Energy Proceedings
Vol 54, 2025
ISSN 2004-2965

Lab-field multi-energy platform: electrolyzer, redox flow battery, and lithium-ion battery energy storage system#

Chunyang Zhao[1], Xin Jin[1*], Bugra Kayaalp[2], Chao Liu[1], Magnus Klintström[1], Frank Alan Hauer[1], Shi You[1], Chresten Træholt[1]

1 Department of Wind and Energy Systems, Technical University of Denmark, Kgs. Lyngby, 2800, Denmark

2 Siemens Energy AG, Mülheim an der Ruhr, Nordrhein-Westfalen, 45473, Germany

(Corresponding Author: cijin@dtu.dk)

ABSTRACT

The recent transition in the power system brings challenges like load and demand imbalance, intermittent renewable energy recourses, and the risk of lumping load from power-to-X applications. The battery energy storage system (BESS) is a viable solution for short-term and long-term balancing. Combined with the upcoming major load type of the electrolyzer, we propose the lab-field multi-energy system platform for validating a demonstration of a virtual power plant for grid-connection synergies. Based on the field tests, we summarize the characteristics of the redox flow BESS, lithium-ion BESS, and electrolyzer. The response time of these components varies from one second for the redox flow BESS to a few hours for the electrolyzer. As these components have different response times, efficiency, and capacity, our work provides a reference for the hardware performance and lays the foundation for further implementation and optimization.

Keywords: power-to-X, all-iron redox flow battery, anion exchange membrane electrolyzer, ancillary service, virtual power plant, grid connection.

1. INTRODUCTION

With the transition to sustainable energy resources, wind and solar power are becoming the primary sources of future energy systems [1]. However, intermittent has emerged as a significant concern in recent developments. Ancillary services, which rely on energy storage and demand response, possess the capacity to balance short-term and long-term imbalances between demand and supply, which is crucial for ensuring a stable power system [2]. As the primary binary energy resources of the power system, energy storage systems are the most critical component for frequency and voltage regulation[3]. Recently, the Power-to-X has been observed to have the most significant load growth in the power system, bringing opportunities and challenges for the power system stability regarding energy volume and flexibility [4]. Therefore, integrating advanced energy technologies such as battery energy storage systems (BESS), flow batteries, and electrolyzers into the electrical grid is a pivotal step toward a more resilient, efficient, and sustainable energy infrastructure [5].

Lithium-ion BESS is at the forefront of this transformation, providing the grid with flexibility and enabling the storage of excess energy from renewable sources. This stored energy can be dispatched during high-demand or low-renewable generation periods, enhancing grid stability and reliability [6]. BESS also supports grid operations through ancillary services by quickly injecting or absorbing power to balance supply and demand. They also offer voltage support through reactive power compensation, enhancing the quality and stability of the electrical supply. Furthermore, BESS can serve as spinning reserves, ready to provide immediate power in case of sudden outages, thereby ensuring continuous service and preventing blackouts.

Redox Flow BESS offers a unique solution for large-scale and long-term energy storage, storing energy in liquid electrolytes in external tanks [7]. This design allows for scalable energy storage capacity and long cycle life, particularly suitable for long-duration storage applications. By integrating flow batteries with the grid, utilities can manage energy supply and demand for longer. They can deliver sustained voltage and frequency support over extended periods, crucial during prolonged grid disturbances [8]. Additionally, their ability to provide large-scale energy output makes flow batteries suitable for peak shaving and load leveling, thus reducing strain on the grid during high-demand periods and enhancing overall system reliability.

Along with the energy storage components support in the power system, the ongoing Power-to-X installation is a significant power consumption increment in the

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

modern power system, where electrolyzers play a crucial role in producing green hydrogen from water using electricity. When connected to the grid, electrolyzers can utilize surplus renewable energy to produce hydrogen, which can be stored and later converted to electricity or used as a clean fuel for various industrial processes.

When connected to the grid, electrolyzers can modulate their power consumption in response to grid signals, effectively acting as flexible loads [9]. This demand response capability helps to balance supply and demand, especially with the increasing penetration of intermittent renewable energy sources. By adjusting their operations, electrolyzers can contribute to frequency regulation and peak load management. Moreover, the hydrogen produced can be stored and converted back to electricity during high-demand periods or used in industrial applications, adding a layer of flexibility and resilience to the grid.

The recent challenge of integrating electrolyzers into the power system contains two parts: the high cost of hydrogen production and grid connection requirements. The green hydrogen produced in the power system is reported to be more than twice as expensive as conventional grey hydrogen [10]. The power system operators are increasingly concerned that such a large load will increase the grid stability challenge, which is already under the burden of transportation electrification. Specifically, the connection requirements are getting stricter, including the power quality support, power ramp rate, fault run-through, etc. Therefore, coordinating and integrating different energy storage components with electrolyzers can enable grid connectivity and ancillary service provision.

In the evolving energy landscape, integrating lithium-ion BESS, redox flow BESS, and electrolyzers into the electrical grid transforms energy storage and supply and enhances the provision of ancillary services. Ancillary services are critical for maintaining grid stability, reliability, and efficiency. These services include frequency regulation, voltage support, spinning reserve, and black start capabilities. The deployment of advanced energy technologies offers a robust solution to meet these operational demands.

This work proposes a real-world multi-energy platform integrating the lithium-ion BESS, redox-flow BESS, and the electrolyzer. The hardware components are physically connected to the power system in the laboratory and field, and the remote supervisory control and data acquisition system are established. The detailed hardware performance is assessed by several tests, focusing on the setpoint accuracy, response time, and efficiency. Our work gives a tangible answer to hardware capacity and the possibility of ancillary service provision. Our multi-energy framework validates the grid connection and ancillary service provision by various grid components, and it gives tangible testing results of the hardware performance for further modeling and optimization work.

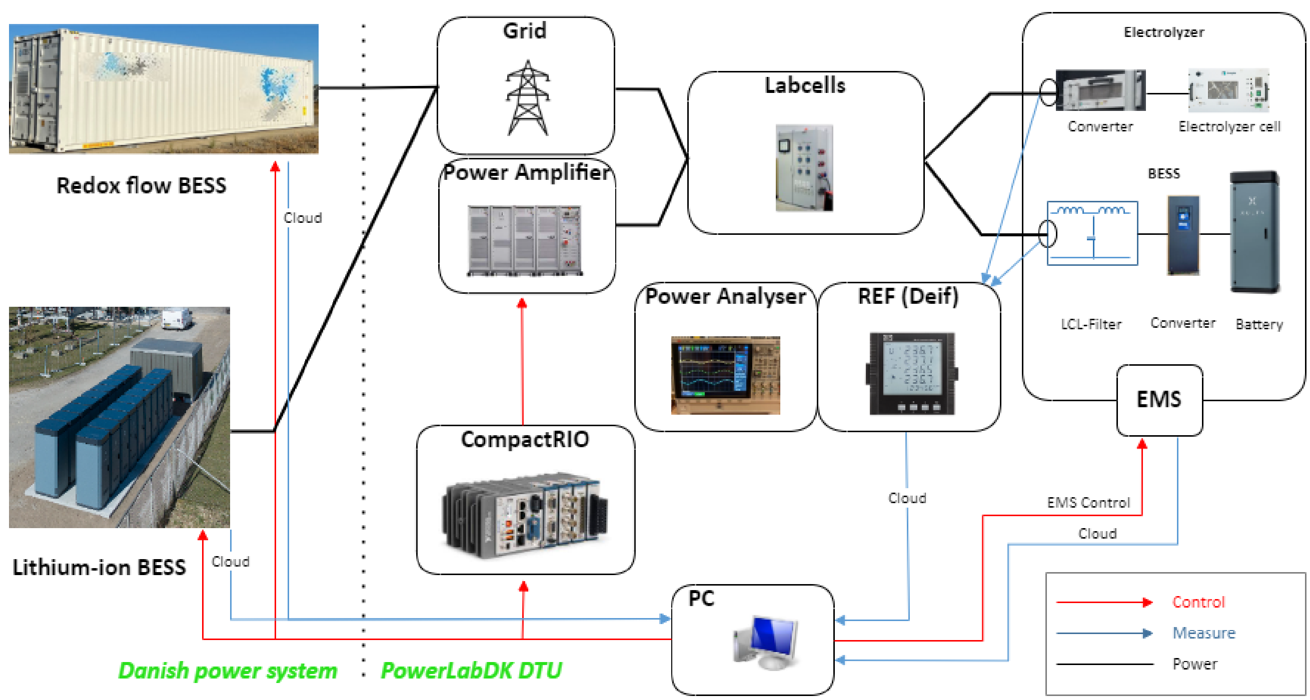


Fig. 1 Lab-field coordination framework

2. MATERIAL

To test the collocated and virtual multi-energy system, a lab-field coordination framework is proposed and implemented, as shown in Fig. 1. In the PowerLab DTU, there are two power sources: grid and power amplifier. If the LabCells are connected to the grid, the electrolyzer and BESS are directly synchronized to the Danish power system, and the real-life ancillary system can be implemented. If we switch to the power amplifier, the energy system operates in the artificial grid-connected mode, and the frequency and voltage of the grid are programmable. During the operation of the power system, the power analyzer and Deif reference (REF) are. In the lab, the energy storage and consumption components are connected; for instance, the Xolta lithium-ion BESS is connected through the Danfoss converter to the LabCell, and similarly, the anion exchange membrane electrolyzer (AEM) is connected to the LabCell. Specifically, the lithium-ion BESS capacity is 79kWh/55*2Kw, and the electrolyzer is 3*3 kW.

Besides the laboratory setup, commercial energy storage systems are also connected to the Danish power system integrated into this framework, including a 75kW/500kWh redox flow BESS and a 1 MW/MWh BESS. The redox flow BESS is based on the commercial Iron-flow battery connected to the 400 V-AC point of interconnection at the Brande Brint test site of Siemens Gamesa Renewable Energy. The lithium-ion BESS is connected to the Aakirkeby substation of the Danish island - Bornholm. Though the components are located in different physical places, remote control is achieved through the application programming interface. At the same time, the measurements are synchronized by the cloud solution and storage at the enegydata.dk platform.

3. METHODS AND RESULTS

Response time, power quality, and efficiency are the primary requirements for grid connection and ancillary service provision for multi-energy systems. Therefore, some individual tests are carried out to test the performance of the components. As shown in Fig.3, the testing cycle of the redox flow BESS is presented, where the BESS is charged from 20% to 80% and discharged back to 0% with the power setpoint of 37.5 kW, aiming at the operation range test of the 20% to 80%. The redox flow BESS requires significant auxiliary power to operate. Therefore, the DC output is lower than the AC power output during charging and higher than the AC power output during discharging, which may lead to lower efficiency. There are two power set point changes, one is from cold start at hour 10, and another is the change from charging to discharging at hour 26. As shown in Fig 3., the detailed performance of the power response of the AC power output of the redox flow BESS is presented. The cold start is set at 37kW for charging at the time of 38717 seconds. At 38798 seconds, the AC power output starts to operate around 0.5kW and operates until 41047 seconds to descend and then gradually grow to 36.96 kW, as shown in Fig.3 (a). For the power setpoint change during the operation, the change of power setpoint happens at 93907 seconds, which is to change the power from 37kW to -35kW for discharging. The redox flow BESS responds immediately, and the AC power output shifts to -34.88kW at the exact second.

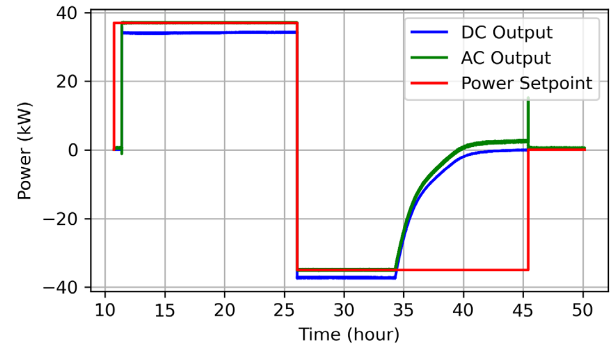
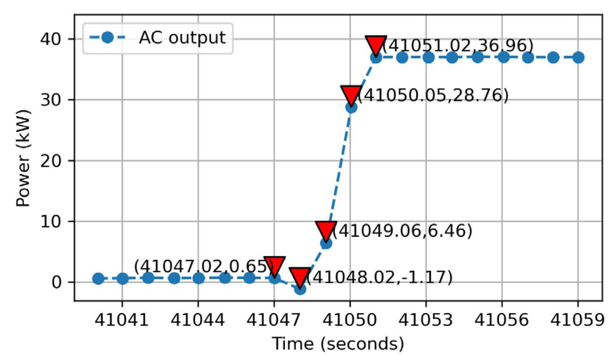
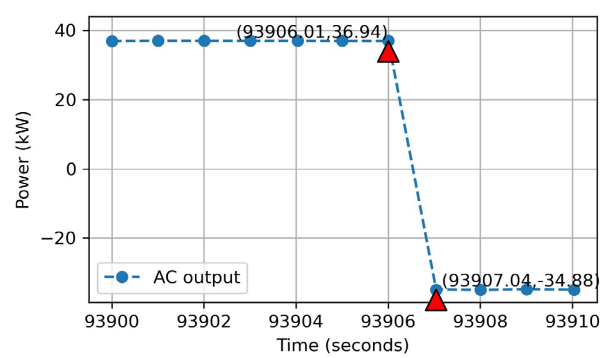


Fig. 2 Testing cycle for redox flow BESS



(a) response at the cold start



(b) response during operation

Fig. 3 Redox flow BESS power response behavior

	Redox flow BESS	Lithium-ion BESS	AEM electrolyzer
Power setpoint accuracy (charging)	99.89%	98.75%	
Power setpoint accuracy (discharging)	99.66%	94.11%	
Response time (cold start)	2334 seconds (4 seconds)	N/A (2 seconds)	5.06 hours (2.06 hours)
Response time (warm switch)	< 1 second	2.6/5.6 seconds	390 seconds
Power efficiency (charge)	91.92%	99.91%	
Power efficiency (discharge)	93.81%	99.06%	

Table. 1 Summary and comparison of the testing results

As shown in Fig. 4, the testing cycle of the lithium-ion BESS includes two charging cycles and one discharging cycle in the middle. From the resting state, when the battery is idle, it is set to charge at 8kW, discharge at 8kW, and charge at 40 kW. It is observed that the lithium-ion BESS has a quick response time and good AC-DC accuracy. As the nature of the lithium-ion battery, it is not a challenge to stay in idle mode until the power setpoint changes. Specifically, the response behavior is presented in Fig. 5, where the response at cold start, discharging setpoint, and charging setpoint are detailed. A general response time of a few seconds is observed, and the larger the setpoint changes, the longer the response is required.

The AEM electrolyzer is tested for a single cold-start run and stop, as shown in Fig.6. Different from the BESS, three stages of operation are presented, including the cold start, operation, and stop stages. The Cold start takes significantly longer, reaching 5.06 hours, including the unlabeled standby time. After the power consumption increases, it still takes 2.06 hours to reach the full capacity, around 2.6 kW.

As shown in Table. 1, the power setpoint accuracy, response time, and power efficiency are used to summarize and quantify the hardware performance of the test. The power setpoint accuracy is defined as,

$$Power\ setpoint\ accuracy = \frac{AC\ power\ output}{Power\ setpoint}$$

and the power efficiency is defined as,

$$Power\ efficiency\ (charge) = \frac{DC\ power\ output}{AC\ power\ output}$$

$$Power\ efficiency\ (discharge) = \frac{AC\ power\ output}{DC\ power\ output}$$

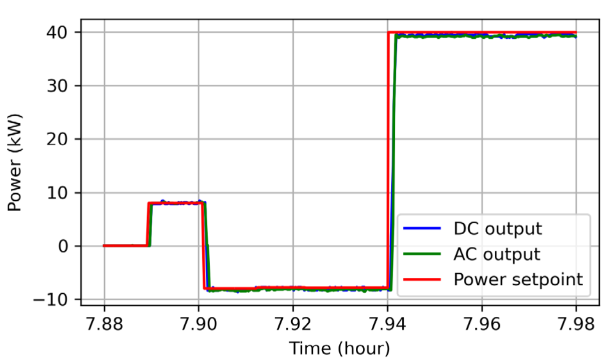
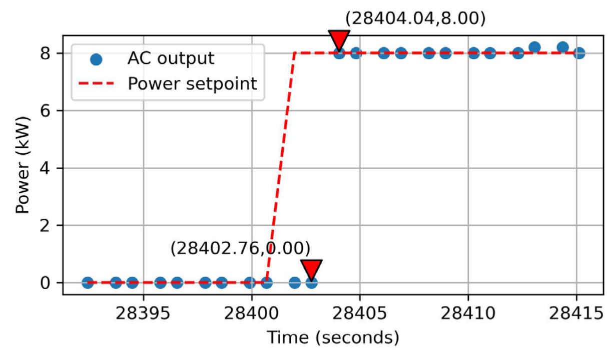
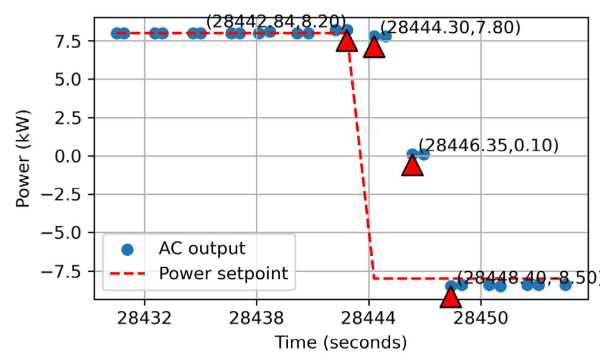


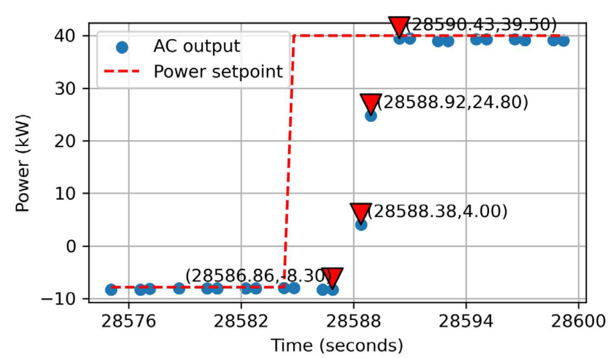
Fig. 4 Testing cycle for lithium-ion BESS



(a) response at the cold start



(b) response during operation - discharging



(c) response during operation - charging

Fig. 5 Lithium-ion BESS power response behavior

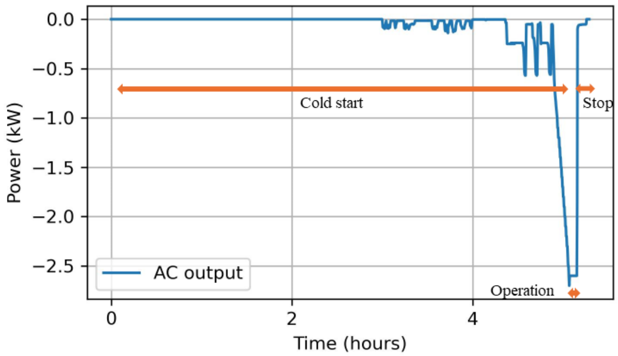


Fig. 6 Testing cycle for electrolyzer

4. DISCUSSION

Generally, the BESS is equipped with an efficient power conversion system and can provide precious power setpoint control. We observed the difference between redox flow BESS and lithium-ion BESS, where the more precise power setpoint accuracy is achieved by the redox flow BESS, which is more than 99% for charging and discharging recorded from the built-in monitoring system. The lithium-ion BESS has lower power setpoint accuracy, especially for discharging, around 95%. However, the significant auxiliary energy consumption of the redox BESS is observed, leading to a considerable AC-DC loss of around 10%, whereas the lithium-ion BESS only has a 1% loss despite charging and discharge use cases. The response time of redox flow BESS is complex; it takes 2334 seconds (around 39 minutes) to start charging gradually from the time it receives the power setpoint at cold start and impressively quick after it starts to operate. For the electrolyzer, we saw significantly high response time and less-regulated power output, which need to be refined or supported by the BESS.

5. CONCLUSIONS

Energy transition reshapes our power system towards a more sustainable operation and brings the challenge of power supply security. The recent development of the power-to-X application leads to a more significant burden on the power system and requires better cooperation of the components in the power system to deal with the potential imbalance and turbulence in the power system. BESS and electrolyzer are promising to support the power system because of their excellent controllability. In this work, we proposed an integrated framework for multiple energy components and gave tangible characteristic testing results to reveal hardware performance. Our work depicts the details of the BESS and electrolyzer operation in the power system and builds the foundation of realistic hardware coordination and optimization.

ACKNOWLEDGEMENT

This work is supported by the EUDP FerroBAT and BOSS project at Technical University of Denmark (DTU).

REFERENCE

[1] Kittner N, Lill F, Kammen DM. Energy storage deployment and innovation for the clean energy transition. Nat Energy 2017;2:1–6. https://doi.org/10.1038/nenergy.2017.125.

[2] Zhao C, Andersen PB, Træholt C, Hashemi S. Grid-connected battery energy storage system: a review on application and integration. Renewable and Sustainable Energy Reviews 2023;182:113400. https://doi.org/10.1016/j.rser.2023.113400.

[3] Engels J, Claessens B, Deconinck G. Techno-economic analysis and optimal control of battery storage for frequency control services, applied to the German market. Appl Energy 2019;242:1036–49. https://doi.org/10.1016/j.apenergy.2019.03.128.

[4] Cozzolino R, Bella G. A review of electrolyzer-based systems providing grid ancillary services: current status, market, challenges and future directions. Front Energy Res 2024;12:1358333. https://doi.org/10.3389/fenrg.2024.1358333.

[5] Huang C, Zong Y, You S, Traholt C. Analytical Modeling and Control of Grid-Scale Alkaline Electrolyzer Plant for Frequency Support in Wind-Dominated Electricity-Hydrogen Systems. IEEE Trans Sustain Energy 2023;14:217–32. https://doi.org/10.1109/TSTE.2022.3208361.

[6] Zhao C, Hashemi S, Andersen PB, Traholt C. Data-driven State of Health Modeling of Battery Energy Storage Systems Providing Grid Services. 2021 11th International Conference on Power, Energy and Electrical Engineering (CPEEE), IEEE; 2021, p. 43–9. https://doi.org/10.1109/CPEEE51686.2021.9383356.

[7] Rodby KE, Jaffe RL, Olivetti EA, Brushett FR. Materials availability and supply chain considerations for vanadium in grid-scale redox flow batteries. J Power Sources 2023;560:232605. https://doi.org/10.1016/j.jpowsour.2022.232605.

[8] Omine E, Murakami S, Kusunose N, Kitano R, Ooka T, Shibata T. Demonstration of Application of Redox Flow Battery for Securing Demand-Supply Reserve Power and Improvement of Grid Resiliency. IEEJ Transactions on Power and Energy 2024;144:250–6. https://doi.org/10.1541/ieejpes.144.250.

[9] Chehade Z, Mansilla C, Lucchese P, Hilliard S, Proost J. Review and analysis of demonstration projects on power-to-X pathways in the world. Int J Hydrogen Energy 2019;44:27637–55. https://doi.org/10.1016/j.ijhydene.2019.08.260.

[10] Daiyan R, Macgill I, Amal R. Opportunities and Challenges for Renewable Power-to-X. ACS Energy Lett 2020;5:3843–7. https://doi.org/10.1021/ACSENERGYLETT.0C02249.