Journal of Power Sources 216 (2012) 376–386

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

# Selection of battery technology to support grid-integrated renewable electricity

Jason Leadbetter*, Lukas G. Swan [1]

Dalhousie University, Mechanical Engineering C360, 5269 Morris St., Halifax, NS, Canada B3H 4R2

## HIGHLIGHTS

- ► Renewable electricity places additional strain on the electricity grid.
- ► Grid support services to provide flexibility are becoming more important.
- ► Battery energy storage systems offer a broad range of storage abilities.
- ► Lithium-ion and lead–acid batteries are suitable for short duration services.
- ► Sodium–sulfur and vanadium redox batteries are suitable for long duration services.

ARTICLE INFO

*Article history:*
Received 26 April 2012
Received in revised form
25 May 2012
Accepted 28 May 2012
Available online 1 June 2012

*Keywords:*
Battery energy storage
Renewable energy storage
Battery technologies
Renewable energy integration

ABSTRACT

Operation of the electricity grid has traditionally been done using slow responding base and intermediate load generators with fast responding peak load generators to capture the chaotic behavior of end-use demands. Many modern electricity grids are implementing intermittent non-dispatchable renewable energy resources. As a result, the existing support services are becoming inadequate and technological innovation in grid support services are necessary. Support services fall into short (seconds to minutes), medium (minutes to hours), and long duration (several hours) categories. Energy storage offers a method of providing these services and can enable increased penetration rates of renewable energy generators. Many energy storage technologies exist. Of these, batteries span a significant range of required storage capacity and power output. By assessing the energy to power ratio of electricity grid services, suitable battery technologies were selected. These include lead-acid, lithium-ion, sodium-sulfur, and vanadium-redox. Findings show the variety of grid services require different battery technologies and batteries are capable of meeting the short, medium, and long duration categories. A brief review of each battery technology and its present state of development, commercial implementation, and research frontiers is presented to support these classifications.



## 1. Introduction

It is well established that dependence on fossil fuel resources creates vulnerability to price fluctuations in international fuel markets and leads to anthropogenic greenhouse gases causing human induced global warming. With a peak in global oil production likely occurring before 2020, the pressure to use alternative energy sources is greater than ever [1]. Governments around the world are developing aggressive renewable energy and electricity plans focused on increasing the installed capacity of wind, solar, and other intermittent renewable generation devices (e.g. in-stream tidal). Worldwide wind turbine generating capacity grew from 17,400 MW in the year 2000 to 197,039 MW in the year 2010 and continues to show exponential growth rates worldwide [2]. Solar energy is observing similar growth with cumulative global installed photovoltaic capacity doubling since the year 2007 to 39,800 MW at the end of the year 2010 [3,4]. With such rapid growth of these technologies, the implications of high penetration levels of renewable generation must be carefully considered.

To consider the impact intermittent renewable generation has on the existing electricity grid, Fig. 1 gives a time series plot of measured values of electricity demand and several renewable generation types within Nova Scotia, Canada. Electricity demand is the total provincial load on the electricity grid[2]; tidal stream speed is approximated as the time derivative of tide height in the Bay of

* Corresponding author. Tel.: +1 902 494 6196; fax: +1 902 423 6711.
*E-mail addresses:* js886289@dal.ca (J. Leadbetter), Lukas.swan@dal.ca (L.G. Swan).
[1] Tel.: +1 902 494 4643; fax: +1 902 423 6711.

[2] Nova Scotia Power Incorporated. Hourly Total Net Nova Scotia Load. http://oasis.nspower.ca/en/home/default/monthlyreports/hourly_ns.aspx.

0378-7753/$ – see front matter 
10.1016/j.jpowsour.2012.05.081

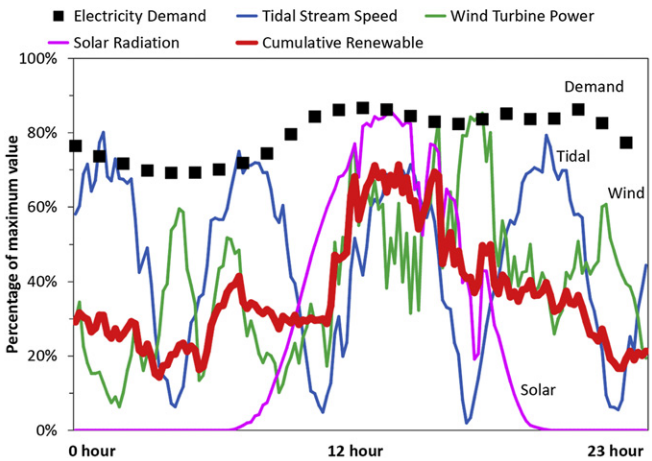


**Fig. 1.** One day profile of electricity demand and renewable generation for the province of Nova Scotia (10 September 2011).

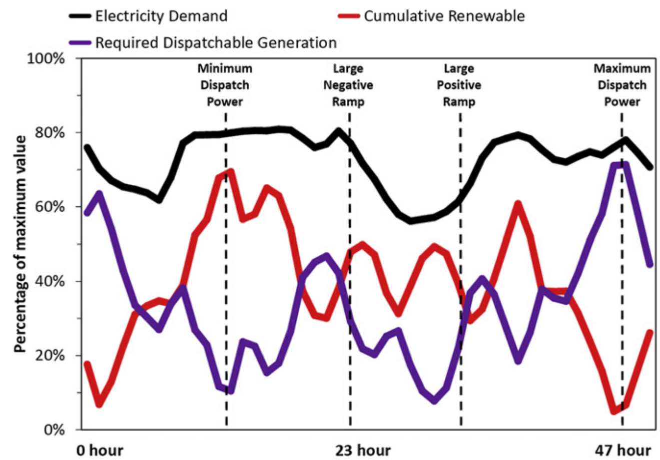


**Fig. 2.** Two-day profile of electricity demand, cumulative renewable generation, and the resultant required dispatchable generation for the province of Nova Scotia (16–17 September 2011).

Fundy[3]; wind turbine power is the output of a single 0.8 MW rated wind turbine in the Cobequid Mountains[4]; solar radiation is the total incident upon a collector inclined 45° and facing due south at Dalhousie University[5]; and cumulative renewable represents the combined output of the three renewable energy types. All values are normalized by maximum monthly value and are based on 10-min averages with the exception of 1 h electricity demand.

Fig. 1 shows electricity demand fluctuating with higher daytime and lower nighttime values. The three renewable resources are distinct with tidal being sinusoidal, wind being stochastic, and solar occurring only during daytime. It is evident from the cumulative renewable profile that using several renewable resources has a smoothing effect, although it does not mitigate peaks or valleys and does not align with the electricity demand.

In addition to the obvious mismatch of renewable resources with electricity demand, there exist operational issues related to fossil fuels being used as backup for high penetration rate renewable generators Fig. 2 shows the required dispatchable generation which is the difference between the electricity demand and cumulative renewable output. This represents the performance requirements of controlled output generators such as fossil fueled thermal units. As noted in Fig. 2, the dispatchable generation must be capable of throttling back to minimum power output while also having sufficient capacity to meet nearly all of the electricity demand. Furthermore, renewable resources may be decreasing while electricity demand is increasing (or vice versa). This requires the dispatchable generation to have positive and negative ramp rate capabilities (i.e. change in power output per unit time) that are significantly greater than would be expected based on electricity demand alone. Conventional steam cycle generators suffer in both regards as they are limited to minimum power output of one-half rated capacity, and ramp rates of 1% per min [5].

In-stream tidal generation is predictable and reasonably consistent, a unique quality of this resource. In contrast, wind and solar renewable resources are such that they respond on timescales of seconds and minutes due to gusts and clouds. Fig. 3 illustrates this characteristic by providing high rate minimum/maximum values recorded during each 10-min timestep. Wind turbine power varies considerably throughout each 10-min period, often ranging from 20% to 95% of the maximum monthly value. In this example the variation of solar radiation is minimal during the morning, but with the onset of afternoon clouds the minimums drop to less than 10%. These brief renewable resource variations may be partially mitigated through the use of geographically separated generators. However, this assumes that sufficient transmission capacity is available within the transmission and distribution electricity grid.

The preceding figures and discussion clearly identify the range of variation in renewable resources corresponding to resource type, influence on conventional generators, and individual renewable generator response. These variations necessitate the use of energy storage if renewable resources are to meet a significant portion of electricity demand without curtailment or fossil fuel backup. There are a variety of options available for both small- and large-scale energy storage systems. Numerous literature reviews compare these various energy storage technologies using several assessment methods [6–13]. Many of these comparison/review articles recommend certain technologies for certain applications and an applicability map is created showing technologies plotted as duration versus power. An example is given in Fig. 4.

The ranges shown in Fig. 4 include installed energy storage projects to the year 2008. The product of duration and power is energy storage capacity, and thus Fig. 4 shows that PSH and CAES

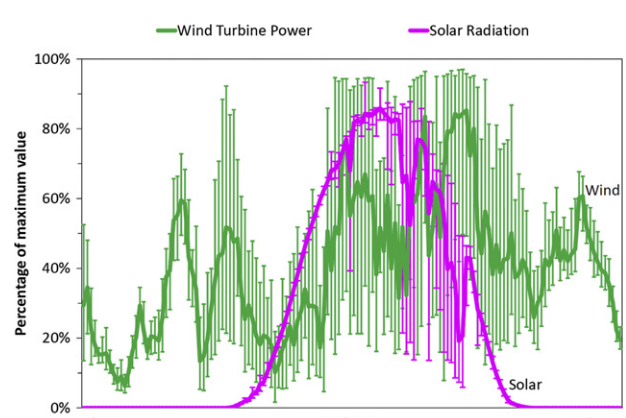


**Fig. 3.** One day profile of 10-min timestep renewable generation with 1-s minimum/maximum values for the province of Nova Scotia (10 September 2011).

[3] Fisheries and Oceans Canada. Saint John Station #65 Tide and Water Level Archive. http://www.charts.gc.ca/twl-mne/index-eng.asp.

[4] Colchester-Cumberland Wind Field Incorporated. Contact Lukas Swan (Lukas.Swan@Dal.Ca) for further information.

[5] Dalhousie University, Halifax. Contact Peter Allen (Peter.Allen@Dal.Ca) for further information.