Biomass: Maize, 55 t/ha per year harvested (wet). *Wind:* Location is Northern Schleswig Holstein (2,000 full-load hours). *Coal:* Transportation not included. *Nuclear:* Enrichment 83 % centrifuge, 17 % diffusion. *PV:* Roof installation. *Solar CSP:* Grid connection to Europe not included.
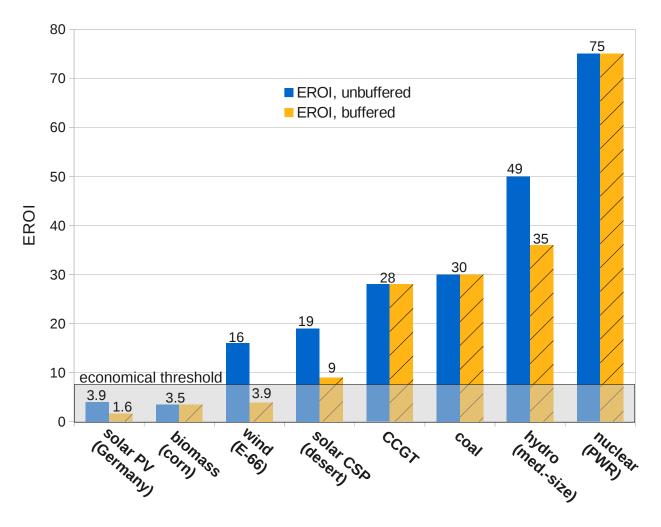
Figure 3: (Color online.) EROIs of all energy techniques with economic "threshold".

Biomass: Maize, 55 t/ha per year harvested (wet). *Wind:* Location is Northern Schleswig Holstein (2,000 full-load hours). *Coal:* Transportation not included. *Nuclear:* Enrichment 83 % centrifuge, 17 % diffusion. *PV:* Roof installation. *Solar CSP:* Grid connection to Europe not included.