Optimisation model with degradation for a battery energy storage system at an EV fast charging station

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***Abstract*—The electrification of the energy sector challenges the conventional methods to meet the increased load demand. The rapid increase of electric vehicles and the desire for shorter charging time at fast charging stations (FCS) contributes to higher power peaks in local distribution grids. This may lead to capacity issues, where a battery storage can be considered as an alternative to reinforcing the grid. This paper proposes a novel optimisation model including degradation that minimises operational costs for an actual FCS in Norway with a battery system. A case study is performed, where installing a battery system is compared to traditional grid reinforcement. The result of the case study shows that the total cost was 0.9 million NOK[1] higher for installing a BESS than reinforcing the grid, which corresponds to 44 % of the battery investment cost. Sensitivity analyses are done on time step, grid tariffs and degradation. The sensitivity analysis on degradation shows that calendar aging dominates battery degradation.**

***Index Terms*—electric vehicles, fast charging station, battery energy storage system, degradation, optimisation, peak shaving**

I. Introduction

A. Motivation and background

The transport sector is responsible for more than 25 % of the global CO_2 emissions [1]. Thus, electrification of the transport sector, in combination with development of renewable energy sources, is an essential part in the transition towards a more environmentally-friendly future. The number of electric vehicles (EVs) is increasing rapidly, and the associated charging demand from the transport sector is rising. In the remainder of this article, the term EV will denote electric cars. Up until today, most of the charging demand from EVs has come from home charging. The last few years, however, the number of fast charging stations (FCS) and the range of modern EVs have increased rapidly [2], making long-distance travel with EVs more popular. In order to avoid bottlenecks in the power system due to fast charging of EVs, stationary battery energy storage systems (BESS) could be installed at the FCS. In this paper, an optimisation model of a local BESS at an FCS for EVs is proposed. The optimisation model includes a detailed BESS degradation model. The proposed optimisation model is then applied to a real case study in Norway.

B. Relevant literature

FCS for EVs can represent a substantial load to the electric distribution system, with a potential aggregated load of several megawatts. This load will vary during the day, depending on factors such as the traffic flow and demographics in the area. In [3, 4, 5, 6], methods for modelling the aggregated load of an FCS for EVs were proposed. In the case study performed in [6], it was shown that the peak-to-average power ratio of an FCS along a highway is very high. Thus, the use of a local BESS could be of great benefit to deliver the peak power demand of the FCS and reduce the grid tariffs and potential grid investment needs related to the FCS.

Several papers have studied BESS in connection with a FCS. In [4], an algorithm for sizing the BESS as a function of available grid connection was presented. Ref. [7] proposed a coordinated control of photovoltaic (PV) and BESS integrated in an FCS to avoid transformer overloading. Ref. [8] described a case study of a FCS with BESS to reduce the grid connection fees and the contracted power of the FCS. The BESS operation was simulated with a control strategy including degradation for peak shaving and providing frequency control. In [9], various scenarios for a FCS with PV and BESS were considered to improve the economics for the FCS. The results showed that the scenarios were not economically viable under the current PV and BESS prices, but that they might become so in 5 to 10 years depending on cost reduction scenarios. None of the references above optimised the operation of the BESS, but rather used control strategies. In this paper, an optimisation model for the BESS including degradation constraints is presented.

C. Contribution and structure

This paper presents an optimisation model that incorporates BESS operation, degradation and load modelling. The main contributions of the work presented in this paper are:

- A proposed methodology for combining BESS operation and degradation in a single optimisation model
- Evaluation of how time step interval, degradation and grid tariffs affect the economic assessment.

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[1]NOK: Abbreviation for Norwegian currency (Norwegian kroner). Exchange rate 2021-03-01: 10.4 NOK/EUR.

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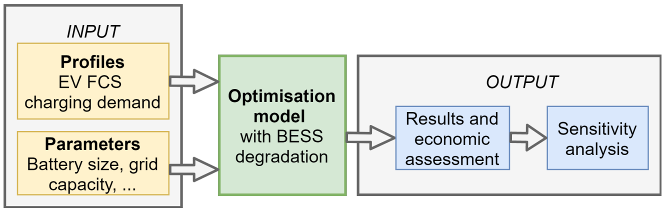

Fig. 1. General overview of method.

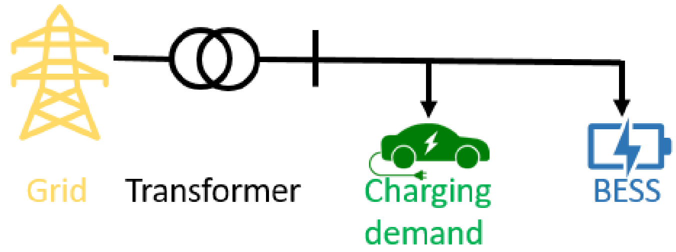

Fig. 2. General overview of the local grid.

This paper has five sections. Section II presents the method for the optimisation model including degradation, economic assessment equations and methods for sensitivity analysis. Section III presents the details of the case study, including the modeling of the load profile of the FCS. In Section IV, the results from the case study are presented. Section V discusses the results. Finally, in section VI, conclusion and further work are presented.

II. Method

Fig. 1 shows the overall structure of the work. Profiles and parameters are given as input to the optimisation model. Then, the optimisation model is run including the BESS degradation model. From the output of the optimisation model, an economic assessment is done and at last, sensitivity analyses for key parameters are conducted.

A. Input to optimisation model

The optimisation model requires input as indicated in Fig. 1. The load must be determined and in this paper a modelled EV charging demand is used. Some parameters must also be determined, such as BESS size, grid capacity, degradation constants, minimum and maximum values of SoC. All constants required are described in Table I. The optimisation model assumes a perfect forecast by having the load and spot price of electricity as known entities.

B. Optimisation model

For a given power and energy capacity of a BESS, the optimisation model will calculate the cost-optimal operation. The objective of the optimisation model is to minimise the total operational costs as shown in (2a). The objective function consists of a discounted sum over the years of the costs of buying energy from the hourly spot market price (c_h^{spot}) and the monthly varying grid tariffs (power and energy term: $c_m^{E,tar}$ and $c_m^{P,tar}$). The spot price and energy tariff is multiplied with the energy drawn from the grid ($P_t^{grid}\Delta t$) and the power tariff is multiplied with the monthly maximum power drawn from the grid (P_t^{grid}). The discount factor α_y is given by (1), where y is the year and r is the discount factor.

$$\alpha_y = (1+r)^{-y} \tag{1}$$

The active power balance at the node where the BESS, grid, and FCS are connected, is defined in (2b). Fig. 2 provides a visualization of the local grid. The BESS power is the difference between the two non-negative variables representing charging power (P^c) and discharging power (P^d), restricted by (2c). The energy balance is calculated with (2d). Constraints (2e)-(2l) regarding BESS degradation are explained separately in subsection II-C. The constraints (2m) to (2o) are limiting P^c, P^d and P^{grid}. The BESS must be capable of keeping the active power drawn from the grid within the capacity limits of the local power system, due to e.g. transformer or power line ratings. Description of variables and parameters in the optimisation formulation is in Table I. The optimisation model is formulated here:

$$\min_{P_{grid}^{max}} \sum_{y\in Y} \alpha_y \Big[\sum_{h\in H} \left(c_h^{spot} + c_m^{E,tar}\right) \sum_{t\in T_h} P_t^{grid}\Delta t + \sum_{m\in M} c_m^{P,tar} \cdot \max(P_t^{grid}) \Big] \tag{2a}$$

s.t.

$$P_t^L = P_t^{grid} + P_t^B \qquad \forall t\in T \tag{2b}$$
$$P_t^B = P_t^d - P_t^c \qquad \forall t\in T \tag{2c}$$
$$\Delta E_t^B = \eta_c \cdot P_t^c \Delta t - \frac{1}{\eta_d} \cdot P_t^d \Delta t \qquad \forall t\in T \tag{2d}$$
$$E^{B,cap} = SoH_t \cdot E^{B0} \qquad \forall t\in T \tag{2e}$$
$$SoC_t = \frac{E_t^B}{E^{B,cap}} \qquad \forall t\in T \tag{2f}$$
$$C_t^r = \frac{P_t^B}{E^{B0}} \qquad \forall t\in T \tag{2g}$$
$$\Delta FEC_t = \frac{P_t^c + P_t^d}{2E^{B0}\cdot (SoC_{max} - SoC_{min})}\Delta t \qquad \forall t\in T \tag{2h}$$
$$SoH_t = SoH_{t_0} - k_K \cdot \sqrt{t} - f_t^c \cdot FEC_t \qquad \forall t\in T \tag{2i}$$
$$f_t^c = k_{C_{r0}} + k_{C_{r1}} \cdot C_t^r \qquad \forall t\in T \tag{2j}$$
$$SoC_t \geq SoC_{min} \qquad \forall t\in T \tag{2k}$$
$$SoC_t \leq SoC_{max} \qquad \forall t\in T \tag{2l}$$
$$P_t^c \leq P_{max}^{inv} \qquad \forall t\in T \tag{2m}$$
$$P_t^d \leq P_{max}^{inv} \qquad \forall t\in T \tag{2n}$$
$$P_t^{grid} \leq P_{max}^{grid} \qquad \forall t\in T \tag{2o}$$

C. Degradation model

Constraints (2e)-(2l) describe the degradation part of the optimisation model. The BESS's initial energy capacity is multiplied with SoH to compute the actual energy capacity at

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TABLE I
DESCRIPTION AND UNITS FOR VARIABLES AND CONSTANTS IN THE OPTIMISATION MODEL.

	Variables		
Name	***Description***	***Unit***	
P_t^{grid}	Power drawn from the grid	kW	
P_t^B	Power drawn from the BESS	kW	
P_t^d	BESS discharging power	kW	
P_t^c	BESS charging power	kW	
SoC	State of charge	%	
FEC	Full equivalent cycle	cycle	
f^c	Cyclic aging function	%/cycle	
SoH	State of health	%	
	Constants		
Name	***Description***	***Unit***	***Case study***
P_t^L	EV charging demand	kW	
P_{max}^{grid}	Grid capacity	kW	1250
η_c	BESS charging efficiency	%	95
η_d	BESS discharging efficiency	%	95
SoC_{min}	Minimum level of SoC	%	90
SoC_{max}	Maximum level of SoC	%	20
k_K	Calender aging factor	$1/\sqrt{\text{min}}$	0.00977
$k_{C_{r0}}$	Cyclic aging factor	%/cycle	0.001903
$k_{C_{r1}}$	Cyclic aging factor	h %/cycle	0.001809
E^{B0}	BESS energy capacity	kWh	225
P_{max}^{inv}	BESS power capacity	kW	300
	Economic parameters		
Name	***Description***	***Unit***	***Case study***
c_h^{spot}	Spot price	NOK/kWh	Nordpool[a]
$c_m^{E,tar}$	Energy tariff	NOK/kWh	Table II
$c_m^{P,tar}$	Power tariff	NOK/kW	Table II
α_y	Discounting factor	-	(1)
	Sets		
Name	***Description***	***Unit***	***Case study***
T	Minutes in analysed period	-	[1,2628000]
T_h	Minutes in one hour	-	[1,60]
H	Hours in one year	-	[1,8760]
M	Months in one year	-	[1,12]
Y	Years in analysed period	-	[1,5]

[a]Historic 2019 day-ahead market prices from Nordpool.

TABLE II
GRID TARIFFS [17].

Time period	Tariff terms per month		
	Fixed fee [NOK]	***Energy tariff [NOK/MWh]***	***Power tariff [NOK/kW]***
Grid tariffs in Mid Norway (Case study)			
Oct to Apr	8,818	65.1	81.6
May to Sep	8,818	65.1	0
Alternative grid tariffs (Sensitivity analysis)			
Dec to Feb	1,065	70	150
Mar & Nov	1,065	70	80
Apr to Oct	1,065	39	23

all times as shown in (2e). The state of charge (SoC), stated in (2f), is the energy stored at each time step divided by the current BESS energy capacity [10]. The SoC is constrained in (2k) and (2l), where the limits should be chosen wisely regarding degradation and lifetime.

The degradation model distinguishes between *calendar aging*, which is due to a non-avoidable capacity decrease with time, and *cyclic aging*, which is degradation from the BESS's operation, charging, and discharging [11]. The level and pace of BESS degradation depend on temperature, time t, C-rate C^r, and *full equivalent cycles* (FEC) [12]. This degradation model assumes a constant temperature to investigate the operational properties. The two other quantities, C-rate and FEC, are defined in (2g) and (2h), taken from [13].

The equations describing the degradation in the optimisation model is deducted with a basis in a degradation model first published in 2011 [14]. In (2i) the calendar aging is modeled as a temperature-dependent factor (k_K) multiplied with the square root of time as in [12, 15, 16]. In (2i) the cyclic aging is modeled as a product of FEC and a function f_t^c which depends on temperature and C-rate, as in [14, 15]. A detailed deduction of how to make a linear relationship between f_t^c and C_t^r in (2j), is shown in [17]. The linear C-rate function in combination with FEC make the optimisation model quadratic which increases the necessary computational effort to solve the problem.

D. Economic assessment

The economic assessment is performed as a comparison between installing a BESS and reinforcing the grid for a given FCS load. The net present value (NPV) is shown in (3) and includes operational costs ($C_{y,m}^{op}$), investment costs (C^I), and the residual value of the equipment (V^R). The operational costs in (2a) are the main output from the optimisation model.

$$NPV = C^I + \sum_{y \in Y} \alpha_y \sum_{m \in M} C_{y,m}^{op} - V^R \tag{3}$$

E. Sensitivity analysis

In this section, it is explained how the sensitivity analyses on degradation, time steps and grid tariffs are performed.

1) Degradation sensitivity: The degradation sensitivity is a comparison between three different modelling assumptions: no degradation, only calendar aging and only cyclic aging. To do so, the following adjustments are made in the optimisation model:

- No degradation: $SoH_t = 0 \ \forall t \in T$, and constraints (2g) to (2j) are omitted
- Only calendar aging: constraints (2g), (2h) and (2j) are omitted and the last term in (2i) is removed
- Only cyclic aging: the second term in (2i) is removed

2) Time step sensitivity: In the original optimisation, the EV charging demand is modeled on a minute basis and the optimisation is thus also done on a minute basis. The time step sensitivity is done by transforming the EV charging demand (P^L) to hourly time resolution ($P^{L,H}$) with (4) and running the optimisation model with hourly time resolution.

$$P_h^{L,H} = \frac{1}{60} \sum_{t=1}^{60} P_{t+60\cdot(h-1)}^L \qquad \forall h \in H \tag{4}$$

3) Grid tariff sensitivity: The grid tariff sensitivity is done by changing the grid tariffs to the grid tariffs marked with "Alternative grid tariffs" in Table II.

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III. Case study

A. Description of case study

The case study is based on a real-life FCS connected to the grid through a transformer in Norway. The analysis period for the optimisation is five years. It is assumed that the FCS operator wants to increase the number of chargers by 50 % (from today's situation), leading to an overloading at the transformer. The number of chargers will increase to three 22 kW, three 50 kW and 18 150 kW chargers due to the fast development of EVs in Norway. The transformer has a rating of 1,250 kVA and a residual value of 250 kNOK, if replaced. The potential peak load increases from 1,044 kW to 1,566 kW with the 50 % increase in number of charging points. The maximum thermal capacity of the transformer is constraining the power drawn from the grid in (2o). Hence, there are two possible investment alternatives, referred to as case 1 and 2:

- Case 1 is to purchase a new transformer with a 1,600 kVA rating for 500 kNOK
- Case 2 is to install a BESS to peak shave enough to be able to keep the existing transformer.

Fig. 2 show the general grid situation for the cases, however case 1 does not include a BESS but upgrade the transformer instead. For case 2, the operational costs are calculated with the same optimisation model with a BESS capacity of zero.

The BESS size used as input to the optimisation model in the case study is 225 kWh/300 kW [17]. The specific investment costs are assumed to be 1,700 NOK/kWh for energy storage capacity, and 5,525 NOK/kW for power capability with a projected 2020 battery price level based on [18] and an exchange rate of 8.5 NOK/USD. According to [19], the BESS terminal voltage is approximately proportional to the SoC in the region between 20 % and 90 %, hence these values are chosen for minimum and maximum level of SoC. The residual value of the BESS after the five year analysis period is assumed to be 25 % of the BESS's investment cost. For the economic assessment a 4.5 % discount rate is applied.

B. EV charging demand

The charging demand at the FCS was modelled by considering time to next arrival, EV model and initial EV battery SoC as stochastic variables, as described below. A detailed description can be found in [17]. The EV charging demand for four days in different months is the blue graph in Fig. 3.

The initial SoC of an incoming EV's battery is chosen to be log-normally distributed [20]. The log-normally distributed vehicle kilometers travelled can be found in [21], which describes Norwegian charging behaviour. From this, the expectation value and standard deviation of initial SoC are calculated to be 42.3 % and 20.3 %. The calculation of initial SoC based on vehicle kilometers travelled is under the assumption that all EVs stop charging when the EV battery SoC reaches 90 % and that the relation between driving ranges and driven distances are constant.

The EVs are assumed to arrive following a Poisson process, and the number of EVs arriving each hour is Poisson distributed [3]. The expectation value and standard deviation vary over the day (24 hours) and year (12 months). Each hour has a specific value of the expectation value and the standard deviation, which remains the same during that hour and is based on empirical data for charging behavior in Norway [21]. The inter-arrival time between two Poisson distributed events with constant expectation value is exponential. For implementation, either a Poisson distribution on EV arrival or an exponential distribution on inter-arrival time can be used. The EV model distribution is a clustered group based on the top ten sold EVs in Norway at the end of 2019 and the distribution can be found in [17].

Nonlinearities in the optimisation model presented in subsection II, combined with a time step resolution of minutes, results in high running time for five years. Therefore each month is represented by the day with the highest peak. The optimisation model was implemented in Julia. IPOPT, which applies interior point method [22], was used as solver.

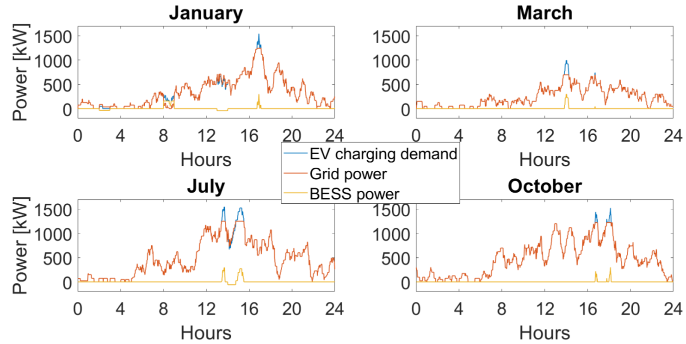

Fig. 3. Four days to illustrate the operation of the FCS.

IV. Results

This section shows the results from the case study, as well as sensitivity analyses on degradation, grid tariff and time step.

A. Case study results

Fig. 3 shows the resulting profiles for EV charging demand, grid power and BESS power for four days in different months.

As mentioned, for case 1 the operational costs are calculated with the same optimisation model with a BESS capacity of zero. The numbers are summarised in Table III. The final NPV for the total costs in case 2 is 11,226 kNOK. By

TABLE III
ECONOMIC RESULT DIVIDED INTO COST ELEMENTS, ALL NUMBERS ARE PRESENT VALUE (DISCOUNTED).

Cost element	Options in case study	
	Case 1 [kNOK]	*Case 2 [kNOK]*
Sales value year 0	-250	0
Investment cost year 0	500	2,040
Spot cost, sum	5,800	5,791
Energy tariff cost, sum	983	984
Power tariff cost, sum	3,618	2,831
Residual value year 5	-334[a]	-420
Total cost	10,317	11,226

[a]Assuming 30 years life time and linear value decrease.

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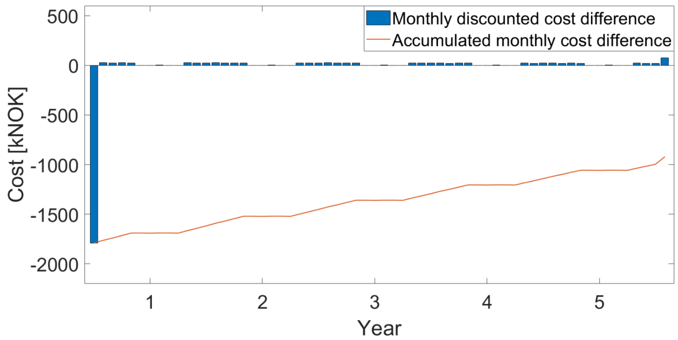

Fig. 4. NPV difference between case 1 and case 2. The cost difference is the cost of grid reinforcement subtracted the cost of BESS installation.

installing a BESS, the peak power is reduced by 19 % during the months with the highest load demand. Fig. 4 shows the monthly discounted difference and accumulated difference between the two cases for each month. The final difference in total costs is 906 kNOK, where the major differences are in investment costs and power tariff costs. The grid tariff savings by installing a BESS do not fully finance the installation cost. The value of SoH at the end of the fifth year is 81.1 %. If cyclic aging is omitted, the SoH value at the same time would be 84.2 %.

B. Sensitivity on degradation

To consider the degradation impact on the total costs, the optimisation model with BESS is run with no degradation, only calendar degradation, and only cyclic degradation as explained in subsection II-E. With only calendar aging, the operational costs increase with 0.022 % and 0.019 % the first and last year, respectively compared to no degradation. With only cyclic aging, the operational costs increase with 0.007 % and 0.004 % the first and last year, respectively, compared to no degradation. The numbers clearly show that degradation constraints do not have a large impact on the operational cost.

C. Sensitivity on grid tariffs

To consider how the tariffs affect the total costs, the optimisation model is run with alternative grid tariffs, as shown in Table II. The NPV for total costs when installing BESS is 12,023 kNOK and for reinforcing the grid it is 11,384 kNOK.

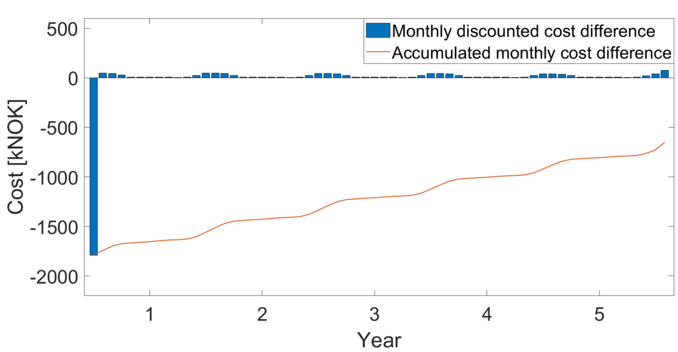

Fig. 5. NPV difference between case 1 and case 2. The cost difference is the cost of grid reinforcement subtracted the cost of BESS installation.

Fig. 5 shows the difference between the discounted costs as in the case study for the alternative grid tariffs.

The increase in grid tariffs results in a 6.7 % increase in total costs for the case 2 and a 10.3 % increase in total costs for case 1. The total costs in case 1 is 639 kNOK less than in case 2 with alternative grid tariffs. Hence, the gap between the two cases has decreased with 30 %, compared to the initial case study results.

D. Sensitivity on time step

The last sensitivity investigates how optimisation models with different time step will give different economic results. Table IV shows the peak power of the EV charging demand and the peak shave level for both minute and hour time resolution. The peak shave level is never above 150 kW with hourly time resolution, and is 0 kW in three months. In comparison, the peak shave level is 300 kW in seven months with a time step resolution of minutes. The operational cost in case 2 is 265 kNOK less for time steps of an hour, compared to a minute. Of the 265 kNOK annual cost difference, 194 kNOK is related to the power tariff. The objective function when using hourly resolution ends up with a value 15 % lower than optimising with a time step of minutes.

V. Discussion

The result in the case study implies that reinforcing the grid will give cost savings of 906 kNOK compared to installing a BESS. The BESS investment costs are high and the cost savings the BESS provides are not enough to compensate for the high investment cost, in this particular case study. However, with decreasing BESS prices or higher cost savings for applying BESS, it might become profitable.

The sensitivity analysis implies that the degradation has a minimal impact on the operational costs, but rather an impact on the investment costs. The BESS must be able to peak shave the necessary amount each day, and the degradation reduces the capacity by time and use. Hence, the initial BESS capacity is forced to be higher than when degradation is not regarded. Also, calendar aging is the dominant term in the degradation

TABLE IV
TIME STEP ANALYSIS

Month	Minute resolution: *Peak power charging demand [kW]*	Minute resolution: *Peak shave [kW]*	Hour resolution: *Peak power charging demand [kW]*	Hour resolution: *Peak shave [kW]*
January	1,280	300	830	150
February	1,200	300	977	104
March	1,120	300	812	73
April	1,200	300	835	150
May	1,280	294	838	150
June	1,360	122	935	0
July	1,200	294	859	150
August	1,200	166	869	0
September	1,240	16	867	0
October	1,200	300	827	100
November	1,200	300	933	88
December	1,280	300	827	88

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and thus it can approximately describe the capacity fade and is a linear contribution to the optimisation, unlike cyclic aging.

A rise in the grid tariffs will increase the profitability of installing a BESS compared with traditional grid reinforcement. On the other hand, the downside of such a cost rise is the negative effect on the expanding charging infrastructure and electrification: higher specific power tariff costs will reduce the number of profitable projects. Thus, there is a balance between the realisation of new projects and incentives for increased flexibility that the DSO should be aware of.

Time step selection in the optimisation model affects the result of the optimisation model. The EV charging demand is simulated on a minute basis and thus the optimisation is on a minute basis. When simulating for hours, the load peaks are reduced as well as the potential for power tariff savings. On short time intervals, small energy amounts can reduce the peak power significantly, an ability which mitigates with increased time steps. Longer time steps gives lower grid tariff costs without BESS and with BESS. Shorter time steps give a more accurate EV charging demand and higher economic precision.

VI. Conclusion and further work

This paper aimed to combine BESS operation and degradation into one optimisation model with a stochastic-generated load for FCS as input. The sensitivity analyses show a large impact from grid tariffs and optimisation time steps on BESS profitability. The results also show that the degradation constraints do not directly impact the operational costs significantly, e.g. the increased costs of hourly time steps instead of minutes have considerably higher impact than including cyclic aging in this case. As discussed in section V, the degradation ensures that the BESS is sized to be able to complete its objective throughout the analysing period and thus requires higher investment costs. The degradation has an indirect effect on the total costs associated with investment.

Further work includes developing a linear optimisation model with calendar aging with two modifications. That is to keep the optimisation model linear and to keep a time step resolution of minutes. A linear optimisation model can have BESS size as a variable and the model can be a useful tool to dimension the BESS and estimate the costs before pursuing a more detailed analysis. Another topic for further work could be to include reactive power in the optimisation model, e.g. to investigate the use of reactive power for voltage control by using the bidirectional converter of the BESS.

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