2nd International Conference on Energy and Environment: bringing together Engineering and Economics
Guimarães, Portugal
18-19 June, 2015

USING VANADIUM REDOX FLOW BATTERIES FOR THE ELECTRICITY STORAGE TOWARDS THE ELECTRIC VEHICLES FAST CHARGING PROCESS

Álvaro Cunha[1], Jorge Martins[1], Nuno Rodrigues[2], Vítor Monteiro[3], João L. Afonso[3], F. P. Brito[1*]

[1] Department of Mechanical Engineering, University of Minho, Portugal
[2] Petrotec, Inovação e Indústria S.A., Portugal
[3] Department of Industrial Electronics Engineering, University of Minho, Portugal

* Corresponding author: francisco@dem.uminho.pt, University of Minho, Portugal

KEYWORDS
Energy Storage, Vanadium Redox Flow Battery, Electric Vehicles Fast Charge

ABSTRACT

The multitude and magnitude of the problems deriving from the use of fossil fuels for road transport is widely known. Therefore, electric mobility associated with renewable energy sources seems to be a good solution for minimizing these problems. However, the time required to charge the batteries of Electric Vehicles (EVs) and the availability of charging stations are seen as critical factors for their market viability. The use of fast charging stations is a possibility to mitigate the long time required to charge the batteries, but the high cost for power availability makes their operation very expensive. Moreover, it might be difficult to find suitable and affordable locations for installing these stations, so gas stations seem to be good candidates for this purpose. This paper assesses the use of fast charging stations for EVs in conjunction with Vanadium Redox Flow Batteries (VRFBs). Taking into account the low energy density of VRFBs, they are especially suited for situations where volume and weight are not limiting factors. Moreover, their liquid nature allows their installation inside deactivated underground fuel tanks located at gas stations. A preliminary assessment of a VRFB system for EVs fast charging stations taking advantage of existing gas stations infrastructures is presented. An energy and cost analysis of this concept is outlined, including a sensitivity analysis which shows that the project is technologically and economically viable for the conditions tested, although with long payback times.

INTRODUCTION

The disruptive proliferation of urban traffic along the last decades is posing serious sustainability concerns, mainly those related to urban air quality and the need to comply with greenhouse gases (GHG) emissions targets, as well as the excessive dependence of developed economies on fossil fuels. It is expected that by 2030 the transportation sector will be responsible for 55% of total oil consumption (International Energy Outlook, 2009). It is also expected that the population will grow 1.7 times and the number of cars even more (3.6 times) between 2000 and 2050 (Zdenek and Pavel, 2011). In this context, the current policies promoting emissions reduction and the improvement of the energy efficiency of Internal Combustion Engines (ICE) are contributing to palliate these issues (Martins et al., 2013). Various strategies have been explored, such as engine downsizing enabled by intake-charging (Silva et al., 2009), the strategy of over expansion explored by the authors (Ribeiro and Martins, 2007) and used in several efficient hybrid powertrains or waste energy harvesting such as exhaust thermal energy recovery in form of Organic Rankine Cycle or Seebeck effect thermoelectric generators (Brito et al., 2013). Nowadays, the main alternatives to the traditional ICE are the Plug-In Hybrid Electric Vehicles (PHEVs) and the full Electric Vehicles (EVs) (Boulanger at al., 2011). Hawking (Hawkins et al., 2013) presents an environmental life cycle comparison between conventional vehicles and EVs. As an example, the global GHG emissions of EVs can be cut from 10% to 24% when compared to conventional diesel or gasoline vehicles. Camus and Farias (Camus and Farias, 2012) highlighted the EV as a means to contribute to the overall reduction of the fossil sources and energy used for transportation, although certainly this will depend on the electricity production performance. Unfortunately, the success of PHEVs and EVs is currently hampered by some notable disadvantages, mostly related with energy storage and grid charging (Cadoux and Gross, 2013). Their main disadvantages are their typically low autonomy (usually up to 150 km) which results from the low energy density of current battery technologies and the long time required to perform standard battery charging processes (typically, a full charge will require around 8 hours to complete) (Ribeiro et al., 2010). The combination of these two factors is known to induce the so-called range anxiety phenomenon which, along with the high cost of batteries, is still preventing the broad adoption of electric mobility (Faria et al., 2012). A range extender unit may be added to the powertrain to prevent range anxiety and the authors have confirmed the merits of efficiency-oriented range extenders on a Life Cycle basis (Ribau et al., 2012). However the use of such systems increases design complexity and cost, as the price tag of some existing models incorporating range extenders indicate. In order to minimize the aforementioned shortcomings, some EVs allow to perform the battery charging process using the fast charging mode, namely through the ChadeMo protocol (Role of Chademo, 2013). However, the high power output required by these chargers is especially demanding in terms of infrastructure and power grid integration. A high power consumption plan must be contracted with the electric grid service provider, representing a substantial cost. Moreover, EV charging demand will normally occur at daytime, coinciding with costly electrical peak demand periods.

Fortunately, many of the aforementioned disadvantages of fast charging may be averted by decoupling grid consumption from consumption due to vehicle charging by means of stationary energy storage systems. In fact, the energy needed for high power vehicle charging may be stored previously and more gradually (with lower average power) at off-peak demand schedules, usually during the night. Therefore, it is possible to reduce both the contracted power and the cost of electricity. In this context, the present work explores the use of a specific energy storage technology to perform EV fast charging during daytime using night off-peak periods. Moreover, the proposed energy storage technology could also be integrated into microgrids, to store the energy produced by nearby intermittent renewable power sources contributing to smooth their output and adapt it to power demand (Saber and Venayagamoorthy, 2011).

The literature identifies two processes for the storage of energy during low demand periods: the load levelling and the peak shaving (Kerestes et al., 2012; Kerestes, 2011). The main goal of the load levelling process is to stabilize the electrical load, avoiding fluctuations in the consumed power, while in the case of peak shaving process the main goal is to use the stored energy solely to remove the load peaks consumption. For both processes the energy stored during the night will be the energy supplied by the storage system during the day. They have several advantages, the first of all being the reduction of the maximum power consumed from the power grid and consequently the reduction of the contracted power. Secondly it allows a better management of the energy demanded from the power grid taking into account the different energy prices throughout the day. Thirdly it permits a greater incorporation into the grid of energy derived from renewable sources like solar and wind, which are unpredictable sources, often with the peak power generation occurring in counter-cycle with demand. This means that the availability of an energy storage buffer will avoid wasting the energy produced during low demand periods, storing it and releasing it later during high demand events.

There are several energy storage technologies that can be used for load levelling and peak shaving processes. The most commom are pumped hydro storage systems, compressed air storage and batteries (mainly the use of lead acid (Nakayama, 2004), sodium sulphur (NaS) (Kerestes et al., 2012), lithium ion (Iwahori, 1999), and redox flow batteries (Shibata and Sato, 1999)). Many of the aforementioned systems have requirements not easily achieved for the application proposed in this work. Among the various battery technologies, the Redox Flow Batteries (RFB) have several advantages over the remainders, as they have total independence between the energy capacity and the rated power (Hagedorn and Thaller, 1982). Other advantages of these batteries are related to their liquid nature and their storage (in tanks), which can be of any shape. Wang (Wang, 2013) reviewed the recent developments and studies of RFB concerning electrolytes, electrodes, membranes, and aqueous and non-aqueous systems. There are many types of RFB with various redox couples used. However, the Vanadium Redox Flow Battery (VRFB) is currently among the most studied and promising technologies of this kind. These batteries have the advantage of using the same material in both half cells which, in the case of the cross mixing of the electrolytes, there is no damage of the battery (as in the case of other RFBs) but only a self discharge (Skyllas-Kazacos et al., 1988). This is one of the main reasons for their fairly extended life even when compared with the latest Li-ion battery chemistries. As a main disadvantage, complete VRFB systems are still expensive, although the growing maturity of this technology and its attractiveness as an enabler for the wide adoption of intermittent renewable sources is likely to decrease its cost in the midterm (Kear et al, 2012). The authors have recently published a revision article on this technology (Cunha, 2014). As an alternative to the costly and laborious deactivation/disposal of surplus large fuel storage tanks in gas stations, a retrofit of these deposits could be performed, adapting them for VRFB electrolyte storage and using the storage system for EV fast charging with the strategy explained before. One merit of such an approach would be to easily obtain EV fast charging spots in places which are already strategically located for vehicle traffic, optimizing otherwise wasted space and infrastructures and complementing the ICE vehicle fuel supply business with the emerging plug-in vehicle charging business in one place. This would additionally enable a smooth transition of gas stations' business model towards the emerging electric mobility paradigm. Figure 45 shows the proposed system architecture. As it can be seen, the VRFB can receive energy from the power grid or from renewables sources and can deliver energy to the EV fast charging process or to the power grid aiming to contribute to the load levelling and peak shaving processes.

OPERATING PRINCIPLES OF A VANADIUM REDOX FLOW BATTERY

The operating principle of RFB is partly similar to the operation of a conventional battery, but it has as a major distinction, the fact that the energy storage unit (the active materials) is physically separated from the energy production unit (the cell stack). So, in a RFB the active materials are not permanently sealed inside the cell (like in a conventional battery), but are stored separately in tanks and pumped into the cell according to the energy demand. This process is represented in Figure 46, which represents the two tanks, one for positive electrolyte (cathode) and the other for negative electrolyte (anode), the cell and the pumps. When the liquid electrolytes flow through the cell an electrochemical reaction (oxidation-reduction or redox) occurs, with movement of electrons along the electric circuit, as there is an exchange of ions through the membrane to maintain charge neutrality between the different ionic solutions. Therefore, the battery power (which depends on the cells) and the battery capacity (which depends on the the amount of liquid electrolyte stored) are virtually independent when designing a VRFB.

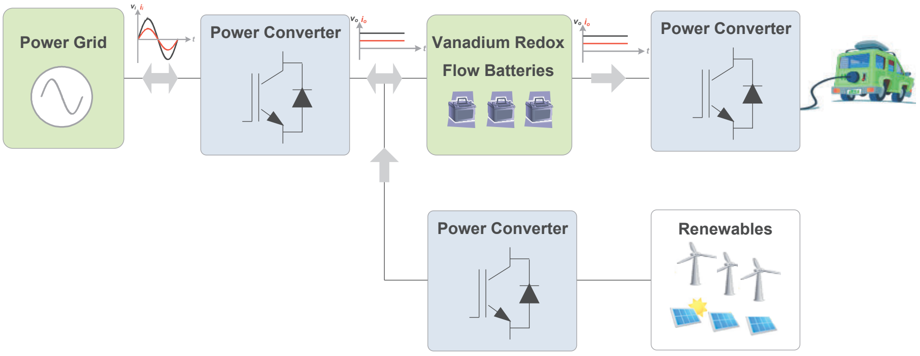


Figure 45: Proposed system architecture.

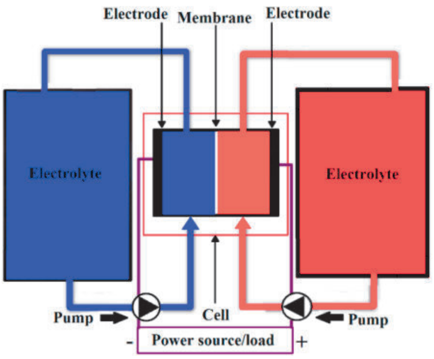


Figure 46: Operating principle of a Redox Flow Battery (RFB).

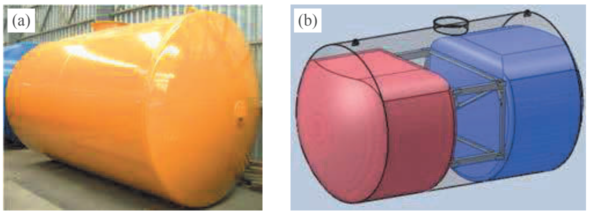


Figure 47: (a) Typical fuel tank used in gas stations; (b) Scheme of rubber tanks for VRFBs.

Figure 47 (a) shows a typical steel fuel tank used in gas stations. The present work has considered this tank for the storage of the liquid electrolytes. The shape and material of the tanks raises some concerns. As they are typically made of steel, the liquid electrolytes cannot be in direct contact with them due to their corrosive nature. To avoid that contact two smaller flexible tanks made from an acid resistant rubber may be installed inside the steel tanks, each one containing a different liquid electrolyte. Rubber tanks with a shape which reasonably conforms to the interior of the steel tanks should be made, as illustrated in Figure 47 (b), including a support structure to separate both tanks and leaving free space below the manhole to allow installation and the entry of service staff.

ECONOMIC ANALYSIS

For the economic analysis it is necessary to roughly estimate the total cost of the proposed system, even if there is a substantial uncertainty concerning its real cost. Nevertheless, estimations based on information obtained from the manufacturers have been done. Firstly, it is necessary to calculate the overall system efficiency using this VRFB connected to two ChadeMo chargers each one with an assumed efficiency η_{ch}, one VRFB AC-DC charger with an assumed efficiency $\eta_{AC\text{-}DC}$, and the VRFB with a total efficiency of η_{VRFB}. So, the overall system efficiency (η_{system}) can be calculated by the following expression:

$$\eta_{\text{system}} = \eta_{\text{AC-DC}}\ \eta_{\text{ch}}\ \eta_{\text{VRFB}} \tag{1}$$

So, to make the economic evaluation of the project the net present value (*NPV*) and the payback time (*PT*) criteria will be used. As a general rule, the project will be economically viable when the *NPV* has a positive value. A 20 year life cycle is considered for the project, with 26 cars being charged per day, during 365 days for year. The electrical energy will be purchased at a price (*p*) of 0.08 €/kWh (low demand period price) and sold at a price (*s*) of 0.40 €/kWh. The inflation rate (*i*) is considered to be 3%, the tax over gains (*TOG*) 25%, and the minimum acceptable rate of return (*MARR*) 5%. The loss of value of the equipment translated into the amortizations (*A*) is also taken into account. It is considered that at the end of the 20 years the value of the equipment is null, so a devaluation of the equipment around 5% a year may be considered. The amortization is taken into account in the calculation of the Cash-Flows (*CF*) because it brings advantages in taxes and it is assumed that there is no requirement for external funding. Table 1 shows the input data required for the calculation of the *CF* of this project and Table 2 shows the calculation of the *CF* for 5 years, during the 20 years considered, where: *EBITDA* means the earnings before interest, taxes, depreciation and amortization; *Amort*. means amortization; *RBT* means results before taxes; and *LR* means liquid result.

Table 1: Input data required for the calculation of the cash-flows of the project.

Energy charged per car	14.8 kWh
Number of cars per day	26
Days per year	365
s (Electrical energy selling price)	0.4€
p (Electrical energy purchasing price)	0.08€
Amortization rate (*A*)	5%
Taxes Over Gain (*TOG*)	25%
i (Inflation rate)	3%
Minimum Acceptable Rate of Return (*MARR*)	5%
η_{VRFB}	80%
η_{system}	72.2 %

Table 2 - Cash flows of the project for the 20 years considered.

Year	**Investment (k€)**	**Sales (k€)**	**Cost (k€)**	***EBITDA* (k€)**	***Amort.* (k€)**	***RBT* (k€)**	**Taxes (k€)**	***LR* (k€)**	***CF* (k€)**
0	324.0								-324.0
5		55.1	15.3	39.8	16.2	23.6	5.9	17.7	33.9
10		63.9	17.7	46.2	16.2	30.0	7.5	22.5	38.7
15		74.1	20.5	53.5	16.2	37.3	9.3	28.0	44.2
20		85.9	23.8	62.1	16.2	45.9	11.5	34.4	50.6

From the *CF* showed in Table 2 it is possible confirm that the project is economically viable for the conditions showed in Table 1. So, the payback time can be calculated by successively adding the *CF* of each year (cumulative) until it becomes a positive value. The recovery time will correspond to the moment at which the cumulative crosses zero. It is important to refer that the price of this system is still high because it is not yet a mature technology and there are still just a few manufacturers worldwide. It is expected that for the next few years the price of this technology will decrease.

RESULTS AND DISCUSSION

Figure 48 (a) and Figure 48 (b) shows the variation of the flow rate for each liquid electrolyte during discharge and charge cycles, respectively. These calculations are not detailed for lack of space, but they have been made integrating the performance information gathered for each component of the system, including the estimation of pumping power requirements. It can be seen that there is an exponential increase of the flow rate along time during charge and discharge due to the need to increase flow rate when the SOC of the VRFB is low. It can be seen that this system will have very high flow rates during the ending of the discharge and so a very high pumping power will be needed, resulting in a very low efficiency for these conditions. It will then be useful to avoid excessive charge depleting, using the VRFB with SOCs above, say, 10%. Figure 49 shows the variation of the *NPV* and the *PT* as a function of the VRFB efficiency (with pumping losses), where the efficiency of 80% is the value announced by a manufacturer. In this situation the maximum and minimum efficiencies calculated for one or two cars in simultaneous charging process are 92% and 93%, respectively. As aforementioned, it is expected that the price of this kind of system will tend to decrease along time. Therefore, it is useful to analyse the variation of the NPV with the percentage of the system cost, as represented in Figure 50. As it can be seen, it would be possible to triple the *NPV* with a 30% reduction in the system cost.

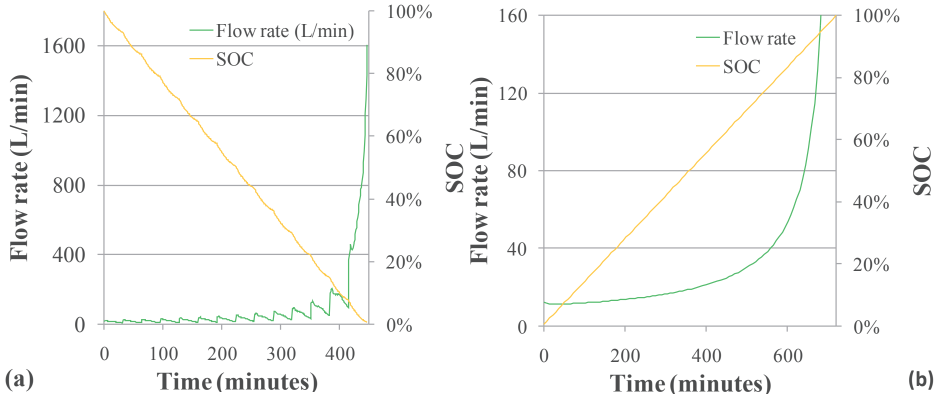
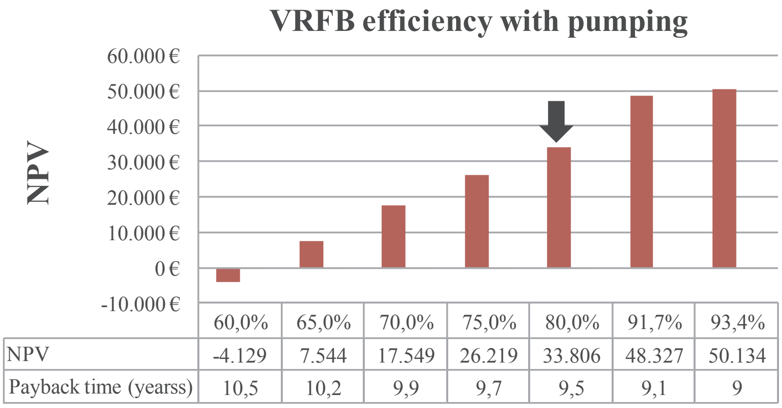
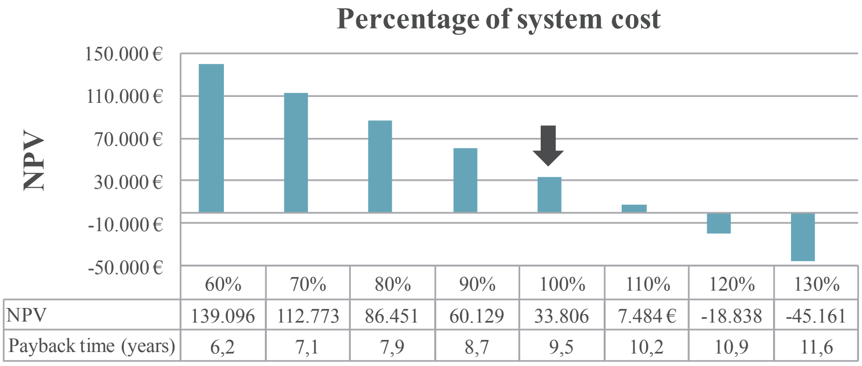


Figure 48:Variation of flow rate during discharging (a) and charging (b) cycles.



	60,0%	65,0%	70,0%	75,0%	80,0%	91,7%	93,4%
NPV	-4.129	7.544	17.549	26.219	33.806	48.327	50.134
Payback time (yearss)	10,5	10,2	9,9	9,7	9,5	9,1	9

Figure 49: *NPV* and *PT* as a function of VRFB efficiency with pumping losses (with 91.7% and 93.4% corresponding to the efficiencies obtained by the present analysis with 2 and 1 cars in simultaneous charging, respectively).



	60%	70%	80%	90%	100%	110%	120%	130%
NPV	139.096	112.773	86.451	60.129	33.806	7.484 €	-18.838	-45.161
Payback time (years)	6,2	7,1	7,9	8,7	9,5	10,2	10,9	11,6

Figure 50: Variation of the *NPV* and the *PT* as a function of the percentage variation of system cost.

CONCLUSIONS

The proliferation of Electric Vehicles (EVs) will bring a higher demand for battery fast charging locations. Nevertheless, the high power demanded for fast charge stations is a disadvantage. The use of energy storage systems and in particular Vanadium Redox Flow Batteries (VRFBs) seems to be a good solution for reducing the installed power with a peak shaving strategy. Existing or recently deactivated gas stations are privileged locations for this purpose and many of them have available space and unused fuel storage tanks. Furthermore, flow batteries also provide the possibility of taking advantage of the availability of deactivated fuel storage tanks. The present work outlines a preliminary project of a Vanadium Redox Flow Battery to be used in gas stations for supplying electric energy for two ChadeMo chargers (50 kW each) working simultaneously. The VRFB is charged for 12 h during off-peak power demand (at night). The same cell stack is used for charging and discharging the liquid electrolytes. This preliminary project was conceived using data from commercially available system components. A method for storing the liquid electrolytes of VRFBs in rubber tanks (installed inside the fuel storage tanks normally used in gas stations) has been proposed. This will prevent the corrosion of the fuel tanks, which are normally made of steel, while allowing the storage of both liquid electrolytes (anode and cathode) in the same fuel tank without mixing. Furthermore, the flexibility of the rubber enables the use of large rubber tanks that can still be inserted through the manhole entry of these fuel tanks. An efficiency of near 92% (including pumping losses) has been predicted when using the VRFB system to fast charge 26 EVs per day. Although specific input parameters have been used, the methodology used allows the assessment of diverse configurations. A cost analysis of the preliminary project was also performed in terms of Net Present Value (NPV) for 20 years (the life time considered for the system) and the Payback Time. In the midterm, if the energy density of flow batteries substantially increases, the philosophy proposed in the present work will be easily adapted in order to charge the EVs by substituting their discharged liquid electrolytes by charged electrolytes, instead of indirectly charging the vehicle electrically via a fast charging station. This would eliminate one of the major current disadvantages of EVs which is their long charging times. The time required to charge an EV would then be of the same order of magnitude of the time required to supply a conventional fuel vehicle. Additionally, local energy storage may help to solve the problems associated with the management of the electrical power grid, and also allow easier incorporation of intermittent renewable energy sources (like wind power and solar photovoltaic), with the benefits of reducing fossil fuel dependency and associated emissions.

REFERENCES

Brito F.P.; et al.; 2013. “Influence of Heat Pipe Operating Temperature on Exhaust Heat Thermoelectric Generation,” SAE International Journal of Passenger Cars - Mechanical Systems 2013-01-0559.

Boulanger, A. G.; et al.; 2011. “Vehicle Electrification: Status and Issues,” Proceedings of the IEEE, pp.1116-1138.

Cunha A.; Brito F.P.; Martins, J; Rodrigues,; N. 2014. “Vanadium Redox Flow Batteries: A Technology Review” International Journal of Energy Research, Elsevier International, 2014 (Article first published online: 29 OCT 2014) DOI: 10.1002/er.3260

Cadoux F. ; Gross, G.; 2013. “Integration of Vehicles with Rechargeable Batteries into Distribution Networks,” in Smart Grids, John Wiley & Sons, Inc. pp.243-261.

Camus C.; Farias, T.; 2012. “Electric vehicles as a mean to reduce, energy, emissions and electricity costs,” EEM European Energy Market.

Faria R.; et al.; 2012. “A sustainability assessment of electric vehicles as a personal mobility system,” Energy Conversion and Management, pp.19-30.

Hagedorn, N. H.; Thaller, L. H.; 1982. “Design Flexibility of Redox Flow Systems,” National Aeronautics and Space Administration Lewis Research Center, DOE/NASA/12726-16, NASA TM-82854.

Hawkins, T. R.; et al.; 2013. “Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles,” Journal of Industrial Ecology, pp.53-64.

International Energy Outlook 2009, May 2009, Energy Information Administration Office of Integrated Analysis and Forecasting U.S. Department of Energy Washington DC.

Iwahori, T.; et al.; 1999. “Development of lithium secondary batteries for electric vehicles and home-use load leveling systems,” Journal of Power Sources, pp.872-876.

Kear, G.; Shah, A. A.; Walsh, F. C.; 2012. “Development of the all-vanadium redox flow battery for energy storage: a review of technological, financial and policy aspects,” International Journal of Energy Research, pp.1105-1120.

Kerestes, R. J.; Reed, G. F.; Sparacino, A. R.; 2012. “Economic analysis of grid level energy storage for the application of load leveling,” IEEE Power and Energy Society General Meeting.

Kerestes, R. J.; 2011. “Economic Analysis of Grid Level Energy Storage for the Application of Load Leveling”, University Of Pittsburgh.

Martins, J.; et al.; 2013. “Real-Life Comparison Between Diesel and Electric Car Energy Consumption,” in “Grid Electrified Vehicles: Performance, Design, and Environmental Impacts” Nova Science Publishers: New York.

Nakayama, T., et al.; 2004. “Development of a long life 35 Ah capacity VRLA battery for load-leveling applications,” Journal of Power Sources, pp.135-140.

Ribau, J.; et al.; 2012. “Analysis of four-stroke, Wankel, and microturbine based range extenders for electric vehicles,” Energy Conversion and Management, pp.120-133.

Ribeiro, B.; Brito, F.P.; Martins, J.; 2010. “A Survey on Electric/Hybrid Vehicles,” in Electric and Hybrid-Electric Vehicles - Overviews and Viewpoints, 2010: Edited by Ronald K. Jürgen, SAE International, Warrendale, USA.

Ribeiro, B.; Martins, J.; 2007. “Direct Comparison of an Engine Working under Otto, Miller and Diesel Cycles: Thermodynamic Analysis and Real Engine Performance,” SAE SP.

Role of Chademo. [11/10/2013]; Available from: http://www.chademo.com/wp/role/challenge/.

Saber, A. Y.; Venayagamoorthy, G. K.; 2011. “Plug-in Vehicles and Renewable Energy Sources for Cost and Emission Reductions,” IEEE Trans. Ind. Electron., vol.58, no.4, pp.1229-1238.

Shibata A.; Sato, K.; 1999. “Development of vanadium redox flow battery for electricity storage,” Power Engineering Journal, pp.130-135.

Silva, C.; Ross, M.; Farias, T.; 2009. “Analysis and simulation of “low-cost” strategies to reduce fuel consumption and emissions in conventional gasoline light-duty vehicles,” Energy Conversion and Management, pp.215-222.

Skyllas-Kazacos, M.; Rychick, M.; Robins, R.; 1988. “All-vanadium redox battery,” US Pat., 4 786 567.

Wang, W.; et al.; 2013. “Recent Progress in Redox Flow Battery Research and Development,” Advanced Functional Materials, pp.970-986.

Zdenek, C.; Pavel, M.; 2011. “Electric, hybrid electric and combustion engine driven cars and their impact on environment,” EPE Conference on Power Electronics and Applications.