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On boundaries and 'investments' in Emergy Synthesis and LCA: A case study on thermal vs. photovoltaic electricity

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ABSTRACT

Indicators of efficiency and environmental performance are fundamental to marking progress toward more sustainable patterns of human development. Central to indicator development is a common framework through which the wide range of environmental assessment methods may make comparative analysis. Clear and consistent definitions of system boundaries and input categories are essential to their interpretation, and form a necessary pre-requisite for meaningful comparisons of competing systems. A common framework of foreground and background categories, consistent with both LCA and Emergy Synthesis, is identified and discussed as the basis for the calculation of performance indicators. In this paper a revised operational definition of the Emergy Yield Ratio (EYR) is introduced, in light of the proposed categorization scheme, for consistent application to technological processes. Two case studies, namely CdTe PV and oil-fired thermal electricity production, are investigated. The Unit Emergy Value (UEV) of electricity generated by the thermal plant was calculated as 5.69E5 seJ/J with services and 5.11E5 seJ/J without services. The UEV for electricity generated by the PV system is 1.45E5 seJ/J with services, and 7.93E4 seJ/J without services. The computed EYRs including services are 6.8 for thermal electricity and 2.2 for PV electricity.

1. Introduction

1.1. A matter of consistency

Assessing the efficiency and environmental performance of technological and economic systems has been, and still is, a crucial aspect for the understanding of progress toward more sustainable production and consumption. Systems delivering similar products (be they kWh of electricity, € of GDP, or more complex functional units of product or service) are often compared on the basis of their demand for input resources per unit of final output. For such comparison to be reliable, and in order to avoid the methodological inconsistencies which regrettably still affect many published studies, a common evaluation framework must be ensured for all the compared systems.

The choice of spatial scale and boundary conditions, as well as the appropriate categorization of input flows, strongly affect the very meaning of a performance indicator (making it more or less suitable to answering a specific question). This paper will focus specifically on the Emergy Synthesis method, and its two core indicators, the Unit Emergy Value (UEV) and the Emergy Yield Ratio (EYR), but many of the considerations made are more general in nature and applicability, and are not constrained to a specific method or indicator.

EYR in particular has suffered from a lack of agreement on its operational definition, as well as numerous conflicting interpretations of its ultimate meaning, sometimes resulting in oversimplified and arguably counterproductive policy indications (Raugei et al., 2005). In this paper, we propose a revised and unified operational definition for it, borrowing the standard categorization scheme for process inputs that is widely adopted in Life Cycle Assessment (LCA). Finally, a practical case study on thermal vs. photovoltaic electricity provides the basis for a critical discussion of the ensuing results.

1.2. A brief historical overview

Energy efficiency has been the most common performance indicator since the early 1970s, driven by concern about energy conversion losses and based on the 1st and 2nd Laws of Thermodynamics. Such indicator focuses on the local scale of the process,

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including all the steps within the system boundaries and treating the system as a black box.

The Gross Energy Requirement (GER) indicator (Slesser, 1974), also referred to as Cumulative Energy Demand (CED) (Gurzenich and Wagner, 2004; Wagner and Pick, 2004; Nussbaumer and Oser, 2004) was developed as an effort to also include in the assessment the flows of commercial energy that are used at larger space and time scales to make and deliver those energy and matter flows which are required on the process scale. The GER indicator is thus defined as the total commercial energy input (i.e. disregarding free renewable resources) per functional unit of output. It is applicable in principle to any functional unit and process, and may also be defined as a measure of efficiency assessed on the life cycle scale. In fact, parallel approaches such as Material Flow Analysis (Hinterberger et al., 2003) and Life Cycle Assessment (SETAC, 1993; ISO, 2006a,b) are rooted in a similar conceptual framework that calls for the largest possible inclusiveness, 'from the cradle to the grave'.

Both efficiency and GER indicators have also been assessed in terms of exergy, a measure of useful work potential (Szargut et al., 1988), with a follow-up in terms of cumulative or extended exergy (Sciubba, 2001; Szargut, 2007).

The Energy Return on Investment (EROI) (Hall et al., 1986) is defined as the ratio of the energy delivered by a given resource flow to the economic system to the energy 'invested' to make such flow available. EROI has been proposed as a performance indicator capable of highlighting the energy benefit that society receives in return for a resource exploitation effort. In its more recent development, the energy investment related to societal-driven input flows (labour, services) has also been included by means of money-to-energy conversion factors (Cleveland, 2008). The lack of a universal agreement on how to define such 'investments', though, has caused many inconsistencies and misunderstandings in the published literature in terms of the EROI of competing technological options (Raugei et al., 2010).

The introduction of the Emergy Synthesis method (Odum, 1988, 1996; Brown and Ulgiati, 2004a,b, 2005a) further expands the space and time boundaries, in order to include resource generation by natural processes. By accounting for direct and indirect flows of solar and solar-equivalent available energy, also non-commercial energy and matter flows come into play (e.g. direct solar radiation, wind, geothermal energy, topsoil, ground water, among others). The method also calls for an assessment of the time needed for resource generation, which in turn translates into a quantitative distinction between renewable and non-renewable resource flows. The final result of an emergy evaluation is a set of performance indicators, referred to the space and time scales of the biosphere, and, as a consequence, inevitably characterized by larger uncertainty. The most straightforward emergy indicator is the so-called Unit Emergy Value (UEV, previously referred to as transformity or specific emergy), which is essentially the Emergy Synthesis homologue of GER. The UEV is defined as the equivalent solar emergy required to generate a unit of output and is commonly measured in seJ/J or seJ/g (solar equivalent joules per unit of available energy or mass in output). In other words, UEVs are inversely related to the system efficiency on the scale of the biosphere, just like GER has a similar meaning on the scale of the commercial energy market. Another important emergy indicator is the Emergy Yield Ratio (EYR) (Odum, 1996; Brown and Ulgiati, 2004b), loosely defined as the ratio of the total emergy allocated to a processes' output (namely the emergy supporting the output) to the fraction that comes from (previous) investments. Consistent with the dictates of the emergy method, the calculation of the EYR includes non-commercial resource flows, commercial energy and material inputs, and services (labour and human services).

2. Theory

2.1. Emergy Yield Ratio: definition(s) and methodological issues

Over the years, two definitions of the EYR have emerged. The first, relatively simple, one states that "*The EYR is the ratio of the emergy yield from a process to the emergy costs*" (Odum, 1996). Later, seeking more clarity, the definition was expanded to "*The ratio of total emergy* (*local and imported*) *driving a process or a system to the emergy imported*" (Brown and Ulgiati, 2004b, p. 333). This second definition introduced a spatial dimension to the concept of Emergy Yield Ratio, and therein lies much of the problem with operationally defining and using this indicator.

A secondary concern relates to the past use of a statement accompanying the definition that describes the utility of the EYR, namely: "*The ratio is a measure of how much a process will contribute to the economy*" (Odum, 1996, p. 71), followed by further elaboration: "*The ratio is a measure of the potential contribution of the process to the main economy, due to the exploitation of local resources*" (Brown and Ulgiati, 2004b). Both of the definitions and the elaborations that followed were an expression of the ongoing debate about an unclear issue, and resulted in a multiplicity of operational definitions of EYR and an inability to compare results from one analysis to another. While EYR aims to provide needed information related to the performance of processes, there have been methodological differences over the past several decades (Ulgiati et al., 1995; Raugei et al., 2005) that now require clarifying and to which this paper is directed.

2.2. Definition of 'investments'

The calculation of the EYR requires that we draw a distinction between the total emergy required to make a product or service and the fraction thereof that was previously invested into the supply chain for extraction, processing, and delivering of all the directly needed inputs. The choice of space and time boundary conditions obviously affects how input flows are categorized for calculation, and hence the results. If such results are to be used for comparison between different products or processes, it is of paramount importance that the calculation procedure be applied in a consistent and unbiased manner.

The well-known Life Cycle Assessment methodology (ISO, 2006a,b; JRC, 2010) draws a distinction between 'foreground' and 'background' inputs, which may provide an appropriate categorization to distinguish between process inputs and previous investments. LCA refers to foreground inputs as those which are directly supplied to the analyzed system during its operational lifetime and background inputs as those which were previously required along the individual supply chains of the foreground inputs in order to make the latter available. To be more specific, the LCA definition of foreground refers to those processes

> "...that are under direct control of the producer of the good or operator of the service, or user of the good or where he has decisive influence...This covers firstly all in-house processes of the producer or service operator of the analyzed system. Secondly...also all processes and suppliers of purchased made-to-order goods and services, i.e. as far as the producer of service operator of the analyzed system can influence them by choice or specification". (JRC, 2010, p. 97)

While background data

> "...comprises those processes that are operated as part of the system, but that are not under direct control or decisive influence of the producer of the good (or operator of the service, or user of the good). The background processes and systems are

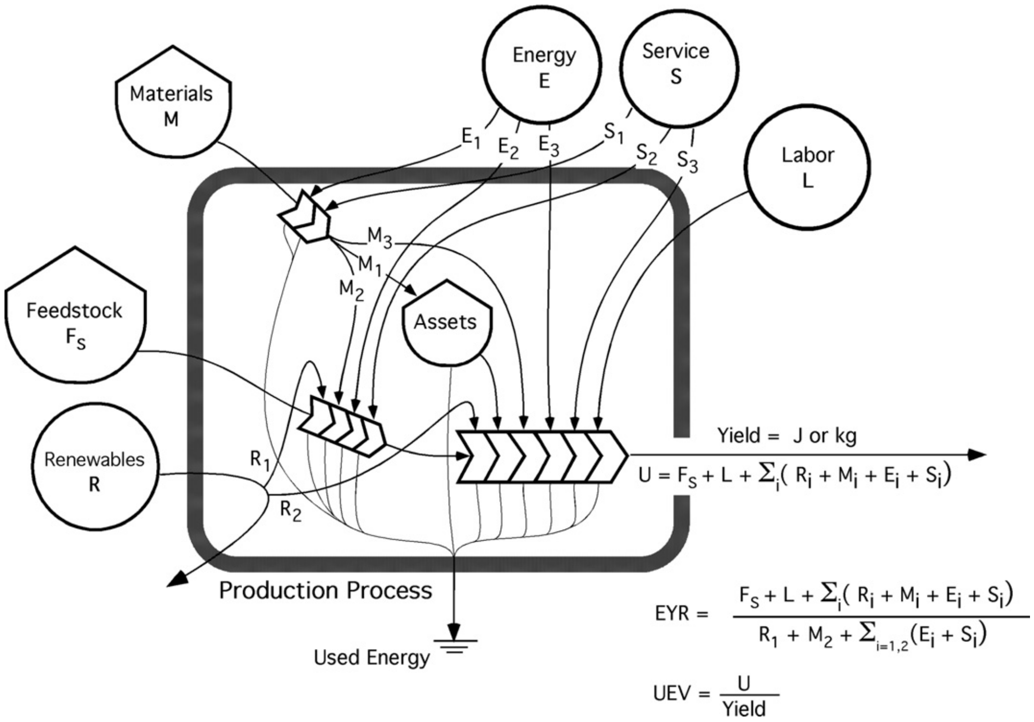

Fig. 1. Systems diagram of a generic process showing inputs and intermediate steps that are required to generate a given yield product. Symbols in Figure and formulas are referred to in Tables 1 and 2, as labels of some inputs listed therein.

hence outside the direct influence or choice of the producer or service operator of the analyzed system." (JRC, 2010, p. 98)

Using the LCA categorization, data within the emergy framework can be assigned as falling within foreground or background based on the following assumptions:

- *Foreground* emergy flows are those flows that are directly input to the process expressed in the emergy of the raw resources from which they are derived (i.e. if the input is heavy oil, then its foreground emergy value is the emergy of the crude oil, not the refined oil, since the additional inputs for refining would be considered background investments).
- *Background* inputs are the emergy investments required previously to extract, refine, and deliver foreground input flows.

Fig. 1 is an aggregated diagram showing foreground and background inputs and processes that are required to produce a given yield product. By definition, the emergy (U) supporting the yield (Y) is the sum of all emergy inputs to the system.

According to this approach, and looking at the aggregated system diagram in Fig. 1, inputs are categorized as follows:

- Foreground renewable and non-renewable emergy inputs:
  - Renewable emergy input (R_2).
  - Fossil feedstock emergy (F_s) at mine or well-head (not including emergy for extraction, processing and delivery).
  - Emergy of fuels and electricity (E_3) directly used in the system's operating phase.
  - Emergy of materials (M_1) for the system structure (not including emergy for extraction, processing and delivery).
  - Emergy of materials (M_3) directly used in the systems operating phase (not including emergy for extraction, processing and delivery).
  - Emergy of labour (L) directly used in the operational phase.
- Background renewable and non-renewable inputs (*these are considered investments*):
  - Renewable emergy inputs in the supply chain (R_1).
  - Emergy of fuels and electricity (E_1) previously used in extraction, processing and delivery of the additional materials for construction and materials directly input to the system.
  - Emergy of fuels and electricity (E_2) previously used in extraction, processing and delivery of the feedstock.
  - Emergy of materials (M_2) previously used in extraction, processing and delivery of the feedstock.
  - Emergy of services ($S_1 + S_2$) previously used in extraction, processing and delivery of the materials and feedstock for construction and materials directly input to the system.

It is important to note that all the inputs that actually drive the process during the operation phase are classified as 'foreground', including the system structure itself, which is a crucial contributor to the process' functioning. In fact, this is arguably a more rigorous classification that effectively does away with the arbitrary conceptual differentiation of 'feedstock' vs. 'non-feedstock' inputs, and provides a unified view of 'renewable' and 'non-renewable' energy systems. For instance, both photovoltaic (PV) and thermal power systems require foreground inputs of renewable emergy (respectively, sunlight for PV vs. wind for pollutant dispersal for thermal), non-renewable emergy (respectively, plant structure for PV vs. plant structure plus feedstock fuel for thermal), and labour.

In principle, the background flows of materials, energy and services are infinite in extent, since each investment also required investments. Here we adopt the LCA cut-off criterion which advocates "... omission of not relevant life cycle stages, activity types..., specific processes and products ... and elementary flows from the system model." (JRC, 2010, p. 102). Cut-off is useful to determine the appropriate boundary between flows that are relevant (and therefore should be included) and flows that, due to their magnitude, will not affect the final outcome of the analysis.

All in all, the LCA framework may provide a common basis for data generation and extraction, based on the very large number of cases investigated worldwide and accurate assessment of data quality, source, uncertainty, and age.

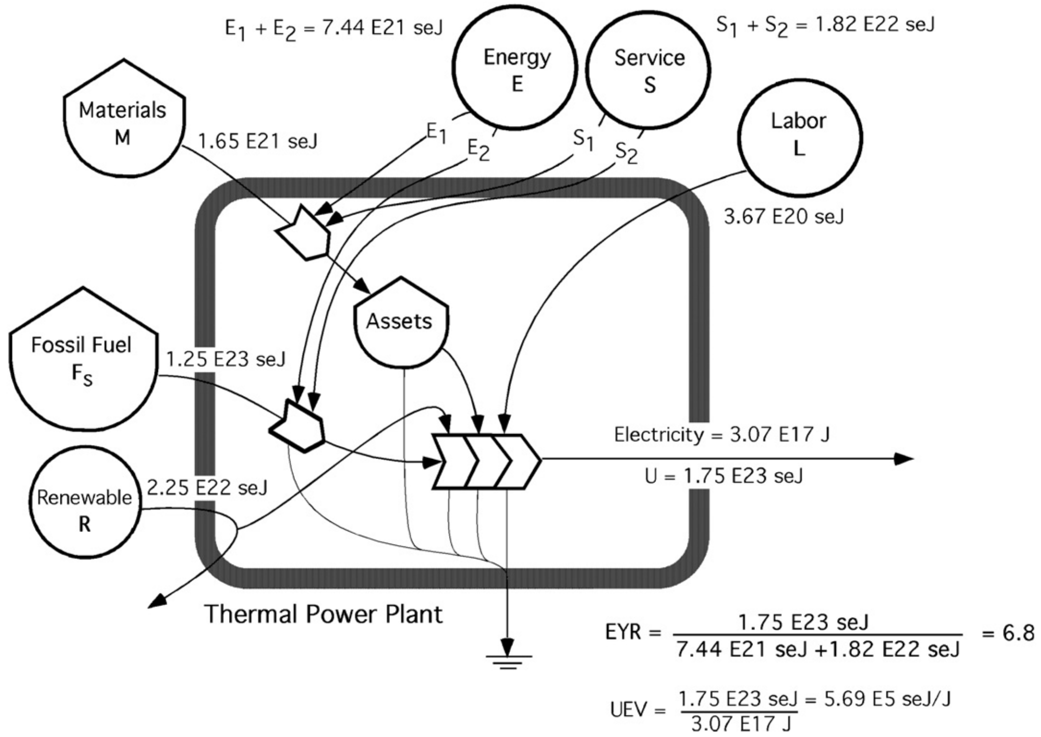

Fig. 2. Diagram of a thermal power plant, showing the renewable flow (*R*) of wind for dispersal of combustion emissions, the feedstock of fossil fuels (F_s), the material flow (*M*) for plant structure, the investment of energy (*E*) and services (*S*) required for feedstock supply and plant construction, and finally the labour (*L*) supplied during the operating phase. Equations calculate performance indicators UEV and EYR according to the LCA foreground and background framework. Numerical data from Table 1.

In light of the foregoing issues, the EYR can be stated as the total emergy (*U*; the sum of all the emergy required) divided by the background invested emergy (*I*), as follows:

$$\mathrm{EYR} = \frac{U}{I} = \frac{F_S + L + \sum_i (R_i + M_i + E_i + S_i)}{R_1 + M_2 + \sum_{i=1,2} (E_i + S_i)} \qquad (1)$$

As Fig. 1 shows, it is also important to differentiate between labour and services. Labour (activity directly applied to a process) and services (activities indirectly applied to a process from the larger scale of the economy) are key and crucial production factors. They are the information carriers and generally are evaluated separately. In lack of a more direct way to account for them, services are customarily evaluated from the prices of goods and energy, under the general assumption that price is a proxy for society's supporting investments. Labour on the other hand is evaluated based on working time or sometimes on wages. Working and money flows (wages and prices) are converted into emergy flows using appropriate UEVs.

2.3. Further important clarifications

Conceptually, as the ratio of the total emergy supporting a process' yield (*U*) to the emergy investment (*I*), EYR expresses a sort of 'gain' or 'multiplier effect' of the process itself. For instance, an EYR of 5:1 suggests that the emergy 'value' of the yield (defined as the total energy required to support it) is 5 times greater than the emergy (previously) invested in acquiring it. However, this often says little about the process' contribution to an economy (the latter commonly being intended as a user-side utilitarian concept). Instead, we maintain that EYR provides a characterization of the donor-side intensity of the analyzed process, by expressing how much overall emergy is ultimately required in support of its output, per unit of investment.

Also, there needs to be a clear distinction between the EYR of a process (as discussed so far) and the application of EYR concept to much larger systems such an entire production sectors, or even a whole regional or national economies.

The commonly used geographical distinction of 'local' versus 'imported' investment, while potentially useful when evaluating the advantage of an imported resource compared to one extracted and/or produced within an economy, should be avoided when dealing with individual processes. The introduction of the 'local versus imported' differentiation was originally a direct outcome of a concern for self-reliance, and as such had more to do with regions and economies than with processes. After all, taking extreme cases, all inputs to a process would be imported if its boundaries were drawn around the process itself, whereas none of them would be imported if the boundaries were extended to the entire planet. When dealing with processes, the 'imported versus local' construct looses rigour and even significance, and leads to confusion. As a result, the EYR of a process should be defined considering only the temporal domain rather than a spatial (political) one. We are not going to deal with EYR as applied to regions or nations in this paper, as it falls outside the intended scope of the present paper.

3. Case studies

3.1. System descriptions: conventional (oil-fired thermal) and renewable (PV) electricity production

The theoretical framework described in Section 2.2 has been applied and tested on two case studies, namely oil-fired thermal electricity production and CdTe thin film photovoltaic (PV) electricity production, with the focus on analysing the performance of these processes. Figs. 2 and 3 provide aggregated energy systems diagrams of the two systems, thermal and PV respectively, showing renewable (*R*), material (*M*), available energy (*E*) and information (*S*) input flows.

Life cycle inventory data for the emergy evaluation of the thermal power plant were obtained from the latest Ecoinvent, v.2

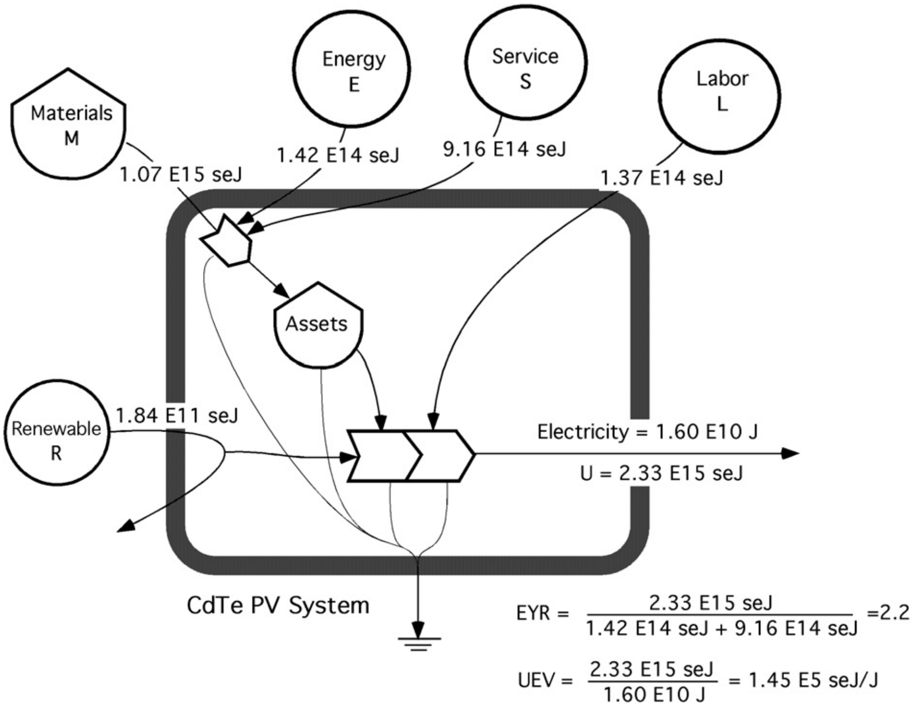

Fig. 3. Diagram of a photovoltaic power plant, showing the renewable flow (R) of solar energy, the material flow (M) and the investment of energy (E) and services (S) required for plant construction, and finally the labour (L) supplied during the operating phase. Equations calculate performance indicators UEV and EYR according to the LCA foreground and background framework. Numerical data from Table 2.

database (Ecoinvent, 2011), and were aggregated in order to simplify the description to the largest possible extent without losing generality and reliability. Other specific information needed for the emergy evaluation of the thermal power plant was derived from Brown and Ulgiati (2002), where a 1280 MW unit was investigated. In the present investigation the lifetime of the thermal plant was taken as 30 years (consistently with Ecoinvent).

The emergy evaluation of the PV power plant (1 m^2 unit surface) was based on a thorough life cycle analysis performed by one of the authors (Raugei, 2010; Fthenakis et al., 2009), making use of foreground data provided by the PV module manufacturer (First Solar, 2005, 2008), combined with literature data on balance of system (BOS) components for a large-scale ground-mounted installation (Mason et al., 2006), and background data sourced from Ecoinvent, v.2. The lifetime of the PV plant was taken as the industry-standard 30 years, according to the recommendations provided by the IEA PVPS experts (Alsema et al., 2009).

3.2. Methods

Operation of the thermal power plant requires a foreground input of heavy fuel oil (F_s, non-renewable feedstock) which previously required background flows of energy (E_2) and services (S_2) for processing and refining. The foreground material input to the power plant (M) also required background flows of energy (E_1) and services (S_1) for the refining and construction of the assets. The additional background flows of non-energy carrying materials for the supply chains of F_s and M were considered negligible and therefore are not shown in the diagram. Direct (foreground) material, energy and service inputs to the operational phase (other than assets) were also considered negligible and omitted from the diagram. Finally, the operation of the power plant requires a direct (foreground) input of labour (L), plus renewable energy (R) in the form of cooling water and wind for dispersal of pollutants.

The operation of the PV plant requires a direct (foreground) flow of solar radiation (R) hitting the photoactive components, but no non-renewable feedstock (F_s). All other inputs are similar in a broad sense to those described for the thermal plant except there is obviously no refining of the feedstock.

Unit Emergy Values (UEVs) of fuels are from Brown et al. (2011); UEVs of mineral ores are from Cohen et al. (2007); UEVs of renewable flows are from Brown and Ulgiati (2010); UEVs of economic flows are from CEP (2000); all values were updated to the new emergy reference baseline described in Brown and Ulgiati (2010).

We considered the information input to processes to be expressed primarily by the emergy of labour and services. The emergy of services is the total amount of emergy supporting the societal infrastructure and related processes, which allow the investigated process to function (from technical ones to administrative, regulatory, etc.). Due to the difficulty of tracking all the steps involved in such a complex network of societal activities, the assumption was made here that the economic cost of the delivered flows is a rough but reliable estimate of the societal investment needed for their delivery. The emergy of labour was calculated separately from services, based on the wages paid for labour. The emergy value of both investments is obtained by multiplying such economic cost by the average UEV of the GDP generated in the country (the emergy supporting one unit of GDP, in units of seJ/€).

According to the emergy framework, an emergy evaluation table was constructed for each system. All material and energy input flows are listed in the leftmost column of each table (item). In the first data column the quantity of each primary resource corresponding to the input flow is given (metals, ores, and raw fossil fuels). The emergy evaluation tables list the flows of materials, energy and services of plant construction and feedstock refining (thermal plant only) separated from the operational flows. This structure is the direct consequence of the categorization of inputs into background and foreground as well as the separation of inputs by phases (construction versus operation) that is typical of the LCA framework. The footnotes to the tables describe assumptions and calculation details for converting foreground input into its origin raw resource. The input data in column one are multiplied by their appropriate UEV (in data column two) to obtain the emergy of each input flow in column three.

The UEV of the generated electricity is calculated by dividing the total emergy from column 3 by the Joules of the product. UEV for both systems was calculated first with and then without including the emergy of labour and services, which is customary in order to understand the societal influence on the final results. Equation 1 is used to calculate the EYR of each process.

4. Results

Results of the evaluations are provided in Tables 1 and 2 and summarized in Figs. 2 and 3 for the thermal and photovoltaic power plants, respectively.

The largest input to the thermal plant is the feedstock, i.e. heavy fuel oil (1.25E + 23 seJ/30 years). Other dominant flows included the renewable flows of wind to disperse pollutants (2.24E + 22 seJ/30 years) and services in the refining phase of the feedstock (1.53E + 22 seJ/30 years).

As might be expected, for PV, the actual solar energy driving the electricity generation process in the modules is not the major emergy source, due to its low UEV. Instead, the emergy of services (9.16E + 14 seJ/30 years) and the emergy of photoactive materials (8.12E + 14 seJ/30 years) dominate.

The very large differences in the magnitudes of input flows to the two analyzed systems are the result of the differences in the scales of the analysis (i.e. a full thermal power plant vs. 1 square meter of PV system), and in no way affect the comparability of the results.

Computed UEVs and EYRs of electricity generated by both systems are given at the bottom of each table. The UEV for electricity generated in the thermal plant was 5.69E5 seJ/J with services and 5.11E5 seJ/J without services, about a 10% difference. The UEV for electricity generated by the PV module was 1.45E5 seJ/J with services, and 7.93E4 seJ/J without services. The computed EYRs including services were 6.8 for thermal electricity and 2.2 for the PV electricity.

5. Discussion

The combination of the EYR and the UEV of electricity produced by the thermal and PV systems provides an illustration of the dichotomy associated with comparing systems that rely mainly on non-renewable feedstocks to those that run on renewable energy to produce similar products. Since the EYR of thermal electricity is higher than that of PV electricity, at first glance one might consider the former to be more desirable since it requires a smaller investment per unit of total emergy assigned to the output; in other words, thermal electricity is characterized by a smaller share of its supporting emergy being required as investment. However, the UEV indicator, a measure of the actual performance of the process on the scale of the geo-biosphere, suggests the opposite, since the UEV of PV electricity is much lower than that of electricity produced by the thermal plant.

One simple explanation is that the PV system mainly relies on a renewable source of energy for its operation (sunlight) that is characterized by the lowest possible UEV (1). In fact, when comparing Tables 1 and 2 it is apparent that the emergy of renewable inputs is almost invariably negligible, in spite of PV being nominally a ‘renewable’ technology. This reflects the fact that most flows of renewable energy typically require comparatively little in the way of previous support by the biosphere, which is what emergy ultimately accounts for. On the other hand, it should also be noted that processes which mostly rely on renewable energy sources for their operation tend to deliver lower power, because renewable sources are constrained in availability (i.e. they are flow limited), at least more so than fossil fuels, and they are also limited in intensity (power per unit area).

We have maintained for many years that for any given product there is an unlimited number of ways to make it, each with a

Table 1
Emergy evaluation of a 500 MW oil-fired power plant.

No.	Item	Units	Primary resource input [a]	UEV of primary resource (seJ/unit)	Emergy (seJ)
Foreground inputs (plant structure)					
1	*Material inputs (M)*[b]				
1.1	Concrete (as limestone)[c]	g	1.20E+11	1.30E+10	1.56E+21
1.2	Lubricants (as crude oil)[d]	g	8.78E+07	6.22E+09	5.46E+17
1.3	Cu (as metal)[e]	g	7.50E+08	1.02E+11	7.65E+19
1.4	Al (as metal)[f]	g	3.00E+08	5.73E+09	1.72E+18
1.5	Steel (as iron metal)[g]	g	3.38E+09	1.24E+10	4.19E+19
1.6	Plastics (as crude oil)[h]	g	3.00E+08	6.22E+09	1.86E+18
1.7	Rock wool (as basalt rock)[i]	g	3.69E+08	3.35E+10	1.24E+19
Background inputs for plant construction phase					
2	*Fuel inputs (type E_1)*[j]				
2.1	Diesel (as crude oil)[k]	g	6.92E+09	6.22E+09	4.31E+19
2.2	Heavy fuel oil (as crude oil)[l]	g	6.95E+09	6.22E+09	4.32E+19
3	*Electricity input (type E_1)*	J	2.00E+13		
3.1	Oil (as crude oil)[m]	J	1.94E+12	1.48E+05	2.88E+17
3.2	Coal (at the mine)[n]	J	3.33E+13	9.71E+04	3.24E+18
3.3	Natural gas (at well head)[o]	J	5.39E+12	1.70E+05	9.16E+17
3.4	Uranium (as metal)[p]	g	3.28E+04	1.68E+11	5.51E+15
3.5	Hydropower[q]	J	8.50E+11	1.70E+04	1.44E+16
3.6	Wind power[r]	J	9.72E+11	2.50E+03	2.43E+15
4	*Background energy and machinery (oil eq.) (type E_1)*[s]	J	1.11E+15	1.48E+05	1.64E+20
5	*Background construction services (type S_1)*[t]	$	7.00E+08	2.80E+12	1.96E+21
Background inputs for feedstock					
6	*Feedstock services (type S_2)*[u]	$	5.47E+09	2.80E+12	1.53E+22
7	*Energy and machinery (crude oil eq.) (type E_2)*[v]	J	4.85E+16	1.48E+05	7.18E+21
8	*Refining services (type S_2)*[w]	$	3.28E+08	2.80E+12	9.18E+20
Foreground inputs (operation phase)					
9	*Wind for pollutant dispersal (type R)*[x]	J	8.98E+18	2.50E+03	2.24E+22
10	*Water for cooling (type R)*[y]	J	1.20E+16	1.10E+04	1.31E+20
11	*Heavy fuel oil feedstock (as crude oil) (F_s)*[z]	J	8.41E+17	1.48E+05	1.25E+23
12	*Operational labour (L)*[A]	$	1.31E+08	2.80E+12	3.67E+20

Table 1 (*Continued*)

No.	Item	Units	Primary resource input [a]	UEV of primary resource (seJ/unit)	Emergy (seJ)
Output					
13	*Electricity generated* (Y)[B]	J	3.07E+17 $I = E_1 + E_2 + S_1 + S_2$ = 2.57E+22	U = 1.75E+23	
Indicators					
	UEV with labour and services (U/Y)	seJ/J		5.69E+05	
	UEV w/out labour and services ($[U - S_1 - S_2 - L]/Y$)	seJ/J		5.11E+05	
	EYR (incl. labour and services) (U/I)			6.8	

[a] Primary resource is the quantity of raw resource that is required. Data source: Ecoinvent (2011) (500 MW power plant located in Germany).

[b] Quantity of materials required to construct the power plant. Materials reported represent > 90% of total material inputs.

[c] The quantity of concrete required in the construction of the power plant = 1.2E11 g which requires approximately the same amount of limerock (Ecoinvent, v.2). The transformity for limerock = 1.3E10 seJ/g (Brown and Ulgiati, 2010).

[d] The quantity of lubricants used in the construction of the power plant = 6.0E7 g which requires 1.33 times as much diesel, in turn corresponding to 6.0E7 g × 1.33 g × 1.1 g of crude oil (Ecoinvent, v.2). The UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[e] The quantity of copper used in the construction of the power plant = 7.5E8 g (Ecoinvent, v.2). UEV of copper metal in the ground from Cohen et al. (2007).

[f] The quantity of aluminium used in the construction of the power plant = 3.0E8 g (Ecoinvent, v.2). UEV of aluminium metal in the ground from Cohen et al. (2007).

[g] The quantity of steel used in the construction of the power plant = 3.45E9 g (Ecoinvent, v.2). Steel is between 99.8 and 98% iron, we used 98%. UEV of iron metal in the ground from Cohen et al. (2007).

[h] The quantity of plastics used in the construction of the power plant = 3.0E8 g which requires approximately the same amount of oil (Ecoinvent, v.2). The UEV of oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[i] The quantity of rock wool (an insulation product) used in the construction of the power plant = 3.0E8 g which required 3.69E8 g of primary basalt rock resource (Ecoinvent, v.2). The UEV of basalt rock is 3.35E10 seJ/g (Brown and Ulgiati, 2010).

[j] Quantity of fuel used in the construction phase.

[k] The quantity of diesel fuel used in the construction phase is 2.7E8 MJ (Ecoinvent, v.2); LHV of diesel is 42.9 kJ/g; the amount of crude oil required is 1.10 times the amount of diesel (Ecoinvent, v.2). UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[l] The quantity of heavy fuel oil used in the construction phase is 2.7E08 MJ (Ecoinvent, v.2); LHV of diesel is 40.4 kJ/g; the amount of crude oil required is 1.04 times the amount of diesel (Ecoinvent, v.2). UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[m] Production of 1 kWh of the national electricity mix in Germany requires 0.35 MJ of crude oil on the life-cycle scale (Ecoinvent, v.2). UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[n] Production of 1 kWh of the national electricity mix in Germany requires 6 MJ of coal on the life-cycle scale (Ecoinvent, v.2). UEV of coal is 9.71E4 seJ/J (Brown et al., 2011).

[o] Production of 1 kWh of the national electricity mix in Germany requires 0.97 MJ of natural on the life-cycle scale (Ecoinvent, v.2). UEV of natural gas is 1.7E5 seJ/J (Brown et al., 2010).

[p] Production of 1 kWh of the national electricity mix in Germany requires 0.0059 g of uranium (Ecoinvent, v.2). UEV of uranium metal in the ground is 1.68E11 seJ/g (Cohen et al., 2007).

[q] Production of 1 kWh of the national electricity mix in Germany requires 0.153 MJ of geopotential energy in water for hydropower (Ecoinvent, v.2). UEV of avg. geopotential of water is from (Odum, 2000), adapted to new baseline.

[r] Production of 1 kWh of the national electricity mix in Germany requires 0.175 MJ of kinetic energy in wind for windpower (Ecoinvent, v.2). UEV of average global wind from (Odum, 2000), adapted to new baseline.

[s] Primary energy embodied in construction resources and equipment expressed in average oil equivalents (Ecoinvent, v.2). The UEV of crude oil is 1.48E5 seJ/J (Brown et al., 2011).

[t] Includes the labour and services in construction. Assumed that the cost of construction is a measure of construction services. For a European thermal power plants the cost is between \$0.8 and \$2.0 million/MWe installed, therefore cost = 500 MWe × \$1.4E6 = \$7.0E8. UEV from CEP (2000).

[u] Services in oil feedstock based on price of oil. Quantity of oil required over lifetime of plant = 8.4E17/41860 J/g oil eq.)/1.3e5 g/bbl = 1.54E8 bbls. World median oil price (2000) = \$35.50 (EIA, 2011). Total cost = 1.54E8 bbls × \$35.50 = \$5.47E9. UEV from CEP (2000).

[v] Primary energy embodied in resources and equipment for fuel production. Taken as 0.06 times the energy in the feedstock fuel (Ecoinvent, v.2) expressed as "oil equivalent". The UEV of crude oil is 1.48E5 seJ/J (Brown et al., 2011).

[w] Services in refining feedstock based on price of oil used for refining. Quantity of oil required over lifetime of plant for refining taken as 6% of the total feedstock cost = \$5.47E9 × 0.06 = \$3.28E8. UEV from CEP (2000).

[x] Required winds to dilute pollutants released by combustion processes based on 11 J per J of oil (Brown and Ulgiati, 2002).

[y] Emergy of the water necessary for power plant cooling based on 6.8E8 kg water/MW (Brown and Ulgiati, 2002) which absorbs 2.44E13 J/MW calculated from the difference between input and output water temperature (8.6 °C). UEV for heat is 1.1E4 seJ/J (after Odum, 1996, updated to new base line). 500 MW emergy of water cooling = 2.44E13 J/MW × 500 MW = 1.22E16 J.

[z] Quantity of primary source (crude oil) based on Ecoinvent, v.2; total lifetime electricity production = 8.54E10 kWh (note 16). Converted back to primary oil assuming 3.6E6 J/kWh, plant efficiency of 38% and oil refining efficiency of 96% (8.54E10 × 3.6E6 × 1.04)/0.38 = 8.41E17 J of primary oil. The UEV of crude oil is 1.48E5 seJ/J (Brown et al., 2011).

[A] Operational labour is estimated as 145 workers based on 0.3 labourers per MW capacity (Brown and Ulgiati, 2002) and \$30,000 annual salary. Total labour emergy = 145 × \$30,000/year × 30 years = 1.31E08. UEV from CEP (2000).

[B] Electricity production (lifetime) = 500 MWe × 65% load factor × 30 year life = 500 MWe × 0.65 × 30 years × 365 days/year × 24 h/day = 8.54E10 kWh × 3.6E6 J/kWh = 3.07E17 J. Emergy is total of all inputs. The UEV is calculated by dividing total emergy input by the energy of the electricity produced (2.08E23 seJ/3.07E17 J = 6.78E5 seJ/J.

corresponding UEV and EYR (Brown and Ulgiati, 2005b). Of course, there must be a thermodynamic minimum UEV below which it is not possible to make the product. Yet, such minimum may not be the most appropriate choice of process, since systems under natural selection tend to optimize rather than minimize (Odum and Pinkerton, 1955; Schneider and Sagan, 2005). The question is thus not which is the 'best' UEV, but rather which is the most appropriate energy source for a given use and level of development. It is observed that, when comparing processes delivering the same product (electricity in this case), those that result in lower UEVs also appear to tend to have lower EYRs.

In the most general sense, EYR and UEV are both strongly influenced by three variables: the local-scale efficiency of the process, the nature of the main energy source driving the operation phase, and the quality and quantity of the required investments. Each of these variables affects the indicators in different ways and there are no hard and fast rules, but most important of all is the effect that investments have on EYR. Investments are present both in the numerator and denominator of this ratio, but it is their position in the denominator that has the most significant non-linear effect.

Investments include two aspects: (i) the 'background' energy and material investments and (ii) the services required. While the former depend on the technological state of the process, service inputs by and large depend on the development stage of the society. As a result, in a developing economy, where labour does not depend on large resource flows, the EYR of a process might be quite

Table 2
Emergy evaluation of 1 m^2 ground-mounted CdTe PV system (PV modules + balance of system).

Note	Item	Units	Primary resource input [a]	UEV of primary resource (seJ/unit)	Emergy (seJ)
Foreground inputs (CdTe PV system)					
1.	*Material inputs (M)*[a]				
1.1	Photoactive materials (ores)[b]	g	1410	5.76E+11	8.12E+14
1.2	Glass (as quartz + limestone)[c]	g	21,869	8.00E+09	1.75E+14
1.3	Cu (as metal)[d]	g	870	1.02E+11	8.87E+13
1.4	Al (as metal)[e]	g	1414	5.73E+09	8.10E+12
1.5	Steel (as iron metal)[f]	g	3332	1.24E+10	4.13E+13
1.6	EVA and plastics (as crude oil)[g]	g	727	6.22E+09	4.52E+12
1.7	Water[h]	g	219,000	1.59E+06	3.47E+11
Background inputs for CdTe PV system production					
2	*Fuel inputs (diesel as crude oil) (type E)*[i]	g	94	6.22E+09	5.82E+11
3	*Electricity input (type E)*[j]	*J*	*1.03E+05*		
3.1	Oil (as crude oil)[k]	J	9.98E+03	1.48E+05	1.48E+09
3.2	Coal (at the mine)[l]	J	1.71E+05	8.17E+04	1.40E+10
3.3	Natural gas (at well head)[m]	J	2.76E+04	1.70E+05	4.70E+09
3.4	Uranium (as metal)[n]	g	1.68E-04	1.68E+11	2.82E+07
3.5	Hydropower[o]	J	4.36E+03	1.70E+04	7.41E+07
3.6	Wind power[p]	J	4.99E+03	2.50E+03	1.25E+07
4	*Energy and machinery (crude oil eq.) (type E)*[q]	J	9.55E+08	1.48E+05	1.41E+14
5	*Module construction services (type S)*[r]	$	327	2.80E+12	9.16E+14
Foreground inputs (operation phase)					
6	*Sunlight (R)*[s]	J	1.84E+11	1	1.84E+11
7	*Labour (L)*[t]	$	4.91E+01	2.80E+12	1.37E+14
Output					
8	*Electricity generated (Y)*[u]	J	1.60E+10	U = 2.33E+15 $I = E + S$ = 1.06E+15	
Indicators					
	UEV with services (U/Y)	seJ/J		1.45E+05	
	UEV without services ($[U - S - L]/Y$)	seJ/J		7.93E+04	
	EYR (incl. services) (U/I)			2.2	

[a] Primary resource is the quantity of raw resource that is required. Data sources: First Solar (2005, 2008), Mason et al. (2006), Ecoinvent (2011).

[b] Direct process inputs aggregated for confidentiality (First Solar, 2005); primary sources = Zn ore (Cd) + mix of copper ores (Te) + others. Quantity of primary ores based on Ecoinvent, v.2. UEV of sedimentary ores is 5.76E11 seJ/g (Brown and Ulgiati, 2010).

[c] Quantity of glass required = 1.78E4 g (First Solar, 2005) which requires 2.19E4 g of quartz + limestone (Ecoinvent, v.2). UEV used is an average between sand (3.04E9) and limestone (1.3E10) (Brown and Ulgiati, 2010).

[d] The quantity of copper used in the manufacture of the PV system = 870 g (after First Solar, 2005; Mason et al., 2006). UEV of copper metal in the ground from Cohen et al. (2007).

[e] The quantity of aluminium used in the manufacture of the PV system (BOS) = 1414 g (after First Solar, 2005; Mason et al., 2006). UEV of aluminium metal in the ground from Cohen et al. (2007).

[f] The quantity of steel used in the construction of the manufacture of the PV system (BOS) = 3400 g (after Mason et al., 2006). Steel is between 99.8 and 98% iron, we used 98%. UEV of Iron metal in the ground from Cohen et al. (2007).

[g] The quantity of plastics used in the manufacture of the PV system = 727 g (after First Solar, 2005; Mason et al., 2006) which approximately the same amount of oil (Ecoinvent, v.2). The UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[h] The quantity of water used in the manufacture of the PV system = 219,000 g (after First Solar, 2005 and Mason et al., 2006). The UEV is an average between surface (6360seJ/J) and ground water (6.36E5 seJ/J) multiplied by 4.94 J/g. ((6.36E3 seJ/J + 6.36E5 seJ/J)/2) × 4.94 J/g = 1.59E6 seJ/g.

[i] Diesel fuel as crude oil. The quantity of diesel fuel used in the construction phase is 85 g (after Mason et al., 2006); the amount of crude oil required is 1.10 times the amount of diesel (Ecoinvent, v.2). UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[j] First Solar (2008).

[k] Production of 1 kWh of the national electricity mix in Germany requires 0.35 MJ of crude oil on the life-cycle scale (Ecoinvent, v.2). UEV of crude oil is 1.48E5 seJ/J or 6.22E9 seJ/g (Brown et al., 2011).

[l] Production of 1 kWh of the national electricity mix in Germany requires 6 MJ of coal on the life-cycle scale (Ecoinvent, v.2). UEV of coal is 9.71E4 seJ/J (Brown et al., 2011).

[m] Production of 1 kWh of the national electricity mix in Germany requires 0.97 MJ of natural on the life-cycle scale (Ecoinvent, v.2). UEV of natural gas is 1.7E5 seJ/J (Brown et al., 2010).

[n] Production of 1 kWh of the national electricity mix in Germany requires 0.0059 g of uranium (Ecoinvent, v.2). UEV of uranium metal in the ground is 1.68E11 seJ/g (Cohen et al., 2007).

[o] Production of 1 kWh of the national electricity mix in Germany requires 0.153 MJ of geopotential energy in water for hydropower (Ecoinvent, v.2). UEV of avg. geopotential of water is from (Odum, 2000), adapted to new baseline.

[p] Production of 1 kWh of the national electricity mix in Germany requires 0.175 MJ of kinetic energy in wind for windpower (Ecoinvent, v.2). UEV of average global wind from (Odum, 2000), adapted to new baseline.

[q] Previously invested energy and machinery for fuel production and embodied in primary resource inputs (includes direct energy and energy embodied in machinery) expressed in average oil equivalents (Raugei, 2010). UEV of oil from Brown et al. (2010).

[r] Calculated on the basis of 3$/Wp PV system retail price (First Solar, 2010) and module efficiency of 109 Wp/m^2. Services = 3$/Wp/m^2 × 109 Wp/m^2 = $327. UEV from CEP (2000).

[s] Calculated on the basis of 1700 kWh (m^2 year) irradiation (NASA, 2008) and 30-year lifetime. 1700 kWh × 3.6E6 J/kWh × 30 years = 1.84E11 J.

[t] Assume minor maintenance and repair services over the 30 year lifetime = 15% of PV system retail price (3$/Wp/m^2), module efficiency = 109 Wp/m^2. 3$/Wp/m^2 × 15% × 109 Wp/m^2 = $49.10.

[u] Calculated based on 10.9% module efficiency (First Solar, 2009) and 80% performance factor (Alsema et al., 2009). Electricity = 1700 kWh × 3.6E6 J/kWh × 30 years × 10.9% × 80% = 1.6E10 J.

different than in an industrialized economy. Finally, a major source of uncertainty in interpreting EYR and UEVs in the future is how the changes in fossil fuel availability will affect the emergy value of services, and ultimately the development of technological processes. For instance, services represent roughly 40% of the inputs for PV electricity vs. only 9% of those for thermal electricity, thus changes in the emergy of services will have a much greater effect on the EYR of PV than on that of thermal electricity.

6. Concluding remarks

We identified a number of important issues that resulted in a multiplicity of past operational definitions of EYR, and caused a lack of comparability from one analysis to another. By discussing how to address the conceptual definition of investments and suggesting a categorization of input flows that is typical of the common LCA framework (i.e. 'background' vs. 'foreground' processes), we generated a new definition and formula that apparently removes most of the inconsistencies of past emergy evaluations of processes. The former practice of classifying the input flows to a process according to their origin (i.e. 'local' vs. 'imported') was discarded, since on the life cycle scale such concepts of 'local' versus 'imported' do not relate to the ultimate performance of the process (the latter is not intrinsically affected by the origin of its input flows, other than by way of the distance from which inputs are derived, which should simply be taken into proper account in the investment for delivery, without resorting to arbitrary boundaries).

The new operational definition of EYR introduced here was applied to two case studies, namely PV and thermal electricity production. The results obtained from the case study provided the basis for discussion of the complementary information provided by UEV and EYR. This comparison was only made possible by adopting a consistent definition for the EYR of processes, thereby avoiding the misunderstandings that would have resulted from mixing scales between nations and processes.

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