Economic Evaluation of Battery Energy Storage Integration into Plant with Cyclic Load

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***Abstract*—This paper deals with the simplified economic evaluation of the peak shaving by a battery-based energy storage system in plants with cyclic load profile (typically steel plants) and its own electrical energy source – typically the steam turbine. There are several possible motivations and/or benefits to be explored. The paper focuses on the optimal sizing of the turbine and BESS in relation to the total costs of investment and operation. There is proposed a methodology of integration into these plants. A control strategy of Battery Energy Storage System (BESS) operation is proposed. The impact is put on the inclusion of all economically important factors. Finally, the case study is defined and evaluated, based on the steel plant load diagram and other key factors. The technical-economic potential of this application is discussed in the conclusion.**

Keywords*—Battery Energy Storage, Cooperation, Cyclic load, Economic Evaluation, Integration, Li-ion, Steam Turbine, Steel plants

I. Introduction

There is an increasing trend of the battery energy storage systems (BESS) integration in the energy grid to compensate the fluctuating renewable energy sources [1], [2]. The number of installations is expected to grow exponentially based on the prediction of IEA Energy World Outlook [3]. There are a variety of applications, based on the target function [4], [5], [6] - the storage can be connected directly to the fluctuating renewable energy sources to improve the stability of supplied power, to the energy grid itself to improve the grid quality and power balance, or directly into the consumer or prosumer in an industrial or commercial facility for peak shaving of its production and/or consumption. This paper is focused on the peak shaving function in the industry plants.

Usage of BESS for peak shaving is frequent application because there is typically sufficient low capacity to cover energy supply in short periods and short response time which are characteristics typical for BESS.

There are heavy industry plants (typically steel plants) with cyclic load profile caused by operation of electric furnaces. In addition, these plants have their own energy sources (typically steam turbines). Plant operation can be due to the cyclic load profile and own energy source optimized in a lot of ways described for example in [7] or [8].

The focus is paid on the optimal sizing problem of both turbine and BESS from a technical-economic point of view. The designed case study is based on the real load profile of a typical steal plant, described the employed methodology, evaluated the case study, and discussed the conclusions. Additional possible pros and cons of BESS integration in the steel plants are discussed as well.

II. Basic Assumptions

A. Load profile

In the presented case study, it is used the load profile described in [9]. Specifically, 40 t alloy steel furnace (5 min load discretization) with 8.4 MW baseload which can be seen in Fig. 1. This profile periodically repeats during whole day (12 times per day).

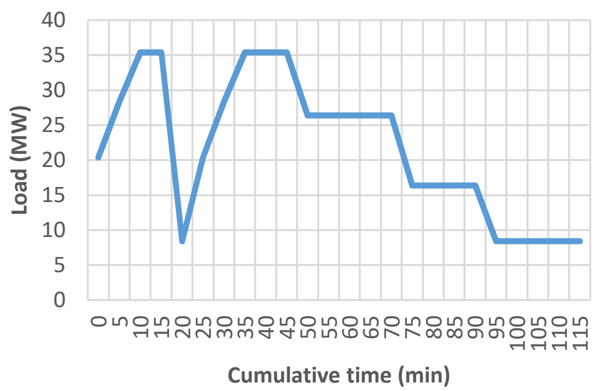

Fig. 1. Assumed load profile

B. Battery technology and converter

A battery comparison methodology (including lifetime) was developed in the previous work [10]. According to this the Li-ion battery technology is assumed due to its capability of optimal sizing (power and capacity ratio). Costs quantification is provided in the case study section.

C. Steam turbine

Steam turbine has its own control and operation limits provided by cooperating turbine manufacturer. On the one side there is control limitation noted in TABLE I. On the other side there is an erosion limitation due to operation on a low power approximated by (1) and shown in Fig. 2. Maximal value of the erosion during the turbine lifetime is 20 mm.

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TABLE I. TURBINE CONTROL LIMITATIONS

Case num.	*Load Changes*	*Time Constant (min)*	*Abs. Load Range MIN*	*Abs. Load Range MAX*	*Load Range Change MIN*	*Load Range Change MAX*	*Max. rate of load change (%Q/min)*	*Limitation (-)*
1	STEP	1	0 %	17 %	40 %	100 %	no limit	
2	FAST	3	17 %	40 %	40 %	80 %	1 %	
3	FAST	3	17 %	40 %	40 %	80 %	5 %	Max 10,000x
4	FAST	3	17 %	40 %	80 %	100 %	3 %	
5	NORMAL	4	40 %	60 %	40 %	100 %	5 %	Max 3,000x

$$erosion = 4 \times 10^6 \times Q^{-3.989} \quad (1)$$

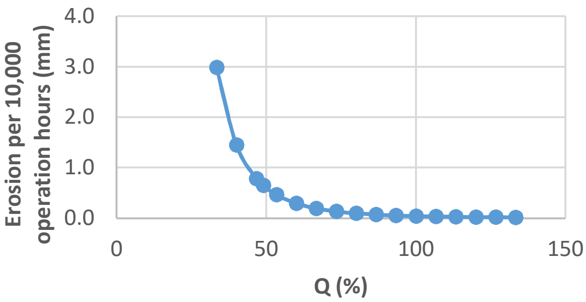

Fig. 2. Turbine erosion assumption

Where Q (%) is ratio of the steam flow through the turbine.

III. INTEGRATION METHODOLOGY

The basic idea is the reduction of the nominal power of the electric energy source integrated in steel plant which should provide capital costs reduction and subsequent control reduction which should provide longer lifetime of the turbine due to previous section.

There is calculated mean value as an arithmetic average of the load profile which serves as a reference value to load profile stabilization.

In the case where the load profile exceeds the control limits (see TABLE I.) of the turbine there, is considered cooperation with power grid from which is energy consumed (supplied).

The calculations are provided for one day. The economic effectiveness and energy balances then consider the same calculated values for each subsequent day considered due to lifetime of the BESS.

A. BESS state and lifetime

From default load profile P_z (MW), it is calculated the equivalent consumed energy E_z (MWh) by (2). Due to the fact the load profile is discretized into 5 min steps, every power step needs to be divided by 12 for energy expression in MWh.

$$E_z = P_z/12 \quad (2)$$

The BESS will then be charged whenever the power consumption is below the mean value (arithmetic mean of the all steps in the load profile) and discharged whenever the power consumption is above the mean, incorporating the efficiency of the charge / discharge cycle into half charging losses and half when discharging. The limitations are maximum power and capacity of the BESS.

B. Energy grid

In the following case study, a constant price is considered for 1 MWh of energy consumed from the grid, as well as the price of 1 MWh of energy supplied from the grid.

Furthermore, the ¼ hourly maximum power limitation is included in the case studies, which is a certain reserved power (monthly and annually) via the grid operator, from which the energy according to (2) is derived, which must not be exceeded within fifteen minutes. Thus, if at some point the energy is higher than the agreed ¼ h maximum, the ¼ h sum of energy has to be adjusted by the opposite deviation. It is assumed the value of ¼ h is not exceed in the case study.

C. Total net income

The operation costs of the different turbine powers are considered as the same. Total profit can be thus calculated by balance equation (3).

$$P_c = (C_z - C_u) + (E_z - E_u) \times C_{1MWh} \times L + (C_{Rz} - C_{Ru}) \times L \quad (3)$$

Where P_c (EUR) is total net income, C_z (EUR) are capital costs of the turbine for 100 % load profile cover, C_u (EUR) are capital costs of the proposed turbine, E_z (MWh) is the amount of the energy generated by default turbine, E_u (MWh) is the amount of the energy generated by proposed turbine, C_{1MWh} (EUR) is the price of 1 MWh generated by turbine, L (years) is the lifetime of the BESS, C_{Rz} (EUR) is the total cost balance of the default turbine, including flat-rate payments and revenues as well as expenditures for the purchase and sale of underproduction and overproduction of energy needed for plant-self consumption and C_{Ru} (EUR) is the same total cost balance of the proposed turbine.

IV. CASE STUDY

There is presented a case study based on descriptions in the previous sections. The comparison between default (without BESS) option and proposed (with BESS) option is provided.

A. Input parameters

Assumed input parameters are noted in TABLE II.

TABLE II. INPUT PARAMETERS

Parameter	*Unit*	*Value*
BESS capacity	(MWh)	7.5
Possible overload	(-)	2
BESS cycle efficiency	(%)	80
BESS lifetime L	(years)	15
Battery capital costs	(EUR/MWh)	400,000
Converter capital costs	(EUR/MW)	134,615.4
Turbine capital costs	(EUR/MW)	384,615.4
Cost of energy generated by turbine C_{1MWh}	(EUR/MWh)	49.5
Cost of purchased grid energy	(EUR/MWh)	84.62

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Parameter	Unit	Value
Revenues of sold grid energy	(EUR(MWh)	49.5
Rate payment ¼ h maximum yearly	(EUR/MW)	37,714.8
Rate payment ¼ h maximum – yearly sum of monthly payments	(EUR/MW)	67,841.54
Maximal load	(MW)	35.4

B. *¼ h maximum*

Specified ¼ h maximum is noted in TABLE III.

TABLE III. SPECIFIED ¼ H MAXIMUM

Reserved power	*Unit*	*Value*
Monthly	(MW)	0
Yearly	(MW)	1.7

C. *Results*

There are presented calculated results of the evaluated case study for 1 year of the BESS lifetime in this section. Grid energy balance is noted in TABLE IV. ., turbine limits are noted in TABLE V. and financial results are noted in TABLE VI. All quantified terms were defined in the previous sections.

TABLE IV. GRID ENERGY BALANCE

Parameter	*Unit*	*Value*
Option without BESS		
Total energy purchased yearly	(MWh)	1,257.1
Total energy sold yearly	**(MWh)**	**20,936.8**
Exceeding ¼ h maximum yearly	(MW)	0
Rate payment for ¼ h maximum yearly	(EUR)	117,365
Total regulatory energy balance yearly	**(EUR)**	**-812,692**
Option with BESS		
Total energy purchased yearly	(MWh)	0
Total energy sold yearly	(MWh)	0
Exceeding ¼ h maximum yearly	(MW)	0
Rate payment for ¼ h maximum yearly	(EUR)	0
Total regulatory energy yearly	**(EUR)**	**0**

TABLE V. TURBINE LIMITATIONS

Parameter	*Unit*	*Value*	*Note*
Option without BESS			
Case num. 1	(1/year)	26,280	
Case num. 2	(1/year)	0	
Case num. 3	**(1/year)**	**8,760**	**Max 10,000**
Case num. 4	(1/year)	0	
Case num. 5	(1/year)	0	Max 3,000
Other	(1/year)	26,280	
Erosion	(mm/year)	2.9167	Max 20 mm
Option with BESS			
Case num. 1	(1/year)	0	
Case num. 2	(1/year)	0	
Case num. 3	(1/year)	0	Max 10,000
Case num. 4	(1/year)	0	
Case num. 5	(1/year)	0	Max 3,000
Other	(1/year)	0	
Erosion	(mm/year)	0.2212	Max 20 mm

TABLE VI. FINANCIAL RESULTS

Parameter	*Unit*	*Value*
Finacial results		
BESS capital costs	(EUR)	3,000,000
Converter capital costs	(EUR)	2,221,153
Capital costs for source without BESS C_z	(EUR)	13,615,384
Capital costs for proposed turbine C_u	(EUR)	8,747,151
Operation costs of BESS	(EUR)	6,293,512
Total net income (*not annual*) P_c	**(EUR)**	**-763,146**
Daily BESS energy balance		
Positive and negative regulation energy provided by BESS	(MWh)	197.39
Netto energy charged to BESS	(MWh)	104.5
Netto energy discharged from BESS	(MWh)	92.89
Daily total energy loses	(MWh)	23.22
Proposed steam turbine		
Minimal proposed power	(MW)	22.74
Power saving	**(MW)**	**12.66**

In Fig. 3 financial results are shown again in graphical representation for better clarity.

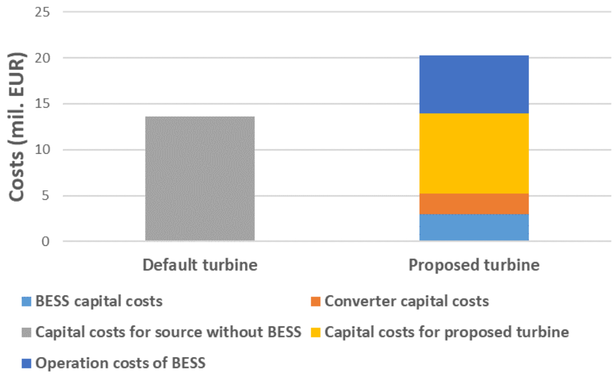

Fig. 3. Financial results – graphical representation

In Fig. 4, there are shown power - per unit - operations of the default and proposed turbine for the selected case and load profile.

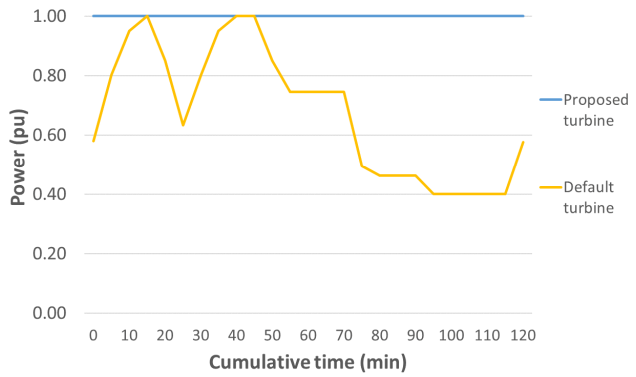

Fig. 4. Steam Turbine Power Comparison – the case with and without BESS.

V. DISCUSSION

Although, this case study is probably close to the real operation of the turbine and BESS, there may be some limitations of trust caused by control strategy of the charging of the energy storage, or by control and sizing (to cover 100% of load profile) the default turbine. However, this case study should provide the rough potential insight for the battery energy storage integration in steel plants.

The effect of power saving (12.66 MW) caused by the energy storage is outweighed by the operation costs (energy losses) of the energy storage itself. Despite the fact mentioned before the assumed sizing (15 MW and 7.5 MWh) in the presented case study is not profitable (net income is negative). Despite the reduced ability of the turbine (due to control limitations) to cover the load profile (especially by reducing the power, as it can be seen in TABLE IV. – bold), this phenomenon does not have a negative economic effect

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due to the setting of energy sale prices. The effect of power saving, and the control effect is thus almost balanced by the operation costs (energy losses) of the energy storage.

However, as it can be seen in TABLE V. – bold, the control effect of the energy storage in this case has a significant positive effect on the control limitations (service life) of the turbine. According to the chosen methodology, it is practically impossible to operate the default turbine under similar conditions, as the turbine control limits in terms of permitted control would be exceeded within two years of operation and erosion limits within seven years of operation.

VI. Conclusion

As it can be seen from the case study presented above, at the prices presented for the generation, sale and purchase of energy, integration into steel plants do not give economic significance. The 20 % energy losses in the operation of the energy storage either negate or outweigh the considered reduction of the default turbine power, without mentioning the investment costs of the system.

However, the situation may change with the rising price of the primary energy source, emission permits, or penalties for varying electricity supply and/or demand or the absence price-advantageous long-term contracts.

Moreover, the integration of the energy storage also allows more flexible participation in the energy market and/or in the grid support services. The energy storage used in this way can probably reach the economic return easier than in the exclusively peak shaving function in the steel plants. In addition, the energy storage system can prolong the life of the turbine by reducing fast control requests and/or thermal stress of the turbine. In addition, it can reduce the power supply from the electrical grid (in case of insufficient turbine control abilities).

The technical-economic potential of an energy storage system integrated in the plants with cyclic load lies apparently in the combination of following: peak shaving dimensioned just to a partial load of the load diagram, participation in the grid support services and the energy market, limitation of the power and frequency of turbine controls and consequently extending its lifetime, while reducing grid supply in the event of insufficient turbine control abilities.

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