

Comment

# LCOE: A Useful and Valid Indicator—Replica to James Loewen and Adam Szymanski

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## 1. Introduction

Recently, in two publications, Loewen expressed skepticism on the validity of the levelized cost of energy (LCOE) indicator, used to compare the economics of energy technologies [1,2]. According to Loewen, ‘... LCOE is an undiscounted metric that distorts comparisons, with the distortion increasing with discount rates and with the length of the analysis period. Because it inaccurately disfavors resource types whose costs are front-loaded, LCOE also disfavors renewable resources vis-a-vis fossil resources’ [2]. In an era calling for the rapidly increasing deployment of capital-intensive renewable energy technologies, with high upfront costs, as opposed to expenditure-intensive technologies, e.g., coal power plants, this criticism weighs heavily on the LCOE indicator. ‘As ... LCOE is not a good metric to use in any context ...’ Loewen instead proposes ‘... the present value of the cost of energy (PVCOE) ... which avoids these distortions ...’ [2]. Meanwhile, Szymanski used the mathematical mean value theorem to demonstrate the inconsistency of the definition of LCOE from an economic point of view [3]. This theorem is used to prove statements about a function on an interval starting from local hypotheses about derivatives at points of the interval. Szymanski argues there is ‘... no point in using it. The incorrect treatment of the discounting procedure is a source of problems’ [3].

With this short replica to Loewen and Szymanski, I would like to contribute to the discussion on the usefulness and validity of LCOE for technology comparison and argue in favor of the indicator. I would like to suggest the comparison of LCOE with the PVCOE proposed by Loewen. Though recognizing criticisms of the basic LCOE definition, e.g., cost assumptions for environmental damage, dispatchable production, and various other factors [4], I would like to argue that LCOE is a useful and valid metric for energy technology comparison. However, it is important not to compare apples with oranges. Malaguzzi Valeri expresses this as ‘Not all electricity is equal ...’ [5]. Reverting to a methodical concept used by life cycle assessment (LCA) experts [6], it is a prerequisite to define a functional unit (FU) and to be clear about the system boundaries in order to enable a meaningful comparison of different technologies. A FU is a quantified description of the function of a product that serves as the reference basis for all calculations regarding impact assessment. Generally, a function can be based on different features of the product under study, such as performance, technical quality, additional services, costs, etc. In the case of electricity, it might be the controllable generation of a certain quantity. It might also be the generation of variable renewable energy in another case. To be clear, the simple comparison of controllable electricity generation (e.g., natural gas combined cycle) to variable renewable energy (e.g., PV) is meaningless if the functional unit is the controlled delivery of electricity. In order to overcome this functional unit hurdle, LCA methods propose the adaptation of system boundaries, which might be coupling PV-based electricity generation with storage or the use of grid-based electricity.

Before reproducing the mathematics, I would like to introduce an interpretation of LCOE, which is rather consistent with discounted cash flow (DCF) analysis and supports the further use of LCOE as a valid indicator, albeit not for a full and comprehensive



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economic assessment of investment activities. Besides cost comparisons, comprehensive assessments need further analysis of the attractiveness of projects, e.g., net present value (NPV) or internal rate of return (IRR), and of market flexibility, e.g., variable cost (VC) [7]. LCOE is a finance-mathematical cost equivalent reflecting the lifetime of a technology, the cost structure, the rates and temporal allocation of the cost components (expenditures), and an adequate return for the investor. Hence, the interpretation leads to LCOE as a break-even value indicating a constant ‘price’ of electricity that is needed as revenue over the lifetime of the technology in order to justify an investment in a particular energy generation facility, covering all expenses and the payment of an acceptable minimal return to investors [8]. This interpretation of LCOE is widely supported (e.g., [7,9]). With this understanding, and keeping in mind functional unit and system boundary prerequisites, LCOE enables the comparison of competing technologies regarding a constant minimum revenue in real terms in order to break even the present value of the cost and a minimum return to the investors. This is different from the prevailing understanding of LCOE, enabling comparison of the cost of different technologies. It is also different from PVCOE, which describes the unit cost of the generation of energy with a specific technology. In the first case, with the consistent DCF-based interpretation of LCOE, the calculus depends on the assumption that the net present value (NPV) of lifetime costs is equal to the NPV of lifetime revenues, which, in fact, requires the project to have an NPV of zero. PVCOE calculation solely represents the cost side of a project focusing on the NPV of lifetime costs, ignoring any time value of electricity generation. It is worthwhile emphasizing that, based on these interpretations, LCOE exceeds PVCOE except in some abnormal and practically irrelevant cases, such as zero or negative fixed and variable OM costs or negative discount rates (I will show this later).

## 2. Literature Review

There is a vast literature using LCOE for technoeconomic analysis of energy technologies. A random selection comprises recent publications on concentrated solar power in Spain [10], utility-scale PV [11], wind power [12], wave energy [13], small wind turbines [14], energy storage and renewable technologies [15,16], carbon capture and utilization [17], power to methane [18], hydrogen [19], and biomass technologies [20]). Comparing renewable and conventional energy technologies, consultancies (e.g., [21]), manufacturers (e.g., [22]) and international institutions (e.g., IRENA [23], IEA [24], and IAEA [25]) also use the indicator for cost assessments. The authors aim to assess technology-specific energy generation, based on new developments, recent technology expertise, new data, and within different global, regional, or national contexts. IRENA highlights that ‘the analysis of costs can be very detailed, but for comparison purposes and transparency, the approach used . . . is a simplified one that focuses on the core cost metrics for which good data are readily available. This allows greater scrutiny of the underlying data and assumptions, improves transparency and confidence in the analysis, while facilitating the comparison of costs by country or region for the same technologies, enabling the identification of the key drivers in any cost differences’ [23]. It also states that the approach ‘. . . is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. This has the advantage, however, of producing a transparent and easy-to-understand analysis’ [23].

A second strand of publications engages in the analysis of LCOE in comparison to financial models and indicators for investment decision-making, such as internal rate of return (IRR), net present value (NPV), and payback time (PB), just to mention a few. Additionally, the focus is on the implications of financial aspects for assessment. A random selection comprises recent publications on economic evaluation methodologies for renewable energy projects [26], financial modeling [27], and financing costs [28–30].

A third strand engages in the critical reviewing of the concept of LCOE and develops methodical adaptations in order to overcome possible deficiencies [31]. Aspects, typically not covered by LCOE assessments, comprise, e.g., externalities [32]. With respect to the

integration of renewable energy technologies, from a system perspective, the question appears what the costs of variable renewables are and how to deal with integration costs. These questions refer to the economics of electricity in a renewable era, as a random selection of publications shows [33–37].

Recently, in two publications, Loewen pronounced a very critical view on LCOE, and the validity of the indicator, especially when used to compare the economics of renewable and conventional energy technologies [1,2]. According to Loewen, LCOE is a metric that distorts comparisons, disfavors resource types with high upfront costs, such as renewable resources vis-a-vis fossil resources, and is not a good metric to use in any context. He states that the distortion is increasing with discount rates and with the length of the analysis period and underpins this critical view mathematically comparing ‘conventional’ LCOE with a new indicator called the present value of the cost of energy (PVCOE).

Loewen’s criticism is radical with respect to the validity and usefulness of the LCOE indicator. However, the widespread and transdisciplinary use of LCOE, mainly by engineers and economists, fundamentally requires confidence in and validity of the indicator, even though further development of the methodological concept of LCOE is necessary as requested in the mentioned literature, especially on the critical reviewing. On the contrary, the following passages show the credibility of LCOE, if used methodically correctly, demonstrating that these radical propositions rely on assumptions concerning technology costs and interest rates, which are practically irrelevant, and from a methodical perspective, ignore the time value of electricity generation.

### 3. The Metrics

#### 3.1. LCOE

The idea of LCOE as the ‘price’ component of a constant minimum return of the project (constant in real terms) for the investor translates to the simple net present value calculation in (1) and (2).

$$\text{NPV (project)} = -\text{NPV of lifetime cost} + \text{NPV of lifetime revenue} \quad (1)$$

With  $C_t$ : cost of project,  $M_t$ : electricity generation;  $N$ : lifetime of the project,  $r$ : discount rate, and  $\bar{p}$ : ‘price’ of electricity (delivered), the NPV is given in (2).

$$\text{NPV (project)} = - \sum_{t=0}^N C_t * (1+r)^{-t} + \sum_{t=0}^N \bar{p} * M_t * (1+r)^{-t} \quad (2)$$

Setting  $\text{NPV} = 0$  leads to the solution of  $\bar{p}$  and the internal rate of return IRR that equals the discount rate for the chosen calculation. With  $C_t$  comprising initial investment cost  $I_0$ , variable  $C_t^v$ , and fixed operation and maintenance (OM) costs  $C_t^f$ , with the simplifying assumptions of constant electricity generation  $M_t = \bar{M}$  and constant variable and fixed OM cost  $C_t^v + C_t^f = \bar{C}$ , some simple mathematical transformations lead to the well-known LCOE formula (3). The uniform present value factor  $\text{UPV} = \frac{(1+r)^N - 1}{r * (1+r)^N}$  results from the general solution of a geometric series of a constant flow and is widely used in life cycle cost analysis [38].

$$\bar{p} = \text{LCOE} = \frac{I_0}{\bar{M} * \text{UPV}} + \frac{\bar{C}}{\bar{M}} \quad (3)$$

Formula (3) corresponds to the simple levelized cost of energy indicator (sLCOE), according to the NREL website [39], used also in Formula (1) in [2]. It can be easily calculated that the higher the investment  $I_0$  and OM cost  $\bar{C}$ , the higher the value of  $\bar{p}$ , and, conversely, the higher electricity generation  $\bar{M}$ , the lower the value of  $\bar{p}$ .

$$\frac{\partial \bar{p}}{\partial I_0} = \frac{1}{\bar{M} * \text{UPV}} > 0 \quad (4)$$

$$\frac{\partial \bar{p}}{\partial \bar{C}} = \frac{1}{\bar{M}} > 0 \quad (5)$$

$$\frac{\partial \bar{p}}{\partial \bar{M}} = \frac{-(I_0 * UPV + \bar{C})}{(\bar{M} * UPV)^2} < 0 \quad (6)$$

### 3.2. LCOE in Relation to PVCOE

Now, the interesting question is whether  $\bar{p} = \text{LCOE}$  always exceeds the present value of cost of energy (PVCOE), the indicator proposed by Loewen, except for the trivial cases of zero discount rate  $r$  or zero project lifetime  $N$  (Figure 1 in [1] and Table 1 in [2]). Loewen interprets the relation  $\frac{\text{LCOE}}{\text{PVCOE}}$  as the LCOE distortion. The question of any distortion is analyzed here irrespective of the validity of the PVCOE indicator in itself which indeed can be questioned from an economic perspective [40].

$$\text{LCOE} > \text{PVCOE?} \quad (7)$$

With the definition of PVCOE from Loewen and the previous assumptions, (8) holds for the present value cost of energy.

$$\text{PVCOE} = \frac{\text{TLCC}}{\sum_0^N M_n} = \frac{I_0 + \bar{C} * UPV}{N * \bar{M}} \quad (8)$$

Inserting (3) and (8) into (7) leads to Condition (9) for LCOE to be greater than PVCOE.

$$\frac{I_0}{\bar{M} * UPV} + \frac{\bar{C}}{\bar{M}} > \frac{I_0 + \bar{C} * UPV}{N * \bar{M}} \quad (9)$$

Mathematically, Condition (9) is fulfilled if (10) holds, which is the case for nontrivial parameter constellations for OM costs  $\bar{C}$ , the uniform present value factor UPV of a geometric series, and the discount rate  $r$  ( $\bar{C} \geq 0; UPV \geq 0; r > 0$ ).

$$I_0 > -\bar{C} * UPV \quad (10)$$

The ‘distortion’, which Loewen argues exists, is the equivalent of the simple mathematical relation of two indicators, which, from a mathematical perspective, must prevail under trivial, respectively irrelevant conditions for variable and fixed OM costs and the discount rate (e.g.,  $OM \leq 0, r \leq 0$ ). From an energy-economic perspective, based on the interpretation of LCOE as the constant price (in real terms) guaranteeing a minimum revenue for the investor to justify an investment, it should be intuitively clear that this price is higher than just the technology cost, ignoring the time value of electricity generation.

### 4. Same Technologies, Different Functional Units

In order to highlight the functional units’ implications for LCOE, let us take a simple example of electricity generation technologies probably to be present in the energy system in 2050, namely coal power, utility-scale PV, and wind-onshore. The data in Table 1 for the technologies and further assumptions such as possible CO<sub>2</sub> certificate prices or discount rates are based on a compilation of the German VEREKON project [41].

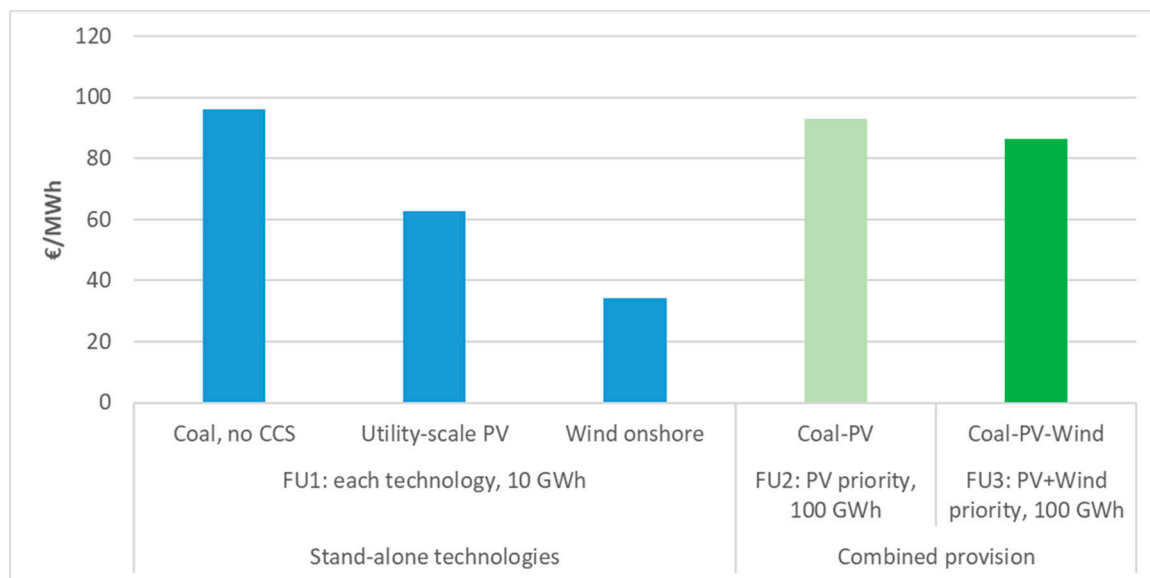
**Table 1.** Technical and cost parameters for exemplary electricity generation.

	Units	Coal, No CCS	Utility-Scale PV	Wind-Onshore Generation
Technical parameters				
Net capacity	MW <sub>el</sub>	600	10	3
Net efficiency	%	46.5	-	-
Full-load hours (FLH)	h/year	4500	1000	3500
CO <sub>2</sub> emission factor	t/MWh <sub>el</sub>	0.34	0	0
Lifetime	year	40	25	25
Cost parameters				
Investment cost	€/kW	1600	500	1000
OM cost	€/kW-year	36	12.5	30
Fuel price	€/GJ	2.79	-	-
CO <sub>2</sub> certificate	€/t	30		
Financial parameter				
Discount rate	%		7.5	

Data source: [41].

Let us further assume different functional units FU1, FU2, and FU3. FU1 is the electricity generation of 10.5 GWh from each of the technologies based on the technology-specific data including full-load hours (FLH) from Table 1. For the example, 10.5 GWh is chosen because this is the maximum generation of the wind-onshore facility. Keep in mind that for coal this is the controllable provision of electricity, whereas, for PV and wind, the provision is variable. FU2 is the electricity generation of 100 GWh by combining coal and PV. In this simplified example, the noncontrollable renewable technology is assigned feed-in priority, and the controllable coal technology is the swing producer, guaranteeing the controlled delivery of 100 GWh of the combined system. FU3 combines coal with PV and wind and, again, generates 100 GWh of electricity. For renewable energy technologies, priority feed-in prevails for PV and wind. For the sake of simplicity, the examples do not recognize the generation unit's flexibility, ramping costs, accurate prediction of renewable energy generation, or other technological characteristics. In order to focus on the functional units' aspect, the example does not pretend to cover a comprehensive analysis of the technologies in a supply system.

Figure 1 shows the resulting LCOEs based on the chosen functional units FU1, FU2, and FU3. For FU1, the LCOE results reflect expectations on the development of the economics of generation technologies, with coal power being relatively expensive, medium-level utility-scale PV in the middle, and wind-onshore as the technology showing the lowest LCOE in terms of standalone variants. In the case of FU2, accounting for the combined provision of electricity by coal and PV, unsurprisingly, the LCOE is lower than the standalone coal solution. However, there is only a small difference (−4%), as the share of PV-based electricity is only 10% in line with the capacities given in Table 1. For FU3, the LCOE further declines compared to standalone coal (−10%), as now, besides PV, wind generation provides 10.5% of the supply, and the coal share reduces to 79.5%.



**Figure 1.** Levelized cost of energy (LCOE) for different functional units and technology combinations.

This simple, probably oversimplistic, example does not claim to demonstrate the adequacy of the chosen FUs for all possible cases and even does not claim to be realistic for future energy systems settings; rather, it has a didactical appeal, demonstrating the necessity of thorough functional unit definition in order to get valid and comparable results.

## 5. Conclusions

This research contributes to the previous literature, demonstrating the credibility and usefulness of LCOE if used methodically correctly. It also shows that recent radical criticisms of the LCOE approach [1,2], denying credibility and usefulness rely on assumptions concerning technology costs and interest rates, which are practically irrelevant, and from a methodical perspective, on a misconception of the time value of electricity generation.

LCOE is an indicator widely used to compare the economics of energy technologies. It is also widely accepted that the use of LCOE as an exclusive indicator for energy technologies is insufficient for a comprehensive assessment, let alone for an investment decision. Yet, it is accepted as an important indicator for energy technology assessment, which enables a transparent and easy-to-understand analysis not only used for academic purposes but also by international institutions such as IRENA, IEA, and others.

However, Loewen and Szymanski express general skepticism toward the use of the indicator. Whereas Loewen's focus is on the definition of the LCOE indicator and its comparison to another indicator—the present value of the cost of energy—Szymanski uses the mathematical mean value theorem in order to discredit the validity and rigidity of LCOE. Although discussions on the pros and cons of commonly used indicators in different research areas are very much needed, both their arguments are unconvincing. Loewen especially uses a concept of the present value of the cost of energy, which is not in line with the basics of economic present value calculation and ignoring the time value of monetary flows. It also does not recognize the relations between expenditures for generating electricity in time, cost of electricity generation as LCOE, and the hurdle rate for an electricity price to justify an investment in energy technology. This replica to Loewen particularly shows that the distortion he asserts to exist by comparing LCOE with his adjusted indicator present value cost of energy (PVCOE) does not exist and, mathematically, only exists in the case of trivial parameters for variable and fixed operating and maintenance costs (OM) and discount rates ( $r$ ) (e.g.,  $OM \leq 0$ ,  $r \leq 0$ ).

Bringing in the rather continuative interpretation of LCOE as a break-even value, indicating a constant 'price' of electricity that is needed as revenue over the lifetime of

the technology in order to justify an investment in a particular energy generation facility, covering all expenses and the payment of an acceptable minimal return to investors, demonstrates the attractiveness of the indicator. However, to avoid meaningless comparisons of energy technologies demands a thorough consideration of the system boundaries and functional units. Using a simplified example, this replica demonstrates huge differences for the LCOE of coal-based electricity generation, utility-scale PV, or wind-onshore generation, based on standalone use of the technologies, which, in principle, expresses basic expertise. It also expresses different LCOEs across different functional units, which, in turn, depend on the expected generation of electricity, the technologies needed to deliver, and possible technology combinations. These methodical elements describe the technological options and the need to take into account the generation by different electricity sources, especially in terms of the amount and quality of electricity, in order to fulfill a more comprehensive assessment. Keeping in mind that the examples fully demonstrate this, and acknowledging that a comprehensive technology assessment and comparison requires a set of indicators, the replica underpins the usefulness and validity of LCOE.

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