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Energy Ratio analysis and accounting for renewable and non-renewable electricity generation: A review

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ABSTRACT

This review collates energy assessment data for the most common electricity generation methods and evaluates five Energy Ratios. The considered ratios are Energy Return on Investment (EROI) – standard and external, Energy Payback Time (EPT), Primary Energy Factor (PEF), and Resource Utilisation Factor (RUF). A common energy analysis framework, together with three energy accounting methods based on energy value, exergy, and primary energy, are described. The concept of the time-value for energy as an analogy to the time-value for money is proposed and has a significant impact on the calculated Energy Ratios. In total, this review brings together data for 45 electricity generation projects. Based on the Energy Return on Investment (external), the generation methods fall into three tiers: (1) nuclear, natural gas combined cycle, and geothermal (in New Zealand) with ratios > 30, (2) hydro, wind, and geothermal (in Iceland) with ratios between 5–30, and (3) solar PV with ratios less than 5. High Energy Return on Investment ratios correspond to short Energy Payback Times and vice versa. Energy Ratio performance levels for renewable energy generation sources – hydro, wind, geothermal and solar – heavily rely on the quality of the primary natural resource available. This review recommends Energy Return on Investment (external) and Resource Utilisation Factor as the most useful metrics for inclusion in full sustainability assessment.

1. Introduction

Sustainability metrics and indices are important tools to quantify the environmental, social, and economic impact of industrial processes and human activity [1]. Where economic analyses may be affected and blurred by dynamic market prices, capital cost competition, and government policy, sustainability metrics are established based on fundamental science and engineering principles [2]. In this way, these metrics describe an independent outlook of the value for or against investigated activities and strategic plans. A few examples of sustainability assessment metrics and indices include footprint analysis [3], carbon emissions analysis [4], energy intensity, energy return on investment, energy payback [5], emergy [6], energy security [7], human risk assessment [8], as well as multidimensional metrics and analysis [9]. This paper focuses on analysing and comparing energy ratio-based sustainability metrics.

Energy Ratios (ER) are dimensionless metrics where an energy output (or input) is typically divided by an energy input (or output). The concept of an ER is valuable for analysing the fundamental viability of a resource. It can also include the energy cost of mitigating environmental issues such as carbon emissions through the addition of Carbon Capture and Sequestration (CCS) as an integral process [10]. The calculation of ERs metrics requires Life Cycle Assessment in combination with Net Energy Analysis. The difference between the various ER depends on what and how each energy flow is included in an ER. Various types of ERs have been proposed in the literature as energy planning and sustainability metrics. This review paper focuses on three categories of ERs: Energy Return on Investment (EROI), Energy Payback Time (EPT), and Primary Energy Factor (PEF). The literature also contains several similar metrics and ratios. Emergy provides a fundamental measurement of the energy required to output a product or service. As a result, the Emergy Yield Ratio [11] bears a strong resemblance to some EROI definitions. Another worthy mention is the full fuel-cycle [12], which has a similar meaning to PEF.

1.1. Energy Ratio assessments and factors in the literature

EROI (Energy Return on Investment) was proposed by Hall et al. [13] and continues to be the subject of ongoing research in recent literature [14]. Conceptually, EROI is simple. It compares the amount of

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Nomenclature

$\dot{E}$	Energy flow (GJ/y)
EPT	Energy Payback Time (y)
EROI	Energy Return on Investment
n	Plant lifetime (y)
P	Energy penalty associated with CCS
PEF	Primary Energy Factor
RUF	Resource Utilisation Factor
α	Construction (start of life) energy capital annualization factor
β	Deconstruction (end of life) energy capital annualization factor
ε	CO_2-equivalent emissions factor (kt CO_2-e/TJ_{el})
γ	Generation degradation factor
ϕ	Generation usability factor
ω	Energy weighting and conversion efficiency

Subscripts

acc	Acceptable value
ave	Average
ccs	Carbon capture and sequestration
con	Construction
dec	Deconstruction
ext	External
grid	Electricity grid
gross	Total energy input
is	Inflow self-use
L	Linear
loss	Energy losses
net	Net generation
os	Outflow self-use
om	Operating and maintenance
sec	Secondary natural resources
std	Standard
T	Time value of energy
Y1	First year

useful energy derived divided by to the amount of energy expended to process, generate, and distribute the useful energy. As a common example, crude oil extraction with an EROI of, say, 100, would represent that the energy equivalent of 1 barrel of oil, in various forms such as embedded energy and electricity to drive pump shafts, is required to extract 100 barrels of crude oil. Several studies have reported EROI values [15] but comparisons are challenging due to the need for a more consistent EROI analysis framework [16]. For relatively simple cases, EROI is easy to define but, for more complicated cases where the energy inputs come from multiple direct and indirect (embedded) sources, the ratio becomes more difficult to apply, quantify, and fairly compare [10]. Other sources of differences in EROI studies include the boundary conditions of the Life Cycle Analysis, the accounting (or non-accounting) for external renewable energy inputs [17], and the assumptions for the primary energy equivalent of electricity flows [18]. EROI analysis can also incorporate environmental impacts to try and capture the wider picture of overall sustainability [19]. Further complications arise when considering critical factors, such as electricity production, reliability and variability [5]. It is important to understand, there is no single absolute EROI for each resource and technology rather there are multiple EROI values that may be determined depending on the selected system boundary and the unique situation of the process [20]. Ambiguity can compound without clear explanations for how EROI is determined and what it represents [21].

In addition to methodological differences, EROI is dependent on the type and quality of the natural energy resource, where it is geographically located, what existing infrastructure is already in place and nearby, whether it be renewable or non-renewable, and the vintage and efficiency of the technologies used for extraction, processing, and conversion [15]. Large-scale electricity production has traditionally been generated from fossil fuels and hydro. The EROI of fossil fuels primarily depends on the energy needed during extraction. For example, to extract crude oil, the well location and depth strongly impact the EROI. A declining EROI for oil indicates the average required depths to extract oil is increasing with time. Court and Fizaine [22] project the long-term decline in EROI for oil and gas production will continue. The decline in EROI for fossil fuels may be accelerated if governments and society elect to mandate cleaner production technologies such as CCS.

For renewable energy resources, the extraction, processing, and electricity generation operations tend to be a single operation. Hydro dams collect river water and mountain run-off and use a turbine to produce electricity housed within the same infrastructure. Wind farms harness the power of wind to turn blades, which are connected to a shaft and electric generator. Geothermal power plants extract geothermal fluids from geologic formations beneath the earth's surface and may directly or indirectly use the steam and hot water in conventional and organic Rankine cycles. The EROI of renewable resources are dependent on geography and climate but, in the cases other than hydro, continue to benefit from technological advancements [10], which has led to higher EROI values. As a result, the EROI values vary greatly from project to project, as demonstrated in the meta-analysis of wind energy farm EROI values by Kubiszewski et al. [23]. Significant technological advancements also impact on the range of renewable energy EROI values. For example, new solar PV technology has achieved significant reductions in the cost of production and energy consumption. A renewable energy system may include multiple technologies to determine the complementary EROI values, e.g. a hybrid solar-hydro mini-grid system with battery storage where EROI exceeded 30 [24].

The EROI concept and values have found a wide variety of applications [25]. EROI, as a metric representing an energy resource, has been linked to the quality of life [26]. Weißbach et al. [5] suggested the minimum acceptable EROI is 7, below which there is an insufficient return to justify action. It has been applied to try to explain the decline in oil production from the viewpoint that as conventional oil runs out, unconventional oil reserves will be more energy intensive to access, which will result in lower financial returns of investments [27]. EROI has also been used in combination with Carbon Emissions Pinch Analysis for energy planning of electricity grids [10], transport systems [28], and industrial process heat analysis [29]. Most recently, it has been linked with Greenhouse Gas footprint including embedded and virtual emissions that exist when importing materials and parts for power station construction and maintenance [30]. In the case of the Californian electricity system, EROI was correlated with long-run levelised cost, which was adjusted to not include tax subsidies or levies [31]. Similarly, a correlation between oil prices and EROI over time has been attempted [32]. These applications highlight the benefits of knowing and understanding the EROI for different natural resources.

The EPT (Energy Payback Time) was proposed after EROI. It determines how quickly an energy project re-pays the total invested energy capital. The first application of EPT focused on solar PV [33] and, like EROI, relies on a Life Cycle Assessment to obtain meaningful energy flows [34]. As a result, EPT is often reported in combination with EROI [5]. Energy inputs and outputs for the Life Cycle Assessment are required in terms of primary energy equivalent. In the event of the use