Demand Side Flexibility Potentials of Redox Flow Batteries

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ABSTRACT: In an energy system where the majority of the energy consumption will be covered from wind- and PV-plants more options to enhance the demand side flexibility are needed. To achieve higher flexibility conventional power plants, storage systems, increased power grid interconnections, demand side management (DSM) and power-to-gas (PtG) technologies can be used. DSM manages the power demand within a flattened load curve to increase the utilization of generation units and ensure higher economic efficiency for grid participants. It also can be used as a primary control reserve action to stabilize grid frequency in a short period of time by deceleration or shutdown of domestic or industrial appliances. Additional integration of battery systems can hone the grid balancing. However, conventional battery systems are not able to operate continuously in high frequency charge and discharge mode. In this context, redox flow batteries are a promising alternative with large area of application.

1. INTRODUCTION

Due to the increasing demand for electrical energy and the intentions of climate- and energy strategies for renewable energy consumption, electricity storage will play an even greater role in the future energy supply. Electrical generation from renewable sources, such as wind or solar power, have a high flexibility in its output. To operate a power grid, it is necessary to balance the demand and the supply of the electrical energy at any point and time. As the electricity grid has no storage capacity on its own, the balancing can be ensured with very fast reacting technologies. Besides the classical flexibility options, grid and storage systems are not alternatives but complement each other. Grids allow shifting energy related to the location and storage systems shift energy available in time. To ensure grid stability and efficient grid operation, demand side management or storage technologies such as redox flow batteries are flexible options for load balancing.

2. FLEXIBLE GRID OPTIONS

In terms of storage technologies for electricity, demand flexibility is becoming a more important role in a power generation system. Demand side management describes the compensation of an existing load by reducing (peak clipping), increasing (valley filling) or shifting consumption. The advantages of managing the power demand is a flattened load curve which contributes to a steadier utilization of generation units and in order to decrease generation costs. In Figure 1 shows the three types of demand side management.

Peak clipping is used in high demand periods where the demand peaks are reduced and the load curve get flattened. For instance, the daily peak in households can be reduced by DSM programs in terms of air conditioners or water heating. Valley filling smooth out the load and contributes to an economic efficiency. Load shifting can be applied to shift consumption to times of lower market prices to reduce costs and is

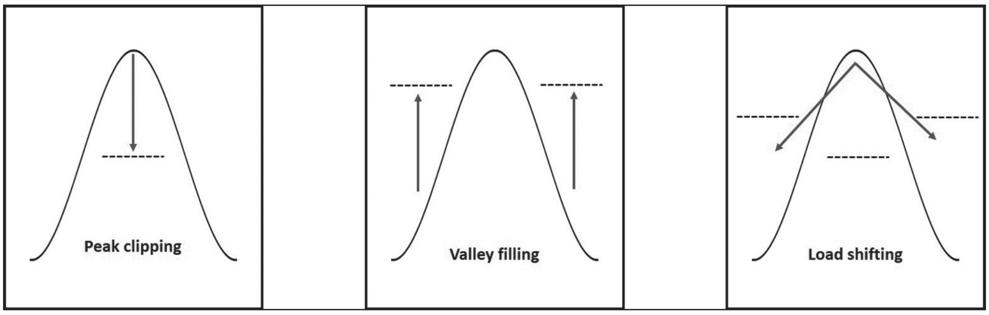

Figure 1: Types of demand- side management (Moseley & Garche, 2015)

often combined with storage applications. In terms of grid participants, there are different advantages by operating demand side management (Table 1):

Table 1: Advantage of demand side management for grid participants (Oberhofer, 2013)

Grid participant	Advantages of DSM
Energy producer	• less wear due to gentle operation mode • guaranteed feed-in of renewable energy
Energy distributor	• further source of procurement for grid control • more adequate use of components
Energy user	• cheaper and more flexible rates

Demand side management can be implemented in various applications inside the energy system and forms an alternative to conventional energy storage systems. It is applicable in different part of the electric load, industrial processes, households and in the service sector.

To secure net stability and keep the net frequency constant, reserve power plays an important role. Germany, Austria and further Western European Nations are members of the ENTSO-E (European Network of System Operators for Electricity), which is responsible for the coordination and expansion of the European electricity network. This network is to be regarded as a composite block in which the networks of the individual partners are interconnected in synchronous parallel operation. In order to be able to technically control the energy flow in the international interconnected grid, the transmission grid is divided into control zones. The international network is thus composed to many areas, which are basically operated independently. A control zone manager is responsible for a control area. Since January 2012 Austria only consists of the control area APG (Austrian Power Grid), in which further zones of the past were summarized. For the best use of electrical energy, it is desirable for the supply voltage to have a constant frequency with a perfect sinus curve and a constant level. As already mentioned, electrical energy cannot be stored directly on the way from generation to the consumer. An unbalanced power balance in the system, which occurs as a difference between generation and consumption, will result in a charge of grid frequency. The control zone manager has to adjust production in its control zone and is responsible for keeping the balance between generation and consumption. Three different control markets are differentiated, Primary Control Reserve (PCR), Secondary Control Reserve (SCR) and Tertiary Control Reserve. PCR and SCR are activated automatically and Tertiary Control Reserve has to be manually done. Instantaneous Reserve is the resistance of the system against frequency change in terms of load and generation. Instantaneous reserve can be provided by the inertia of the rotating masses of synchronous generators or quickly responding storage systems such as battery storage systems with a fast logic. To react against the changing frequency instantaneous reserve has to be activated within seconds (maximum 30 seconds) after an interference as showed in Figure 2.

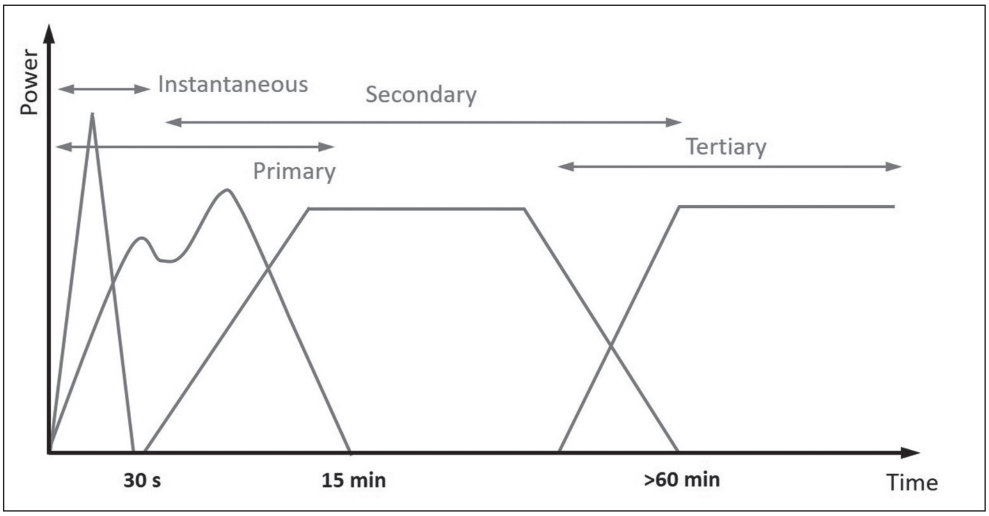

Figure 2: Activation scheme for different frequency control reserves in Germany (Moseley & Garche, 2015)

Primary Control is achieved by using turbine speed regulators from the power plant blocks, which react to deviations of the speed (frequency) from their setpoint due to an imbalance between generation and consumption throughout the synchronous interconnected network. In terms of charging energy storage systems, the demand for electricity can be increased and negative PCR is available. Secondary control reserve compensates load fluctuations on the timescale from a few minutes to several hours. It is activated in case of a long-lasting interference and relieves the PCR. SCR is a paid service to the system that is provided by prequalified generation units. Tertiary control reserve is activated as long as the frequency imbalance exists and replaces secondary reserve simultaneously. It is activated from the control zone operator and has to be fully available within 15 minutes.

The integration of more than 12-15 % renewable energy to the electrical grid will lead to severe grid instability problems that can only be managed by effective storage systems to maximise the utilization of renewable energy. Of all the different storage system possibilities on the market, electrochemical storage systems offer the highest efficiency, especially for electrical storage of wind and solar power (PV) combined with a great flexibility, performance and cost effectiveness. As an alternative to the widely used lithium ion batteries which are too expensive for large-scale storage compared to other storage systems, redox flow batteries offer the greatest flexibility in power to energy rating as well as a long cycle life under deep discharge operations (Moseley & Garche, 2015).

3. REDOX FLOW BATTERIES

The redox flow battery (RFB) is an energy storage system, which is characterized by its decentralised applications and its high degree of efficiency. The main elements of RFB are two external storage tanks and the reaction cells within the electrochemical conversion takes place. The two external storage tanks contain the electrolytes in which the redox-active species are present in dissolved form. By means of the pump, the respective electrolyte is circulated and passed through the electrochemical cell. The cell itself consists of two electrodes, which are isolated from each other by an ion-selective membrane. The basic scheme of a RFB is shown in Figure 3. The membrane (also separator) is needed to prevent the mixing of both reactants and to allow the ion exchange activity in both half-cells.

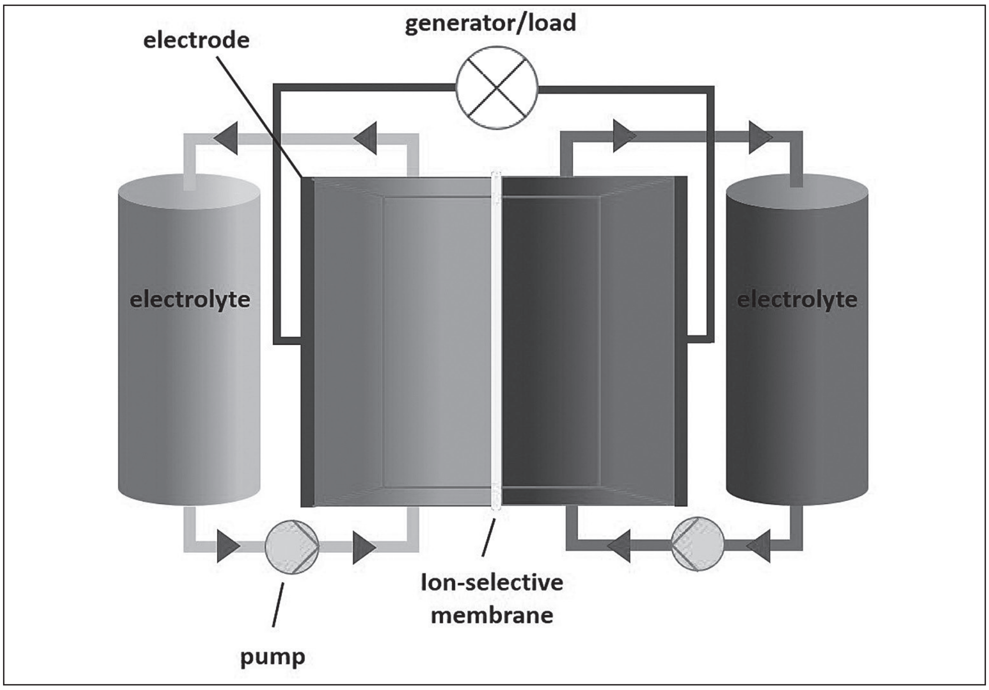

Figure 3: Redox flow battery scheme (Winsberg et al., 2017)

During charging of the battery, the electric current is passed to the respective electrodes and simultaneously the electrolytes are pumped through the cells. Oxidation and reduction of dissolved redox species take place on the surface of the electrodes. Charging and discharging only differences in the exchange of oxidation and reduction of the accordingly electrode. For instance, during the discharge of the battery oxidation occurs at the anode and during battery charge at the cathode. Owing to the redox reactions, further changes occur in the oxidation states of active molecules. The result is an electron flow that is forced through an external circuit. To close this circuit, electrical charges in the form of ions travel through the membrane. After charging completion, the electrolyte remains in the respective external storage tank. When discharging the battery, the entire process takes place in the opposite direction.

As shown in Figure 4 the redox pair within redox flow applications have different standard potentials. An ideal redox pair should have good reversible reaction kinetics, possess the ability to store multiple electrons per molecule, exhibit excellent chemical stability and achieve high cell voltage. The standard potential of each redox pair on the cathode or anode side can be obtained via the reference voltage measurement of a standard hydrogen electrode.

RFB store energy in dissolved redox species in the electrolyte, for which the capacity of the system is determined by the size of the electrolyte tanks, while the system power is determined by the size of the cell stacks. Another type of flow batteries are hybrid flow batteries. In a hybrid flow battery (HFB), a redox couple is used, which deposits itself on the electrode of the battery during the charging process. In that case the metal ions do not remain in the dissolved phase and get deposited at the negative electrode. Example for HFB are the zinc-bromine (Zn/Br_2) battery and the zinc-chlorine (Zn/Cl_2) battery. In both HFB-applications, capacity is determined by the quantity of zinc metal deposited.

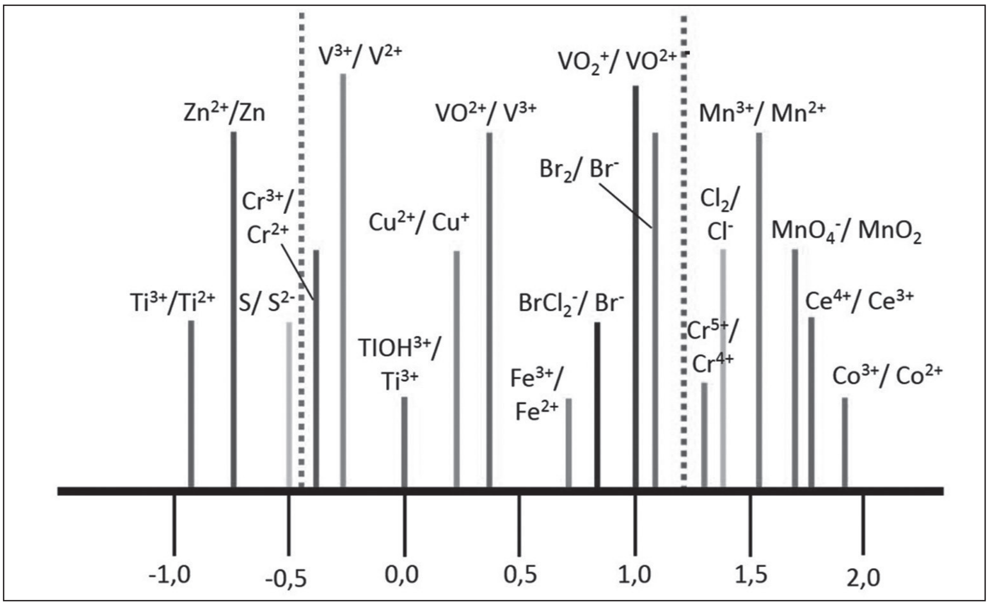

Figure 4: Different redox species with its standard potential [V] (Chalamala et al., 2014)

4. USE CASE OFFICE BUILDING

Since fluctuating production profiles from wind and PV power plants, contain also a significant seasonal component, long-term energy storage essential in the future. In order to provide such long-term storage services the integration of Power-to-Gas technologies (PtG), is the only alternative (Gahleitner, 2013 und Jentsch, 2014). However, the short-term dynamic behavior of such systems are limited so that the minimum power ramp rate is in the order of several minutes (Heschl et al., 2017). Consequently, electrochemical short-term storage systems should be cover storage time scales from several milli-seconds to hours. To investigate the self-consumption and grid stabilization requirements for RFB-systems an office building use case was utilized based on the living lab ENERGETIKUM. The ENERGETIKUM has a central air condition system with separate variable volume rate control unit for each office room and has over 7000 monitoring points (temperature, humidity, CO_2, VOV, water and air enthalpy flow, mass flow, electric energy etc.) to ensure a detailed energy flow analysis (see Figure 5). Additional the ENERGETIKUM has an open platform communication and a building automation and control network interface which enables the development of intelligent thermal and electrical energy storage systems under real environment conditions.

Figure 6 shows an extraction of the electrical load profile of the living lab ENERGETIKUM. The load profiles were measured with a sample rate of 50 Hz (blue line). The supply line of the heat pump was excluded to retain the random part of the energy demand. The measured electrical profile shows low- and high-frequency power distributions with stochastic peaks. If PtG-technology such as reversible solid oxide cell systems (rSOC) are used for long-term energy storage, specific control strategies must be applied to avoid high temperature gradients in the stack. An appropriate method to do this is the historical data driven control. This control strategy uses historical data to align the energy production to the energy demand. Based on a previous time window the demand data were analysed and the set value of the rSOC system performance adapted in such a way that the temperature gradient constraints in the stack can be considered. Figure 6 show the power production of a RSOC system with a dynamic constrain of 0.5 kW/min (dash-dotted).

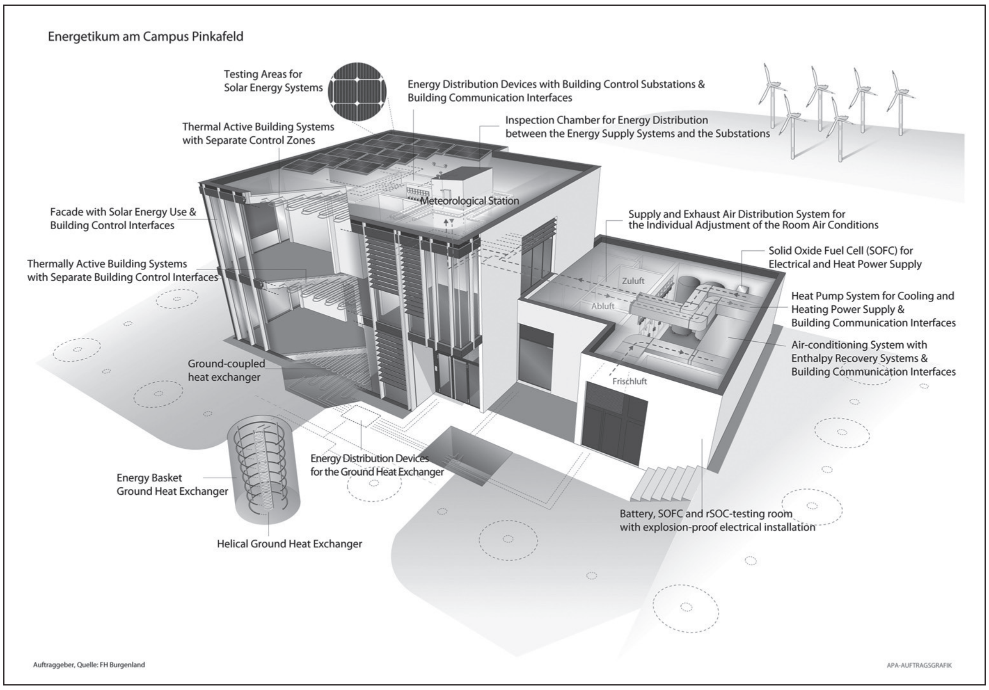

Figure 5: The living lab ENERGETIKUM

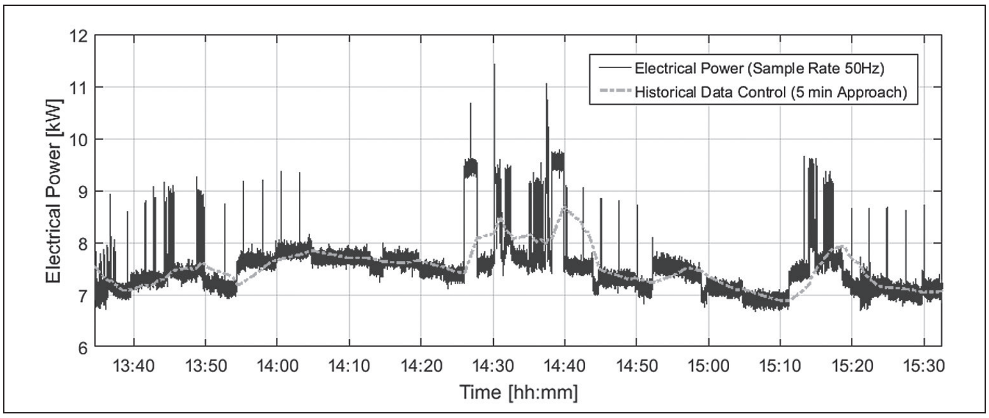

Figure 6: Typical electrical load profile of the living lab ENERGETIKUM

The moderate dynamic behaviour of long-term storage system necessitate additional fast compensation. Figure 7 shows the relative frequency of the power deviation between the energy demand and the energy supply due to the rSOC system. The power gap spans from about -1 kW to +2 kW and the most deviations are occur in the +/-0.5 kW band. Substantial more interesting is the time gradient of the power deviation. According to Figure 6 the time gradients are in the +/-10 kW/s domain. To bridge this outstanding dynamic capacity particularly energy storage systems are needed. Conventional battery systems avoid such severe charge and discharge cycles. Therefore, they are not suitable for such applications. However, redox flow batteries can theoretically handle this dynamic operating condition.

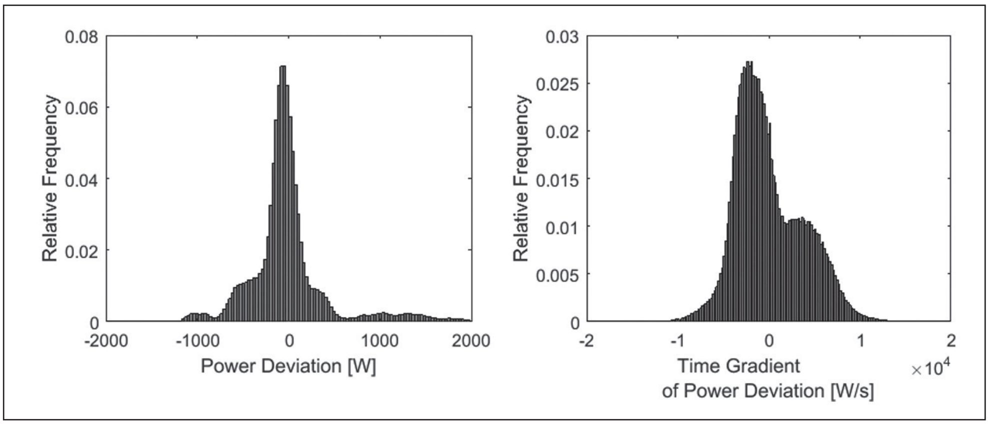

Figure 7: Relative frequency distribution. Left: Electrical power deviation between real energy consumption and available energy supply from SOFC-system. Right: Determined required time gradient for short-term storage system

5. CONCLUSION AND OUTLOOK

To achieve the 2050 targets long- and short-term storage are needed to align the energy yields from renewables with the energy demand. Effective long-term storage systems such as rSOC are highly efficient and a promising technology. However, additional electrochemical energy storage systems are required to balance the short-term gaps in the time scale from milliseconds to hours. Theoretically, redox flow batteries are able to close this gap. However, experimental findings regarding high frequent charge and discharge cycles are hardly available. Furthermore, experiences with historical data driven RFB energy management systems are still missing. For this reason a RFB test bench with a short-term dynamic yield and demand simulation interface will be developed. Based on this test facility, step function response tests as well as real profile response analysis will be carried out.

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