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The cost of storage - how to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation

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Abstract

This paper provides a new framework for the calculation of levelized cost of stored energy. The framework is based on the relations for photovoltaics amended by new parameters. Main outcomes are the high importance of the C rate and the less dominant role of the roundtrip efficiency. The framework allows for comparisons between different storage technologies. The newly developed framework model is applied to derive the LCOE for a PV and storage combined power plant. The derived model enables quick comparison of combined PV and storage power plants with other forms of energy generation, for example diesel generation. This could prove helpful in the current discussion about diesel substitution in off-grid applications. In general, the combined levelized cost of energy lies between the LCOE of PV and LCOE of storage.

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Storage; energy storage; renewable energy; levelized cost; LCOE; storage cost

1. Introduction

As markets for energy storage emerge it becomes more and more important to gain unobstructed and unbiased insights into the economic performance of different storage technologies.

In many countries including Germany, energy produced from renewable energies has already reached grid parity on a retail level. With steadily decreasing investment cost, especially for photovoltaic, long sustained subsidies will

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be phased out sooner or later. As this process will start eventually everybody involved in the renewable energies industry knew from the beginning. Yet, the speed of this change obviously caught some by surprise (see the struggle of the European PV industry for example).

Policy makers will eventually lose a very important policy tool to control the market growth of renewable energies as especially captive power generation becomes commercial viable and independent of subsidy schemes leading to serious challenges [4].

We see a growing public interest to participate in the energy transformation, for example in public associations at regional level. Growing research interest rises in the optimal sizing of storage solutions and the right mix of hybrid storage systems to meet the requirements [5]. A common understanding in the storage community is the fact, that one storage systems shall serve different non-conflicting applications [6, 7]. This paper outlines the methodology to calculate the levelized cost of energy for combined PV and storage power plants. However, the methodology is applicable to other scenarios as well.

2. Modeling the levelized Cost of Energy

The Levelized Cost of Energy (LCOE) is defined as the total lifetime cost of an investment divided by the cumulated generated energy by this investment. For a discussion of the underlying assumptions see [2]. An alternative (but mathematically identical) approach is the definition by means of the net present value (NPV). The LCOE is the (average) internal price at which the energy is to be sold in order to achieve a zero NPV. In order to derive the model for combined power plant, the LCOE of PV generation and storage must be expressed. A fair comparison of different technologies on the basis of LCOE is suggested.

The following convention shall be applied to simplify the calculations: The notation of the discounted sum from period *0* to Period *T* is as follows:

$$\sum_{t=0}^{T} Value_t \cdot (1+i)^{-t} = \sum Value, \tag{1}$$

with *T* the assumed project lifetime. This calculation implicitly assumes a constant discount rate of *i* for the time period. However, the model can be calculated with varying discount rates. It is obvious that the project lifetime is crucial for the result. By default, a lifetime of 25 years is assumed.

2.1. LCOE of PV

The following formula calculates the LCOE of PV generation under the assumption that only some amount *X* of the generated energy will be used.

$$LCOE_{PV}(X) = \frac{\sum C_{PV}}{\sum Eout_{PV}(X)} = \frac{LCOE_{PV}}{X}, \tag{2}$$

with the directly used actual energy output per period being a function of *X* and $LCOE_{PV}$ the standard-calculated levelized cost of energy for PV. This models the direct usage of generated energy. For $X = 1$, the formula reduces to the commonly known formula for calculating the LCOE of PV generation [2]. The parameter *X* will become meaningful in combined models.

2.2. LCOE of a Storage System

The levelized cost of energy for storage systems is calculated in a similar manner as for PV generation. The total cost of ownership over the investment period is divided by the delivered energy (Note: This is a definition.) and hence calculates to:

$$LCOE_{St} = \frac{\sum C_{St} + \sum p_{int,t} \cdot E_{IN,St}}{\eta_{St} \cdot \sum E_{IN,St,t}} = \frac{\sum C_{St} + p_{int,0} \cdot K_T \cdot \sum E_{IN,St}}{\eta_{St} \cdot \sum E_{IN,St,t}} = \frac{\sum C_{St}}{\eta_{St} \cdot \sum E_{IN,St,t}} + K_T \frac{p_{int,0}}{\eta_{St}}. \tag{3}$$

The cost consists of a term similar to PV, in which total cost during lifetime is divided by the cumulated energy delivered by the system. Due to the fact, that no energy is generated a second term exists that models the energy purchase from generation plants or from the grid. The energy input into the storage system will be a certain amount of the total generated energy output. The energy output of the storage system is the energy input reduced by the average energy roundtrip efficiency η_{St} of the storage system over the lifetime. Sometimes it is more convenient to consider the output energy of the storage system. The levelized cost of energy is then calculated:

$$LCOE_{St}(\sum E_{OUT}, T) = \frac{\sum C_{St,t} + \sum p_{int,t} \cdot E_{IN,St,t}}{\sum E_{OUT,St,t}} = \frac{\sum C_{St,t} + p_{int,0} \cdot K_T \cdot \sum E_{IN,St,t}}{\sum E_{OUT,St,t}} = \frac{\sum C_{St}}{\sum E_{OUT,St,t}} + K_T \frac{p_{int,0}}{\eta_{St}} \quad (4),$$

with

$$K_T = \frac{\sum_{t=1}^{T} E_{int,t} \frac{\left(1+PIF_{p_{int}}\right)^t}{(1+i)^t}}{\sum_{t=1}^{T} E_{int,t} \frac{1}{(1+i)^t}} \approx \frac{\sqrt[T]{\prod_{t=1}^{T} \left(1+PIF_{p_{int}}\right)^t} + \frac{1}{T} \sum_{t=1}^{T} \left(1+PIF_{p_{int}}\right)^t}{2}, \quad (5)$$

approximately the average of geometric and arithmetic average price increase factor (PIF) over the considered period T. The maximum error for a $PIF = 9\%$ is below 5% (Note: This approximation is derived empirically), see Figure 1.

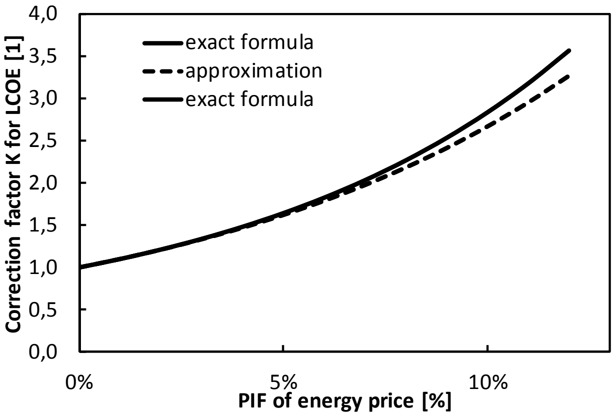


Figure 1: Correction factor K for LCOE calculation. Comparison between exact formula with approximation formula.

It is reasonably valid for price increase rates up to 6%. The approximation has the clear advantage of not depending on the discount interest rate or stored energy leading to a much easier calculation.

A storage device, by definition, cannot generate energy. Therefore, an internal transfer price $p_{int,t}$ weighs the value of the stored energy per period and $p_{int,0}$ is the internal price at the beginning of the period. In other words, it defines the internal cost at which the storage system "buys" the energy from the generation system, from the grid or any other source. The factor K describes the price change over the years if a constant PIF is assumed.

The lower limit for the LCOE is determined by the maximum energy turnover during lifetime. This state shall be defined as 100% utility of the storage device. Every deviation inevitably leads to higher LCOE. Figure 2 depicts the behavior of the LCOE for a given but arbitrarily chosen technology.

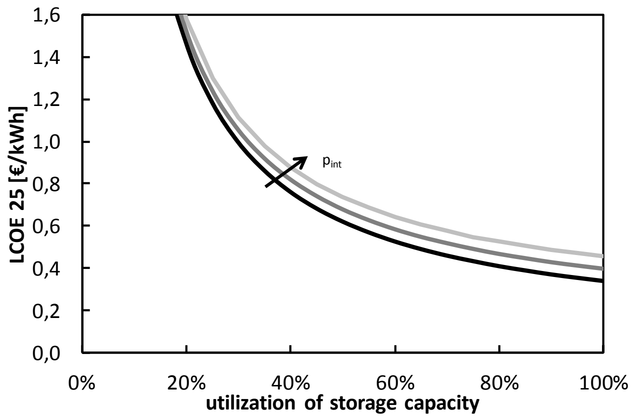


Figure 2: LCOE 25 (T=25 years) as function of utilized storage capacity per cycle with varying energy price for charging as parameter, other parameters see Table 1/Technology 1.

The C rate has major influence on the LCOE of the storage technology. This behavior is depicted in Figure 3, clearly showing the fact to reduce c-rate in order to improve LCOE. However, one must consider the fact, that this holds only true if the number of full cycles per year is not affected, i.e. a full cycle per day must be physically possible and it is only true since the model evaluates the cumulated stored (and released to some purpose) energy over the whole lifetime[†].

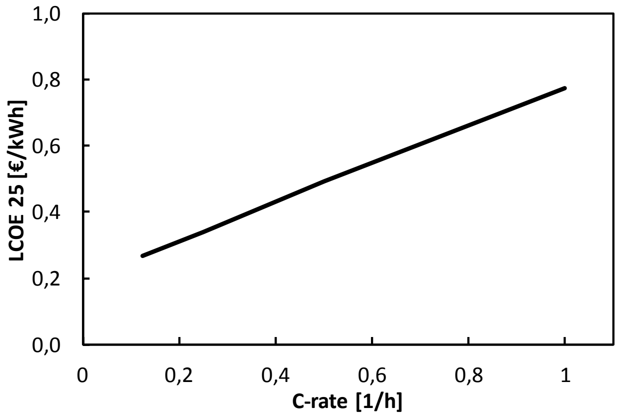


Figure 3: LCOE 25 (T=25 years) as function of c rate for chosen technology. Every c rate implies specific investment cost. All other parameters are as given in Table 1/Technology 1.

When discussing performance of energy storage systems it is often assumed that energy efficiency has a great impact. The derived model takes into account the energy efficiency. In eq. 4, the influence of efficiency can be seen in the second term. It serves as "acceleration factor" for the energy price, since the price is divided by the energy efficiency and increasing prices are accounted for by factor K_T. With all parameters equal, Figure 4 shows the influence of ac energy efficiency on LCOE at different initial price levels. Two important things can be observed: a) the influence is more pronounced at elevated energy prices. b) the influence is biggest at very low efficiencies below

[†] In project evaluation the revenue comes into play and storage systems may be rewarded for providing a certain capacity and/or positive and negative reactive power compensation among others.

50%. Above 50%, the effect has much lower impact, e.g. the difference between a technology with 90% efficiency and 70% efficiency is not too important. This is a very important result of this modeling.

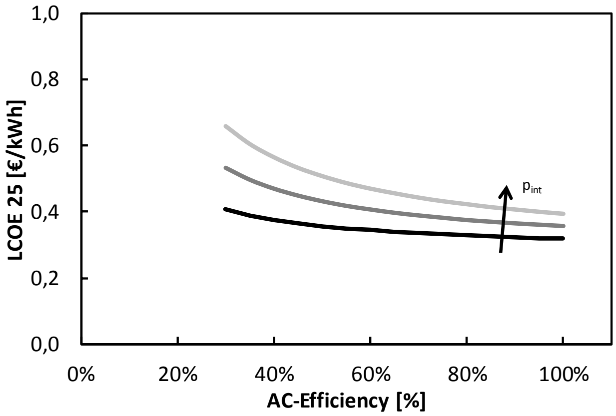


Figure 4: LCOE as function of AC-efficiency of storage system with energy price for charging as parameter, see Table 1/Technology 1.

2.3. Comparison of different storage technologies

The chosen methodology allows for quick and easy assessment of different storage technologies. It emphasizes the fact that not up-front investment cost but total cost of ownership over the project lifetime are important (Of course, investment cost play a vital role when it comes to financing and risk assessment for investments). An example comparison with all model parameters is given in Table 1‡.

Table 1: Comparison of LCOE 25 (T=25 years) for different exemplary storage technologies

Parameter	Redox-Flow	Lithium-Ion	Lead-Acid
Project-specific parameters			
Installed storage power [MW]	1.0	1.0	1.0
Investment Cost [Mio. €]	5.0	2.4	1.2
C-Rate (nominal)	0.25	1	1
Utilization of usable storage capacity	100%	100%	100%
Number of cycles per year	365	365	365
External parameters			
Energy price [€/kWh]	0.03	0.03	0.03
PIF energy price	2%	2%	2%
Loan period	10 years	10 years	10 years
WACC	3.5%	3.5%	3.5%
Storage specific parameters			
Residual value after end of lifetime (discounted) of invest cost	15%	0%	0%
Efficiency	70%	80%	65%
Maintenance Cost of Investment	2%	1%	5%
Degradation storage capacity per year	0.1%	2.0%	3.7%
Calendar lifetime	25	7	3
Usable storage capacity	100%	80%	50%
LCOE of storage [€/kWh]	**0.338**	**1.678**	**3.072**

As can be clearly seen, Redox-Flow with by far the highest initial investment cost turns out to be the most economic one when the cumulated energy over the investment period is considered. It outperforms the second-best

‡ The given numbers are not related to specific products. They reflect the best knowledge of the author while he's aware of very different opinions in the field. Besides the investment cost, the most disputed parameters are lifetime (cycle lifetime) and usable storage capacity (DoD). A change of the C-rate for Li-Ion from 1.0 to 0.25 gives a LCOE of 0.455 €/kWh. On the other hand, a C-rate change from 0.25 to 0.5 for Redox-Flow gives a LCOE of 0.653 €/kWh. All readers are encouraged to collaborate in the discussion.

technology Li-Ion by a factor of 6. However, it should be pointed out, that in reality not just the cumulated energy may be economically relevant, e.g. for power quality purposes. By definition, the LCOE metric disregards any generated revenues from the investment. For that reason a net present value calculation is suggested to gain better insight into the underlying business case of the planned investment. Now let us consider an example for application of the derived model.

2.4. LCOE PV + Storage

The combination of a PV plant with storage is considered a PV & Storage Power Plant. The simple model is shown in Figure 5. By means of such a model one can compare the energy cost of PV & storage with alternative methods to provide energy, e.g. diesel generation.

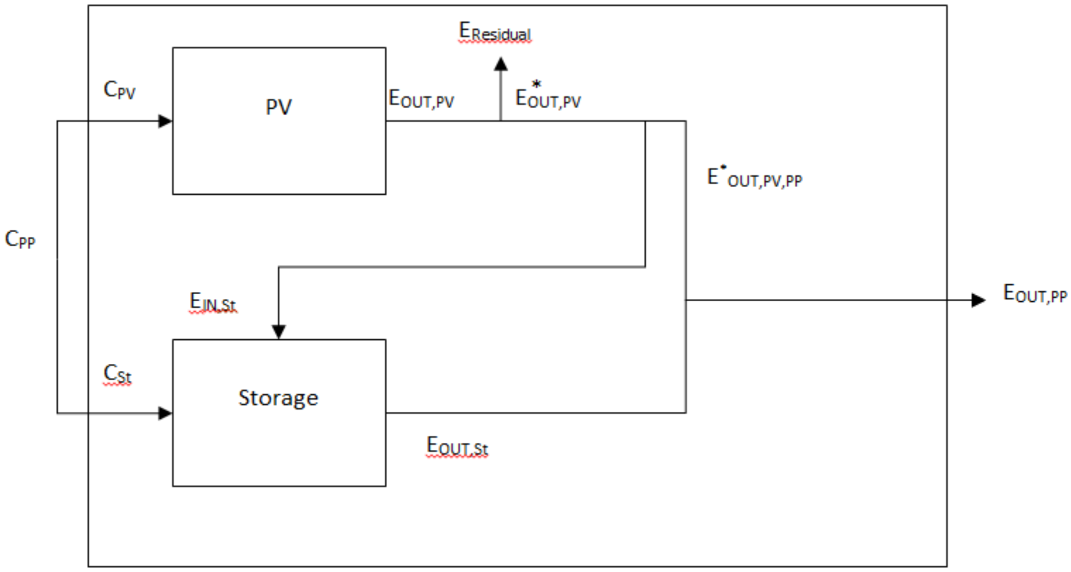


Figure 5: Model of combined PV and storage Plant

It consists of a PV park, a storage system, an energy management system (which can be part of the storage system). The total lifetime cost is the sum of the cost of PV energy generation and the cost of storage. The energy output of the PP is the sum of directly used energy from PV and the amount that is taken from PV to the storage system and then released to the output of the PP. What can be used directly should be used directly leading to a minimization of the storage system [1]. This principle is an immediate consequence from the LCOE considerations where the effect of 100% utilization of the installed storage capacity on LCOE is clearly outlined.

If a storage system is considered it might be uneconomical to dimension it so big to use the total generated energy either directly or via storage system. The model parameter $E_{OUT,PV,Residual}$ is the amount of energy that cannot be stored. It could instead be used for feed into the grid. The usable energy is therefore:

$$E^*_{OUT,PV} = E_{OUT,PV} - E_{Residual}. \tag{6}$$

Of this effective energy only a certain amount will be stored, since it cannot be used directly:

$$E_{IN,St} = A \cdot E^*_{OUT,PV}, \tag{7}$$

with A the usage factor of PV into storage. The remainder of the energy will be used directly:

$$E_{OUT,PV,PP} = (1 - A) \cdot E^*_{OUT,PV,PP}. \tag{8}$$

For a PV & Storage Power Plant (Index PP), we have the following relationship for the levelized cost of energy:

$$LCOE_{PP} = \frac{\sum C_{PP}}{\sum E_{OUT,PP}}. \tag{9}$$

The total cost of the power plant is the sum of PV generation and storage:

$$\sum C_{PP} = \sum C_{PV} + \sum C_{St,total}. \tag{10}$$

The total output of the system is the direct output of PV and the output of the storage system:

$$\sum E_{Out,PP} = \sum E_{Out,PV,PP} + \sum E_{Out,St} = \sum E_{Out,PV,PP} + \eta_{St} \cdot \sum E_{IN,St}. \tag{11}$$

By means of eq. 2,3,10,11 eq. 9 can be expanded resulting in:

$$LCOE_{PP} = \frac{\sum C_{PV} + \sum C_{St} + p_{int} \cdot \sum E_{IN,St}}{\sum Eout_{PV},PP + \eta_{St} \cdot \sum E_{IN,St}}. \tag{12}$$

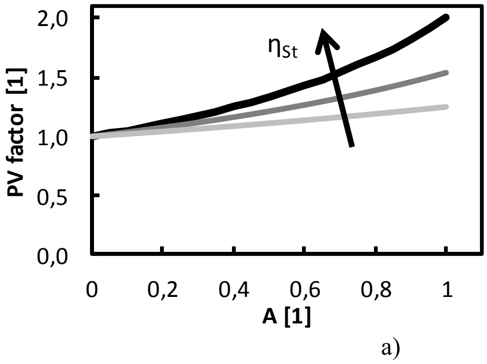
Taking into account eq. 6-8 yields:

$$LCOE_{PP} = \frac{\sum C_{PV} + \sum C_{St} + p_{int} \cdot A \cdot \sum E^*_{Out,PV}}{(1-A) \cdot \sum E^*_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^*_{Out,PV}}. \tag{13}$$

After some calculation and rearrangement the following formula for the LCOE of the combined PV & storage Power Plant can be derived (for detailed calculation see the Appendix A.):

$$LCOE_{PP} = LCOE_{PV} \underbrace{\frac{1}{1-A(1-\eta_{St})}}_{PV\ factor} + LCOE_{St}\left(A; E^*_{Out,PV}\right) \underbrace{\frac{A \cdot \eta_{St}}{1-A(1-\eta_{St})}}_{storage\ factor}. \tag{14}$$

In the obvious case of no storage system the formula simply reduces to the LCOE of the PV plant alone. Let's have a look on the two terms of the equation separately with their respective LCOE equal to 1 depicted in Figure 6.



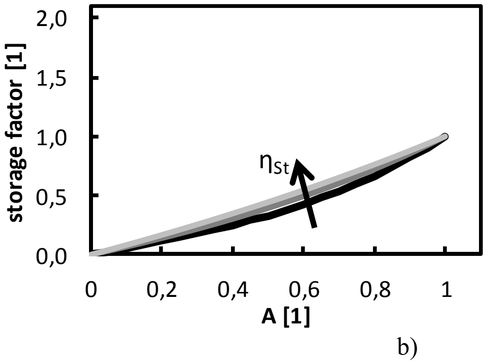


Figure 6: Dependency on the ratio of stored PV energy with ac efficiency of storage system as parameter. a) PV factor b) storage factor

It is obvious, that without storage the levelized cost will equal that of PV alone. On the other extreme, for a very high ratio of storage, the total levelized cost is much higher and consists of the cost of storage (factor of 1) and the geared cost of PV due to efficiency losses[§].

With $LCOE_{St} = 0.338$ €/kWh (taken from Table 1/Technology 1) and $LCOE_{PV} = 0.1$ €/kWh one can sketch the implied cost of energy for the complete system under the underlying assumptions, see Figure 7. It is assumed that for each value of A the optimal storage size is selected and LCOE of storage is constant for each value of A. For small storage sizes, the influence of storage efficiency can be neglected. The effect becomes more pronounced as the storage size increases. This is very important for micro grid layouts, e.g. substitution of power generation by means of diesel gensets.

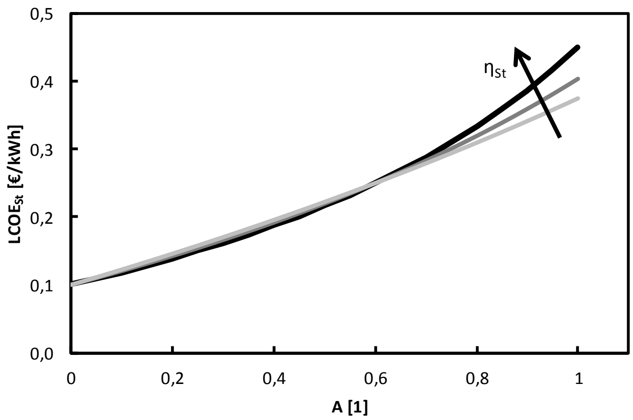


Figure 7: LCOE of the combined power plant (PV and storage) for different ratios of storage and with ac efficiency of storage system as parameter. It is assumed that for each value of A the optimal storage size is selected and LCOE of storage is constant.

It is very important to point out that the cost curve in Figure 7 establishes a lower limit (optimal case) for the LCOE of storage. The parameter "*Utilization of usable storage capacity*" in Table 1 models this effect. The results are given in Table 2.

Table 2: Influence of the utilization factor of the storage system on total LCOE of the power plant (PV & storage). Ratio of storage A = 0.5, η_{St} = 65%.

Uitilization of usable storage capacity	100%	75%	50%
$LCOE_{St}$ [€/kWh]	0.339	(+27.7%) 0.433	(+82.9%) 0.620
$LCOE_{PP}$ [€/kWh]	0.255	(+14.5%) 0.292	(+43.1%) 0.365

In the combined system, the effect of under-utilization of the storage system is significantly lower compared to the respective LCOE. This emphasizes the need to consider the aggregated cost of energy when comparing different and maybe mutually exclusive solutions.

The discount rate undoubtedly has major influence on any calculation based on discounted cash-flow (DCF). In this paper we assumed the weighted average cost of capital (WACC) to be the appropriate discount rate. The commonly known formula to calculate the WACC is:

$$WACC = \frac{E}{E+D} c_E + \frac{D}{E+D} c_D \cdot (1 - Tax_{Corp}). \tag{15}$$

With E and D equity and debt, c_E and c_D the associated cost of equity and cost of debt and the corporate tax of Tax_{Corp}, respectively.

[§] With ac energy efficiency $\eta_{St} = 1$, the total levelized cost are simply the sum of cost of PV and cost of storage.

Figure 8 illustrates the effect of discount rate on the LCOE of storage. It turns out to be a very strong dependency. A 5% change in discount rate implies a 50% change in LCOE. This underlines the necessity to carefully choose the appropriate discount rate. However, the correct calculation of WACC is somewhat complicated procedure with several methodologies and may be outlined in future publications in greater detail.

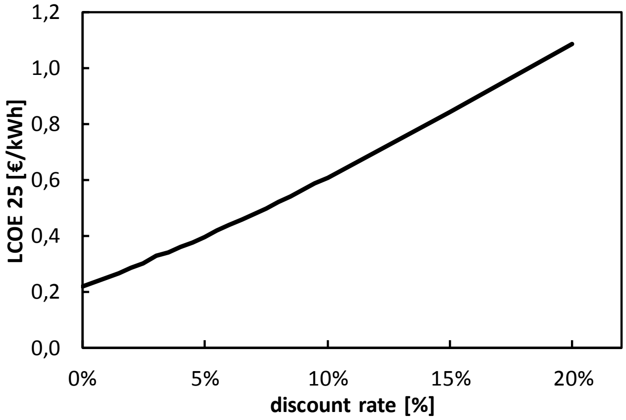


Figure 8: Influence of discount rate on levelized cost of energy for storage. Parameters from Table 1/Technology 1.

3. Summary

This paper aims at providing an overview over calculation of levelized cost of energy from generation and from storage in particular.

In the first part the general relations for PV and storage were derived and various parameter variations were discussed for both systems separately. For storage it is assumed that solely the cumulated stored energy determines the LCOE of the storage system. It turned out that C rate is the most important parameter for the LCOE of storage. In contrast, the efficiency plays a less dominant role as often assumed in current technology discussions. The derived model was then used to compare different technologies. This comparison could easily be expanded to more technologies to foster technology comparison.

In reality, project assessment should not be solely based on LCOE calculations but rather one should involve the expected revenue of the project to derive a net present value of the project. However, in this paper, revenue considerations were omitted.

Instead, a model for the calculation of LCOE for a PV and storage combined power plant was derived and some aspects of parameter variation were discussed. The derived model is applied to a combined PV and storage power plant in order to derive an analytical expression. The derived model enables quick comparison of combined PV and storage power plants with other forms of energy generation, for example diesel generation. This could prove helpful in the current discussion about diesel substitution in off-grid applications. No cumbersome and time-consuming simulations are needed. Simply put the combined levelized cost of energy lies between the LCOE of PV and LCOE of storage.

The next steps are the systematic analysis of business opportunities related with energy storage and their quantitative assessment using the framework and assumptions outlined in this paper and the detailed investigation of cost of capital calculations for different projects and its influence on project realization and financing.

Acknowledgements

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Appendix A.

This appendix contains the step-by-step derivation of eq. 14.

$$LCOE_{PP} = \frac{\sum C_{PV} + \sum C_{St} + p_{int} \cdot A \cdot \sum E^*_{Out,PV}}{(1-A) \cdot \sum E^*_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^*_{Out,PV}},$$

$$LCOE_{PP} = \frac{\sum C_{PV}}{(1-A) \cdot \sum E^*_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^*_{Out,PV}} + \frac{\sum C_{St} + p_{int} \cdot K \cdot A \cdot \sum E^*_{Out,PV}}{(1-A) \cdot \sum E^*_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^*_{Out,PV}},$$

$$LCOE_{PP} = \left(\frac{(1-A) \cdot \sum E^*_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^*_{Out,PV}}{\sum C_{PV}}\right)^{-1} + \left(\frac{(1-A) \cdot \sum E^*_{Out,PV} + \eta_{St} \cdot A \cdot \sum E^*_{Out,PV}}{\sum C_{St} + p_{int} \cdot K \cdot A \cdot \sum E^*_{Out,PV}}\right)^{-1},$$

$$LCOE_{PP} = \left(\frac{(1-A) \cdot \sum E^*_{Out,PV}}{\sum C_{PV}} + \frac{\eta_{St} \cdot A \cdot \sum E^*_{Out,PV}}{\sum C_{PV}}\right)^{-1} + \left(\frac{(1-A) \cdot \sum E^*_{Out,PV}}{\sum C_{St} + p_{int} \cdot K \cdot A \cdot \sum E^*_{Out,PV}} + \frac{\eta_{St} \cdot A \cdot \sum E^*_{Out,PV}}{\sum C_{St} + p_{int} \cdot K \cdot A \cdot \sum E^*_{Out,PV}}\right)^{-1},$$

$$LCOE_{PP} = \left(\frac{1-A}{LCOE_{PV}} + \frac{A \cdot \eta_{St}}{LCOE_{PV}}\right)^{-1} + \left(\frac{1}{LCOE_{St}(A)} \frac{1-A}{A \cdot \eta_{St}} + \frac{1}{LCOE_{St}(A)}\right)^{-1}.$$

$$LCOE_{PP} = LCOE_{PV} \frac{1}{1-A(1-\eta_{St})} + LCOE_{St}\left(A; E^*_{Out,PV}\right) \frac{A \cdot \eta_{St}}{1-A(1-\eta_{St})}.$$

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