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Assessment of the use of vanadium redox flow batteries for energy storage and fast charging of electric vehicles in gas stations

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ABSTRACT

A network of conveniently located fast charging stations is one of the possibilities to facilitate the adoption of Electric Vehicles (EVs). This paper assesses the use of fast charging stations for EVs in conjunction with VRFBs (Vanadium Redox Flow Batteries). These batteries are charged during low electricity demand periods and then supply electricity for the fast charging of EVs during day, thus implementing a power peak shaving process. Flow batteries have unique characteristics which make them especially attractive when compared with conventional batteries, such as their ability to decouple rated power from rated capacity, as well as their greater design flexibility and nearly unlimited life. Moreover, their liquid nature allows their installation inside deactivated underground gas tanks located at gas stations, enabling a smooth transition of gas stations' business model towards the emerging electric mobility paradigm. A project of a VRFB system to fast charge EVs taking advantage of existing gas stations infrastructures is presented. An energy and cost analysis of this concept is performed, which shows that, for the conditions tested, the project is technologically and economically viable, although being highly sensitive to the investment costs and to the electricity market conditions.

1. Introduction

The disruptive increase of urban traffic along the last decades is posing serious sustainability concerns, mainly those related to urban air quality and GHG (greenhouse gases) emissions, as well as the excessive dependency of developed economies on fossil fuels. It is expected that in 2030 the transportation sector will be responsible for 55% of total oil consumption [1]. 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 [2]. In this context, the current policies promoting emissions reduction and the improvement of the energy efficiency of ICE (Internal Combustion Engines) are contributing to palliate these issues [3]. Various strategies have been explored along time to address these issues, such as engine downsizing achieved with turbo-charging [4], the strategy of over expansion explored by the authors [5,6] 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 [7,8].

Nevertheless, the increase of the overall efficiency of conventional powertrains does not seem sufficient by itself to achieve the efficiency and emissions goals set by national and international agreements, nor does it improve the desired diversity of energy sources. Nowadays, the main alternatives to the traditional ICE are the PHEVs (Plug-In Hybrid Electric Vehicles) and the full EV (Electric Vehicles) [9]. These alternatives allow the reduction of the global fossil fuels consumption that is allocated to the traditional transports systems and are a key technology to the future smart grids [10]. Some of these alternatives are now available in the market with substantial success [11], such as Toyota Prius (PHEV) or the Nissan Leaf (EV). These vehicles are globally more efficient than ICE vehicles, mainly under urban traffic since they have no idling

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Nomenclature

Greek letters

ε	roughness (mm)
η_{Ch}	CHAdeMo charger efficiency (−)
η_{AC-DC}	VRFB charger with an efficiency (AC/DC) (−)
η	efficiency of the VRFB without pumping losses (−)
$\eta_{total\ VRFB}$	VRFB efficiency with pumping losses (−)
η_{system}	overall system efficiency (−)
μ	dynamic viscosity ($N.s/m^2$)
v	cinematic viscosity of the fluid (m^2/s)
ρ	specific mass of the liquid electrolyte (kg/m^3)

Acronyms

DoD	depth of discharge
EV	electric vehicle
G1	all vanadium redox flow batteries
G2	vanadium bromide redox flow battery
GHG	greenhouse gases
ICE	internal combustion engine
PHEV	plug-in hybrid electric vehicles
PSB	polysulfide/bromide technology
RFB	redox flow battery
SoC	state of charge
VRFB	Vanadium Redox Flow Batteries (G1 and G2 technologies)
ZBB	zinc/bromine technology
ZCB	cerium/zinc technology

Variables

A	amortizations (€)
A_{cs}	permeated cross section area of the electrodes (m^2)
A_r	amortization rate per year (−)
C_{in}	concentration of vanadium in the solution before the cell (mol/L)
C	costs associated (€)
CF	cash-flows (€)
C_{out}	concentration of vanadium in the solution after the cell (mol/L)
D	internal diameter of the pipe (m)
DpY	operating days per year (−)
E	energy density of the liquid electrolyte (Wh/L)
E	equilibrium potential \(V)
$EBITDA$	EARNINGS before interest, taxes, depreciation and amortization (€)
Er	REAL discharged energy (W)
E_a	available stored energy (W)
E_{sold}	energy supplied/sold to charge a car (W)
F	Faraday constant (9.6485×10^4 C mol^{-1})
f	coefficient of friction (−)
g	gravitational acceleration (m/s^2)
H	head loss (m)
I	current (A)
Inv	investment (€)
i	inflation rate (−)
i'	real interest rate (−)
k	coefficient of head loss (−)
L	length of the section (m)
Le	equivalent piping length (m)
l	permeated specimen length of the electrode (m)
le	thickness (m)
$MARR$	minimum acceptable rate of return (−)
N	number of cells (−)
Nd	number of cars per day (−)
NPV	net present value (€)
OCV_{disch}	open circuit voltage of the stack during discharge (V)
OCV_{chg}	open circuit voltage during charge (V)
P_{pump}	pumping power (kW)
Δp	total pressure loss (Pa)
Δp_{stack}	pressure loss in the Stack (Pa)
Δp_{pipe}	PRESSURE loss in the pipes (Pa)
P	permeability of the electrodes (m^2)
P_{Leaf}	power consumption of the Nissan Leaf during charge (kW)
P_r	real discharge power (kW)
P_{out}	power output (kW)
P_{in}	input power (kW)
Pt	payback time ($years$)
p	electrical energy purchasing price (€)
R	electrical resistance (Ω)
r	universal constant of ideal gases (8,3145 J mol^{-1} k^{-1})
Re	Reynolds number (−)
re	resistivity (Ωm)
RBT	results before taxes (€)
LR	liquid result (€)
S	gain from sales (€)
SoC_{min}	minimum state of charge of VRFB during cycle (−)
s	electrical energy selling price (€)
Tax	taxes (€)
T	temperature (K)
TOG	taxes over gain (−)
t	time (s)
t_{chg}	defined time to charge VRFB (s)
t_{disch}	defined time to discharge VRFB (s)
V	volume of liquid stored (m^3)
V	velocity of the fluid (m/s)
V_{disch}	voltage output of stack during discharge (V)
V_{chg}	intput voltage of the stack during charge (V)

Subscripts

chg	Charge
disch	Discharge
in	Input
n	Year
out	Output

losses, they have good low end torque without the need for inefficient clutching, and they can recover some of the kinetic energy lost during the braking [3,11]. In Ref. [12] a comparative environmental life cycle comparison between conventional and electric vehicles has been presented. As an example, using EVs, the global GHG emissions can decrease from 10% to 24% when compared with conventional diesel or gasoline vehicles. In Ref. [13] a study 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 power grid charging [14]. The main

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