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PNNL-20407

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

FVB Energy Inc. Technical Assistance Project

JG DeSteese

May 2011

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The request made by FVB asked for advice and analysis regarding the value of recapturing the braking energy of trains operating on electric light rail transit systems. A specific request was to evaluate the concept of generating hydrogen by electrolysis. The hydrogen would, in turn, power fuel cells that could supply electric energy back into the system for train propulsion or, possibly, also to the grid. To allow quantitative assessment of the potential resource, analysis focused on operations of the SoundTransit light rail system in Seattle, Washington.

An initial finding was that the full cycle efficiency of producing hydrogen as the medium for capturing and reusing train braking energy was quite low (< 20%) and, therefore, not likely to be economically attractive. Because flywheel energy storage is commercially available, the balance of the analysis focused the feasibility of using this alternative on the SoundTransit system. It was found that an investment in a flywheel with a 25-kWh capacity of the type manufactured by Beacon Power Corporation (BPC) would show a positive 20-year net present value (NPV) based on the current frequency of train service. The economic attractiveness of this option would increase initially if green energy subsidies or rebates were applicable and, in the future, as the planned frequency of train service grows.

This constitutes the final report in response to a request for assistance submitted to Pacific Northwest National Laboratory by FVB Energy, Inc. (FVB). This effort was performed under the terms of Technology Assistance Program (TAP) Agreement #11-14.

Abstract

The request made by FVB asked for advice and analysis regarding the value of recapturing the braking energy of trains operating on electric light rail transit systems. A specific request was to evaluate the concept of generating hydrogen by electrolysis. The hydrogen would, in turn, power fuel cells that could supply electric energy back into the system for train propulsion or, possibly, also to the grid. To allow quantitative assessment of the potential resource, analysis focused on operations of the SoundTransit light rail system in Seattle, Washington.

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Background

All electrically powered locomotives and trains have the potential of switching their traction motors into generators as a means of supplementing friction braking. The reverse electromotive force in the motor-turned-generator opposes the rotation of the wheel-axle assembly on which it is mounted and thereby slows the vehicle down when power is extracted. In diesel-electric locomotives, this braking energy is dissipated in large, air-cooled resistor grids and cannot be otherwise reused. The situation is different with straight electric locomotion supplied by an electric catenary or third rail. In these circumstances, the energy generated by the vehicle as it decelerates can be fed back into the power distribution system.

Some high density electric train systems in the world (Zurich, Switzerland, for example) are scheduled so that the regenerative braking energy of some trains in the act of stopping feeds directly to other trains that are in the process of accelerating away from stops. While this does not provide for a perfect reuse of braking energy, it offers a time-averaged net benefit of allowing reductions in the size and frequency of electric substations needed to supply the transportation system as a whole. On systems operating at lower service frequencies, this type of schedule coordination may not be possible. The question then arises whether or not energy storage could be an economically viable solution for effectively rescheduling the availability of train braking energy to times when it would be useful.

Two energy storage options applied in this manner were evaluated, as discussed below.

Braking Energy Capture via Hydrogen Generation

The first option reviewed is the storage of braking energy in the form of gaseous hydrogen that could be used later to generate electric power in a fuel cell. First, the regenerated power would need to be converted to a direct current (dc) voltage/current form compatible with the requirements of water electrolysis equipment. The generated hydrogen would need to be separated from other electrolysis products and stored in a compressed state. Its use in a fuel cell would by subject to the conversion efficiency of the fuel cell and the electrical demands of the fuel cell's peripheral equipment. Finally, the fuel cell's electrical output would need to undergo dc/dc conversion to a voltage acceptable for supplying the electric grid of the transit system.

The general efficiencies of these steps are as follows:

- Conditioning regenerative power to a form suitable for electrolysis (~ 90%)

- Electrolysis efficiency (maybe only be ~50%)

- Hydrogen separation, purification and storage (~85%)

- Fuel cell conversion efficiency including power consumed by peripheral equipment (~ 55%)

- Power conditioning suitable for reuse by the transit system or transmission to the grid (~95%).

Combining the efficiencies of the above steps suggests that the overall efficiency of the process is on the order of 20% which does not seem high enough to warrant further interest. Furthermore, the concept would require the acquisition of facilities for hydrogen production and storage, and personnel skilled in the safe handling of this potentially hazardous gaseous fuel. No analysis was performed to establish the economics of this concept because of these seemingly overwhelming disadvantages.

Braking Energy Capture via Flywheel

Flywheels have been developed and are commercially available as a means of temporarily storing energy in a variety of applications. For example, Beacon Power Corporation of Tyngsboro, Massachusetts has demonstrated modular flywheel systems that regulate power supply frequency on parts of the electric power grid. A similar connection of a flywheel to an electrified transit system would provide the cyclic energy storage and discharge required to capture regenerative train braking energy and deliver it either back into the system or allow power to be sold back to the grid.

An analysis of SoundTransit's 1500-Vdc light rail system was performed to establish the general economic value of using a BPC Smart Energy 25 unit. This is a modular flywheel with a 25-kWh energy storage capacity and a 100-kW charge/discharge rate. It would be used to recover train braking energy based on the present frequency of train dispatch. This effort was aided by complying with FVB's recommendation to consult with Mr. Akio Nunes Oeno who has expert knowledge of SoundTransit's operations.

Braking Energy Available   An estimate for the braking energy available based on current SoundTransit light rail operations is as follows:

The number of trains that operate per day is double the aggregate frequency per hour published on SoundTransit's website because frequency data apply to both directions - therefore:

Number of train movements per day (Sundays excluded):

$$2 \times (4 + 20 + 39 + 28 + 21 + 12) = 248.$$

Also from the website, a train unit is described as being "Double articulated, with three sections riding on six axles." One of the two-axle trucks is under an integral center section that connects two cab-ended sections by a turntable-like connection. Thus the 95-foot, 105,000-lb specifications appear to reasonably describe a single train unit. The passenger load will add to the inertia of the train. Of course, this will vary throughout the day and even from stop to stop on a single trip. For the purposes of this analysis, a passenger load equivalent to about half occupancy, i.e., 100 persons weighing 130 lb on average was used.

Therefore, a representative train weight would be:

[105,000 + (100 x 130)] lb = 118,000 lb or 53,454 kg.

Mr. Oeno advised that maximum train speeds between closely spaced stations on the northern end of the line would generally be lower than speeds between the more widely spaced stations on the south end. For simplicity, I divided trains operations into two classes, one class attaining a maximum speed of 30 mph and the second class reaching 50 mph when braking energy becomes available. The 30-mph limit was assumed for the six station stops at the north end of the line while 50-mph speeds were considered reasonable between the six stations on the southern portion. Also, I did not take credit for the trains producing any regenerative effect below 10 mph. This is because it is generally not customary or economic to design traction motors and related switch gear to produce a dynamic braking effect below this speed.

Energy released by one train stop from 50 mph is:

$$0.5 \times 53454 \times (22.35^2 - 4.47^2)\ \text{J} = 12.82\ \text{MJ or } 3.56\ \text{kWh}.$$

Energy released by one train stop from 30 mph is:

$$0.5 \times 53454 \times (13.41^2 - 4.47^2)\ \text{J} = 4.27\ \text{MJ or } 1.19\ \text{kWh}.$$

Potential electrical energy generated by trains stopping at six stations from 50 mph is given by:

248 trains x 6 stops x 3.56 kWh = 5.30 MWh/day.

Potential electrical energy generated by trains stopping at six stations from 30 mph is given by:

248 trains x 6 stops x 1.19 kWh = 1.77 MWh/day.

Thus, total gross regenerated energy would be about 7.1 MWh/day. With electric energy worth 6 cents/kWh, this represents a value of about $426/day. Annually, excluding Sundays (i.e., 52 x 6 days per year), brings the energy value up to about $133,000/yr.

Mr. Oeno advised that about 30% of dynamic braking energy spontaneously offsets the power demand of other trains. This energy would be likely to be consumed by other trains accelerating before it could be intercepted (i.e., metered) at the flywheel storage unit. He also estimated that another 10% would be consumed by motor/generator inefficiency and line losses.

The above considerations reduce the net amount of the braking energy resource that might be temporarily captured and stored to:

7.1 x 0.7 x 0.9 = 4.47 MWh/day.

The value of the net storable resource is also reduced from $133,000/yr down to about $84,000/yr.

Flywheel Cost Effectiveness The principal remaining issue is whether this order of potential savings could pay back the capital and maintenance expense of the storage medium. Personal communication with BPC suggested that we use $500,000 as the capital cost of the company's Smart Energy 25 flywheel module and about 3% of this capital cost as the annual cost of maintenance.

A spreadsheet is attached that considers the above values together with alternative values provided by FVB for annual energy, flywheel maintenance cost and fixed charge rate assumptions.

The results show that applying the above considerations, use of a single BPC flywheel would have a 20-year net present value of about $275,000. Using FVB's assumed values increases this to about $297,000. In the latter case, the reduced rate assumed for annual maintenance more than offsets a higher cost of capital. If such a project were to receive green energy credits in the form of a conservation rebate, these NPVs would be yet larger.

Power Handling Considerations It is important to consider how long a single BPC Smart Energy 25 (100-kW, 25-kWh) flywheel would be adequate as traffic increases. Assuming a train decelerates from cruising speed to a stop in 1 minute, it would deliver 70% of its kinetic energy (0.7 x 3.56 kWh) per minute to the flywheel, representing a power source averaging 150 kW during this time. The number of flywheels modules necessary depends on how many trains would be in the process of slowing down simultaneously. The present maximum scheduled frequency is 16 trains/hour. Assuming scheduling could help plan a favorable sequence, it is still, perhaps, reasonable to say that only one train at a time would be delivering its instantaneous maximum power and that, using its short time overload capacity, a single flywheel would be adequate. With the energy recovery possible from the present schedule, the spreadsheet shows that adding a second flywheel to gain more power handling capacity sends the NPV negative. However, if future train frequency doubles as planned, two or more flywheel modules would be economically viable. This is also illustrated in the spreadsheet.

Waste Heat Recovery About half the 12% round-trip inefficiency of the flywheel may be recoverable by reclaiming low-grade heat from the power electronics cooling system. In principle, this resource is also potentially available from the conventional power rectifiers in each substation. The flywheel's associated power conditioning system would likely be operating close to its100-kW rated limit on a 2-minute round-trip charge/discharge cycle during more heavily scheduled periods. It would be loaded less frequently at other times. Without a detailed analysis of moment-to-moment energy balances on the system, it may be reasonable to credit the flywheel system as about an average 6-kW heat source while it is working.

Concluding Remarks

It is concluded that an electric light rail system such as that operated by SoundTransit would benefit operationally and financially by installing a means of energy storage for capturing the regenerated braking energy of trains. Upon discharge, this stored energy could be used to supply a part of the energy needed to accelerate other trains on the system or sold back the electric power grid.

This review of two energy storage options concludes that using hydrogen and fuel cells as the means of storage and redistribution, respectively, is inherently a complex concept with the low round trip efficiency of about 20%. In contrast, currently available commercial flywheels have a round-trip efficiency of about 88% and have the potential of converting electric train braking energy into an economically viable conservation resource.

While this brief assessment is encouraging, a much more detailed analysis would be required to establish the value proposition of applying flywheel storage to SoundTransit operations and light rail systems, in general. For example, the spreadsheet was used to explore NPV sensitivity to the amount of braking energy captured. It showed that, with a single flywheel and present-day train scheduling, NPV goes rapidly to zero when energy capture is reduced to between 75% and 80% of the assumed value (i.e., when only 53 to 56% of the potential braking energy is captured).

Many issues that impact the economics of energy recovery are beyond the scope of this TAP. For example, knowledge of train operational statistics, including frequency, speed and loading data, would be essential to properly account for the energy recovery potential of the present and future system. The energy recovery potential of multiple unit train operations would be another factor to consider. A new metering system would be required to determine the net braking energy processed by the storage element over each metering cycling. Furthermore, a detailed analysis would likely reveal many essential extra cost items not considered in this effort that would strongly affect the NPV. Finally, the performance of flywheels should be compared with other energy storage options such as batteries and capacitors. However, initial indications, as discussed above, are positive for this application of flywheel energy storage.

Spreadsheet to Calculate NPV

Sound Transit
Flywheel NPV.xls...