Energy 106 (2016) 701–711

Contents lists available at ScienceDirect

Energy

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

Sustainable integration of intermittent renewable energy and electrified light-duty transportation through repurposing batteries of plug-in electric vehicles

Shahab Shokrzadeh*, Eric Bibeau

Mechanical Engineering Department, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form
2 February 2016
Accepted 5 March 2016
Available online 13 April 2016

Keywords:
Sustainable transportation
Plug-in electric vehicles
Battery repurposing
Intermittent wind energy
Renewable energy ratio

ABSTRACT

This study presents a framework for the integration of electrified light-duty vehicles and intermittent renewable energy towards a sustainable transportation system. Batteries of plug-in electric vehicles, obtained at their automotive end of life, are repurposed as stationary storage systems to integrate with intermittent wind power. The objective is to investigate how electric mobility can effectively meet the challenges of sustainability when the ultimate goal is to displace fossil fuels with new generation of low-cost intermittent renewable energy. The developed model of the framework considers future market penetration scenarios of electric vehicles, calculates availability of batteries at their automotive end of life, and estimates the storage capacity required to generate base-load wind power in the region of study. A new cost model is proposed to calculate the cost of delivering base-load power from renewables when they rely on intermittent sources. To evaluate the performance of the proposed framework, the renewable energy ratio is used as a measure of sustainability. A sample case study is performed for Canada, and the results suggest a self-sufficiency of the integrated system to address concerns of the impact of vehicular charging energy with renewable energy.

1. Introduction

Global energy drivers—peak oil, energy security, climate change, growing demand, and emissions—have resulted in adopting strategic policies towards sustainability that can mitigate risks from a business-as-usual approach [1]. Electrification of transportation and incorporation of renewable energy sources are the key solutions to address the energy drivers [2]. However, the current trends of global energy consumption and environmental emissions are not sustainable [3], and substantial investments are needed to promote towards a sustainable energy system [4].

Transportation is one of the major contributing sectors to the global energy consumption. Moreover, the transport sector has significant environmental impacts as it mostly relies on ICEs (internal combustion engines) driven mainly by fossil fuels. In 2012, transportation accounted for 20% of the global primary energy consumption, and was responsible for 25% of the energy related GHG (greenhouse gas) emissions [5]. The IEA (International Energy Agency) has proposed a scenario in which the earth's average temperature increase should be limited to 2 degrees Celsius (2DS) by 2050. In this scenario, the transport sector accounts for 21% in CO_2 reductions in 2050 [6]. To achieve such targets and to develop a sustainable approach for LDVs (light duty vehicles), electrification of transportation is emerging as the promising solution [7]. Automakers have started mass production of new technologies like PHEVs (plug-in hybrid electric vehicles) and BEVs (battery electric vehicles), collectively known as PEVs (plug-in electric vehicles), which provide higher fuel efficiency and extended electric range [8]. However, high cost of traction batteries of PEVs and public perception of electric mobility are among the challenges that should be addressed [9].

The other strategic path towards clean alternatives with less environmental impacts is to incorporate more renewable energy in the energy mix. Expansion of intermittent sources like wind and solar energy is the crucial component to the growth of electricity generations from renewables [10]. The global installed capacity of wind power has approached 300 GW in 2013, *i.e.*, almost double the cumulative capacity in 2008 [11]. The global installed capacity of solar PV (photovoltaic) has also drastically increased reaching more

* Corresponding author. Tel.: +1 204 230 7251.
E-mail address: Shahab_Shokrzadeh@umanitoba.ca (S. Shokrzadeh).

http://dx.doi.org/10.1016/j.energy.2016.03.016
0360-5442/

than 95 GW in 2012 [12]. Higher penetration of intermittent wind and solar, however, has technical and economic implications, and can be limited by their stochastic nature. Moreover, according to the IEA's World Energy Outlook 2013, the share of fossil fuels in the global energy mix has remained constant at 82% for last 25 years. The report also predicts that with significant adoption of renewable energy this figure will only drop to around 75% in 2035.

These statistics highlight the necessity of effective sustainable initiatives which can impact the current trend of the global energy and related emissions status. The sensible approach is to simultaneously replace fossil fuels with ***R***enewable energy sources, increase energy ***E***fficiency, and reduce energy ***D***emand that collectively can be referred to as the ***RED*** approach [13]. Therefore, real sustainable approaches need to be formulated to impact global energy policy, and provide economically affordable and environmentally viable energy resources.

Battery repurposing is proposed as a sustainable energy framework for the integration of energy and transportation in compliance with the RED approach [14]. The aim of this article is to investigate how electric mobility can support greater share of renewable energy to mitigate fossil fuels in the transport sector through repurposing batteries of plug-in electric vehicles. To this end, the developed model calculates the number and capacity of batteries available at their automotive EOL (end of life), and estimates the size of storage required to generate base-load wind power in the region of study. The components of the framework model include market penetration forecast rates of PEVs, vehicular lifetime of batteries and consequent energy requirement while onboard, availability of batteries at their vehicular EOL, and the storage capacity required to produce base-load capacity of wind turbine in the region of study. To assess the sustainability performance of the proposed approach, RER (renewable energy ratio) is defined as the ratio of total renewable energy generated to the total primary energy used for a jurisdiction in a given year [15]. The RER can be used as a critical indicator of sustainability and a policy tool that can govern technology implementation. By performing a sample case study, the model shows that while electrification of transportation improves the energy efficiency in the transport sector and increases the RER by 0.91% for Canada in 2050, repurposing batteries of PEVs to support base-load wind power can further increase the RER by 1.65–4.11%, depending on the confidence level, thus resulting in a much more effective policy.

Following the introduction, Section 2 describes the components of the framework. In Section 3, the simulation model of the proposed concept is developed for Canada. The model selects an annual market penetration rate representing the new sales of electric vehicles in the region of study. Annual aggregate energy demand due to introduction of PEVs to the grid is then calculated to determine the energy impact of the growing market of electric cars. The storage capacity available from PEV batteries in their post-vehicular life is then determined. A storage sizing methodology is used to support wind turbine to deliver generation at a more steady level. In Section 4, the framework investigates how the improved quality wind energy addresses new PEVs charging load to increase the RER and address energy drivers simultaneously. Also, a new expression is proposed in Section 5 for the capital cost of renewable energy that includes the cost of storage when they are intermittent. The outcome of the study followed by the concluding remarks are finally discussed in Section 6.

2. Battery repurposing framework

Using PEVs for the integration of intermittent renewable energy in power systems has been addressed by several studies, for example, see Ref. [16] for the case of Brazil. Re-using of traction batteries of PEVs at the automotive EOL has also been a topic of research in the literature. Authors in Ref. [17] investigate the environmental feasibility of electric vehicle batteries reusing. Ref. [18] studies the energy efficiency of Li-ion battery packs for stationary applications. Climate and energy effects of second-life application of electric vehicle batteries in California is studied by Ref. [19]. However, these studies attempt to look at challenges and potentials in a broader scope. The main innovation of the study is focusing on one application and synthesizing a framework for the proposed integration of intermittent renewable energy and light-duty vehicles through repurposing of their batteries. Fig. 1 illustrates the concept with the specific application of supporting intermittent wind energy to meet the charging load of the electric cars.

2.1. Vehicular life

This period starts with the installation of manufactured batteries in electric vehicles. The vehicular lifetime of these batteries is dependent on various parameters such as their chemistry, charging approach, driving patterns, and weather conditions of where they serve [20]. The forecast of market penetration of PEVs, the annual sales of these vehicles to the total annual sales of LDVs, determines how many batteries will be available in the market each year. Also, the annual charging load of PEVs should be calculated to determine the yearly energy demand required for charging these batteries. These two subjects are discussed in the following sections.

2.1.1. PEV market penetration forecasts

The future of electric transportation as a promising solution in addressing energy and climate issues has been the subject of many research studies [21]. Consumers, automakers, governments and electric utilities are among the stakeholders in the market of PEVs. Several studies have attempted to forecast market penetration rates for electric vehicles under different scenarios and assumptions, see Ref. [22] for a comprehensive review. Various models have been developed to forecast the penetration rates of different technologies of PEVs. The main simulation techniques for the penetration forecast models include diffusion and time-domain models, consumer choice models and agent-based models [23]. Many governments in the world have implemented decisive policies and

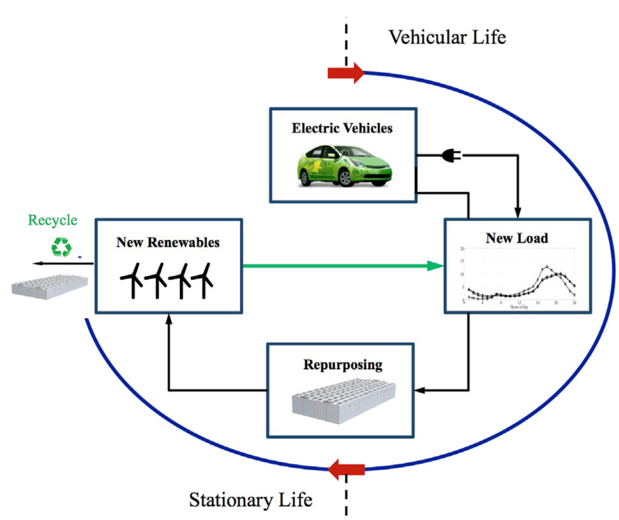

Fig. 1. Illustration of the battery repurposing concept where the battery's life cycle begins with the installation on vehicle. The secondary life begins when the used battery is repurposed for new stationary applications before being recycled.