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Short communication

A commentary on the US policies for efficient large scale renewable energy storage systems: Focus on carbon storage cycles

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HIGHLIGHTS

- Recently proposed carbon storage cycle for GWh-level energy storage is presented.
- Details of DME-cycle for large scale energy storage is demonstrated.
- Current US energy storage regulations and policy initiatives are investigated.
- The potential of chemical energy storage in a sustainable economy is demonstrated.
- It is recommended to include chemical storage options in R&D portfolio.

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ABSTRACT

The inevitable depletion of fossil resources and increasing atmospheric greenhouse gas concentrations demonstrate the need for renewable energy conversion technologies for a sustainable economy. Intermittencies and variability in availability of renewable energy sources are the challenges for uninterrupted energy supply, which can be overcome by large scale energy storage facilities. Pumped hydroelectric energy storage is an efficient but a very low energy density energy storage method that dominates the current energy storage market with ~96% share. We first present a recently developed potential solution for large scale efficient and dense energy storage: closed loop carbon storage cycles and a specific example dimethyl ether storage cycle. We then discuss the relevant US energy storage regulations, policy initiatives, their status, and potential modifications that will contribute to the invention and implementation of novel energy storage systems.

1. Introduction

The global energy sector is predominantly dependent on fossil resources. In 2014, approximately 87% of the world energy consumption was provided by fossil resources (oil, natural gas and coal) (EIA, 2015). Although the natural gas share in the energy mix is highly sensitive to the natural gas price and carbon tax from gas production (Bistline, 2014), discoveries of shale oil and shale gas will likely postpone the inevitable end of fossil resources. Yet, in less than 100 years fossil fuel reserves will be substantially diminished (EIA, 2015) and replaced by renewable energy sources. Finding the best strategies for utilization of the remaining resources is critical for a smooth transition to a sustainable economy. Furthermore, continuous increase in atmospheric greenhouse gases (GHG) mainly carbon dioxide (CO_2), which is one of the main causes of global warming, is also a severe consequence of extensive utilization of fossil resources (Dlugokencky and Tans, 2013).

In 2014, 67% of the electricity generation in the U.S. was provided by fossil resources, primarily coal and natural gas with respective contributions of 39% and 27%. The 19% nuclear energy share was followed by 13% total renewable power, for which the predominant sources were hydroelectricity by 7% and wind by 4.4%. The solar electricity share was only 0.4% (EIA, 2015).

All of these facts point to the importance and urgency of finding, developing and implementing sustainable energy systems. Among renewable energy sources, solar energy is the most promising due to its tremendous potential. Solar irradiance on the earth's surface in 1 h is comparable to the annual global energy consumption (Lewis and Nocera, 2006). A future solar economy vision anticipates fulfillment of human needs from solar energy (Agrawal and Mallapragada, 2010). However, despite its enormous potential, the share of the solar energy in the energy mix has only

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recently started to increase. Though the growth curve of solar energy is presently very steep, its current share in the global primary energy consumption is less than 1% (EIA, 2015). Yet, solar energy is expected to play a critical role in meeting future energy demand. The long-term predictions show that share of solar energy in the global primary energy supply mix will exceed 10% by 2050 (Timilsina et al., 2012). The large scale implementation of renewable energy sources depends on many factors, such as on the consumer side: (i) willingness to pay the price for green power (Aldy et al., 2012; Burtraw et al., 2013), and (ii) changing consumption habits (Sanquist et al., 2012). And on the technological side, (i) the effect of lower capacity factor compared to fossil fuel power plants (Lesser and Su, 2008); (ii) the ability to meet the ancillary services (Cappers et al., 2013); (iii) the availability of infrastructure (Delucchi and Jacobson, 2011), and (iv) the reliability of the renewable power (Burtraw et al., 2013). However, besides all these factors, limitations such as variations and intermittencies in availability create a real challenge for grid stability for high renewable energy penetration. Intermittencies can be overcome by proper energy management for low and medium penetration (Schaber et al., 2012); however, energy storage is indispensable for renewable energy penetration above 80% (Denholm and Hand, 2011).

A major barrier to widespread implementation of solar technologies is the inadequacy of the current energy storage systems to overcome intermittencies (Timilsina et al., 2012). For energy storage, the harnessed solar energy must be first transformed into a storable form and, subsequently, used to generate electricity. To give a perspective, on average the solar energy in the U.S. is available for only one-fifth of a day (Lewis and Nocera, 2006). To supply an average of 100 MW solar electric power over a 24 h cycle, electricity equivalent energy must be stored for the remaining four-fifths of the day, which means $\sim$2 GWh of electricity equivalent energy storage is needed on a daily basis.

Energy storage systems are also important for the fossil fuel based electricity production sector. Currently, electricity is supplied by two classes of power plants: base load power plants that have constant output, and peaking power plants that supply electricity to overcome peaks and spikes in consumer demand. A base load energy storage system that meets the peak electricity demand may eliminate the need to operate peaking power plants. An integrated coal-fueled power plant and compressed air energy storage system has been shown to successfully follow load variations without significant effect on efficiency (Nease and Adams, 2014). Hence, fossil fuel power plants can be operated at almost constant power output at their optimum operating conditions. Yet, the design and control of any energy storage system integrated with either renewable or fossil generation system requires careful consideration to prevent suboptimal operation (Morandin et al., 2012; Siirola and Edgar, 2012).

1.1. Background on U.S. energy policies

Current U.S. energy policy initiatives can be divided into three main categories: fuel economy regulations, regulations to decrease GHG emissions, and regulations to increase renewable energy share. Fuel economy regulations like new CAFE (Corporate Average Fuel Economy) regulations (2011) may change the expected consumption patterns of remaining fossil fuel resources that are anticipated to be used as bridge solutions (Dauenhauer and Huber, 2014; Gençer et al., 2014b; Mallapragada et al., 2014; Onel et al., 2015).

President Obama and the U.S. Environmental Protection Agency have announced the Clean Power Plan, which is an important step in reducing carbon pollution form power plants that aims to define state-based standards to reduce carbon pollution across the U.S. in agreement with each state's energy mix. The plan envisions reducing carbon pollution from the power sector 32% below 2005 levels by the year 2030 (EPA, 2015). Clean Air Interstate Rule (CAIR), Cross-State Air Pollutant Rule (CSAPR), National Emissions Standards for Hazardous Air Pollutants (NESHAP) are other examples of legislation and regulations on GHG level control. Targets to increase renewable energy share include 10–40% renewable energy inclusion by 2015 and onwards. Renewable Portfolio Standard (RPS) or similar law that applies to 30 of the states and the District of Columbia has set these targets. The aforementioned policies will definitely increase the renewable energy share in the U.S. energy consumption, but they should be supported by suitable energy storage regulations to make the initiative stronger.

1.2. Large scale energy storage systems and their global penetration

Current wind and solar power integration, which is mainly in the introductory phase, corresponds to a small share of renewable energy in the energy mix. However, to move to the next phase, which includes integration of fluctuating renewable energy sources in large scale, the grid stability concern should be met (Frisari and Stadelmann, 2015; Lund et al., 2012; Orecchini and Santiangeli, 2011). A reliable robust large scale energy storage system can bring stability and reliability to the renewable energy sector.

An energy storage system for renewable energy resources should receive electricity and renewable energy in other forms (if available) and deliver electricity. High roundtrip storage efficiency, high storage capacity and high storage density are the important features for a suitable energy storage method (Chen et al., 2009). Since large scale energy storage systems require high investments, they should provide benefits, such as ensuring grid stability (Lund et al., 2012). Furthermore, storage systems must be long lasting and non-degradable over time (Chen et al., 2009). The current large-scale energy storage options are pumped hydroelectric, electro-chemical (batteries), electro-mechanical (compressed air energy storage, CAES), gaseous hydrogen and liquid hydrogen storage (Barnes and Levine, 2011). A comparison of current large-scale storage options in terms of storage efficiency and storage density is given in Fig. 1. Energy storage options such as flywheels and supercapacitors can deliver electricity rapidly, which is critical to maintaining grid stability. These systems are not truly large scale energy storage options, but likely to be implemented in tandem with suitable large scale energy systems for uninterrupted power supply (Chen et al., 2009).

Pumped hydroelectric and batteries are the most efficient storage methods ($\sim$80%). Pumped hydroelectric and compressed air storage have very low storage densities: $\sim 5 \cdot 10^{-5}$ GJ/m^3 and $\sim 3 \cdot 10^{-2}$ GJ/m^3, respectively. Batteries have higher storage densities ($\sim$1–1.3 GJ/m^3), but still an order of magnitude lower than that of the H_2 storage ($\sim$3.2–6.5 GJ/m^3) (EPRI, 2010). Furthermore, CAES needs a heat source during delivery mode. Although heat can be supplied from a variety of energy sources, the common practice is the use of hydrocarbon fuels. Short lifetime, issues of disposal and dependence on rare earth elements for batteries, and heat loss from thermal storage especially for CSP systems are examples of concerns (Timilsina et al., 2012).

The global energy storage projects are summarized in Fig. 2. The overall rated power of operational, under construction, contracted and under repair of a total of 1206 energy storage projects is 184 GW (DOE, 2013). More than 96% of this rated power is associated with pumped hydroelectric energy storage. Molten salt thermal storage systems have the second largest total rated power of 2.6 GW (1.4% of the total), and as seen from Fig. 2(a), approximately half of that capacity is under construction. The total rated power of electro-chemical and electro-mechanical storage options is close to 2 GW, but there are few new large scale projects. The