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The necessity to standardise primary energy quality in achieving a meaningful quantification of related indicators

A.A. Solomon [a,*], Nelson Bunyui Manjong [b], Christian Breyer [a]

[a] School of Energy Systems, LUT University, Yliopistonkatu 34, 53850, Lappeenranta, Finland
[b] Department of Energy and Process Engineering, NTNU, 7491, Trondheim, Norway

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ABSTRACT

The representativeness of several important parameters, such as energy return on investment (EROI) and those requiring summing primary energy (PE), are often questioned due to the gap in PE quantification technique. This fundamental gap is systematically investigated in order to clarify the PE quantification problem, its impact, and propose a justifiable solution using a widely used tool, such as EROI, together with appropriate data and scenarios. The analysis shows that present PE estimation lacks scientifically justifiable grounds to compare any parameters that depend on it. For example, present EROI calculation is unsuitable for technology-to-technology or system-to-system or system-to-technology comparisons because of the variation of primary energy quality (PEQ) with a resource-technology combination. The main cause of PEQ discrepancy is the absence of reference energy quality that facilitates proper comparison and interconversion. This study shows that standardising PEQ enables a scientifically meaningful quantification of PE and a justifiable comparison of EROI as well as other relevant indicators depending on it. Electricity emerges as the best option for solving the differences in PEQ in the short-term. However, the logical long-term solution is to standardise the energy unit "joule" to attain a definite value, similar to kilogram, across the various sub-areas of energy.

1. Introduction

1.1. Energy sustainability indicators

Humanity is in the process of energy transition driven by the demand to eradicate the global warming effect of fossil fuel use and the need to replace it with technologies not emitting greenhouse gases (GHG), finally utilising renewable energy (RE) [1]. The replacing technologies come with their tradeoffs, such as, low energy quantity and quality per capacity but improving wind turbine hub heights [2] and solar photovoltaic (PV) performance [3], associated system operational challenges due to variability [4,5], the need for enabling technologies such as energy storage [6–8] and optimised complementarity [9], the need for new mineral inputs such as metallic materials [10], which vary with scenarios [11] and technologies [12,13], and the impact of RE land requirement [14,15], the rise of electricity-based solutions and other related factors [1,16]. Thus, choosing a proper transition path will require consideration of the interaction of various factors at system level. Consequently, society needs a more comprehensive tool that can enable an accurate comparison of the existing and alternative technologies as well as the existing system and its possible replacement in order to avoid possible pitfalls. At present, researchers dominantly use tools that are related to GHG emissions reduction considering cost of electricity of various technologies and the entire system [17], RE resources diversity [18], and conventional technologies and national policy scenarios [19] to develop energy transition paths. Consequently, the composition of these paths diverges significantly. While these tools are very important, indicators that can ensure effective and practical accounting of climate-related energy targets and inform sustainable energy transitions path choices are not emerging. For example, several indicators that are related to total primary energy (TPE) were reported to be misleading due to the absence of a unified way of quantifying primary energy (PE) [20]. At the same time, the field of net energy analysis (NEA), which is considered one of the tools that can measure energy sustainability, is suffering due to lack of consensus to apply the tool accurately [21] (see supplementary material). While various indicators are reported in the field of NEA, the most common tool is the energy return on investment (EROI) [21–42]. Due to observed methodological inconsistencies, researchers question the suitability of EROI to compare technology-to-technology [22] and system-to-system [1,32].

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* Corresponding author.
E-mail addresses: solomon.asfaw@lut.fi, abebe.solomon@gmail.com (A.A. Solomon).

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1.2. Broader perspective of the energy quality debate

The achievement of accurately comparable EROI quantification for various technologies are hampered mainly by a combination of two factors: namely: (i) the absence of clear-cut standards of boundary definition and (ii) the issues related to the difference in primary energy quality (PEQ) estimated for each resource-technology mix [33,43]. The conflict due to boundary conditions can be addressed by adopting the LCA framework, where these issues are addressed in the corresponding ISO standards [21,33]. However, the gap related to the difference in PEQ remains unaddressed. This is due to the fundamental difference between the energy resources and the corresponding technologies, and as a consequence, the technique that LCA and other relevant areas apply to calculate PE per resource-technology mix. For example, one reason for some reported low solar photovoltaic (PV) technology EROI as compared to fossil fuel technologies was shown to be the difference in solar PV PEQ to that of fossil fuels [43]. On the other hand, the reason TPE and indicators relying on it were found to be unrepresentative or even potentially misleading [20], as applied outside the EROI field, was due to the difficulty of having a representative quantification of an energy system in a system that is evolving. A challenge that Kraan et al. [20] summarised by the following question: "How do you account for the joules contained in a barrel of crude oil and the kWh of electricity from a solar panel in a single metric?" In other words, the lack of representativeness is due to the absence of clear PE quantification that enforces an equivalent energy quality for various resource-technology mix.

Primary energy [44] is defined as an energy source that exists in nature, such as solar energy, fossil fuels or waterfalls, and that can be used to generate energy carriers such as electricity, gasoline or steam. However, the absence of a simple way of estimating this energy across various resource-technology mixes has led to varying quantification techniques for different entities and poor effectiveness of the indicators that depend on it [20,45,46]. In addition to the impact of PEQ quantification in the area of net energy discussed above [33], the weakness of PEQ has undermined the effectiveness of energy statistics [47], led to an implementation of electricity as a reference to overcome the PEQ problem [48] and undervaluation of the energy saving potential of RE [49]. Particularly, Lightfoot [47] shows that the use of different PE accounting methods implemented by various organisations produces PE estimates that cannot be compared. Thus, Lightfoot [47] asserts that the joules used by these entities are arbitrary units (a.u) that cannot be matched to the joule defined in physics and chemistry. This is significant as it suggested a violation of key scientific principles as explained in this study.

1.3. Bridging the gap and the role of this study

Numerous attempts were made to solve these problems, but none managed to build consensus because the suggested fixes simply add to existing PEQ techniques than tackle the fundamental weakness. In energy statistics, this discrepancy received attention with an increase in RE, such as wind power and solar PV, for which the first useable commodity is electricity. Kraan et al. [20] have made a thorough analysis of the existing PEQ quantification techniques and grouped them into four broad categories. These methods are: (i) Partial Substitution Method (PSM) that applies a representative efficiency of thermal power plants to estimate PE of a non-combustible source, (ii) Direct equivalent method (DEM) that treats generated electricity as PE of a non-combustible sources, (iii) Physical Energy Content Method (PECM) that treats direct electricity as PE for technologies that directly generate it or heat as PE for those producing heat as an intermediate product, and (iv) Incident Energy Method (IEM) that uses the energy that entered the converter as PE. Table 1 shows how the production efficiencies of non-combustible energy sources change with the grouping of the methods. In general, regardless of the arbitrariness of the conversion factors [20,47,48], the possibility of introducing bias of some kind against one or more resources is high. To solve these discrepancies, Kraan et al. [20] replaced TPE with total final consumption (TFC) though it could suffer the same weakness and was also criticised by Segers [50] due to the mixing of final energy that has different quality.

Table 1

PE to electricity conversion efficiencies of non-combustible energy sources. Names of organisations: United Nations (UN), Energy Information Administration (EIA), BP p.l.c. (British Petroleum), International Energy Agency (IEA), World Energy Council (WEC), International Institute for Applied Systems Analysis (IIASA), Intergovernmental Panel on Climate Change (IPCC) and Organization for Economic Co-operation and development (OECD). Note that Efficiency estimates are given in percentage (%). Adapted from Ref. [20].

Resources	Methods				
	PSM		DEM (UN)	PECM (IEA)	IEM
	BP p.l.c.[a]	EIA[a]			
Wind power	38	35	100	100	26
Solar PV	38	35	100	100	12
Solar Thermal (CSP)	38	35	100	33	21
Hydropower	38	35	100	100	90
Geothermal	38	35	100	10	16
Nuclear power	38	35	100	33	30
Other organisations adopting the method	WEC, IIASA		IPCC	OECD, Eurostat	

[a] The estimates are based on the average fossil fuel efficiency, which is changing as technology improves, the latest value for BP p.l.c. [51]. is 40.5. The difference between BP p.l.c. [51]. and EIA [52] may be related to the geographical range covered by the two entities.

On the other hand, researchers in the area of NEA focused on accounting for energy quality differences between different resources, but as of now, the recommended solutions did not escape the inherent arbitrariness and thus fails to generate consensus. In Ref. [33], energy quality is defined as the relative economic usefulness per heat equivalent unit of different fuels and electricity. Murphy et al. [33] further elaborated energy quality as a complex function of the physical scarcity of the fuel, capacity to do work, energy density, cleanliness, amenability to storage, safety, the flexibility of use, and the cost of conversion, amongst others. As a consequence of this broad concept, the discussion of energy quality adjustment [33] includes (i) price-based correction; (ii) adding externalities such as environmental and social costs associated to the fuel market price; (iii) application of physical unit correction by applying exergy. The first two recommendations simply add the uncertainties of socio-economic factors and associated data quality problem on a physical parameter that should have a scientifically definite meaning. It also impairs alternative methodologies that apply more logical analysis to examine the issues of such externalities as for example in the case of comparing EROI values of REs with fossil CCS technologies [53], for which correction based on physical units is more appropriate. Though exergy is an attractive alternative to performing such a correction, the following two factors limit its effectiveness. First, exergy is estimated based on the potential maximum extractable energy of the initial resources [54], e.g., wind kinetic energy and solar radiation, as compared to the first commercial commodity produced in the form of electricity by wind power and solar PV technologies, respectively. As a result, exergy also has a resource specific meaning, whose estimation is also made based on the corresponding primary energy value [55]. Thus, the lack of a definite quality at the level of all resources is also common to exergy. In other words, a joule of electricity has more exergy than a joule of solar radiation. Second, energy statistics and NEA are based on final energy carriers, such as electricity, gasoline, natural gas, refined oil and coal, etcetera, as opposed to the theoretical maximum energy that can be produced from those resources. This is why some researchers recommend final energy, not exergy, to overcome these challenges both in the area of energy statistics [49] and NEA [56]. Thus, the challenge of measuring embodied energy as in exergy compromises the purpose of energy statistical indicators and NEA tools due to the inherent differences in these resources' quality. Other alternative fixes, such as the use of a constant power system efficiency value to convert electricity to a PE equivalent, were suggested by Raugei et al. [43]. However, the average power system efficiency value could change from place to place and year to year depending on the local power system composition. Such an option is widely used with the recognition that EROI will be a function of the chosen value [41,57]. Thus, the issue cannot be solved by introducing an arbitrary constant conversion factor [43] or the use of a concrete electricity mix to estimate the PE as suggested by Murphy et al. [21]. This is because the PE quantification problem is not the problem of boundary conditions or geographic location but a discrepancy that emanates from lack of proper reference energy quality and associated arbitrariness of the energy unit. All-in-all, the above solutions are just another set of pragmatic fixes that are not derived from scientific evidence of the overall shortcomings of existing primary energy quantification technique. Thus, it is very important to investigate the PE quantification problem to clarify the scientific context of the energy quality gap, illuminate its impact on various indicators/corresponding areas, and develop a justifiable solution. Despite the existence of various techniques to estimate primary energy [20,45] as discussed above, PE is widely applied in evaluations of national energy policies [58], life cycle building energy performance [59], life cycle performance of a product/technology [60], etcetera, on top of its potential use in evaluating sustainability of energy technologies and the achievement of climate targets. Therefore, finding a better alternative that can unify PE quantification using a scientifically sound technique is the prime alternative to achieving meaningful use of PE. For the first time, this study will show that the PEQ quantification discrepancy occurs due to the violation of a key scientific principle, which requires quantifying a given physical entity with the same level of clarity and accuracy when measured by different parties. It will also show that such problems cannot be solved without quantifying all harvested energy forms at an equivalent PE quality. As long as this is not solved, accurate system-to-system, technology-to-technology as well as technology-to-system comparisons will not be possible using any indicators that depend on PE. Thus, this fundamental question is studied in detail using pertinent data by applying the widely used tools of EROI and cumulative energy demand (CED) in order to understand the issue and establish a solution that can work at all conditions. EROI was chosen to represent indicators that involve PE or its sum in some kind of ratio while CED represents indicators that involve adding PE, for example, as in TPE.

2. Fundamental concept and related hypothesis

2.1. EROI, cumulative energy demand and primary energy quality

EROI is a measure of the quality of energy resource-technology combination or a fuel via an indicator calculated by taking the ratio of the final energy that it can produce to meet societal needs, E_{output}, and the energy invested in the conversion and delivery of that energy, $E_{invested}$. Mathematically:

$$EROI = \frac{E_{output}}{E_{invested}} \tag{1}$$

As the EROI ratio is a dimensionless quantity, it is thus imperative that both the numerator and denominator with its subcomponents are estimated with the same energy units as well as equal energy quality for all resource-technology combinations. Note that, as explained below same/equal energy units do not guarantee the same energy quality as well as the dimensionless requirement of EROI.

Cumulative energy demand (CED), which is an estimate of PE consumed to produce a unit of a given product, is one of the impact indicators of life cycle assessment (LCA) [45]. Developing a consistent way of estimating PE of various energy sources was one of the challenges in this area as in the other areas. As an intrinsic energy content of the resource, PE would have been estimated by calculating the embedded energy or energy available for harvesting [45]. However, this is considered complex and challenging [45]. At the same time, due to the diversity of energy resources and conversion technologies, there was a difficulty to arrive at a unifying approach to quantifying this intrinsic energy. Thus, the present preferred way of estimating the intrinsic energy of all types of resources is to apply the "energy harvested" approach [20,45,61]. Table 2 provides a summary of conversion techniques implemented in the ecoinvent database [45,61]. The lack of the same energy quality is clearly visible from this table if one compares the resources that have the same point of measurement, for example, those measured at the level of electricity output as for hydropower, wind power, and solar PV. Due to the technology-dependent point of reference for harvested energy, the same amount of electricity gets a different primary energy value depending on whether it is hydropower (1/0.95) or wind power (1/0.93). Note that the point of measurement and point of reference also varies based on the conversion technology and the harvested energy, even for the same resource as can be seen for solar PV and flat-plate solar collectors. Note that the conversion of electricity to conventional PE follows the conversion factors given in Table 1 for all other organisations, the detail for ecoinvent closely follows the data of IEA [62] as given below.

Thus, the difference in energy quality becomes more pronounced and difficult to compare when other electricity generating technologies and resources are considered. Consequently, indicators calculated based on such data may become arbitrary and often difficult to compare. The most relevant indicators are CED and NEA indicators, such as EROI, which presents typical characteristics of several parameters in energy statistics and corresponding sustainability indicators. The energy statistics and its indicators involve the addition of various resources PE as in CED or a ratio involving the sum of PE values as in EROI.

Raugei et al. [43] noted the effect of PEQ on EROI for electricity generating technologies, for which they suggested a conversion factor estimated as grid electricity efficiency, meaning the efficiency of the

Table 2

Types of energy resources, harvesting facility/activity, point of measurement and point of reference, and efficiency adapted from Ref. [45].

Harvesting facility/ activity		Point of measurement	Point of reference (energy harvested)	Efficiency[a]
1	2	3	4	5
Reservoir	Hydroelectric power	Electricity delivered by generator	Rotation energy of turbine	95%
Rotor and its blades	Wind power plant	Electricity delivered by generator	Rotation energy of rotor	93%
Photovoltaic module	Photovoltaic power plant	Electricity delivered by inverter	Electricity delivered to inverter	93.5%
Flat-plate collector	Solar thermal collector	Energy delivered by storage facility	Energy delivered by the collector	88–89%
Ground heat exchanger	Geothermal energy	Energy delivered to heat pump	Energy delivered to heat pump	100%
Forestry	Wood	Amount leaving forest	Wood harvested	100%
All fossil and nuclear fuels	Crude oil/ natural gas/ coal/ uranium	Amount leaving oil and gas field or mining	Crude oil/ natural gas/ coal/ uranium extracted	100%

[a] The efficiency (column 5) is the ratio of the energy at point of measurement (column 3) to the energy at point of reference (energy harvested, column 4).

power system. However, it is unclear how this factor will be used for other technologies and if it may create a bias of its own for/against some technologies including solar PV. Diesendorf and Wiedmann [63] also point to the temporal instability of the grid electricity efficiency, causing a misleading interpretation of results over time. Murphy et al. [21] underlined the arbitrary nature of such conversion factors and the possibility of solving this by using technology level PE given in LCA databases to estimate it. But they gave no clear way of addressing the above fundamental problem in a way that will alleviate its impact in the present day energy statistics [20,47], LCA databases, and generating consensus on PE estimation in general [20]. In the following, the hypotheses developed to clarify the PE quantification gap and facilitate the identification of a proper solution are presented.

2.2. Hypothesis definition

The foregoing discussion calls for a deeper understanding of the impact of such a gap in order to propose a science-based standard to effectively harmonise the quantification of primary energy. One way of clarifying the nature of such a gap is to demonstrate how the corresponding indicators, namely CED and EROI, may vary arbitrarily when compared to some common standard conditions in response to changes in some factors. Thus, we state the following two hypotheses:

I. Suppose a given product is produced using the same process in two countries that have significantly different electricity mixes. In that case, that same product will have a different CED value based on the present primary energy estimation scheme but still using the same MJ unit.
II. Suppose the present primary energy estimation enforces the energy harvested criteria at relatively equal energy qualities for all electricity generation technologies. In that case, the EROI value estimated using the present primary energy data will have insignificant differences with the value that is estimated at the level of electricity consumption and production for all technologies.

The above two statements are very closely linked. However, their verification will provide important lessons regarding the cause of PE quantification problem, whether it is a lack of accounting quality difference by resource or the unit problem or both. The need to attain standardised primary energy quality will as a result become clear.

3. Methodology

3.1. Primary energy to electricity conversion and back

Systematic use of present LCA databases is the simplest way to test the above hypotheses. The choice of a concrete LCA database is made for two reasons: (i) LCA databases such as ecoinvent provide data that can effectively help test the above two hypotheses in a simple and self-consistent way. Creating specific technology level cases based on LCA databases reduces uncertainties as compared to considering large systems. (ii) this study aims to identify the key scientific problem of the existing PEQ estimation technique and recommend a justifiable solution that may contribute to building consensus. It is also not about studying the impact of the corresponding PEQ technique on CED or EROI, which is an issue that is widely explored under various conditions both for these indicators [43,64] and several others [20]. In this case, the comparison is dominantly focused on cases of the same technology than on inter technology or system-to-system comparisons. Because lack of consistency for one technology shows the possibility of similar problems for systems involving those technologies. At the same time, due to the similarities in typical approaches of all PEQ techniques, the lesson can be logically extended to the other PEQ techniques as discussed in the result section. The detailed information on the utilised ecoinvent dataset [65] per technology type and the use of International Energy Agency [66] data to estimate the average efficiency value of fossil fuel powerplants [65,67] are provided in the Supplementary Material (SM). Moreover, the details on the assumed full load hours (FLH) in Germany [68] and the corresponding adjustment for wind FLH [69] as well as the assumed PV energy learning rate [70], its lifetime [71] and capacity growth [72] is also presented in the SM together with a summary on the representation of fossil invested energy and the fossil fuel EROI [73–77].

3.2. Scenarios and data

Using the eight ecoinvent CED indicators [65], the CED can be re-calculated at various levels of energy quality and electricity mix as described in the SM to test hypothesis I. For this study, two hypothetical scenarios, named case1 and case2, were created to examine how the CED changes with the electricity mix for one energy technology, namely solar PV. Case1 replaces 50% of the existing fossil electricity with hydropower, while case2 fully replaces the fossil and nuclear electricity with 40% hydropower, 30% wind power and 30% solar PV. Note that the total electricity demand (CED in electricity standard) remains the same in all cases even if the share of the subcomponent varies depending on the assumption as discussed in the SM.

For hypothesis II, (CED_{PR}) energy data related to key fossil fuel and renewable electricity generation technologies are extracted from the ecoinvent database (see SM). Three EROI estimates were calculated for each technology by changing the conditions of the calculation as described in Table 3. Note that varieties of EROI estimation techniques exist. In relation to energy quality mix-up, three categories can be found for electricity generation technologies. EROI estimations based on: (i) primary energy or often known by the name thermal energy calculated by weighting electricity with the thermal efficiency of the plant or following LCA techniques [23,24,36,78]; (ii) primary energy equivalent, which applies a constant average grid efficiency factor [22,38,57]; (iii) direct electricity use, either by converting kWh to MJ or by directly using kWh [22]. Option (iii) clearly compromise the non-dimensionality of EROI as it leads to either MJ electricity or kWh in the numerator and MJ (primary energy) in the denominator. Thus, it was excluded from this

Table 3
Scenario names and descriptions.

Approach	Acronym	Description
EROI primary energy traditional	$EROI_{PR-tr}$	The electricity output of each technology is converted to primary energy using the resource-technology specific efficiency given in Table 4 (as per the traditional way of primary energy estimation of LCA) to calculate EROI. Note that the implication of other PE quantification techniques summarised in Table 1 are also discussed in the result in detail.
EROI electricity	$EROI_{el}$	CED_{PR} energy is converted to electricity by applying resource level conversion factors given in Table 4. Note that EROI has been calculated both in terms of electricity and primary energy (PE) delivered. In some cases, $EROI_{el}$ was simply a ratio of electricity delivered to invested primary energy [20,64]. In others, $EROI_{el}$ is calculated by converting CED_{PR} to CED electricity using a constant grid efficiency as in Raugei et al. [38]. As shown below, aggregating CED inadvertently introduces an error of its own. This hidden problem gives the corresponding EROI an arbitrary dimension in both cases as opposed to the aspired non-dimensionality. Thus, the present $EROI_{el}$ is different from both cases and it achieves non-dimensionality.
EROI primary energy equivalent	$EROI_{PE-eq}$	The electricity output of each technology is converted to primary energy equivalent using a constant conversion factor of 0.31 following Raugei et al. [22]. Note that $EROI_{PE}$ of Fthenakis and Leccisi [64] has the same meaning to $EROI_{PE-eq}$.

Table 4

CED value comparison of 1 kWp grid connected solar PV system at various electricity mix conditions. A continual decline of the PV CED value is reported, following an energetic learning curve [70,79], however, these data correspond to year 2012 conditions. For this specific case, the data are used as it is because the important issue relates to the comparative quality of the subcomponents (see SM on the use of energetic learning rates as related to EROI).

	Unit	Energy resource category and CED indicators according to ecoinvent v3.7.1								CED	Comparison [% existing CED]
		Biomass, other	Biomass, forest	Fossil	Nuclear	Geothermal	Solar PV	Hydropower	Wind onshore		
Primary to electricity	–	30%	30%	40%	33%	10%	93.5%	95%	93%	N.A.	N.A.
CED PE traditional indicators of 1 kWp mc-Si PV (calculated from ecoinvent data)	MJ_{pe}/kWp	791	1	26647	2850	39	1	3741	377	34448	100
CED indicators in electricity of 1 kWp mc-Si PV (corresponding to the above data)	MJ_{el}/kWp	237	0	10659	941	4	1	3554	351	15747	N.A.
Calculation of the two cases in its order of precedence (CED electricity and then CED PE traditional)											
CED indicators in electricity case1	MJ_{el}/kWp	237	0	5329	941	4	1	8883	351	15747	N.A.
CED PE traditional indicators case1	MJ_{pe}/kWp	791	1	13324	2850	39	1	9350	377	26735	78
CED indicators in electricity case2	MJ_{el}/kWp	237	0	0	0	4	3481	8193	3831	15747	N.A.
CED PE traditional indicators case2	MJ_{pe}/kWp	791	1	0	0	39	3723	8625	4119	17298	50

study. The suitability of the other two options should be tested further, thus forming two of the three scenarios given below. The CED data were converted to electricity to enable the calculation of EROI at both levels of energy quality.

4. Results and discussion

4.1. Analysis of CED for various electricity mix conditions

Table 4 presents how CED changes with the applied electricity mix for the same output product as the electricity mix changes as compared to the one that exists in the ecoinvent version 3.7.1.

Table 4 shows that the electricity mix significantly affects the total CED estimated based on the present methods. The value is reduced to 78% and 50% of the initial CED when the electricity mix changes to that of case1 and case2, respectively, even though the total electricity consumed by the product (or CED evaluated at the level of electricity) remains the same. This effect occurs due to the lack of harmonised energy quality in the present PE estimation. This may have also contributed to the observed significant difference in the reported CEDs from one literature to another for the same technology [43,64]. The result shows that summing PE of different sources as in the present CED or as in TPE, lacks consistent scientifically justifiable meaning, which leads to poor comparability of these parameters. Note that the units for all the three CED PE traditional values as well as the CED electric were the same MJ, despite the difference in quantity. This confirms that the present practice mixes up different energy quality [50] and the associated arbitrariness of joule [47]. Ecoinvent provides 8 resource level CED indicators in recognition of this discrepancy as unit similarity does not enforce equality [80,81]. The above effect is not a simple arithmetic problem but a violation of key scientific principles that resulted due to the lack of common energy quality reference and the arbitrariness of joule, as correctly stated in Ref. [47]. Adding two resources with arbitrary MJ units of MJ^1 and MJ^2 cannot lead to 2 MJ^1 or 2 MJ^2 or 2 MJ, as we simply do so in CED estimations. Scientifically, it forms a new arbitrary unit, MJ^1+MJ^2. Such hidden arbitrariness is more complex because of the resource diversity in the present CED or TPE than the simplified two resource examples given above. Interestingly the energy system continuously evolves in terms of the mix of electricity generation, which is expected to continue until it is fully replaced with sustainable technologies. TPE and related indicators are currently regarded as important parameters to compare these system changes at national, regional, and global levels. However, the variety of PE quantification methods has undermined the effectiveness and comparability of the indicators used to guide climate change policies [20] and contributed to the confusion in the overall energy statistics area [47–50]. Thus, the creation of a standardised energy quality to calculate PE is an important aspect of achieving a meaningful comparison between PE, TPE and related indicators as well as CED values of various products - independent of the contributing energy system. Without this basic fixes, it should be clear that no other present option properly addresses the present PEQ gap and its impact on associated indicators. Now let us study the result corresponding to hypothesis II.

4.2. Comparability of EROI and broader discrepancy of PE quantification

4.2.1. Comparability of EROI

The lack of harmonised PE quantification also affects the comparability of other indicators, such as EROI, that depend on it. Fig. 1 shows that, except for the fossil fuel power plants, all the three EROI calculations resulted in significantly different EROIs for the same technology. Fig. 1a presents a set of three EROI values calculated by applying three estimation techniques linked to different energy quality scenarios for electricity generating technologies. Fig. 1b shows the relative percentage difference of $EROI_{el}$ and $EROI_{PR\text{-}eq}$ compared to $EROI_{PR\text{-}tr}$ to clarify the significance of the difference. The exceptionality of open cycle gas turbines (OCGT) and coal power plants is because the energy quality conversion resulted in comparatively equivalent energy quality of various forms under all conditions. The PE equivalent constant conversion factor of 0.31 induces minor differences when converting electricity to a PE equivalent as compared to the assumed average efficiency of 0.33 of the two plants. On the other hand, the EROI of combined cycle gas turbines (CCGT), which has an average efficiency of 0.53, shows a larger deviation when its electricity is converted to PE equivalent as compared to the almost equal EROIs under the other two options ($EROI_{PR\text{-}tr}$ and $EROI_{el}$). The equality of EROIs based on the PE traditional approach ($EROI_{PR\text{-}tr}$) and at the level of electricity ($EROI_{el}$) of fossil fuel-based technologies shows that estimating and comparing EROI values of these technologies may be acceptable based on the present energy mix. However, due to the relatively large deviation that was observed while using the PE equivalent techniques for CCGT, the approach clearly introduces a bias for/against some technologies even if they are fossil fuel based. Note that the PE equivalent techniques ($EROI_{PR\text{-}eq}$) convert the electricity output of the technology while maintaining the existing

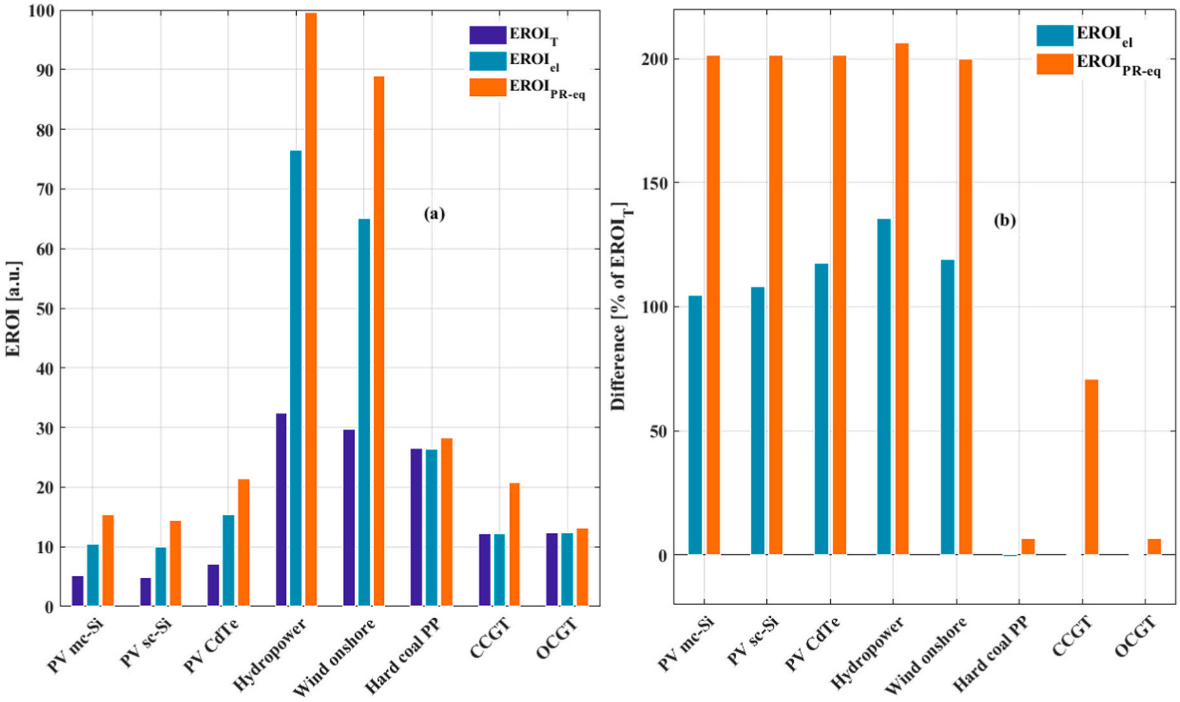

Fig. 1. (a) EROI values of eight energy technologies, namely solar PV systems based on both multi-crystalline (mc-Si) silicon and mono-crystalline (sc-Si) silicon modules and roof integrated cadmium telluride (CdTe) modules, run-of-river (RoR) hydropower, wind onshore, hard coal power plant (Hard coal PP), combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT) power plants, at three different energy quality conditions. See Table 3 for details on scenario names, and the methods section for more information about the approach and related assumptions. Note that EROI_{el} is the only true dimensionless EROI, the other two will have some arbitrary dimension due to the hidden energy quality issue. Reference year for this figure is 2020, see SM for details. (b) Deviation of EROI_{el} and $\text{EROI}_{\text{PR-eq}}$ compared to $\text{EROI}_{\text{PR-tr}}$. The observed negative difference is less than 1%. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

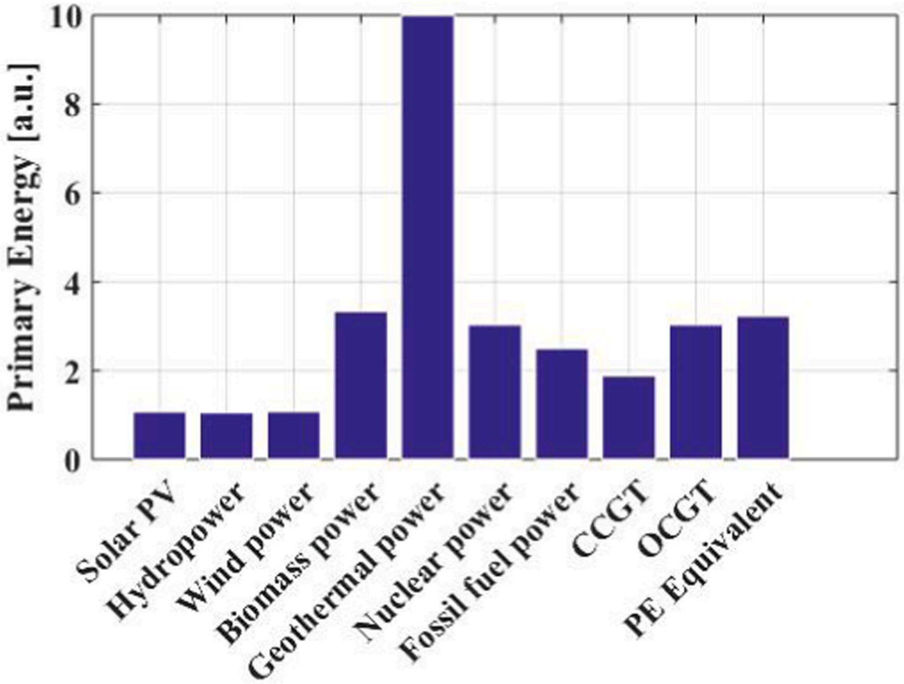

Fig. 2. PE values of 1 unit of electricity for eight CED indicators, primary energy equivalent as well as CCGT and OCGT. Even though by convention the y-axis should have taken the unit of MJ or kWh based on the specific unit of electricity in use, in this case the y-axis unit is set to arbitrary unit (a.u.) because, for example, a MJ solar PV primary energy does not have the same energy quality as a MJ primary energy of geothermal heat or fossil fuels.

CED_{PR}.

On the contrary, none of the above techniques produced comparatively equal EROIs for renewable energy technologies. Had the PE traditional estimation been based on meaningfully equivalent energy values for all resources, at least $EROI_{PR\text{-}tr}$ would have an equal value to that of $EROI_{el}$. The relative difference of $EROI_{el}$ to $EROI_{PR\text{-}tr}$ (Fig. 1) was in a range of 100%–133% for all renewable energy technologies, which grew to approximately 200% for the case of $EROI_{PR\text{-}eq}$ to $EROI_{PR\text{-}tr}$. Note that the relative $EROI_{el}$ difference remains less than 2% for fossil fuel technologies. To understand the cause of these differences, it is easier to convert a unit of electricity back to PE of various resources and compare them. Fig. 2 presents PE traditional values of 1 unit of electricity for eight energy resources related to eight CED indicators and the PE equivalent. Note that this PE traditional technique applies the same conversion factor for all technologies that are based on the same resource category even if the technology efficiency may be different. For example, concentrated solar thermal power (CSP) is based on the same 93.5% conversion factors as solar PV due to the aggregation, even though CSP produces AC electricity without requiring inverters. To clarify, the PE traditional value of 1 unit of electricity also varies depending on resource-technology combinations even for the same resource, the PE traditional corresponding to 1 unit of electricity generated by OCGT and CCGT, which consumes natural gas to generate electricity, is also included in Fig. 2. Fig. 2 shows that the PE takes a little more than 1 for wind onshore, solar PV and hydropower, while scoring as high as 10 for geothermal power for the same unit of electricity. Thus, the height of each bar can be taken as a representative of the relative energy quality of the corresponding resource, where the tallest bar shows that the corresponding resource has the PE estimated at the poorest energy quality level. Such a circumstance occurred because the reference point of energy harvested was set based on the characteristics of the specific resources but without any attention to the corresponding energy quality. But as discussed below, the cause of this discrepancy is not only the difference in point of PE measurement between resources. As a consequence of the difference in point of measurement, PE of biomass is set to approximately 3.3 times the electric energy as compared to the close to 1 unit of electric energy for the case of hydropower. In other words, to generate one unit of electricity approximately 10, 3.3 and 1 PE units of geothermal heat, biomass and hydropower, respectively, are required. Thus, none of the PE traditional for varying technology-resource mix can be added or compared following scientific principles. Thus, both CED of a given product and TPE as well as related indicators lack consistent scientific meaning. Furthermore, as the fossil PE value is estimated using the higher heating value (HHV) of the specific fuel as a reference, the calculation of that value from electricity involves its average conversion efficiency per resource category. By presenting the PE value of CCGT and OCGT, Fig. 2 clarifies that by evaluating PE from the same reference energy quality leads to varying values for different technologies that use the same fuel (specifically fossil natural gas, which is included in an even broader fossil fuel category) depending on their efficiency. In this case, the low PE value corresponding to CCGT is because it uses a lower amount of fossil natural gas to generate a unit of electricity as compared to OCGT. In order to accommodate this difference, $EROI_{el}$ for OCGT is recalculated after replacing the corresponding fuel input energy of the required natural gas with the electricity estimated using the efficiency of CCGT. Then its $EROI_{el}$ dropped by 38% to approximately 7.7. All in all, PE receives a technology-resource mix specific energy quality for the same amount of electrical unit.

4.2.2. The broader PE quantification problem

The PE quantification outside LCA, such as the ecoinvent database, applies an entirely different scheme that varies with the entity (see Table 1). Fig. 3 shows the presence of a significant difference in estimated PE quality between various entities even for the same resources. The figure shows that the various methods applied by different organisations results in significantly different PE values for one unit of electricity for the same solar resources, which is also significantly different from the corresponding value of hydropower and geothermal electricity. In such a circumstance, there is no way of achieving comparability between any statistics or indicators involving PE. This phenomenon is due to the violation of three key scientific principles across this area. First, measurement and conversion of one physical entity should allow the achievement of an equivalent quality/content by all entities and all form of subcategories (in this case energy resources subcategories). Thus, instrument calibration is implemented to avoid errors introduced due to faulty devices. In the present case, it is not even possible to achieve a unifying method that enables converting one energy form to another in a scientifically justifiable way. This is due to fundamental issues to be discussed next. Second, the violation of the scientific principle came as a

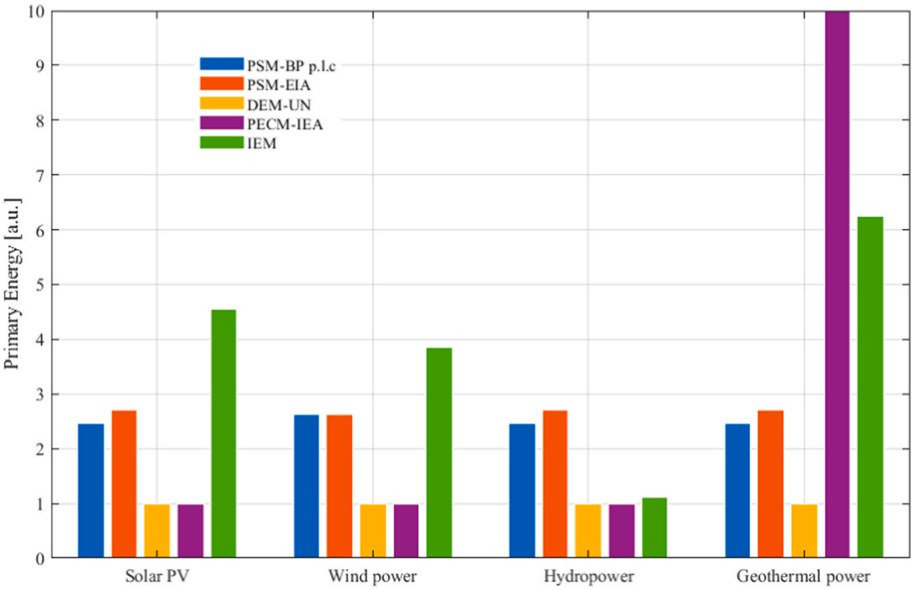

Fig. 3. PE values of one unit of electricity of three RE resources based on various PE estimation techniques currently followed by different methods applied by various entities. Even though by convention the y-axis should have taken the unit of MJ or kWh based on the specific unit of electricity in use, in this case the y-axis unit is set to arbitrary unit (a.u.) because, for example, a MJ solar PV for BP p.l.c. does not have the same energy quality as a MJ PE of solar PV in all other methods.

result of the low attention given to the difference in energy quality when selecting the PE point of quantification for various resources, leading to a situation where the same amount of electrical energy receives different PE energy values for the same resources (as seen in Fig. 3). This effect has emerged due to the complex energy transformation processes of various resource-technology mixes and the dependence of energy quality on the point of measurement. Interestingly, the same unit of energy - "joule"- was used in these varieties of PE forms, causing some researchers to conclude that "joule" received an arbitrary meaning [47]. This leads to the other key fundamental problem, which could have bridged the impact of the difference in the point of measurement of PE. Third, the absence of a specific energy value assigned to the unit joule and ways of ensuring the quantification of energy content follows the same standard for all resource-technology mix. In other words, joule does not have the same specific meaning that a kilogram has to all users. As a fundamental unit, a kilogram (of a given mass) is measured with a defined accuracy across various disciplines and states of substances. However, joule is a derived unit. This derived unit is formed through a combination of various basic parameters, depending on the form of energy. Thus, it is calculated based on the value measured for those parameters. The challenge emanates from this point. Interestingly, one measures the heat content of a fuel using an entirely different way/instrument as compared to how one measures heat (electrical energy) dissipated in a resistor or kinetic energy of water droplets that moves the hydropower turbines or a radiation energy incident on a solar PV module. Thus, it is not easy to apply the same level of accuracy to estimate a joule of energy and maintain the same level of quality without standardising the unit joule and allowing the application of additional correction factors to equalise the use of the unit across various forms of energy and resources. This may also require adding joule to fundamental units and applying it to a situation that only conforms to the specified definition.

4.2.3. *Possible solutions with summarised analysis*

At present, there are two ways of overcoming the PE quantification problems. The first and the easiest way of resolving the present challenge is to choose the common output of a group of resource-technology mixes that produces an output with the same energy quality, such as electricity, as a reference. However, this may still face a challenge of generating consensus, especially when a full energy system is considered, if the fundamental issues related to standardising the energy unit are not addressed because the use of energy will continue to involve non-electricity final energy forms. Thus, the second and logical way of fixing is to standardise the unit "joule" and create a correction factor that can equalise energy estimations in all forms. This will solve all the related problems; however, depending on the point of standard most of the present definitions of joule may have to be updated accordingly as, for example, a Newton-meter may not have an equal value as a Watt-second. However, it may be worth noting that electricity offers an opportunity to bridge the difference between various resources. Assuming that the joule is standardised at the quality of electrical energy, then the existing PE with a value of 1 J, is estimated based on the data presented in Table 1 as given in Table 5. Table 5 presents the conversion factor at each condition to adjust to the standard unit; note that joule of electricity needs no conversion. The table shows the real energy quality of each resource at the point of the chosen reference, as compared to a joule defined at the level of electricity. Multiplying the PE value estimated in Fig. 3 for a unit of electricity with these factors yields 1 J for all cases. Such conversion techniques are what is required to fix this problem.

Table 5

Present unit of PE when converted to joule defined at the level of electrical energy quality will have the values given in the Table for all resources and conversion techniques given in Table 1. Abbreviation: a.u. - arbitrary units.

Resources	Methods				
	PSM [joule/a.u.]		DEM (UN) [joule/a.u.]	PECM (IEA) [joule/a.u.]	IEM [joule/a.u.]
	BP p.l.c.$^{+}$	EIA^{+}			
Wind power	0.38	0.35	1	1	0.26
Solar PV	0.38	0.35	1	1	0.2
Solar thermal (CSP)	0.38	0.35	1	0.33	0.21
Hydropower	0.38	0.35	1	1	0.90
Geothermal	0.38	0.35	1	0.1	0.16
Nuclear power	0.38	0.35	1	0.33	0.30

Finally, present resource level averaging could limit the effectiveness of distinguishing technologies that convert the same resource/fuel. Thus, further analysis that combines the chosen point of reference with various conversion processes and resource combinations may yield a better energy quality standard that suits all conditions.

The foregoing discussion shows that due to the PE quantification gap, the $\text{EROI}_{\text{PR-tr}}$ technique is not suitable to achieve a justifiable comparison between various technologies and systems. The discussion of the $\text{EROI}_{\text{PR-eq}}$ is also not much different because that technique focuses on the final electricity output. Once the PE is summed up as in CED, it forms an arbitrary unit that depends on the nature of mixture, as seen in section 4.1, thus cannot lead to a situation that reduces the deviation from EROI_{el}. This study has tested grid efficiency values other than 0.31. At 0.7, for example, the deviation of $\text{EROI}_{\text{PR-eq}}$ from both EROI_{el} and $\text{EROI}_{\text{PR-tr}}$ remains higher than 30% for renewables, which also increases to more than 50% for some fossil fuels technologies such as coal and gas turbine power plants. Thus, the best way to overcome this discrepancy is to harmonise the PE quantification by applying a common reference energy quality and facilitate proper interconversion. This confirms that using electricity, the common energy output of all corresponding technologies, provides a more straightforward and less laborious solution to standardising the energy quality of the primary energy. Furthermore, the EROI_{el} technique is the only option that can produce scientifically comparable EROI values between different electricity generating technologies as well as different electrical energy systems. This will also enable a truly dimensionless EROI as opposed to the other techniques, which have some arbitrary energy units and, hence, only a technology specific meaning/use. Thus, due to the ongoing energy transition, which is expected to result in an energy system that is dominantly dependent on electricity [1,7,9,17–19,71,82], it is essential to create a primary energy standard using electricity as a reference to solve the problem in short-term. However, the logical long-term solution is to standardise the energy unit "joule" to attain a definite value, similar to kilogram, across the various sub-areas of energy. Specifically, it is crucial to clarify that the present EROI calculation (namely $\text{EROI}_{\text{PR-tr}}$ and $\text{EROI}_{\text{PR-eq}}$) introduces a significant bias against all renewable technologies as detailed in Fig. 1a and b as compared to fossil fuel-based electricity generators, which receive equal values of EROI. Moreover, this bias also affects the results of systems that involve these technologies or any form of its combination. Even though the target of the study is not to compare technology EROI, it is important to warn that low solar PV EROIs in the EROI_{el} as compared to other technologies are partly due to the lower full load hour at the location of reference (Germany, see Methods). For countries with good solar irradiance, the full load hours can be 1700 h or higher as compared to the 980 h for Germany. Thus, the corresponding EROI_{el} can be higher than 17 as compared to 10 for the case of Germany. In addition, solar PV is the technology with the fastest change in CED among all discussed technologies due to a high energy learning rate [70,79] and strong growth of the technology [83].

5. Conclusions

This study systematically evaluates the impact of the primary energy quality difference on various indicators, using CED and EROI as a reference. The analysis shows that due to the inherent energy quality difference of the primary energy of various resources, any indicators that require summing these varying energy quality levels lack a justifiable scientific meaning that enables its comparison. The fundamental cause of this difference is because: (i) the point of measurement of the energy harvested was defined arbitrarily depending on technology-resource mix combinations and (ii) the energy units, such as joule, are derived units that lack a specific meaning as for example the kilogram, which resulted in different energy quality that uses the same energy units. As a result, some of the conventional parameters, such as CED of any product as well as national and global total primary energy estimates, lacks the level of scientific clarity that is intuitionally ascribed to it, unless these parameters are recalculated by applying a standardised energy quality. It is important that the point of primary energy measurement is not confused with LCA boundary conditions as the reported effects were observed for the same technologies without involving any difference in LCA boundary conditions.

Because of the preceding limitations in primary energy calculations, it was shown that EROI also lacks both the property of being dimensionless as well as the ability to support a meaningful technology comparability. The analysis performed at the same energy quality, by using electricity, $EROI_{el,}$ as reference, shows that only fossil fuels-based electricity generating technologies receive the same EROI value as $EROI_{el}$ if the present EROI estimation technique is followed and as a result are not comparable. Thus, to achieve a scientifically justifiable comparability of total primary energy, CED, EROI and other related energy statistics, the corresponding calculation should be performed by estimating all energy resources input and output at the same energy quality. In this specific study, the only truly comparable EROI was the one estimated at the level of electricity quality. While this fixes the immediate challenge, the logical long-term solution may be to standardise the unit joule as kilogram and establish a proper measurement of this quantity under all energy forms. Standardising the primary energy quality will enable technology-to-technology, technology-to-system and system-to-system comparisons using EROI. At the same time, it solves the present limitations of CED estimation in the field of LCA and other related parameters of energy statistics.

Author contributions

SAA conceived and designed the study, gathered the data, tested the hypothesis, and wrote the paper. CB supervised the research, reviewed the analysis, and edited the paper. NBM supported during data collection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100115.

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