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The Potential of Oxygen-Pressure Swing Adsorption Unit Connected with Electricity Storage System

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The pressure swing adsorption (PSA) units are widely used as an oxygen source. The storage of pressurized gaseous oxygen is limited by the capacity of a pressure vessel. The increasing share of renewable electricity sources (RES) causes intraday electricity price fluctuations. These fluctuations can be an opportunity to improve the economy of a plant. This paper aims to analyze the potential of a PSA unit connected to the battery energy storage system (BESS) for more effective on-site oxygen production. The analysis was carried out for the Czech Republic, Germany, and Denmark. These countries differ significantly in the energy mix. The theoretical potential of BESS installation and use in electricity price peak was found to be around 9 - 16 % of cost-saving on average compared with the daily operation of PSA unit when the off-peak average electricity price was from 95 to 91 % of the daily average electricity price respectively. Widening the price gap due to increasing RES share, the potential is growing.

1. Introduction

The Pressure Swing Adsorption (PSA) units are widely used as oxygen sources where oxygen is produced in gaseous form. Start-up time taking minutes is an undeniable advantage of PSA technology compared to cryogenic air separation start-up time taking hours or days. The capacity of a pressure vessel limits the storage of pressurized gaseous oxygen. The increasing share of renewable electricity causes intraday electricity price fluctuations. These fluctuations can be an opportunity to improve the economy of a plant (Miller et al., 2008) depending on market conditions (Cao et al., 2017), and to accumulate electricity in the form of liquefied products (Casperi et al., 2019ab). Casperi et al. (2019b) reported an improvement of 14 % in comparison with quasi-stationary scheduling for the designed flexible air separation unit (ASU) with an integrated liquefaction cycle and liquid assist operation Casperi et al. (2019a). Šulc and Ditl (2021a) analyzed two options for cost-saving: i) liquefied oxygen (LOX) supply at electricity price peak, and ii) liquid oxygen energy storage (LOES). The cold energy needed for oxygen liquefaction was obtained utilizing liquefied nitrogen (LIN) delivered from a large air separation unit. The on-site oxygen liquefaction and storage were found to be effective only for PSA units with double compression when the electricity price in the storage period was approximately three-four times lower than the daily average electricity price.
This paper aims to analyze the potential of a PSA unit connected to the battery energy storage system (BESS) for more effective on-site oxygen production. The analysis was carried out for the Czech Republic, the Federal Republic of Germany, and the Kingdom of Denmark. These countries differ significantly in the energy mix. The effect of intra-day electricity price fluctuations and energy storage system costs will be taken into account during the economic analysis. For comparison, the data used by Šulc and Ditl (2021a) were applied.

1.1 Battery Energy Storage System

The electric energy time-shift is one of the grid applications of battery energy storage systems. Electric energy time-shift involves purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the stored energy can be used or sold at a later time when the price or costs are high. This application has also a potential for CO_2 emission reduction (Kim et al., 2018). The BESS consists of: i) the battery pack, which connects multiple cells with an appropriate voltage

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and capacity, ii) the battery management system (BMS) which protects the cells from harmful operation to achieve reliable and safe operation, and iii) the battery thermal management system (B-TMS) which controls the temperature of the cells according to their specifications (Kim et al., 2018). The following main parameters affect the BESS sizing:

- Nominal capacity represents the amount of energy (as A h or W h) that the battery can nominally deliver from a fully charged state at a nominal discharge current. Capacity depends on C-rate and temperature.
- State of Charge (SOC, %) represents the actual battery capacity as a percentage of nominal capacity.
- Depth of discharge (DOD, %) represents the percentage of battery capacity that has been discharged in a given cycle, i.e., defines the usable capacity. The DOD is expressed as a percentage of nominal capacity.
- Discharge/charge rate (C-rate,1) is the measure of the current in which a battery is charged or discharged.
- Cycle Life represents the number of discharge-charge cycles of the battery before it loses the required performance. Cycle life is affected by the rate and depth of cycles. The higher the DOD, the lower the cycle life.
- Total round-trip efficiency represents the ratio of energy delivered from BESS and the energy supplied to BESS. It takes into account the energy losses from power conversions and auxiliary loads associated with BESS operating.

1.2. Intra-day electricity prices

The electricity cost is a major cost item of oxygen production by pressure swing adsorption. For the analysis, the day-ahead prices reported by ENTSO-E Transparency Platform were used. No taxes (VAT and recoverable taxes) and levies were not taken into account. The prices vary during the year, months, and days. Therefore, the data for the randomly selected 2nd Wednesday in January, April, July, and October of the year 2020 respecting the winter, spring, summer, and autumn seasons, respectively, were overtaken. The analysis was carried out for the Czech Republic, the Federal Republic of Germany, and the Kingdom of Denmark.

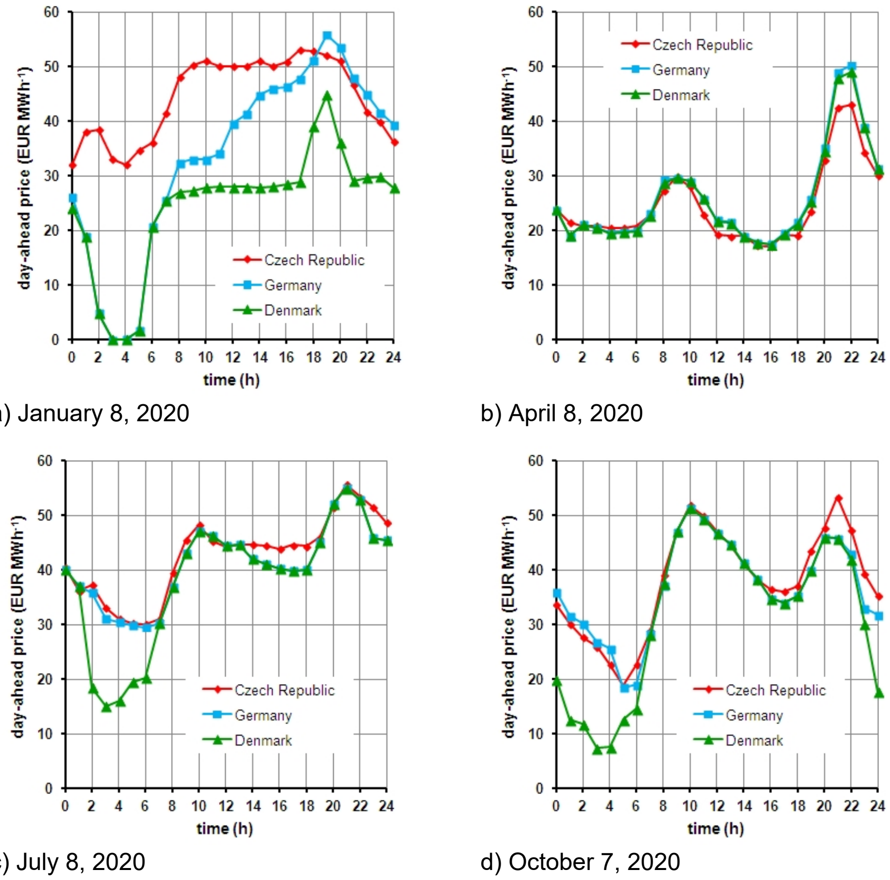

Figure 1: Day-ahead prices for the Czech Republic, Germany, and Denmark: a) January 8, 2020; b) April 8, 2020; c) July 8, 2020; d) October 7, 2020

These countries differ significantly in the energy mix. The Czech Republic generated an average approximately 36 % in nuclear power plants, 49 % in thermal power plants, and 14 % from renewable energy sources on selected days. Unlike this, Denmark generated an average of approximately 25 % of energy in thermal power plants, 75 % from renewable energy sources, and no energy was produced in nuclear power plants. The energy mix of Germany was between both countries. Germany generated an average approximately 12 % of energy in nuclear power plants, 40 % in thermal power plants, and 47 % from renewable energy sources. The day-ahead prices for January 8, April 8, July 8, and October 7 of the year 2020 and their comparison for the Czech Republic, Germany, and Denmark are presented in Figure 1. The significant morning and evening peaks are visible from 7 to 12 a.m. and from 7 to 9 p.m. In some cases, a significant price falls due to an excess of renewable energy sources.

1.3 Oxygen production by Pressure Swing Adsorption

The analysis was carried out for on-site oxygen production using two-bed Pressure Swing Adsorption for 95 % purity and oxygen recovery characterized by the air ratio of 10 Nm^3 Nm^{-3} producing 101 Nm^3 h^{-1} of gaseous oxygen (GOX). For these conditions, Šulc and Ditl (2021b) reported the specific energy consumption of 0.805 kWh kg_{O2}^{-1} and 0.728 kWh kg_{O2}^{-1} for a single and dual compression, respectively. The data mentioned above were obtained for ambient air and compressed air at an outlet temperature of 30 °C and outlet pressure of 750 kPa (a) at the PSA unit inlet. The pressure losses of inter-and after-coolers were taken into account.

2. Methodology

The electricity needed for the PSA unit is supplied by the grid during an off-peak period in which the electricity price is low. When the electricity price is lowest, the electricity from the grid is stored in a battery energy storage system during the charging period. During the electricity price peak, the electricity needed for the PSA unit is supplied by the charged BESS.

The following assumptions were adopted for the following model for calculating the cost-saving:

1) the electricity cost is taken only into account; the investment cost and other operational costs such as depreciation, maintenance, etc. are not included,
2) the BESS efficiency is taken into account by the longer charging period compared to the discharging period.

The daily average electricity price $c_{el\text{-}daily}$ (EUR MWh^{-1}) was obtained numerically by the trapezoidal integration method. The off-peak average electricity price $c_{el\text{-}offpeak}$ (EUR MWh^{-1}) and the charging average electricity price $c_{el\text{-}charging}$ (EUR MWh^{-1}) were calculated analogically by the same procedure but for the off-peak period and the charging period, respectively. The 24 h operation, peak periods from 8 a.m. to 10 a.m. and from 7 p.m. to 10 p.m., and charging period from 0 a.m. to 6 a.m. were assumed.

The electricity cost $C_{el\text{-}PSA\text{-}daily}$ (EUR d^{-1}) for the PSA unit operated for an operation time Δt_{oper} (h) was calculated:

$$C_{el\text{-}PSA\text{-}daily} = c_{el\text{-}daily} \cdot e_{PSA} \cdot \Delta t_{oper} \, , \quad (1)$$

where e_{PSA} (MWh t_{O2}^{-1}) is the specific electricity consumption of the PSA unit. The electricity cost $C_{el\text{-}PSA\text{-}off\text{-}peak}$ (EUR d^{-1}) for PSA unit operated during off-peak period $\Delta t_{off\text{-}peak}$ (h) was calculated:

$$C_{el\text{-}PSA\text{-}off\text{-}peak} = c_{el\text{-}off\text{-}peak} \cdot e_{PSA} \cdot \Delta t_{off\text{-}peak} . \quad (2)$$

The electricity cost $C_{el\text{-}PSA\text{-}peak}$ (EUR d^{-1}) for PSA unit operated during the peak period Δt_{peak} (h) was calculated:

$$C_{el\text{-}PSA\text{-}peak} = c_{el\text{-}charging} \cdot e_{PSA} \cdot \Delta t_{peak} . \quad (3)$$

Then, the gain(+)/loss(-) rate is estimated as it follows:

$$gain/loss\ (\%) = 100 \cdot (C_{el\text{-}PSA\text{-}off\text{-}peak} + C_{el\text{-}PSA\text{-}peak}) / C_{el\text{-}PSA\text{-}daily} \, . \quad (4)$$

The second option, the liquefied oxygen (LOX) supply in the electricity peak proposed by Šulc and Ditl (2021a) was also analyzed for comparison. In this case, the difference between the specific electricity consumption of LOX and GOX produced by the PSA unit is utilized for cost-saving. The oxygen needed for the process is supplied by the PSA unit during a period in which the electricity price is low. During the electricity price peak, the oxygen needed for the process is produced from LOX supplied from large ASU facilities continuously operated throughout the day. LOX is evaporated by ambient air. The LOX price is estimated based on the benchmark specific electricity consumption of LOX production and the daily averaged day-ahead electricity price. The LOX transportation cost is not included.

The LOX cost $C_{LOX\text{-}peak}$ (EUR d^{-1}) for LOX consumed during the peak period Δt_{peak} (h) was calculated:

$$C_{el\text{-}LOX\text{-}peak} = c_{el\text{-}daily} \cdot e_{LOX} \cdot \Delta t_{peak} = c_{el\text{-}daily} \cdot e_{LOX} \cdot (\Delta t_{oper} - \Delta t_{off\text{-}peak}), \quad (5)$$

where e_{LOX} (MWh t_{LOX}^{-1}) is the specific electricity consumption of LOX production. The benchmark specific electricity consumption of liquefied oxygen (LOX) is 638 kWh t_{LOX}^{-1} (EIGA, 2019). Then, the gain(+)/loss(-) rate is estimated as it follows:

$$\text{gain/loss (\%)} = 100 \cdot (C_{el\text{-}PSA\text{-}off\text{-}peak} + C_{el\text{-}LOX\text{-}peak}) / C_{el\text{-}PSA\text{-}daily} . \quad (6)$$

3. Results and discussion

The cost-saving calculated using the proposed model is presented in Tables 1, 2, and 3 for the Czech Republic, Germany, and Denmark, respectively. The theoretical potential of BESS installation and use in electricity price peak was found to be around 9 - 16 % of cost-saving on average compared with the daily operation of PSA unit when the off-peak average electricity price was from 95 to 91 % of the daily average electricity price respectively. The practical potential of BESS installation will be significantly affected by BESS investment cost.

For comparison, the LOX supply in the electricity peak was also analyzed. The theoretical potential of LOX supply for the same conditions was found slightly lower, around 8 - 11 % of cost-saving on average compared with the daily operation of the PSA unit. The values of cost-saving percentages for each country were plotted on the share of renewable energy sources (RES) in the energy mix for each country (Figure 2). The data confirm the effect of RES share on energy mix on the potential of electric energy time-shift.

The analysis was executed for the static charging period from 0 a.m. to 6 a.m regardless of the actual electricity price. The system operated with a dynamically changed charging period based on the forecast prediction model for electricity price may further maximize the cost-saving.

Table 1: On-site PSA unit with Battery Energy Storage System (BESS) – Czech Republic

Description	Unit	January 8	April 8	July 8	October 7
Input data					
Daily average day-ahead price [*1]	EUR MWh^{-1}	44.84	24.54	42.59	38.00
Average electricity price for charging period [*1]	EUR MWh^{-1}	35.05	21.11	33.93	25.62
Off-peak average electricity price [*1]	EUR MWh^{-1}	43.79	22.25	40.84	35.41
LOX price based on daily average el. price[*1,2]	EUR t_{O2}^{-1}	28.61	15.66	27.17	24.24
Single compression [*3,4]					
PSA unit: cost for daily average el. price	EUR d^{-1}	866	474	823	734
PSA unit: cost for off-peak production	EUR d^{-1}	670	340	625	542
PSA unit: cost for peak production with BESS	EUR d^{-1}	141	85	137	103
Oxygen cost using BESS	EUR d^{-1}	811	425	761	645
Gain (+)/loss (-)[*5]	%	6.4	10.3	7.5	12.2
LOX consumed during electricity price peaks	EUR d^{-1}	143	78	136	121
Oxygen cost by combined PSA+LOX	EUR d^{-1}	813	419	761	663
Gain (+)/loss (-)[*5]	%	6.2	11.7	7.6	9.7
Dual compression [*3,4]					
PSA unit: cost for daily average el. price	EUR d^{-1}	784	429	744	664
PSA unit: cost for off-peak production	EUR d^{-1}	606	308	565	490
PSA unit: cost for peak production with BESS	EUR d^{-1}	128	77	124	93
Oxygen cost using BESS	EUR d^{-1}	733	385	688	583
Gain (+)/loss (-)[*5]	%	6.4	10.3	7.5	12.2
LOX consumed during electricity price peaks	EUR d^{-1}	143	78	136	121
Oxygen cost by combined PSA+LOX	EUR d^{-1}	749	386	701	611
Gain (+)/loss (-)[*5]	%	4.4	9.9	5.8	8.0

Note:[*1] Operation time = 24 h d^{-1}, charging period from 0 a.m. to 6 a.m., peak period: from 8 a.m. to 10 a.m. and from 7 p.m. to 10 p.m.

Note:[*2] Specific electricity demand for LOX production: 0.638 MWh t_{O2}^{-1}.

Note:[*3] PSA unit: ambient air: temperature of 20 °C, pressure of 100 kPa (a), relative humidity of 70 %; compressed air; outlet temperature of 30 °C, outlet pressure of 750 kPa (a); specific electricity demand: single compression 0.805 MWh t_{O2}^{-1}, dual compression 0.728 MWh t_{O2}^{-1}.

Note: [*4]: Calculation was performed for the specific oxygen production capacity of 1 t h^{-1}.

Note: [*5] Gain/loss: related to the cost of PSA production for daily average electricity price.

Table 2: On-site PSA unit with Battery Energy Storage System (BESS) – Germany

Description	Unit	January 8	April 8	July 8	October 7
Input data					
Daily average day-ahead price [*1]	EUR MWh^{-1}	33.31	26.01	40.99	36.82
Average electricity price for charging period [*1]	EUR MWh^{-1}	8.23	20.38	33.19	26.74
Off-peak average electricity price [*1]	EUR MWh^{-1}	30.60	23.30	39.08	34.67
LOX price based on daily average el. price[*1,2]	EUR t_{O2}^{-1}	21.25	16.59	26.15	23.49
Single compression[*3,4]					
PSA unit: cost for daily average el. price	EUR d^{-1}	644	502	792	711
PSA unit: cost for off-peak production	EUR d^{-1}	468	356	598	530
PSA unit: cost for peak production with BESS	EUR d^{-1}	33	82	134	108
Oxygen cost using BESS	EUR d^{-1}	501	438	731	638
Gain (+)/loss (-)[*5]	%	22.1	12.7	7.6	10.3
LOX consumed during electricity price peaks	EUR d^{-1}	106	83	131	117
Oxygen cost by combined PSA+LOX	EUR d^{-1}	574	439	729	648
Gain (+)/loss (-)[*5]	%	10.8	12.6	8.0	8.9
Dual compression [*3,4]					
PSA unit: cost for daily average el. price	EUR d^{-1}	582	454	716	643
PSA unit: cost for off-peak production	EUR d^{-1}	423	322	541	480
PSA unit: cost for peak production with BESS	EUR d^{-1}	30	74	121	97
Oxygen cost using BESS	EUR d^{-1}	453	397	661	577
Gain (+)/loss (-)[*5]	%	22.1	12.7	7.6	10.3
LOX consumed during electricity price peaks	EUR d^{-1}	106	83	131	117
Oxygen cost by combined PSA+LOX	EUR d^{-1}	529	405	671	597
Gain (+)/loss (-)[*5]	%	9.0	10.8	6.3	7.2

Note:[*1-5] see Table 1 in detail.

Table 3: On-site PSA unit with Battery Energy Storage System (BESS) – Denmark

Description	Unit	January 8	April 8	July 8	October 7
Input data					
Daily average day-ahead price [*1]	EUR MWh^{-1}	24.44	25.72	38.17	32.50
Average electricity price for charging period [*1]	EUR MWh^{-1}	8.06	20.30	22.70	11.61
Off-peak average electricity price [*1]	EUR MWh^{-1}	22.60	23.11	35.52	29.22
LOX price based on daily average el. price[*1,2]	EUR t_{O2}^{-1}	15.59	16.41	24.35	20.73
Single compression [*3,4]					
PSA unit: cost for daily average el. price	EUR d^{-1}	472	497	737	628
PSA unit: cost for off-peak production	EUR d^{-1}	346	353	543	447
PSA unit: cost for peak production with BESS	EUR d^{-1}	32	82	91	47
Oxygen cost using BESS	EUR d^{-1}	378	435	635	494
Gain (+)/loss (-)[*5]	%	19.9	12.4	13.9	21.4
LOX consumed during electricity price peaks	EUR d^{-1}	78	82	122	104
Oxygen cost by combined PSA+LOX	EUR d^{-1}	424	436	665	551
Gain (+)/loss (-)[*5]	%	10.3	12.3	9.8	12.3
Dual compression [*3,4]					
PSA unit: cost for daily average el. price	EUR d^{-1}	427	449	667	568
PSA unit: cost for off-peak production	EUR d^{-1}	313	320	491	404
PSA unit: cost for peak production with BESS	EUR d^{-1}	29	74	83	42
Oxygen cost using BESS	EUR d^{-1}	342	394	574	446
Gain (+)/loss (-)[*5]	%	19.9	12.4	13.9	21.4
LOX consumed during electricity price peaks	EUR d^{-1}	78	82	122	104
Oxygen cost by combined PSA+LOX	EUR d^{-1}	391	402	613	508
Gain (+)/loss (-)[*5]	%	8.5	10.6	8.1	10.6

Note:[*1-5] see Table 1 in detail.

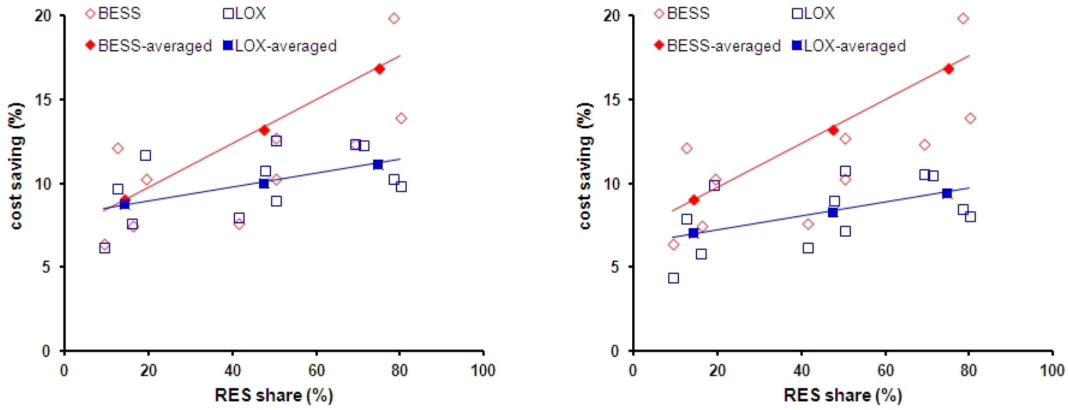

Figure 2: Effect of the ratio of renewable energy sources (RES share) on cost-saving percentage: a) single compression (on the left), b) double compression (on the right)

4. Conclusions

This paper aims to analyze the potential of a PSA unit connected to the battery energy storage system for more effective on-site oxygen production. The analysis was carried out for the Czech Republic, Germany, and Denmark. These countries differ significantly in the energy mix. The effect of intra-day electricity price fluctuations and energy storage system costs will be taken into account during the economic analysis. The theoretical potential of BESS installation and use in electricity price peak was found to be around 9 - 16 % of cost-saving on average compared with the daily operation of PSA unit when the off-peak average electricity price was from 95 to 91 % of the daily average electricity price respectively. Widening the price gap due to increasing RES share, the potential is growing. For comparison, the LOX supply in the electricity peak was also analyzed. The theoretical potential of LOX supply for the same conditions was found slightly lower, around 8 - 11 % of cost-saving on average compared with the daily operation of the PSA unit.

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