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Using a Second-Life Battery to Optimize the Levelized Cost of Electricity in CO_2 Neutral Microgrid

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Executive Summary

The tecno-economical assessment of a CO_2 neutral microgrid that works at least 50% of the time not connected to the grid is calculated. This microgrid is composed of solar energy generation, wind energy generation and a second-life lithium ion battery-based energy storage capacity. The purpose of this paper is to calculate the Levelized Cost of Electricity (LCOE) of the whole system where the Battery Energy Storage System (BESS) operation is optimized. The proposed LCOE estimation approach provides the framework to work with complex models embedded in the most beneficial approach. The results certifies that the optimum operation way of BESS reduces the LCOE of the whole system.

Keywords: microgrid, cost, electricity, modelling, Second-life battery

1 Introduction

The social environmental consciousness is expanding relentlessly, leading to numerous sustainable options related with daily activities. So is this that sustainable solutions are used everywhere, from super markets to the new eco-architectural based buildings. However, among all the environmental sustainable initiatives that are been taken, there are two in concrete that are having and will have huge impact on the environment: the electric mobility and the renewable energy generation. The substitution of inner combustion engines and traditional power plants with electric engines and solar, wind or hydroelectric power plants will suppose an approximate 40% decrease of worldwide greenhouse gas emissions [1].

This substitution, however, is changing the paradigm of operation of these two sectors (electricity generation and transportation). Until now, the energy generation has been something certain and highly controllable and centralized. Now, we are facing a energy decentralization in which the integration of renewable energy generation and electro-mobility needs to be carefully studied and controlled. In the case of renewable energy generation, uncertainties on the weather make impossible to generate energy as wished. In the case of transportation, inner combustion engines are replaced by electric engines, which are no longer energy generation devices, but rather energy consumers. In this scenario, Energy Storage Systems (ESS) are taken as the most interesting solution for both problems. In concrete, lithium ion battery based ESS is positioning first in the market [2][3].

Electric vehicles supported by lithium ion batteries are on the market from many years ago and their sales are only getting higher and higher [4]. Among many others, there are already for years in the market many EVs which contatin a lithium ion batterie such as Tesla cars, the Nissan Leaf, the Renault Zoe, the Opel Ampera or the BMW i3. The use of these electric vehicles decreases the performance of the batteries inside them due to simple wear and tear, which has already led to have many of their ESS replaced. Meanwhile, renewable energy generation percentage is increasing, and the energy balancing problem gets more relevant day by day.

At this point, the sustainable idea of reusing the discarded batteries on energy balancing of renewable energy generation plants emerged [5]. The energy balancing application on a renewable energy generation plant is expected to be less exigent than the transportation application [6], which is the main requirement for reusing purposes. However, current economical assessments are far from properly describing the real second application (or second life) Battery Energy Storage System cost [7].

In this paper, the integration of a more realistic dynamic and degradation behavior of a second life BESS is proposed along with the calculation of the optimized way of operating the BESS. Thanks to the obtained LCOE value, the price that the generated electricity need to be sold is calculated; the price required in order to recover the investment of the whole generation plant on a microgrid context. This proposal follows the 5th future research proposition on the review done in [8].

2 Application requirements

The Green Energy Campus [9] endeavors to develop and implement a CO_2-neutral, self-sufficient microgrid that switches from island mode to grid connected mode in order to decrease its dependence on the grid (Figure 1). It will host interconnected prosumers including a large green data center (>1 MW thermal producer), an incubator for start-ups, a large parking lot (150-400 vehicles) with electric charging infrastructure and 70 companies from different sectors. To generate the demanded energy, the Green Energy Campus will integrate renewable energy production systems (10MW solar and 13.2MW wind Energy) along with energy storage capacity (10MWh batteries) for energy balancing issues.

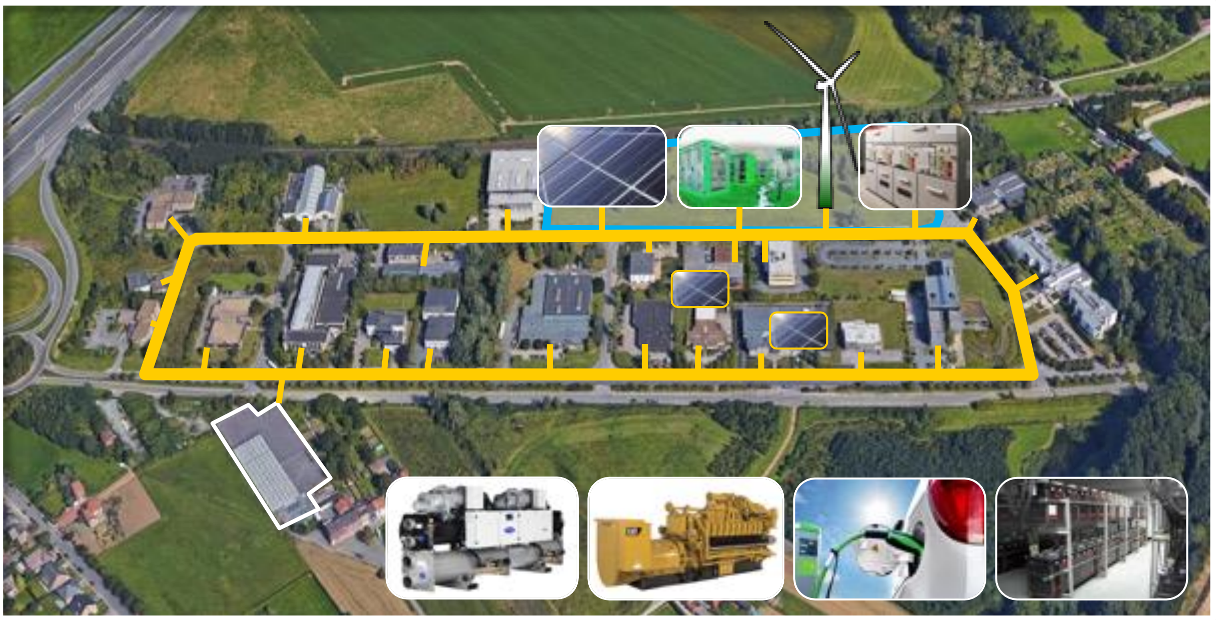

Figure 1: Green Energy Campus's electrical Micro-Grid design [9].

The solar power plant is done with photovoltaic (PV) panels installed in the roof of the different buildings at the Green Campus. The wind power plant is composed by four 3,3 MW wind turbines. The BESS is composed by 1925 second life TESLA model S battery modules, where Panasonic ncr18650B lithium ion batteries are used (each module has 444 Li-ion batteries).

This work is taken from a generation plant owner point of view, where the energy bought from the grid is not considered on the optimization approach, just the generated one. This means that there would be a main customer of electricity of the microgrid, which is the industrial park of 70 enterprises at Zellik. In addition to this, the grid is a second possible customer, who might buy the energy surplus the microgrid generates once the demand of the first customer is covered.

As for simplifications, due to restrictions on data availability, the temperature is assumed to be constant (25ºC) and the yearly solar and wind energy generation is taken as constant (the environmental conditions given on 2017 are repeated every year).

3 LCOE Optimization Approach

The proposed optimization approach searches for the best operating method of the microgrid in terms of cost (LCOE). In this case, the variable component on the operation of the whole microgrid is the BESS, so the whole LCOE optimization approach is focused on the optimization of the operation of the BESS. For that, BESS operation criteria are defined from which the optimum criterion is chosen in terms of the LCOE. This approach comprises two phases (Figure 2):

- An initial energy calculation (raw energy) where the solar and wind energy generation is calculated.
- The BESS energy generation calculation where the battery dynamic behavior and deterioration are modelled so as to make the BESS operation as realistic as possible.

The operation of the whole microgrid is simulated along the operation time of the microgrid. The simulation tracks the deterioration level of the batteries and if required, the replacement of all the battery modules will occur (the BESS is disabled for a replacement time (t_r) and the deterioration of the batteries is reset to the initial values (R_0, SOH_0 and E_{bat_0}). The replacement is done when the End Of Life (EOL) criterion is reached.

As a result, the energy generation given by the whole system as well as the cost of the whole microgrid on the operation time of the microgrid is achieved.

Then, the LCOE of the multi-energy grid system ($LCOE_{system}$) is calculated by Eq. (1), where the calculated cost ($C_{microgrid}$) is divided by the calculated energy ($E_{microgrid}$) [10].

$$LCOE_{system} = \frac{C_{microgrid}}{E_{microgrid}} \quad (1)$$

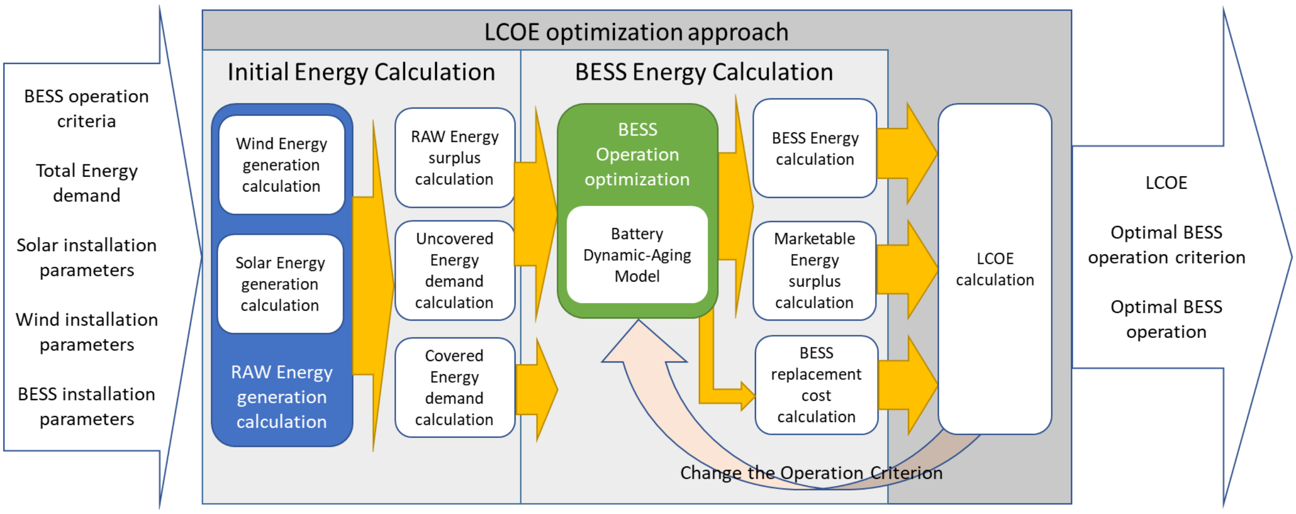

Figure 2: Proposed LCOE optimization approach.

3.1 LCOE calculation

The LCOE is calculated making some assumptions:

- The LCOE is calculated from a generation ownership point of view (we are the owners of the solar power plant, the wind power plant and the BESS and our customer are the industrial park at Zellik as well as the grid manager).
- The microgrid will have to cover the energy demand of the industrial park ($E_{solar\&windDirect}$). The microgrid cannot use the energy to charge the BESS or to sell it to the grid unless this demand is completely covered.
- The grid will buy all the generated energy surplus we generate but he will buy it at a reduced value respect to the one sold to the industrial park at Zellik ($E_{SurplusReduced}$).
- The BESS is only charged with the energy surplus generated by the microgrid (the energy surplus obtained from the solar and wind power plants once the demand of the industrial park at Zellik is covered).
- The BESS is taken as an energy generation power plant where the energy used on charging and the energy losses are taken as self-consumption.

Based on these assumptions and based on the works of C. S. Lai et al [7] and M. Bruck et al [11], the equation to calculate the LCOE is developed (Eq. (2)).

$$LCOE_{system} = \frac{\sum_{t=0}^{N} \frac{C_{solar} + C_{wind} + C_{BESS}}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_{solar\&windDirect} + E_{BESS} + E_{SurplusReduced}}{(1+r)^t}} \quad (2)$$

This equation introduces the yearly costs of the energy generation installations (C_{solar}, C_{wind} and C_{BESS}) as well as the yearly total energy generation ($E_{solar\&windDirect}$, E_{BESS} and $E_{SurplusReduced}$) along the useful lifetime of the whole microgrid (N). This time priod is defined by the installation that has the higher operation expectation. In this case the wind installation is expected to be operable 25 years, more or less as the solar power plant [12] and much more than the BESS. Another element added to the formula is the "discount rate" that represents the currency inflation (r). This parameter considers the investment risk as well as some other economic metrics used on economic assessments. As for this work, the assumed discount rate value is taken from the study on [13].

3.2 Energy calculation

The proposal calculates the production-demand energy data using 2017's data sets. Firstly, the required energy (demand) is calculated from the 2017's energy consumption of the 70 enterprises placed at the Green Campus (Figure 3).

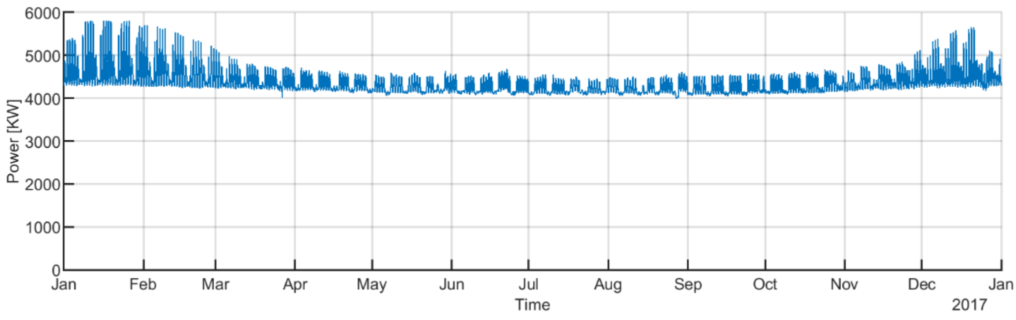

Figure 3: The demand on Zellik on 2017 with an interval of 15 min.

At the same time, the raw energy generation is calculated from solar and wind energy availability in the park. Then, the covered/uncovered energy demand and the raw energy surplus is calculated, which is used as an input to calculate the optimal operation way of the BESS in the "energy calculation" phase of the proposed algorithm.

3.2.1 Wind Energy calculation

The wind power is calculated based on the wind speed measured on Zellik. The wind speed is used on a look up table function where the energy generation of a 3,3 MWh wind turbine and the wind speed is related (Figure 4). In total, 4 wind turbines are installed, making it an installation of 13,2 MWh.

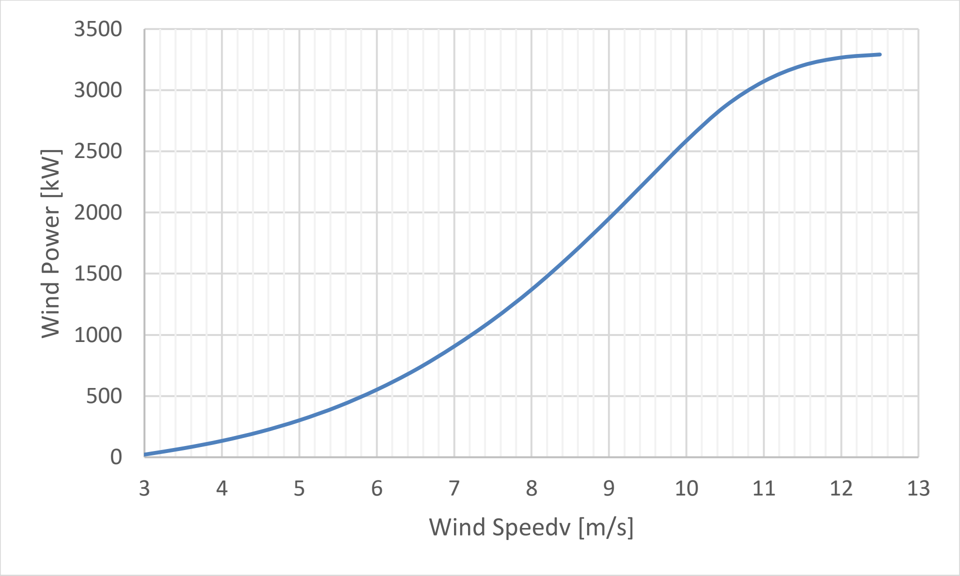

Figure 4: Wind Power generation of a 3,3MWh wind turbine.

3.2.2 Solar Energy calculation

The chosen solar energy generation is Photovoltaic (PV). The PV energy generation calculus is based on a 816 KW peak PV system that is already installed at Zellik. The generation and the installed KW peak are considered to be linearly proportional and the scaling is done dividing the generation data by 816 and multiplying by the installed KW peak, which in this case is 10.000 KW peak.

3.2.3 BESS Energy calculation

The energy given by the BESS depends on its operation. In this study, the set-up criterion of use of the BESS is composed by the next statements:

- Charge only with the energy surplus from the wind and solar plants once the demand is covered.
- Charge only until the End of Charge voltage or until the limited State of Charge (SOC) is reached.
- Charge whenever the charge requirements are fulfilled.
- Discharge only when the energy generation coming from the solar and wind plants are insufficient.
- Discharge only until End of Discharge voltage or until the limited SOC is reached.
- Discharge only when the BESS can deal with the whole demand by itself in a concrete period.
- The demand needs to be covered half of a year each year without relying on the grid (the microgrid needs to work on island mode at least 4.380 hours).

At the same time, some variable statements are done in order to find the best case operating method. These are shown in Table 1.

Table 1: Operation Criteria (OPC) variable statements.

Case	Variable statements
OPC 0	The BESS is not operated.
OPC 1	The operation of the BESS is done with a100% DOD.
OPC 2	The operation of the BESS searches for the case with the minimum aging (in terms of DOD).

The use of the BESS is simulated following the defined operation criterion. As the input, it is used the previous demand-generation data. In this way, the BESS operation is optimized. The dynamic and aging behavior of the battery as well as the energy losses are added to the simulation in order to make the BESS response as realistic as possible, which will be explained next.

- **Battery Aging model**

The proposed aging model is a damage cumulative model that updates the resistance (R) and the State of Health (SOH) of the whole BESS in terms of the use [14]. The SOH reflects the relative dischargeable energy of the BESS. The cycling damage and the calendar damage are linearly added (Eq. (3) and Eq. (4)).

$$R_{k+1} = R_k + \Delta R_{k\ to\ k+1} \quad (3)$$

$$SOH_{k+1} = SOH_k - \Delta SOH_{k\ to\ k+1} \quad (4)$$

In case of the cycling, the factors taken into account are the Depth of Discharge (DOD) and the count of the discharged energy. The operation on a certain DOD will decrease 30% the SOH with certain sum of equivalent cycles, where an equivalent cycle is equal to have discharged the nominal capacity, or in this case, the rated energy. The applied aging values are shown in Table 2.

Table 2: Modified cycling aging parameters representing a decrease of 30% in the SOH [15].

DOD [%]	SOCmin [%]	SOCmax [%]	Equivalent Cycles [cycles]
40	30	70	4000
60	20	80	3500
80	10	90	2800
84	8	92	1500
88	6	94	750
100	0	100	500

The resistance (R) is assumed to increase independently to the DOD, which leads to be dependent only to the discharged amount of energy. It is assumed that the resistance increases 15% with 900 equivalent cycles [16].

In case of the calendar aging, the rest time is the only parameter taken into account. It is assumed that any rest time given to the battery higher than 3 hours will generate calendar aging (rest time lower than 3 h is taken as relax time, which does not deteriorate the battery). As for quantifying it, a decrease of 0,5% on the SOH for each year in rest period (365 days resting) has been added to the model [17]. The calendar aging is assumed not to affect the resistance R.

- **Battery Dynamic model**

The proposed dynamic battery model is based on a simple equivalent circuit model shown in Eq. (5), where the Open Circuit Voltage (OCV) is a look up table function depending on the SOC, R is an output of the aging model and I is the current given or taken by the battery. The proposed model calculates the voltage at battery level in order to integrate the End of Charge (EOC) and End of Discharge (EOD) voltage thresholds into energy calculations [18].

$$V = OCV(SOC) + IR \quad (5)$$

The OCV data is taken from [19] (Figure 5). The data images have been reverse engineered to extract the underlying numerical data available using the WebPlotDigitizer [20].

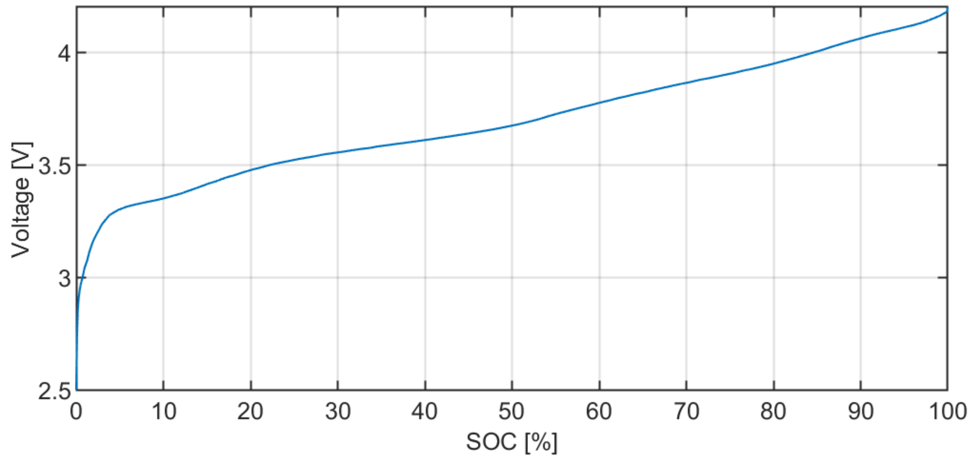

Figure 5: OCV profile of the NCR16850B battery at 25ºC [19].

The SOC is calculated by an energy counting method (Eq. (6)), where the SOH is an output of the aging model, the E_{bat} is the result of the energy counting method (the cumulative energy on the BESS) and the E_{batMAX} is the maximum storable energy on the BESS.

$$SOC = E_{bat} \frac{100}{E_{batMAX} \frac{SOH}{100}} \tag{6}$$

The I is calculated using the power given or taken from the whole solution (P_{bat}), see Eq. (7), where P_{bat} is the power demand or supply of the whole BESS and N_{bat} is the number of battery units on the whole BESS solution.

$$I = \frac{P_{bat}/N_{bat}}{V} \tag{7}$$

Applying Eq. (7) to Eq. (5), and solving the resulting quadratic equation, the resultant voltage calculation is shown in Eq. (8).

$$V = \frac{OCV + \sqrt{OCV^2 + (4R\, P_{bat}/N_{bat})}}{2} \tag{8}$$

- **Energy loses on BESS**

The considered energy losses on the BESS are the ones generated by the DC/AC and AC/DC converter and the joule losses on the BESS.

In the case of the converter, each commercial converter has an efficiency curve which can be used to know the losses on the converter (Figure 6). The chosen converter is the SIEMENS sinvert 200 MS [21]. The images of data has been reverse engineered to extract the underlying numerical data available using the WebPlotDigitizer [20]. In total, 50 converters are required to deal with the installed 10 MWh BESS.

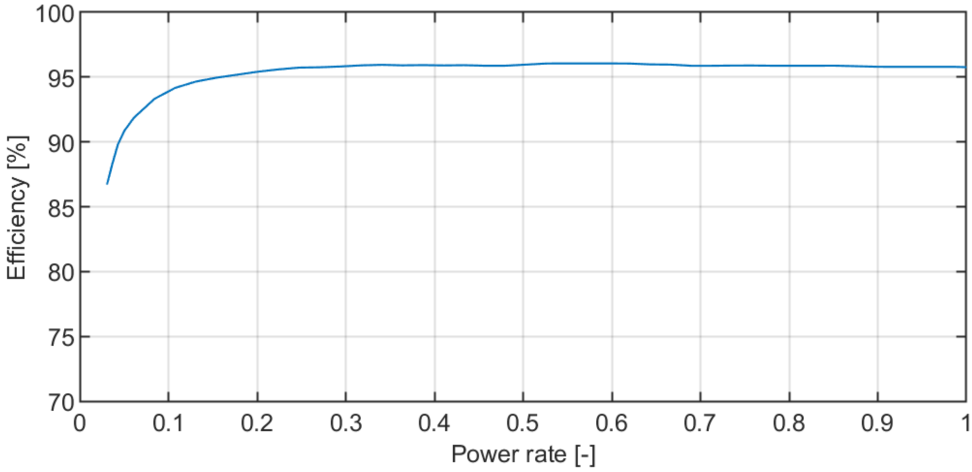

Figure 6: Efficiency of SIEMENS sinvert 200 MS [21].

In the case of the Joule effect losses, the losses depend on the obtained R from the aging model and the power the BESS is operated (Eq. (9)).

$$P_{joule} = I^2 R = \left(\frac{P}{V}\right)^2 R \tag{9}$$

3.3 Cost calculation

The cost of the whole installation has been assumed to be the sum of the costs of each energy generation that the microgrid is composed. This cost comprises the costs of the solar power plant, the wind power plant and the BESS, which are divided in an initial capital investment (CI), the maintenance and operation costs (M&O) and the replacement cost (RC).

The cost of the solar and wind power plants are taken from average cost values calculated by the European Commission [12]. The cost values used on the simulations are shown in Table 3, where in this case, the M&O comprises also the RC. The CI value given by the European Commission and the M&O value given by the Green Campus project is multiplied by the installed MW (13,2 for wind and 10 for solar).

Table 3: Cost values of an average solar and wind power plant on Belgium [12].

Generation type	CI [€/KW]	M&O [€/MWyear]
Solar PV (ground)	800	34,000
Wind onshore	1,767	50,000

In the case of the BESS, the cost has been calculated from the scratch. Firstly, the components of the BESS installation have been defined:

- The batteries.
- The battery module.
- The Battery Management System (BMS).
- The battery container.
- The energy converter.

For the battery module (batteries and BMS included), values from second life TESLA model S battery modules available on AMAZON are considered. The cost of the battery container considers both, the space to stock all the battery modules (industrial containers) as well as the infrastructure to stack them (shelving for heavy loads). The cost for the energy converter is calculated multiplying the required number of converters with the cost of the chosen commercial converter: SIEMENS sinvert 200 MS. The results are resumed in Table 4.

Table 4: Cost values taken into account on BESS CI calculation.

Element	CI [€]
Battery module (+444 batteries)	950
BMS per module	20
Container	11.350
Converter	50.000

Secondly, the M&O is calculated. Based on our experience, the yearly maintenance cost of a 10 MW BESS installation is 15,000 €. The operation cost is assumed to be the cost of have a qualified employee hired to operate the BESS (50,000€).

Finally, the RC is calculated. The replacement is done when the EOL criteria is reached. In that moment, all the batteries and battery modules are replaced. The cost of second life TESLA model S battery module is assumed to decrease 2% each year. With this assumption the RC on the years the replacement is required is calculated.

Once properly defined the CI, M&O and RC, the cost of the whole microgrid is calculated. For that, one more assumption is taken: the initial investment is done with a 10-year loan to the bank with an interest of 5% to pay in 10 yearly payments. The calculus of the payment of each year is done with MATLAB's function "payper". Then, the obtained CI, M&O and RC values for each year is used as the yearly cost on the LCOE calculation (Eq. (2)).

4 Results

The approach is simulated in terms of the values shown in Table 5.

Table 5: Variables of the simulation of the LCOE optimization approach.

Variable	Value
Microgrid operation years	2017-2041
R_0	40 mΩ
R_{EOL}	100 mΩ
SOH_0	80%
SOH_{EOL}	60%
Maximum charge power	4,992 kW
Maximum discharge power	9,998 kW
Residual energy (E_{bat_0})	2,999kWh
Grid surplus reduction	70 %
Discount rate	8.9%
Replacement wait time (t_r)	48 h

The simulation gives us the optimized operation of the BESS each year as well as the LCOE cost for the imposed operation criteria. An example of the yearly BESS operation is shown in Figure 7 and in Figure 8.

Once simulated the optimum operation way of the BESS in the defined operation period (form January 2017 to December 2041), the BESS operation in terms of DOD in the three operation criteria is obtained (Figure 9).

Besides, the yearly time that the demand is covered in island mode can be calculated for the three BESS operation criteria as well as the years the BESS is replaced (Figure 10).

As final result, LCOE values for the three defined operation criteria is displayed in Figure 11.

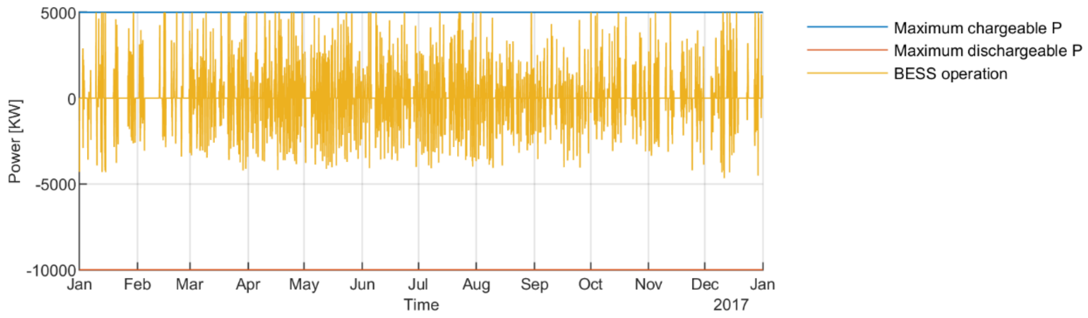

Figure 7: Operation of the BESS in 2017 operated in OPC 1. The blue line represents the maximum chargeable power, the red line represents the dischargeable power and the orange line represent the power taken (negative) or given (positive) to the BESS (converter + BMS + batteries).

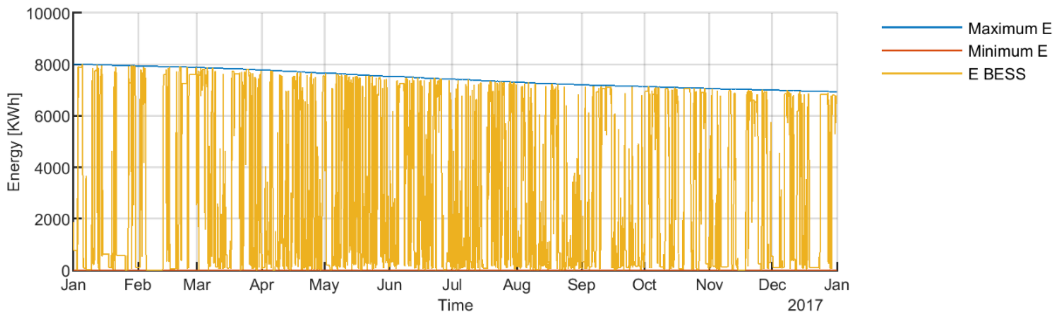

Figure 8: Energy evolution on the BESS in 2017 operated in OPC 1. The blue line represents the containable maximum energy, the red line represents the minimum containable energy and the orange line represents the energy at different time instants.

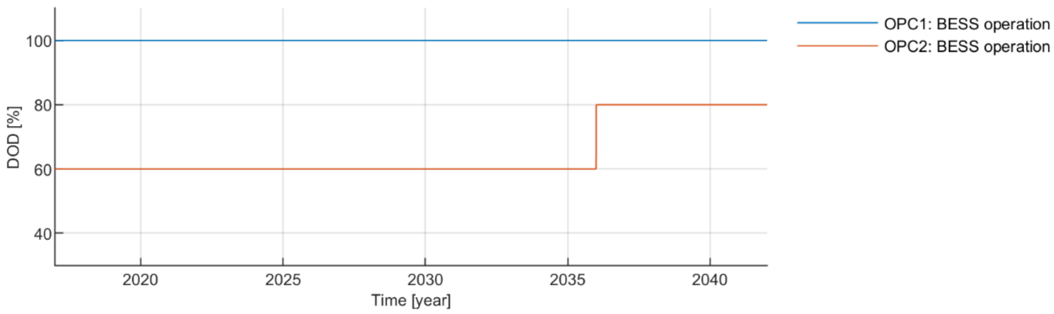

Figure 9: BESS operation in terms of the DOD. The blue line is the DOD at which the BESS is operated in OPC 1 and the red line is the DOD at which the BESS is operated in OPC 2.

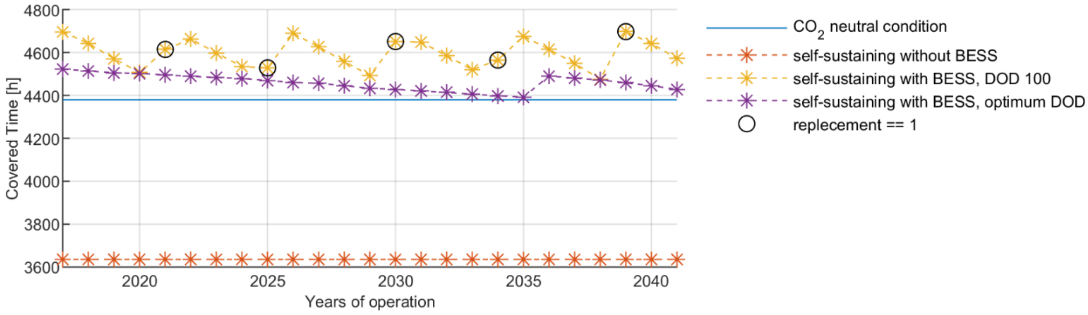

Figure 10: Covered time in each operation criterion. The blue line is the minimum time the demand at Zellik needs to be covered in island mode, the dotted red line is the time the microgrid is able to cover the demand in island mode without operating the BESS, the dotted yellow line is the time the microgrid is able to cover the demand in island mode following the first operation criterion, the dotted purple line is the time the microgrid is able to cover the demand

in island mode following the second operation criterion and the black circles represents the years where the batteries are replaced.

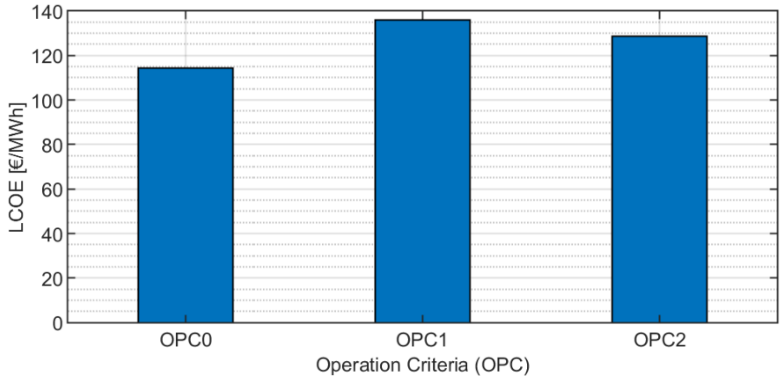

Figure 11: LCOE values for the three defined operation criteria.

5 Discussion

The BESS is always operated inside the power limits imposed by the battery characteristics (4,992 kW at charging and 9,998 kW at discharging) as shown in Figure 7. The algorithm deals with the power losses (such as the converter power loses) and is able to maximize the BESS performance to its limits. Figure 8 shows how the energy is kept always between the imposed energy limits even though having a voltage and SOC control using a battery level dynamic model. Besides, it can be seen how the battery level aging model make the maximum chargeable energy limit go down along the time. Thanks to these two models, the battery level characteristics have been added to a top view level solution such as the proposed BESS operation on a mirogrid with solar and wind energy generation.

The operation of the BESS has been optimized following two criteria. The Figure 9 shows the main difference on the operation of these criteria: the DOD. On one hand, the first criterion (OPC 1) is set up to find the optimum BESS operation using at its maximum storage capacity (operate the BESS always with a 100% DOD). On the other hand, the second criterion (OPC 2) is set up to find the least stressful operation way while fulfilling the auto-imposed 50% island mode criterion (searchs for the minimum DOD). In this case, due to restrictions on data availability, the DOD operation ranges are set in 40%, 60%, 80%, 84%, 88% and 100%. The Figure 9 shows how the BESS is operated at its second minimum DOD until 2036, when a DOD change happens (from 60% to 80%). The change on the operated DOD in OPC 2 can be also seen in the Figure 10, where the covered time in 2035 almost reaches the covered time threshold and suddenly, an increase of covered time happens in the next year (in 2036) even though there is no replacement. This increased time comes when the BESS operation DOD is increased (more storage capacity is used, so the demand is covered more time in island more).

In Figure 10 also shows how the implementation of the solar and wind energy generation plant (OPC 0) is not enough to fulfil the autoimposed 50% island mode criterion. As well, it can be seen that if the BESS is operated in OPC 1, the whole installation covers the demand more hours in island mode than the other options, but it also degrades much more the BESS, having to replace them a total of 5 times in 25 years. In terms of cost, the Figure 11 shows that the best option in terms of cost would be OPC 0, where there is no BESS. However, OPC 0 doesn’t fulfil the auto-imposed 50% island mode criterion, so this solution is not technically appropriate. Between the OPC 1 and OPC 2, the best option is the OPC 2, which gets a LCOE value of 128,7 €/MWh (7 €/MWh less than the OPC1).

6 Conclusions

The proposed approach offers the possibility of integrating more realistic energy generation plant models onto LCOE estimations of a microgrid with multiple generation components (BESS is taken as an energy generation plant). For this paper, the long term behaviour of a second life Li-ion battery is integrated along with its dynamic model and aging model. Thanks to the developed research, more realistic operation and replacement costs (RC) of the whole BESS are obtained, which have led to more accurate LCOE estimations. The obtained results have proved that the optimal operation way of the BESS reduces the LCOE of the whole system in the case energy balancing and/or compensation is required. In this case, a decrease of 7€ on each sold MWh is achievable by an appropriate operation of the BESS.

In a future publication, ancillary services will be added to the operation optimization problem. In this way, complex and multi-disciplinary operations will be available on the developed LCOE evaluation. In addition to this, the developed LCOE evaluation will add as well the effect of the temperature on the BESS, taking into account like this the characteristics of the temperature conditioner onto the dynamic and aging behaviour of the lithium ion batteries.

Acknowledgments

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