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ORIGINAL PAPER

Applications of the levelized cost concept

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Abstract

Levelized cost is a life-cycle cost measure that aggregates investment expenditures and operating costs into a unit cost figure. So far, most applications of this concept have originated in relation to energy technologies. This paper describes the role of the levelized cost concept in cost accounting and synthesizes multiple research streams in connection with electricity, energy storage, hydrogen and carbon capture. Finally, we sketch multiple potential future applications of the levelized cost concept.

Keywords Levelized cost · Full cost · Levelized cost of energy · Levelized cost of energy storage · Levelized cost of hydrogen · Levelized cost of carbon

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1 Introduction

The concept of levelized cost has a long history in the field of energy, frequently referred to as Levelized Cost of Energy (LCOE) (Farrar and Woodruff 1973). The main use of this concept has been to provide a unit cost measure, e.g., euro per kilowatt hour (kWh), to compare alternative energy sources in terms of their cost competitiveness. As a life-cycle cost measure, LCOE aggregates a share of the capital expenditures required for the initial capacity investment with operating expenditures required for the periodic energy generation. Thus, the unit cost of capacity is not a cash outflow, but an allocated cost. For many energy sources, e.g., nuclear, solar, and wind power, this cost component is in fact the dominant part of the overall LCOE.

A commonly accepted verbal definition of the LCOE dates back to a study by MIT on the future of coal (Massachusetts Institute of Technology 2007, Chapter 3). In their study, LCOE is calibrated as the break-even value that must be achieved on average by the energy sold in order to adequately compensate a project’s suppliers, employees and investors for their contributions. This article adopts the formal and generic Levelized Cost (LC) concept in Reichelstein and Rohlfing-Bastian (2015). Accordingly, LC is calibrated as the average unit revenue that allows an investment project to break even (achieve a net present value of zero) over its entire life cycle.

Earlier studies have shown that the LC exceeds the measure of full cost, as usually defined in the cost accounting literature. The reason is that the standard definition of full cost does not include charges for interest, nor those that arise from corporate income taxes. In contrast, these types of expenditures are included in the LC metric in order to make the cost metric compatible with the net present value criterion. Here, we show that even if interest charges are accounted for in an approximate manner, as advocated in some cost accounting textbooks (Friedl et al. 2022), the resulting full cost metric will again be consistently below the levelized product cost.

Conceptualized as a life-cycle cost measure, LC is generally not the relevant cost for short run decisions, such as pricing or production volume decisions. Once an investment decision has been made, the LC metric carries significant sunk cost components. Under certain conditions, however, LC emerges as the relevant unit cost measure for long run decisions such as irreversible capacity investments. In the context of electricity generation, LCOE does allow for an “apples-to-apples” cost comparison of any two similar generation technologies, e.g., nuclear versus coal-fired power plants. In order to assess the competitiveness of electricity obtained from renewable energy sources versus that obtained from fossil fuel sources, however, the LCOE metric is by itself not sufficient. Instead, it must be supplemented with other metrics that effectively summarize the pattern of power generation and power pricing in real time.

Moving beyond electricity, we review multiple applications and variants of the levelized cost concept. In particular, this article covers unit cost measures that have been used to assess improvements in the economic viability of emerging technologies such as energy storage, hydrogen, and carbon capture and sequestration.

The remainder of the paper is organized as follows. Section 2 presents a formal LC framework and relates this metric to the incumbent cost accounting literature.

Section 3 reviews specific applications of the levelized product cost concept in connection with different energy related technologies. Section 4 describes potential future applications. We conclude in Sect. 5.

2 Levelized cost concept

2.1 Model framework

The levelized cost of a product is a unit cost measure that aggregates the expenditures resulting from an upfront capacity investment and subsequent periodic operating expenditures. A commonly known verbal definition has been provided in a 2007 study by MIT on the future of coal. The MIT study defines LC as *the constant dollar price that would be required over the life of the investment project to cover all operating costs, payment of debt and accrued interest on initial project expenses and the payment of an acceptable return to investors* (Massachusetts Institute of Technology 2007, Chapter 3). According to this definition, LC is a break-even value insofar as it yields the minimum price per unit of output that an investor would need in order to break even over the life-cycle of an initial capacity investment. Importantly, the cost measure is to be aligned with present value considerations, as the cost measure requires an acceptable return to both equity and debt investors. While the above definition does not explicitly mention taxes, in particular corporate income taxes, these can be included in the category of operating costs.[1]Reichelstein and Rohlfing-Bastian (2015) provide a formalization of the MIT (2007) definition. They represent the levelized cost as the unit cost of a product associated with an initial investment that allows k units of the product to be produced initially and $x_t \cdot k$ units to be produced in period t. Here, $x_t \leq 1$ is a degradation factor to reflect the possibility that the initial production capacity may diminish over time. Formally,

$$LC(k) = w + f(k) + c(k) \cdot \Delta. \tag{1}$$

In this definition of the levelized cost, the time-averaged unit variable cost is given by:

$$w \equiv \frac{k \cdot \sum_{t=1}^{T} w_t \cdot x_t \cdot (1+r)^{-t}}{L(k)}.$$

The numerator represents the total discounted future variable cost, assuming $x_t \cdot k$ units are produced in period t, with $1 \leq t \leq T$, w_t represents the unit variable cost in period t, and r denotes the applicable cost of capital. To obtain the time averaged unit variable cost, the numerator is divided by the *levelization factor*

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[1] Earlier studies have also adopted a simplified version of the levelized cost concept, for instance, by calculating LC as the annualized initial investment and the total annual cost divided by the total units of output. Clearly, this approach does not presume the payment of a return to investors (Tegen et al. 2012; Brown and Foley 2015).

$L(k) \equiv L \cdot k \equiv \sum_{t=1}^{T} x_t \cdot (1+r)^{-t} \cdot k$. It measures the total discounted output that is attainable from the initial capacity investment over the entire planning horizon of T periods.

The second component of LC is the time-averaged unit fixed cost, given by:

$$f(k) \equiv \frac{\sum_{t=1}^{T} F_t(k) \cdot (1+r)^{-t}}{L(k)},$$

where $F_t(k)$ is the total fixed operating cost in period t that is required for a facility scaled to size of k units of production capacity. Finally, the unit cost of capacity is defined as:

$$c(k) \equiv \frac{v(k)}{L(k)},$$

with $v(k)$ denoting the initial capacity investment expenditure for a facility scaled to size of k units of production capacity. To reflect the payment of income taxes, the LC needs to include a tax factor that acts as a multiplier on the unit cost of capacity:

$$\Delta = \frac{1 - \alpha \cdot \sum_{t=0}^{T} \hat{d}_t \cdot (1+r)^{-t}}{1 - \alpha}.$$

Here, α represents the effective corporate income tax rate and $\hat{d}_t$ is the share of the initial investment that can be written off in period t as a depreciation expense for income tax purposes. The possibility of $\hat{d}_0 > 0$ reflects that the tax code may allow for partial initial expensing. Assuming the $\hat{d}_t$ sum up to one, the tax factor will exceed 1, unless the entire capacity investment can be fully depreciated in the initial year of acquisition. In general, a more accelerated depreciation schedule will increase the depreciation tax shield and lower the LC through a smaller tax factor Δ.

Suppose next that the firm produces $x_t \cdot k$ units of output in period t and furthermore sells each unit at the constant price p. This would result in after-tax cash flows of $CFL_0 = -v(k)[1 - \alpha \cdot \hat{d}_0]$ and

$$CFL_t = (p - w_t) \cdot x_t \cdot k - F_t(k) - \alpha \cdot I_t.$$

Here, I_t denotes the firm's taxable income:

$$I_t = (p - w_t) \cdot x_t \cdot k - F_t(k) - \hat{d}_t \cdot v(k).$$

When discounted at the interest rate r, the present value of the stream of after-tax cash flows CFL_t from 0 to T becomes:

$$NPV(k) = -v(k)[1 - \alpha \cdot \hat{d}_0] + \sum_{t=1}^{T} \big((p - w_t) \cdot x_t \cdot k - F_t(k) - \alpha \cdot I_t\big) \cdot (1+r)^{-t}.$$

By definition, LC is the unit revenue (p) that yields $NPV(k) = 0$. Solving the above linear equation, one obtains $p = LC(k)$, thus establishing $LC(k)$ as the critical price at which the investor breaks even on an investment in k units of capacity that allows $x_t \cdot k$ units of output to be produced in subsequent time periods.

In concluding this section, we note that in the special case of a *constant returns to scale technology*, i.e., $v(k) = v \cdot k$ and $F_t(k) = F_t \cdot k$, the levelized cost measure, $LC(k)$, reduces to a constant unit cost, denoted by LC, as it is independent of the scale of the investment. A further simplification is obtained in a *stationary environment* where $F_t = F$, $w_t = w$ and $x_t = 1$. In that case, the above levelization factor, L, reduces to $A(r, T)$, where $A(r, T)$ is the annuity factor, which makes an investor (with cost of capital of r) indifferent between receiving 1 Euro in each of the next T years, or receiving $A(r, T)$ Euro today.

2.2 Relation to full cost

While the levelized product cost concept, as introduced above, is a comprehensive life-cycle cost measure that aggregates fixed and variable costs incurred over time, this cost measure can generally not be equated with the full cost of a product, as commonly defined in the cost accounting literature. To establish the relationship between these two cost concepts, consider a setting with constant returns to scale in a stationary environment. In such settings, cost accounting books (Datar and Rajan 2018) typically define the unit full cost of a product, of which q_t have been produced in period t as:

$$FC_t(q_t \mid k) = w + \frac{f \cdot k}{q_t} + \frac{d_t \cdot v \cdot k}{q_t}.$$

Here q_t denotes the quantity of the product produced in period t and $\{d_t\}_{t=0}^{T}$ denotes a depreciation schedule that the firm uses for internal, and possibly also external, reporting purposes. Assuming full capacity utilization, i.e., $q_t = k$ in a stationary environment, we note that if the initial investment is depreciated according to the straight-line rule, that is $d_t = \frac{1}{T}$ for $1 \leq t \leq T$, then $LC > FC_t(k \mid k)$ for all t. This observation follows directly because the tax factor Δ exceeds 1, and further:

$$c \equiv \frac{v}{\sum_{t=1}^{T} (1 + r)^{-t}} > \frac{v}{T}.$$

The preceding inequality essentially reflects that the above measure of full cost does not include interest expenses. To account for the time value of money, it is useful to consider the following extended full cost measure:

$$FC_t^1(q_t \mid k) = w + \frac{f \cdot k}{q_t} + \frac{\left[d_t + r \cdot \left(1 - \sum_{i=1}^{t-1} d_i\right)\right] \cdot v \cdot k}{q_t} \cdot \Delta.$$

Once the cost of capacity includes interest charges on the remaining book value of the capacity asset and the cost measure also includes the tax factor Δ, the extended cost measure $FC_t^1(q_t \mid k)$ becomes compatible with the levelized cost measure LC. Key to this compatibility is that the chosen depreciation schedule reflects the intertemporal degradation of the asset, i.e., the pattern of the parameters $\{x_t\}_{t=1}^{t=T}$ (Reichelstein and Rohlfing-Bastian 2015). Specifically, given a stationary environment ($x_t = 1$) and the assumption of full capacity utilization ($q_t = k$), it follows that $LC = FC_t^1(k \mid k)$ for all t, provided the d_t are calculated according to the annuity method.[2] Furthermore, for any given pattern of degradation factors $\{x_t\}_{t=1}^{t=T}$, there always exists a corresponding depreciation factor such that $LC = FC_t^1(k \mid k)$ for all t (Rogerson 2008).

Given an arbitrary degradation pattern $\{x_t\}_{t=1}^{t=T}$ and depreciation schedule $\{d_t\}_{t=1}^{t=T}$, it is still true that the stream of extended full costs $FC_t^1(k \mid k)$ will be equal to LC, on average. Specifically, it follows from the conservation property of residual income (Preinreich 1938 and Lücke 1955) that:

$$\sum_{t=1}^{T} FC_t^1(k \mid k) \cdot (1+r)^{-t} = LC.$$

Some cost accounting textbooks (Friedl et al. 2022) account for interest charges corresponding to the initial capacity investment by adopting straight-line depreciation and imputing an interest charge equal to half of the initial investment in each period. This approach results in an unambiguous relationship between LC and the full cost measure:

$$FC_t^2(q_t \mid k) = w + \frac{f \cdot k}{q_t} + \left(\frac{1}{T} + \frac{r}{2}\right) \cdot \frac{v \cdot k}{q_t} \cdot \Delta.$$

Proposition 1 *Suppose a stationary environment with constant returns to scale. Given full capacity utilization, i.e.*, $q_t = k$,

$$LC > FC^2(k \mid k)$$

for all $1 \leq t \leq T$.

The preceding result shows that while it is true that with straight-line depreciation the asset's remaining book value is, on average, equal to half of the initial investment, the resulting approximation of the imputed interest charges creates a systematic bias such that the resulting full cost measure $FC^2(k \mid k)$ is less than the levelized product cost measure LC. The intuition for this result is that the underlying approximation understates the applicable book value for the first $\frac{T}{2}$ years, yet the interest charges in these years receive relatively large weights due to discounting.

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[2] Under the annuity method, the d_t satisfy $d_{t+1} = d_t \cdot (1+r)$, and d_1 is determined by the balancing requirement that the sum of all d_t is equal to 1.

2.3 Decision relevance

Managerial accounting textbooks emphasize that for different types of managerial decisions, pertaining, for instance, to investments, product pricing and production volume, different cost measures are relevant. For short-run decisions, for instance, managerial accounting textbooks recommend the use of incremental costs rather than full cost measures, due to the fact that full cost measures generally include sunk costs. For long-run decisions, most managerial accounting textbooks do not point to a single unit cost measure, but instead recommend a corporate finance approach that focuses on the discounted stream of future cash flows (Hotelling 1925; Schneider 1961; Mahlert 1976; Swoboda 1979; Luhmer 1980; Kistner and Luhmer 1981; Küpper 1984; Schweitzer et al. 2015; Datar and Rajan 2018). In contrast, Mahlert (1976) and Swoboda (1979) advocate for the use of unit cost measures that are consistent with a corporate finance approach seeking to maximize the net present value of the long-run decision under consideration. In that vein, Küpper (1985) develops guidelines for cost measures grounded in investment theory. A recent synthesis is provided in Ewert et al. (2023).

As a unit cost measure, LC has been shown to be the relevant cost for certain long-run decisions involving capacity investments. Consider, for example, a setting where a firm has to choose between two production technologies that differ in both their required initial capital expenditures as well as their periodic operating costs. The two technologies would result in the same capacity level, k and be subject to the same degradation pattern $\{x_t\}_{t=1}^{t=T}$. Suppose further that in each subsequent period, the sales revenue attainable for each unit of output exceeds the variable cost and therefore the firm will always exhaust the available production capacity, that is $q_t = x_t \cdot k$. In such specific settings, the LC measure then provides the relevant cost in the sense that the technology with lower the LC always generates the higher net present value. This claim also applies in environments where the decision maker faces uncertainty regarding the attainable future sales revenues. The argument here builds directly on the reasoning provided in Sect. 2.1 above, showing that the LC measure is the effective unit cost measure in a net-present value calculation.

Earlier literature has pointed out that LC is not the relevant cost metric for ranking the competitiveness of power generation technologies based on fossil fuels, such as coal or natural gas, in comparison to renewable energy sources, such as wind and solar photovoltaic (PV) installations (Joskow 2011 and Hirth 2013). While both technologies generate the same output (electricity), they differ substantially in their cost structure. Renewable electricity requires a relatively high upfront capital expenditure but, in contrast to fossil fuel based generation, entails almost no variable cost. Nonetheless, a simple comparison of the levelized costs would be misleading in evaluating the profitability and competitiveness of these technologies. Contrary to the arguments provided in the previous paragraph, the renewable power generation source is restricted in producing electricity and revenues during those hours of the year when the natural resource, i.e., the sun or the wind, is available. Electric power generated from fossil fuels, on the other hand, is essentially dispatchable allowing the plant to tailor its output to the revenues available at different hours of the year.

To obtain a relevant cost measure for comparing dispatchable and intermittent power sources, Reichelstein and Sahoo (2015) argue that the levelized cost metric should be adjusted by a co-variation coefficient. As the name suggests this coefficient captures the covariance between electricity generated and the market prices available for electricity at different points in time. The co-variation coefficient is always greater than zero and exceeds one only if there is a positive correlation between the hours of high output generation and above average market prices for electricity. Investment in a renewable power generation source is shown to be profitable, in the sense of a non-negative net present value, if the average price of electricity is at least as large as the LC divided by the co-variation coefficient.[3] In the economics literature, marginal cost is arguably the most common measure of relevant cost, at least in connection with decisions concerning production volume and pricing. Under certain conditions, LC can be identified with the long-run marginal cost of a product. Reichelstein and Rohlfing-Bastian (2015) argue this point in a model setting of a competitive industry in which a large number of firms have access to the same stationary constant returns to scale technology. Demand in each period is subject to random shocks. Given initial capacity investments, firms act as price takers with the consequence that the product price in any given period is either equal to the short-run marginal (variable) cost in case there is excess capacity, or, if the industry's aggregate capacity is fully utilized, the equilibrium price is equal to consumers' willingness to pay at the aggregate capacity level. The main result then is that in equilibrium the initial aggregate capacity level will be chosen such that the expected market price is equal to the LC in each subsequent period. This finding identifies the LC as the long-run marginal cost to the extent that in a competitive equilibrium the (expected) market price "must" be equal to firms' long-run marginal cost.

The LC concept presented here assumes one upfront capacity investment. In the earlier literature on capital accumulation, e.g., Jorgenson (1963) and Arrow (1964), firms make a sequence of overlapping capacity investments in an infinite horizon setting.[4] In these models the cost of *one unit of capacity made available for one period of time* can be identified unambiguously. It can be shown to be equal to:

$$c = \frac{v}{\sum_{t=1}^{T} x_t \cdot (1+r)^{-t}},$$

which aligns with the definition of the capacity cost component of the LC in Sect. 2.1 above. Some microeconomics textbooks, e.g., Carlton and Perloff (2005), define the long-run marginal cost of a product as:

$$LMC = w + v \cdot (r + \delta),$$

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[3] One implication of this result is that if electricity is sold at a constant price under a so-called Power Purchasing Agreement (PPA), then the technology that has the lower LC is more profitable, regardless of whether the generation technology is dispatchable or intermittent.

[4] More recent studies on capital stock accumulation by firms have examined the impact of the choice of depreciation schedules on the relation between historical and long-run marginal cost (Rogerson 2008; Rajan and Reichelstein 2009; Nezlobin 2012; Nezlobin et al. 2012).

where δ is introduced as a parameter that reflects “economic depreciation”. If economic depreciation is equated with capacity degradation, which furthermore is proportional to the remaining capacity in each period, then $\delta = 1 - x$ and $x_i = x^i$. Finally, if the planning horizon is set at $T = \infty$, then

$$c = \frac{v}{\sum_{t=1}^{\infty} x^t \cdot (1+r)^{-t}} = v \cdot (r + 1 - x) = v \cdot (r + \delta).$$

Thus, the microeconomic operationalization of LMC coincides with the levelized product cost, subject to suitable parametric specification and the absence of fixed operating costs and income tax effects.

LC can also be established as the relevant cost for a monopolist seeking to determine an optimal expansion of capacity. Suppose, for simplicity, the monopolist faces an identical demand curve in each of the next T periods, and furthermore has access to a stationary constant returns to scale technology. A central result in Reichelstein and Rohlfing-Bastian (2015) shows that the optimal capacity level is such that the marginal revenue at the production volume corresponding to full capacity utilization in each period is equal to the LC for the product in question. Thus, this result extends the standard textbook prescription of a monopolist choosing the optimal output level such that marginal revenue is equal to marginal cost.

The preceding result can be extended to environments where demand in future periods is subject to random shocks and therefore the monopolist will not exhaust the entire capacity available unless the marginal revenue at the capacity limit exceeds the short-run variable (marginal) cost. In such settings with demand uncertainty it can be shown that the optimal capacity investment is such that the expected marginal revenue evaluated at the sequentially optimal output quantity (given the optimal investment) is equal to the LC. Uncertainty about future demand essentially entails a call option. This real option becomes more valuable with a higher level uncertainty, thus resulting in larger capacity investments.

3 Energy related applications

Dating back to Rosenthal et al. (1965), the concept of levelized product costs appears to have emerged from the literature on electricity generation. In the intervening years, the Levelized Cost of Electricity has become a standard metric approach for benchmarking the economics of different electricity generation technologies (Tran and Smith 2018; Aldersey-Williams and Rubert 2019). Variants of the original LCOE have been adapted and expanded in energy subfields other than electricity. For instance, the Levelized Cost of Energy Storage (LCOS) presents a life-cycle cost measure of electricity storage services provided by batteries, pumped-hydro, or mechanical storage devices. For hydrogen, the Levelized Cost of Hydrogen (LCOH) provides a cost metric that is increasingly used to assess the prospects for a hydrogen economy. Since hydrogen offers multiple applications beyond energy storage, we view it as a separate research stream in this section. Finally, we cover several recent studies that have calculated a Levelized Cost of Carbon (LCOC) in connection with facilities that can capture and

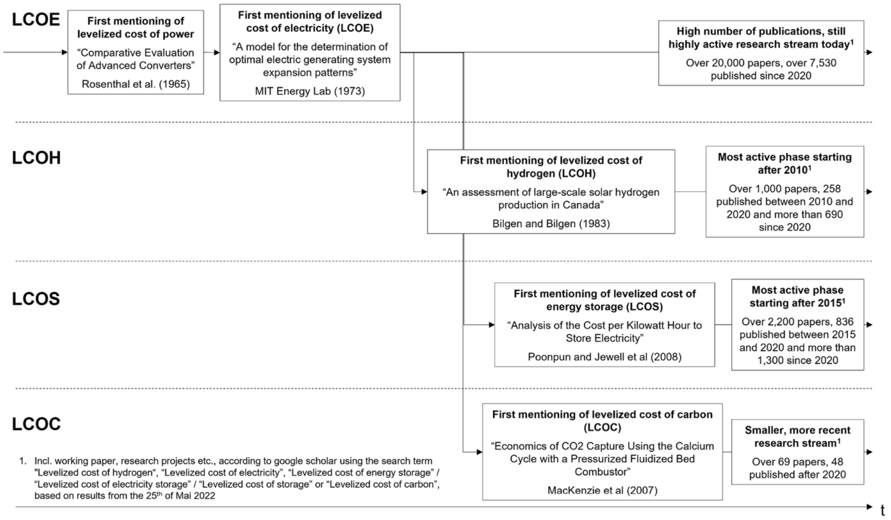

Fig. 1 Emergence of the levelized cost metric for electricity, energy storage, hydrogen and carbon

sequester CO_2. Figure 1 provides a graphic overview of the history of these literature streams.

3.1 Levelized cost of electricity

The term "Levelized Cost of Electricity" goes back at least to the 1973 publication by Farrar and Woodruff (1973). Since then, the LCOE metric has been widely relied on to compare and rank the cost of producing electricity with alternative generation technologies (Short et al. 1995). Power generation provides a natural use case for a life-cycle cost concept that seeks to assess the unit economics of alternative generation technologies that differ substantially in terms of their fixed and variable cost structure; see, for instance, Reichelstein and Yorston (2013); Hernández-Moro and Martínez-Duart (2013); Branker et al. (2011); Massachusetts Institute of Technology (2007).

As a unit cost measure, LCOE is usually expressed in terms of dollars (or Euro) per kWh. The expenditure required for the capacity investment in power generation is expressed in dollars per kilowatt (kW). Of critical importance for the unit cost of capacity (the variable c in Sect. 2) is the levelization factor L, which in electricity related applications typically takes the form:

$$L = \sum_{t=1}^{T} x_t \cdot (1+r)^{-t} \cdot 8{,}760 \cdot CF_t.$$

Here, 8,760 refers to the number of hours in the year, while CF_t denotes the average capacity utilization factor in year t. For dispatchable power generation sources, CF_t could in principle be close to one, i.e., the power plant is a base-load generation facility capable of running at full capacity around the clock (except for select hours of scheduled maintenance). For renewable energy sources, such as solar PV and wind power, the capacity factor CF_t is exogenously determined by the availability of the underlying natural resource. For these technologies, the capacity factors are usually below 0.5, and sometimes as low as 0.15, thereby increasing the unit cost of the corresponding LCOE.

A fundamental drawback of wind and solar PV power is not only their relatively low capacity factors, but also their intermittency, that is, the plant's inability to deliver energy during certain hours of the year. For this reason, it would not be appropriate to conclude that a renewable energy source, which has a lower LCOE than its dispatchable counterpart running on fossil fuels, will also be more profitable in terms of a higher net present value (Joskow 2011; Hirth 2013). Recent studies seek to provide a unified economic assessment framework by introducing the concept of a levelized profit margin that takes into account the correlations between hourly electricity prices and capacity factors (Reichelstein and Sahoo 2015; Glenk and Reichelstein 2022a). The study by Glenk and Reichelstein (2022a) concludes that in both California and Texas the levelized profit margin of natural gas power plants has remained roughly constant despite the tangible decline in the capacity utilization factor of these plants. Yet, this effect has effectively been compensated by higher sales revenues during hours of high electricity prices, typically when renewable energy sources do not feed electricity to the grid. In contrast, both wind and solar PV have seen improved levelized profit margins in large part due to falling life-cycle costs.

For individual power generation technologies, the LCOE metric has been used to gauge the magnitude of cost declines due to learning-by-doing. For example, Hernández-Moro and Martínez-Duart (2013) estimate the LCOE trajectory of solar PV and concentrated solar power (CSP) using learning rates. They find that in comparison to concentrated solar power, solar photovoltaic power generation exhibited a stronger LCOE decline. In the context of wind power, Glenk et al. (2021) find that for the years 1990–2020, the LCOE of wind power has declined at a rate of approximately 23% with every doubling of cumulative deployments. While the capacity acquisition cost of wind turbines (the parameter v in Sect. 2) has not declined nearly that quickly, the overall drop in the LCOE of wind power reflects a significant "denominator effect." Specifically, the capacity factor, CF, of wind turbines has improved substantially, owing to improved materials that entail lower frictions in the rotation of the turbines.

The LCOE metric has also been prominent in studies seeking to evaluate the effect of new regulations, including subsidies and charges for carbon emissions. These studies are important in the context of the global energy transition as governments around the world seek to accelerate the expansion of new low-emission power sources through targeted subsidies. For example, Reichelstein and Yorston (2013) found that in 2013 the LCOE of solar PV in the U.S. would have increased by approximately 70% in the absence of the investment tax credit (ITC) and the availability of an accelerated tax depreciation schedule. Taken together, these two incentive provisions lowered the tax factor (the variable Δ in Sect. 2) from approximately 1.3 to 0.8.

Anticipating the reduction in the ITC for solar PV in the US from 30% to 10%, as specified in the regulations at the time, Comello and Reichelstein (2016) calculated a gradual step-down in the ITC that would leave the LCOE unchanged, provided the investment cost in solar PV systems would continue on its historical decline path. Similarly, Ouyang and Lin (2014) estimate the LCOE for solar PV, wind and biomass in China in order to project the subsidies required to support further expansion of renewables. Simsek et al. (2018) conduct a related study in the context of concentrated solar projects in Chile. Finally, Comello et al. (2018) examine solar PV's competitive position in the U.S. and its potential evolution through technological advances and supportive public policies, including federal ITCs.

In concluding this subsection, we mention several papers that have sought to embed the LCOE metric in a broader context. Xu et al. (2021) adopts a modified LCOE approach in evaluating policies for additional offshore wind production in six Chinese provinces. Darling et al. (2011) focus on highlighting sensitivity and uncertainty in LCOE calculations by proposing a new method for solar PV that relies on parameter distributions of instead of point estimates. Bruck et al. (2018) introduce an expanded LCOE framework, which considers penalty payments for violating contractual minimum or maximum purchase limits.

3.2 Levelized cost of energy storage

The intermittency of renewable electricity generation has created a growing need for energy storage, in particular the storage of electric power. The Levelized Cost of Energy Storage (LCOS) is a generic unit cost measure that allows for a comparison of alternative energy storage services that can be provided, for instance, by a battery, a closed loop pumped hydro system or a mechanical storage device. In terms of the system acquisition, every energy storage system requires both a power and an energy storage component. The power component relates to the amount of energy that can be charged or discharged at any given point in time. Its capacity is typically measured in kW. The size of the energy storage component, in contrast, is measured in kWh. It indicates the total amount of energy that can be charged and discharged in one cycle. Combining these two system components, Comello and Reichelstein (2019) decompose the overall levelized cost of energy storage as follows[5]:

$$LCOS = LCOEC + \frac{1}{D} \cdot LCOPC.$$

Here, LCOEC represents the levelized cost of the energy storage component and LCOPC the levelized cost of the power component. The power component is multiplied by the inverse of the duration, D, which indicates the time required to fully charge or discharge the storage device, assuming the charge or discharge function is performed at maximum capacity. Formally, the duration of the storage device is given by:

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[5] Comello and Reichelstein (2019) abbreviate the levelized cost of energy storage as LCOES.

$$D = \frac{k_p}{k_e}$$

where k_p and k_e represents the size of the power and energy component, respectively. To illustrate the duration concept, batteries that are sold off-the shelf for residential applications frequently have a duration of either two, four or six hours.

The LCOS metric is calibrated as the minimum service fee per unit of energy discharged that an investor will need to receive in order to break even on the initial acquisition of the storage system. This calculation is critically dependent on the number of charge and discharge cycles per year and the round-trip efficiency of the storage device. The round-trip efficiency factor (denoted by η, with $0 \leq \eta \leq 1$) gives the percentage of the energy that can ultimately be discharged. Conversely, $1 - \eta$ is the percentage of the energy lost in the charge and discharge process. If the service fee per kWh discharged is p^o, the overall net present value of the investment becomes:

$$NPV(k_p, k_e) = \sum_{t=1}^{T} N \cdot p^o \cdot \eta \cdot x_t \cdot k_e \cdot (1 + r)^{-t} - v_p \cdot k_p - v_e \cdot k_e.$$

Here, the variables x_t and T are as introduced in Sect. 2, N is the number of annual charge and discharge cycles, while v_e and v_p represent the unit acquisition costs for the energy storage and power component, respectively. Setting the above equation for the $NPV(k_p, k_e)$ equal to zero, Comello and Reichelstein (2019) show that $p^o = LCOS$ is the break-even service fee per kWh for a storage device that initially can store at most k_e kWh of energy in N cycles per year, subject to the device (dis) charging at most k_p kW of power at any given point in time.

The above definition of LCOS as the break-even service fee per unit of energy discharged is consistent with existing studies (Jülch et al. 2015; Pawel 2014; Smallbone et al. 2017; Rodby et al. 2020). In addition to LCOS, several papers discuss related metrics (Belderbos et al. 2017). Lai and McCulloch (2017) proposes a metric labelled *levelized cost of delivery* for a combined solar PV and energy storage system. In connection with battery storage, Rodby et al. (2020) construct a model that allows for storage capacity degradation with the possibility of rebalancing. They find that investors can reduce the overall resulting LCOS by oversizing the battery in the first place. In connection with behind-the-meter battery installations, Comello and Reichelstein (2019) examine the optimal size of a battery system for households with a solar PV rooftop system. Storing the electricity generated by the rooftop system allows the household to economize on grid electricity purchases. An optimally sized battery must balance the benefits of reduced electricity purchases against the LCOS of the battery system.

As a generic unit cost measure, LCOS allows for a comparison of competing storage technologies that can be deployed for alternative use cases. While multiple factors ultimately shape this cost comparison, recent studies have focused on roundtrip efficiency, discharge cycles per period and recycling costs (Mostafa et al. 2020; Rahman et al. 2020; Schmidt et al. 2019). In terms of alternative storage technologies, recent studies have compared li-ion batteries, lead-acid batteries, vanadium redox flow batteries, flywheels, supercapacitors, pumped hydro-storage, pumped heat, power-to-gas (hydrogen), liquid air and compressed air (Jülch et al. 2015; Poonpun and Jewell 2008; Schmidt et al. 2019; Steckel et al. 2021; Smallbone et al. 2017; Xie et al. 2019).

3.3 Levelized cost of hydrogen

In the transition towards a decarbonized energy economy, hydrogen is increasingly viewed as a potentially valuable energy carrier. The list of potential use cases for hydrogen comprises fuel for transport (Jones 2012; Van Renssen 2013; Goodall 2017), energy storage for industrial heat and power (Jacobson 2016; Zakeri and Syri 2015; Evans et al. 2012; Energy 2016), or a feedstock for chemicals processing (Schulze et al. 2017). At the same time, some observers question the economic viability of hydrogen on account of its considerable primary energy requirements and its high production cost.

Recent discussions about the emergence of a hydrogen-based energy economy have focused on electrolytic hydrogen, where the H_2 molecule is obtained by infusing electric current into water. In contrast, traditional "gray" hydrogen is obtained from natural gas (methane) through a steam methane reforming process. If the CO_2 emissions that arise in connection with steam methane reforming (amounting to about 2% of global emissions) are captured and sequestered, the resulting hydrogen is usually labeled "blue". In subsidizing the production of "green" hydrogen, the European Union mandates that the required electricity come from renewable power sources. Regardless of the applicable color scheme, the levelized cost of hydrogen is usually defined as the break-even value per kilogram of H_2 that an investor would need to obtain in the marketplace in order to recover the expenditures associated with the initial capacity investment as well as all subsequent operating costs.[6]

Parkinson et al. (2019) calculate the LCOH of twelve different hydrogen production technologies. Their research indicates that while fossil-fuel-based hydrogen production remains the most affordable option, it only provides a modest level of carbon reduction. Grimm et al. (2020) use the LCOH to compare the production costs of two solar-assisted hydrogen production technologies. Minutillo et al. (2021) investigate the costs of different water electrolysis plant sizes and electricity configurations to re-fuel hydrogen with smaller on-site production units. Franco et al. (2021) rely on the LCOH metric to assess the costs of different offloading pathways for hydrogen production with offshore wind farms. Glenk and Reichelstein (2019) demonstrate that the economics of green hydrogen improves considerably if the initial investment is structured as a hybrid system that combines electrolyzer capacity with a renewable energy source. With electricity prices fluctuating increasingly across the hours of the year, electric power obtained from the renewable power source can then be dispatched to the grid during hours of relatively high prices, or alternatively converted to hydrogen through electrolysis during off-peak hours for

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[6] Some studies have considered closely related life-cycle cost measures; see, for instance, Guerra et al. (2019); Khzouz et al. (2020); Lee et al. (2009).

electricity prices. The key to favorable LCOH values is that the size of the electrolyzer is chosen optimally in relation to the size of the power generation facility. Such hybrid energy systems will be eligible for significant subsidies under both the Inflation Reduction Act in the U.S. and the green hydrogen initiative of the EU.

Electrolyzer technologies have also experienced significant learning effects in recent years. These gains have resulted in both substantial savings on the system prices for electrolyzers and higher conversion efficiencies for electrolytic processes. So-called reversible fuel cells have seen particularly steep learning effects (Glenk and Reichelstein 2022b). A significant advantage of reversible fuel cells is that they can run bi-directionally, that is, they can either convert water and electricity to hydrogen, or, in the opposite direction, hydrogen and oxygen can be converted back to water and electricity. As a consequence, these types of electrolyzers can achieve particularly high capacity factors resulting in lower LCOH values. A recent study by (Glenk et al. 2023b) projects that, assuming continued learning effects for electrolyzer technologies, the variable cost of electricity will account for almost 80% of the overall LCOH of electrolytic hydrogen by the year 2030.

3.4 Levelized cost of carbon

There is widespread agreement that in order to slow, and ultimately stop, climate change, economies around the world will not only need to reduce their CO_2 emissions but also need to deploy negative emission technologies by means of CO_2 removals from the atmosphere. Carbon Capture and Sequestration (CCS) technologies enable the capture of CO_2 from point sources, e.g., power plants and manufacturing facilities, or alternatively from the ambient air, e.g., direct air capture and photosynthesis by trees. The levelized cost concept has been applied to comparing alternative CCS technologies in terms of a *Levelized Cost of Carbon* (LCOC) metric that yields the minimal price per ton of CO_2 that would be required in order for a particular capture technology to deliver an acceptable return to investors.

For CO_2 capture from point sources, Psarras et al. (2017) break the overall levelized cost of capture into three components corresponding to flue gas separation, compression and transport to the ultimate carbon sink, e.g., a geological storage site. As one would expect, higher concentrations of CO_2 in an industrial flue gas is known to decrease the cost of separation. This concentration tends to be relatively high in manufacturing processes such as ethanol, fossil fuel power generation or Portland cement (Rubin and Zhai 2012; Psarras et al. 2017). Several alternative point source capture technologies are principally known and understood today, including Calcium Looping, Oxyfuel, and Amine Scrubbing (İşlegen and Reichelstein 2011; MacKenzie et al. 2007; Friedmann et al. 2020; Glenk et al. 2023a). However, because relatively few large-scale CCS systems have been deployed to date, there is no consensus on which one of these technologies achieves the lowest levelized cost per ton captured.[7]

In the context of the cement industry, Glenk et al. (2023a) conclude that a future CO_2 emission charge of around €100 per ton would be required in order for cement producers to have incentives to install the so-called LEILAC capture technology. LEILAC, which stands for Low Emissions Lime and Cement, refers only to the capture of the process emissions that arise when calcium carbonate is converted to clinker, the main ingredient in Portland cement. In order for cement manufacturers to have incentives for comprehensive decarbonization through other CCS technologies, such as calcium looping, the prevailing CO_2 price would have to be at least in the range of €160 per ton of CO_2.

Direct Air Capture (DAC) is one prominent negative emissions technology. It has the obvious disadvantage that the concentration of CO_2 in the atmosphere is (still!) relatively low in comparison to that of industrial flue gases. At the same time, DAC facilities are entirely flexible in terms of their location, allowing them to economize on both energy costs and CO_2 transportation costs. While early studies put the corresponding LCOC in excess of $300 per ton (Simon et al. 2011), more recent projections by European and North American companies suggest that a unit cost in the range of $ 95–240 per ton might be attainable once additional DAC plants experience the anticipated effects of learning-by-doing (Keith et al. 2018). Finally, the emissions that result from decomposing biomass can be avoided (and therefore yield negative emissions) if the biomass is combusted and the corresponding emissions are captured and sequestered (Lehtveer and Emanuelsson 2021; Cheng et al. 2021). Alternatively, the biomass is directly sequestered before it decomposes and emits CO_2. With carbon removal of biomass still at an early stage, the levelized cost of these processing technologies appears to be still relatively high Clifford (2023). Nonetheless, corporate buyers are willing to pay for these removals in order to acquire carbon offsets in the voluntary carbon markets.

3.5 Other environmental applications

In addition to the research highlighted above, the LC concept has been applied in other environmental contexts. For instance, LC has been employed to assess the unit cost for heating (usually measured by thermal energy output) in order to compare the cost competitiveness of different technologies. Gabbrielli et al. (2014) compare the levelized cost of heat from solar collectors with heat from natural gas, Welsch et al. (2018) and Tian et al. (2018) analyze and optimize district heating systems, Kim et al. (2019) conduct an economic and environmental assessment of a hybrid renewable energy system. Finally, Yang et al. (2021) calculate the levelized cost of heat that is stored as thermal energy.

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[7] McCoy and Rubin (2009) analyze the variability and impact of storage costs on the LCOC. They find that the type of storage reservoirs has considerable impact on the required capital investment and the resulting LCOC.

Similarly, as air conditioning or cooling become more widespread, a developing research stream investigates and utilizes the levelized cost of cooling. Most papers in this field conduct economic analysis of different cooling technologies. For example, Bellos and Tzivanidis (2017), Li et al. (2017) and Altun and Kilic (2020) conduct economic analysis of solar cooling systems and Sadi et al. (2021) calculate the LC of a biomass-based cooling system for buildings.

With globally decreasing freshwater resources, a new research stream investigating the levelized cost of water emerged. For example, Loutatidou and Arafat (2015) and Behnam et al. (2018) calculate the levelized cost of water in combined power, heating and desalination systems. Chong et al. (2019) assess the economic feasibility of specific desalination technologies. It should be noted that all these authors focus on desalination. However, the levelized cost of water can also be applied in other contexts, such as water purification.

In the context of mobility and transport, Comello et al. (2021) have introduced the Levelized cost per X-mile (LCXM) concept. This cost metric is closely related to the total cost of ownership (TCO) model, which has been widely used in transportation studies (Lebeau et al. 2015 and Lajunen and Lipman 2016). The “X” in LCXM refers to alternative cost objects, for instance, ton- or passenger miles. In contrast to the TCO metric, LCXM is a unit cost measure aimed at the cost of transporting one ton of cargo or one passenger for one mile on a particular route. Comello et al. (2021) apply the LCXM metric to optimize the composition of a fleet of transit buses that can either be equipped with Diesel or battery electric transit buses.

4 Potential future applications

In addition to energy-related applications, the LC concept may gain traction in several other contexts. In this section, we sketch potential future LC applications in settings with competing generation technologies or managerial options that may differ in both their required initial capital expenditures as well as their periodic operating costs.

Agricultural commodities: Climate change, supply shocks, and technological advances affect the global agricultural sector. The LC concept can support decisions concerning competing agricultural food commodities by conducting a comparison of the per-unit nutritional value. In addition, LC can support managerial decisions regarding different production technologies for one agricultural product, for example, by comparing traditional food production methods, such as genetically modified crops, vertical farming, or investments in automated farming vehicles and artificial intelligence solutions.

Network industries: Friedl and Küpper (2011) show that adequate cost measures based on the annuity method for calculating depreciation and capital costs can improve the efficiency of investments in regulated markets such as network markets. The LC of network usage could help companies to determine the long-term unit prices in network industries with different production technologies, for example, by comparing the LC of internet access in different regions between a physical fiber network, cell phone towers, and satellite-based solution. In addition, in cases of monopolistic power, LC calculations can determine optimal capacity and output levels.

Cloud storage and computing: Tech companies such as Amazon, Alibaba, Alphabet, Microsoft, SAP, and Tencent generate increasing revenues from cloud storage and computing solutions. In this competitive field, companies need to choose between in-house sourcing or purchasing storage and power. LC can support this decision between a high-upfront investment in in-house capacity or purchasing storage and power on a predominantly variable cost-based structure.

Patent licensing: Intellectual property for patents is associated with ongoing R &D costs or high upfront investments to purchase patent portfolios externally. However, the usage and licensing of intellectual property itself do not require any significant variable costs. From the perspective of an investor deciding between buying or developing a portfolio of patents to use and license, the LC provide a metric to assess which option yields lower life-cycle costs. Historically, licensing fees for patents have often been calculated based on revenues from the associated products (Friedl and Ann 2018). However, there is an ongoing discussion about whether cost-based valuation approaches for intellectual property rights could be a valid alternative (Parr 2018 and Gamarra and Friedl 2023). LC could be a suitable metric to implement as a cost-based approach.

Other potential applications: In addition to the aforementioned potential applications of LC, there is a wide range of other fields where LC could be used, e.g., E-Commerce, FinTechs, or DNA sequencing. For E-Commerce companies, LC can be used to evaluate the size and geographical spread of CAPEX investments in new facilities. In the case of FinTechs, LC can support technological investment or in-sourcing decisions. Lastly, for DNA sequencing, different production technologies determining the order of nucleotides in a DNA can be compared based on their LC.

5 Conclusion

Levelized cost is a generic life-cycle cost product metric that aggregates capacity related investment expenditures and ongoing operating costs into a unit cost figure. Essential to the economic interpretation of this concept is that the allocation of upfront fixed costs to individual product units is consistent with the net present value criterion. Provided this allocation is made judiciously, the LC can be interpreted as the long-run marginal cost of a product, or alternatively, as a break-even product price at which the required investment becomes marginally profitable. This calibration makes the LC the unit cost measure metric relevant for long-run decisions.

As of today, most applications of the levelized product concept have originated in relation to energy technologies. This paper has synthesized multiple research streams relying on levelized cost measures in connection with electricity, energy storage, hydrogen and carbon capture. The widespread use of the LC metric in energy related fields suggests multiple other future applications. In general, we envision future potential for this cost concept whenever decision makers seek to capture the unit economics of projects with a long planning horizon.

Appendix A Proof of Proposition 1

Proof of Proposition 1 Given the assumptions of constant returns to scale, stationarity and full capacity utilization, we have

$$LC - FC_t^2(k \mid k) = v \cdot \Delta \cdot \left(\frac{1}{\sum_{t=1}^{T} (1+r)^{-t}} - \frac{1}{T} - \frac{r}{2} \right).$$

Hence, it remains to be shown that $\frac{1}{\sum_{t=1}^{T} (1+r)^{-t}} - \frac{1}{T} - \frac{r}{2} > 0$. Using the formula for the sum of the geometric series, we can rewrite

$$\frac{1}{\sum_{t=1}^{T} (1+r)^{-t}} = \frac{r \cdot (1+r)^T}{(1+r)^T - 1}$$

and

$$\frac{1}{\sum_{t=1}^{T} (1+r)^{-t}} - \frac{1}{T} - \frac{r}{2} = \frac{(1+r)^T \cdot (r \cdot T - 2) + 2 + r \cdot T}{2 \cdot T \cdot \left[(1+r)^T - 1\right]}. \tag{A1}$$

Since $2 \cdot T \cdot \left[(1+r)^T - 1\right] > 0$, the right-hand side of equation (A1) is positive if the numerator is positive. We define $g(T) := (1+r)^T \cdot (r \cdot T - 2) + 2 + r \cdot T$ and $h(r, T) := -1 - r \cdot T + (1+r)^{T+1}$. We note $h(r, T) \geq 0$ because $h(0, T) = 0$ and $\frac{\partial}{\partial r} h(r, T) = (1+r)^T + T \cdot \left[(1+r)^T - 1\right] > 0$. For $T + 1$, it follows that

$$\begin{aligned} g(T+1) &= (1+r)^{T+1} \cdot (r \cdot (T+1) - 2) + 2 + r \cdot (T+1) \\ &= g(T) + r \cdot \left[g(T) + h(r, T)\right]. \end{aligned}$$

Thus $g(2) > g(1) = r^2$, and more generally $g(T+1) > g(T) > 0$, yielding the claim that $LC(k) > FC_t^2(k)$. □

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References

Aldersey-Williams J, Rubert T (2019) Levelised cost of energy - a theoretical justification and critical assessment. Energy Policy 124:169–179. https://doi.org/10.1016/j.enpol.2018.10.004

Altun AF, Kilic M (2020) Economic feasibility analysis with the parametric dynamic simulation of a single effect solar absorption cooling system for various climatic regions in turkey. Renewable Energy 152:75–93. https://doi.org/10.1016/j.renene.2020.01.055

Arrow KJ (1964) Optimal capital policy, the cost of capital, and myopic decision rules. Ann Inst Stat Math 16(1):21–30

Behnam P, Arefi A, Shafii MB (2018) Exergetic and thermoeconomic analysis of a trigeneration system producing electricity, hot water, and fresh water driven by low-temperature geothermal sources. Energy Convers Manage 157:266–276. https://doi.org/10.1016/j.enconman.2017.12.014

Belderbos A, Delarue E, Kessels K et al (2017) Levelized cost of storage – introducing novel metrics. Energy Economics 67:287–299. https://doi.org/10.1016/j.eneco.2017.08.022

Bellos E, Tzivanidis C (2017) Energetic and financial analysis of solar cooling systems with single effect absorption chiller in various climates. Appl Therm Eng 126:809–821. https://doi.org/10.1016/j.applthermaleng.2017.08.005

Branker K, Pathak M, Pearce JM (2011) A review of solar photovoltaic levelized cost of electricity. Renew Sustain Energy Rev 15(9):4470–4482. https://doi.org/10.1016/j.rser.2011.07.104

Brown C, Foley B (2015) Achieving a cost-competitive offshore wind power industry: What is the most effective policy framework?

Bruck M, Sandborn P, Goudarzi N (2018) A levelized cost of energy (lcoe) model for wind farms that include power purchase agreements (ppas). Renewable Energy 122:131–139. https://doi.org/10.1016/j.renene.2017.12.100

Carlton DW, Perloff JM (2005) Modern Industrial Organization. Pearson Addison Wesley, New York

Cheng F, Small AA, Colosi LM (2021) The levelized cost of negative co2 emissions from thermochemical conversion of biomass coupled with carbon capture and storage. Energy Conversion and Management 237:114115. https://doi.org/10.1016/j.enconman.2021.114115, https://www.sciencedirect.com/science/article/pii/S0196890421002910

Chong ZR, He T, Babu P et al (2019) Economic evaluation of energy efficient hydrate based desalination utilizing cold energy from liquefied natural gas (lng). Desalination 463:69–80. https://doi.org/10.1016/j.desal.2019.04.015

Clifford C (2023) Charm gets $53 million to turn corn leftovers into oil and inject it into abandoned oil and gas wells. https://www.cnbc.com/2023/05/18/frontier-signs-first-co2-removal-deal-with-charm-worth-53-million.html

Comello S, Reichelstein S (2016) The U.S. investment tax credit for solar energy: Alternatives to the anticipated 2017 step-down. Renew Sustain Energy Rev 55:591–602. https://doi.org/10.1016/j.rser.2015.10.108

Comello S, Reichelstein S (2019) The emergence of cost effective battery storage. Nat Commun 10(1):2038. https://doi.org/10.1038/s41467-019-09988-z

Comello S, Reichelstein S, Sahoo A (2018) The road ahead for solar PV power. Renew Sustain Energy Rev 92:744–756. https://doi.org/10.1016/j.rser.2018.04.098

Comello S, Glenk G, Reichelstein S (2021) Transitioning to clean energy transportation services: Life-cycle cost analysis for vehicle fleets. Appl Energy 285:116408. https://doi.org/10.1016/j.apenergy.2020.116408

Darling SB, You F, Veselka T et al (2011) Assumptions and the levelized cost of energy for photovoltaics. Energy & Environmental Science 4(9):3133–3139. https://doi.org/10.1039/c0ee00698j

Datar SM, Rajan MV (2018) Horngren's cost accounting: a managerial emphasis. Pearson

Energy N (2016) Editorial: Hydrogen on the rise. Nat Energy 1:16127

Evans A, Strezov V, Evans TJ (2012) Assessment of utility energy storage options for increased renewable energy penetration. Renewable and Sustainable Energy Reviews 16(6):4141–4147. https://doi.org/10.1016/j.rser.2012.03.048

Ewert R, Wagenhofer A, Rohlfing-Bastian A (2023) Interne Unternehmensrechnung, 9th edn. SpringerGabler

Farrar DL, Woodruff F (1973) A model for the determination of optimal electric generating system expansion patterns

Franco BA, Baptista P, Neto RC et al (2021) Assessment of offloading pathways for wind-powered offshore hydrogen production: Energy and economic analysis. Appl Energy 286:116553. https://doi.org/10.1016/j.apenergy.2021.116553

Friedl G, Ann C (2018) A cost-based approach for calculating royalties for standard-essential patents (seps). The Journal of World Intellectual Property 21(5–6):369–384. https://doi.org/10.1111/jwip.12104

Friedl G, Küpper HU (2011) Historische Kosten oder Long Run Incremental Costs als Kostenmaßstab für die Preisgestaltung in regulierten Märkten? Zeitschrift für betriebswirtschaftliche Forschung 6(64):98–128. https://doi.org/10.1007/BF03373003

Friedl G, Hofmann C, Pedell B (2022) Kostenrechnung: Eine entscheidungsorientierte Einführung, 4th edn. Vahlen

Friedmann J, Fan Z, Byrum Z, et al. (2020) Levelized Cost of Carbon Abatement: An Improved Cost-Assessment Methodology for a Net-Zero Emissions World

Gabbrielli R, Castrataro P, Del Medico F et al (2014) Levelized cost of heat for linear fresnel concentrated solar systems. Energy Procedia 49:1340–1349. https://doi.org/10.1016/j.egypro.2014.03.143

Gamarra YL, Friedl G (2023) Declared essential patents and average total R &D expenditures per patent family. Telecommunications Policy. https://doi.org/10.1016/j.telpol.2023.102575

Glenk G, Reichelstein S (2019) Economics of converting renewable power to hydrogen. Nat Energy 4(3):216–222. https://doi.org/10.1038/s41560-019-0326-1

Glenk G, Reichelstein S (2022) The economic dynamics of competing power generation sources. Renew Sustain Energy Rev 168:112758. https://doi.org/10.1016/j.rser.2022.112758

Glenk G, Reichelstein S (2022b) Reversible Power-to-Gas systems for energy conversion and storage. Nature Communications 13(1):2010

Glenk G, Meier R, Reichelstein S (2021) Cost dynamics of clean energy technologies. Schmalenbach Journal of Business Research 73(2):179–206. https://doi.org/10.1007/s41471-021-00114-8

Glenk G, Anton K, Meier R, et al. (2023a) Cost-efficient pathways to decarbonizing Portland cement production

Glenk G, Holler P, Reichelstein S (2023b) Advances in Power-to-Gas technologies: cost and conversion efficiency

Goodall C (2017) Fuels from air and water. https://www.carboncommentary.com/blog/2017/12/13/fuels-from-air-and-water?utm_source=Carbon+Commentary+latest+posts &utm_campaign=81ca6225cb-Carbon_Commentary_latest_posts11_29_2014 &utm_medium=email &utm_term=0_f81f6d4f31-81ca6225cb-500845613

Grimm A, de Jong WA, Kramer GJ (2020) Renewable hydrogen production: A techno-economic comparison of photoelectrochemical cells and photovoltaic-electrolysis. Int J Hydrogen Energy 45(43):22545–22555. https://doi.org/10.1016/j.ijhydene.2020.06.092

Guerra OJ, Eichman J, Kurtz J et al (2019) Cost competitiveness of electrolytic hydrogen. Joule 3(10):2425–2443. https://doi.org/10.1016/j.joule.2019.07.006

Hernández-Moro J, Martínez-Duart JM (2013) Analytical model for solar pv and csp electricity costs: Present lcoe values and their future evolution. Renew Sustain Energy Rev 20:119–132. https://doi.org/10.1016/j.rser.2012.11.082

Hirth L (2013) The market value of variable renewables. Energy Economics 38:218–236. https://doi.org/10.1016/j.eneco.2013.02.004

Hotelling H (1925) A general mathematical theory of depreciation. J Am Stat Assoc 20(151):340–353. https://doi.org/10.1080/01621459.1925.10503499

İşlegen Ö, Reichelstein S (2011) Carbon capture by fossil fuel power plants: An economic analysis. Manage Sci 57(1):21–39

Jacobson MZ (2016) Clean grids with current technology. Nature Climate Change 6(5):441–442. https://doi.org/10.1038/nclimate2926

Jones N (2012) Liquid hydrogen. Nature Climate Change 2(1):23. https://doi.org/10.1038/nclimate1364

Jorgenson DW (1963) Capital theory and investment behavior. American Economic Review 53(2):247–259

Joskow PL (2011) Comparing the costs of intermittent and dispatchable electricity generating technologies. American Economic Review 101(3):238–241. https://doi.org/10.1257/aer.101.3.238

Jülch V, Telsnig T, Schulz M et al (2015) A holistic comparative analysis of different storage systems using levelized cost of storage and life cycle indicators. Energy Procedia 73:18–28. https://doi.org/10.1016/j.egypro.2015.07.553

Keith DW, Holmes G, Angelo DS et al (2018) A process for capturing CO2 from the atmosphere. Joule 2(8):1573–1594

Khzouz M, Gkanas E, Shao J et al (2020) Life cycle costing analysis: Tools and applications for determining hydrogen production cost for fuel cell vehicle technology. Energies 13(15):3783. https://doi.org/10.3390/en13153783

Kim MH, Kim D, Heo J et al (2019) Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. Energy 187:115916. https://doi.org/10.1016/j.energy.2019.115916

Kistner KP, Luhmer A (1981) Zur Ermittlung der Kosten der Betriebsmittel in der statischen Produktionstheorie. Z Betriebswirt 51:165–180

Küpper HU (1985) Investitionstheoretische Fundierung der Kostenrechnung. Zeitschrift für betriebswirtschaftliche Forschung 37(1):26–46. https://doi.org/10.5282/ubm/epub.5569

Küpper HU (1984) Kosten-und entscheidungstheoretische Ansatzpunkte zur Behandlung des Fixkostenproblems in der Kostenrechnung. Zeitschrift für betriebswirtschaftliche Forschung 36:794–811

Lai CS, McCulloch MD (2017) Levelized cost of electricity for solar photovoltaic and electrical energy storage. Appl Energy 190:191–203. https://doi.org/10.1016/j.apenergy.2016.12.153

Lajunen A, Lipman T (2016) Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy 106:329–342. https://doi.org/10.1016/j.energy.2016.03.075, https://www.sciencedirect.com/science/article/pii/S036054421630319X

Lebeau P, Macharis C, Mierlo Jv, et al. (2015) Electrifying light commercial vehicles for city logistics? a total cost of ownership analysis. European Journal of Transport and Infrastructure Research 15(4). https://doi.org/10.18757/ejtir.2015.15.4.3097, https://journals.open.tudelft.nl/ejtir/article/view/3097

Lee JY, Yoo M, Cha K et al (2009) Life cycle cost analysis to examine the economical feasibility of hydrogen as an alternative fuel. Int J Hydrogen Energy 34(10):4243–4255. https://doi.org/10.1016/j.ijhydene.2009.03.012

Lehtveer M, Emanuelsson A (2021) BECCS and DACCS as negative emission providers in an intermittent electricity system: Why levelized cost of carbon may be a misleading measure for policy decisions. Frontiers in Climate 3. https://doi.org/10.3389/fclim.2021.647276

Li Q, Zheng C, Shirazi A et al (2017) Design and analysis of a medium-temperature, concentrated solar thermal collector for air-conditioning applications. Appl Energy 190:1159–1173. https://doi.org/10.1016/j.apenergy.2017.01.040

Loutatidou S, Arafat HA (2015) Techno-economic analysis of med and ro desalination powered by low-enthalpy geothermal energy. Desalination 365:277–292. https://doi.org/10.1016/j.desal.2015.03.010

Lücke W (1955) Investitionsrechnungen auf der Grundlage von Ausgaben oder Kosten. Zeitschrift für handelswissenschaftliche Forschung 7(3):310–324

Luhmer A (1980) Fixe und variable Abschreibungskosten und optimale Investitionsdauer - Zu einem Aufsatz von Peter Swoboda. Z Betriebswirt 50(8/1980):898–903

MacKenzie A, Granatstein DL, Anthony EJ et al (2007) Economics of CO2 capture using the calcium cycle with a pressurized fluidized bed combustor. Energy & Fuels 21(2):920–926. https://doi.org/10.1021/ef0603378

Mahlert A (1976) Die Abschreibungen in der entscheidungsorientierten Kostenrechnung. Westdeutscher Verlag, Opladen

Massachusetts Institute of Technology (2007) The future of coal. http://web.mit.edu/coal/

McCoy ST, Rubin ES (2009) Variability and uncertainty in the cost of saline formation storage. Energy Procedia 1(1):4151–4158. https://doi.org/10.1016/j.egypro.2009.02.224

Minutillo M, Perna A, Forcina A et al (2021) Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. Int J Hydrogen Energy 46(26):13667–13677. https://doi.org/10.1016/j.ijhydene.2020.11.110

Mostafa MH, Abdel Aleem SH, Ali SG et al (2020) Techno-economic assessment of energy storage systems using annualized life cycle cost of storage (LCCOS) and levelized cost of energy (LCOE) metrics. Journal of Energy Storage 29:101345. https://doi.org/10.1016/j.est.2020.101345

Nezlobin A (2012) Accrual accounting, informational sufficiency, and equity valuation. J Account Res 50(1):233–273

Nezlobin A, Rajan MV, Reichelstein S (2012) Dynamics of rate-of-return regulation. Manage Sci 58(5):980–995. https://doi.org/10.1287/mnsc.1110.1464

Ouyang X, Lin B (2014) Levelized cost of electricity (LCOE) of renewable energies and required subsidies in china. Energy Policy 70:64–73. https://doi.org/10.1016/j.enpol.2014.03.030

Parkinson B, Balcombe P, Speirs JF et al (2019) Levelized cost of CO2 mitigation from hydrogen production routes. Energy & Environmental Science 12(1):19–40. https://doi.org/10.1039/C8EE02079E

Parr RL (2018) Intellectual Property: Valuation, Exploitation, and Infringement Damages, 5th edn. John Wiley & Sons

Pawel I (2014) The cost of storage - how to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation. Energy Procedia 46:68–77. https://doi.org/10.1016/j.egypro.2014.01.159

Poonpun P, Jewell WT (2008) Analysis of the cost per kilowatt hour to store electricity. IEEE Trans Energy Convers 23(2):529–534. https://doi.org/10.1109/TEC.2007.914157

Preinreich GAD (1938) Annual survey of economic theory: The theory of depreciation. Econometrica: journal of the econometric society 6(3):219–241. https://doi.org/10.2307/1907053

Psarras PC, Comello S, Bains P et al (2017) Carbon capture and utilization in the industrial sector. Environmental science & technology 51(19):11440–11449. https://doi.org/10.1021/acs.est.7b01723

Rahman MM, Oni AO, Gemechu E et al (2020) Assessment of energy storage technologies: A review. Energy Convers Manage 223:113295. https://doi.org/10.1016/j.enconman.2020.113295

Rajan MV, Reichelstein S (2009) Depreciation rules and the relation between marginal and historical cost. Journal of Accounting Research 47(3):823–865. https://doi.org/10.1111/j.1475-679X.2009.00334.x

Reichelstein S, Rohlfing-Bastian A (2015) Levelized product cost: Concept and decision relevance. Account Rev 90(4):1653–1682. https://doi.org/10.2308/accr-51009

Reichelstein S, Sahoo A (2015) Time of day pricing and the levelized cost of intermittent power generation. Energy Economics 48:97–108

Reichelstein S, Yorston M (2013) The prospects for cost competitive solar pv power. Energy Policy 55:117–127. https://doi.org/10.1016/j.enpol.2012.11.003

Rodby KE, Carney TJ, Ashraf Gandomi Y et al (2020) Assessing the levelized cost of vanadium redox flow batteries with capacity fade and rebalancing. J Power Sources 460:227958. https://doi.org/10.1016/j.jpowsour.2020.227958

Rogerson WP (2008) Intertemporal cost allocation and investment decisions. J Polit Econ 116(5):931–950. https://doi.org/10.1086/591909

Rosenthal M, Adams R, Bennett L (1965) A comparative evaluation of advanced converters. Tech. rep., Oak Ridge National Lab., Tenn

Rubin ES, Zhai H (2012) The cost of carbon capture and storage for natural gas combined cycle power plants. Environmental science & technology 46(6):3076–3084

Sadi M, Chakravarty KH, Behzadi A et al (2021) Techno-economic-environmental investigation of various biomass types and innovative biomass-firing technologies for cost-effective cooling in india. Energy 219:119561. https://doi.org/10.1016/j.energy.2020.119561

Schmidt O, Melchior S, Hawkes A et al (2019) Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule 3(1):81–100. https://doi.org/10.1016/j.joule.2018.12.008

Schneider D (1961) Die wirtschaftliche Nutzungsdauer von Anlagegütern als Bestimmungsgrund der Abschreibungen. Köln und Opladen

Schulze P, Holstein J, van den Noort A, et al. (2017) Power-to-Gas in a decarbonized european energy system based on renewable energy sources. DNV GL

Schweitzer M, Küpper HU, Friedl G, et al. (2015) Systeme der Kosten-und Erlösrechnung. Vahlen

Short W, Packey DJ, Holt T (1995). A manual for the economic evaluation of energy efficiency and renewable energy technologies. https://doi.org/10.2172/35391

Simon AJ, Kaahaaina NB, Julio Friedmann S et al (2011) Systems analysis and cost estimates for large scale capture of carbon dioxide from air. Energy Procedia 4:2893–2900. https://doi.org/10.1016/j.egypro.2011.02.196

Simsek Y, Mata-Torres C, Guzmán AM et al (2018) Sensitivity and effectiveness analysis of incentives for concentrated solar power projects in chile. Renewable Energy 129:214–224. https://doi.org/10.1016/j.renene.2018.06.012

Smallbone A, Jülch V, Wardle R et al (2017) Levelised cost of storage for pumped heat energy storage in comparison with other energy storage technologies. Energy Convers Manage 152:221–228. https://doi.org/10.1016/j.enconman.2017.09.047

Steckel T, Kendall A, Ambrose H (2021) Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems. Appl Energy 300:117309. https://doi.org/10.1016/j.apenergy.2021.117309

Swoboda P (1979) Die Ableitung variabler Abschreibungskosten aus Modellen zur Optimierung der Investitionsdauer. Z Betriebswirt 4(7/1979):563–580

Tegen S, Hand M, Maples B, et al. (2012) 2010 cost of wind energy review. Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States)

Tian Z, Perers B, Furbo S et al (2018) Thermo-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series. Energy Convers Manage 165:92–101. https://doi.org/10.1016/j.enconman.2018.03.034

Tran TT, Smith AD (2018) Incorporating performance-based global sensitivity and uncertainty analysis into lcoe calculations for emerging renewable energy technologies. Appl Energy 216:157–171. https://doi.org/10.1016/j.apenergy.2018.02.024

Van Renssen S (2013) A business case for green fuels. Nature Climate Change 3(11):951–952. https://doi.org/10.1038/nclimate2038

Welsch B, Göllner-Völker L, Schulte DO et al (2018) Environmental and economic assessment of borehole thermal energy storage in district heating systems. Appl Energy 216:73–90. https://doi.org/10.1016/j.apenergy.2018.02.011

Xie C, Li Y, Ding Y et al (2019) Evaluating levelized cost of storage (LCOS) based on price arbitrage operations: With liquid air energy storage (LAES) as an example. Energy Procedia 158:4852–4860. https://doi.org/10.1016/j.egypro.2019.01.708

Xu Y, Yang K, Yuan J (2021) Levelized cost of offshore wind power in China. Environ Sci Pollut Res 28(20):25614–25627. https://doi.org/10.1007/s11356-021-12382-2

Yang T, Liu W, Kramer GJ et al (2021) Seasonal thermal energy storage: A techno-economic literature review. Renew Sustain Energy Rev 139:110732. https://doi.org/10.1016/j.rser.2021.110732

Zakeri B, Syri S (2015) Electrical energy storage systems: A comparative life cycle cost analysis. Renew Sustain Energy Rev 42:569–596. https://doi.org/10.1016/j.rser.2014.10.011