Applied Energy 101 (2013) 93–102

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Impacts of Electric Vehicle charging under electricity market operations

Aoife Foley [a,b,c,*], Barry Tyther [a], Patrick Calnan [b,d], Brian Ó Gallachóir [a,b]

[a] Dept. of Civil & Environmental Engineering, School of Engineering, University College Cork, College Rd., Cork, Ireland
[b] Environmental Research Institute, University College Cork, Lee Rd., Cork, Ireland
[c] School of Mechanical and Aerospace Engineering, Ashby Building, Queen's University Belfast, Stranmillis Rd., BT9 5AH, United Kingdom
[d] Bord Gáis Energy, 1st Floor, City Quarter, Lapps Quay, Cork, Ireland

HIGHLIGHTS

- In 2008, the Irish government set a target that 10% of all vehicles be powered by electricity by 2020.
- The impact of EV charging in the single wholesale electricity market in Ireland is analysed.
- EV charging under peak and off-peak charging scenarios is examined.
- Results show that off-peak charging is more beneficial than peak charging.
- Only 1.55% of the Non-ETS and 1.45% of the RES-T targets are achieved.

ARTICLE INFO

Article history:
Received 31 December 2011
Received in revised form 17 June 2012
Accepted 19 June 2012
Available online 20 July 2012

Keywords:
Electric Vehicles
Transport system
Power system
Modelling
Energy
Greenhouse gas emissions

ABSTRACT

The Irish government set a target in 2008 that 10% of all vehicles in the transport fleet be powered by electricity by 2020. Similar electric vehicle targets have been introduced in other countries. In this study the effects of 213,561 electric vehicles on the operation of the single wholesale electricity market for the Republic of Ireland and Northern Ireland is investigated. A model of Ireland's electricity market in 2020 is developed using the power systems market model called PLEXOS for power systems. The amount of CO_2 emissions associated with charging the EVs and the impacts with respect to Ireland's target for renewable energy in transport is also quantified. A single generation portfolio and two different charging scenarios, arising from a peak and off-peak charging profile are considered. Results from the study confirm that off-peak charging is more beneficial than peak charging and that charging EVs will contribute 1.45% energy supply to the 10% renewable energy in transport target. The net CO_2 reductions are 147 and 210 kt CO_2 respectively.

1. Introduction

Transport represents one of the fastest growing sectors of the economy in terms of energy use and Greenhouse Gas (GHG) emissions worldwide [1]. This is particularly relevant with concerns over global warming, security of energy supply and environmental pollution. Even though current car sales are sluggish in Europe and North America, brisk growth is predicted in China mostly, with more modest increases in India due to economic development [2]. It is well established that car ownership and economic development are linked to increases in transport related energy demand and GHG emissions [3]. The use of oil as a fuel for transport is almost universal. For example in the Republic of Ireland, it accounted for 98.4% of all transport fuel in 2009 and led to the transport sector accounting for nearly one third of Ireland's carbon dioxide (CO_2) emissions and 41.4% overall energy demand [4]. The transport sector in the Republic of Ireland has seen a reduction in CO_2 emissions and energy demand since 2007 associated with the economic downturn. CO_2 emissions and the transport energy fell by 10.1% and 9.6% respectively in 2009 [4]. Transport energy demand, however is expected to grow annually at 3.2% until 2020 despite this reduction [5], but the Irish government must reduce GHG emissions, fossil fuel energy demand and improve energy efficiency to comply with national policies and European Union (EU)

Abbreviations: BEV, battery electric vehicle; BETTA, British electricity trading and transmission arrangement; CER, commission for energy regulation; CO_2, carbon dioxide; EU, European union; EV, electric vehicle; EWIC, east west interconnector; GNP, gross national product; GHG, greenhouse gas; Non-ETS, =non-emission trading scheme; PSO, public service obligations; PHEV, plug-in hybrid electric vehicle; RES-T, renewable energy in transport; SEM, single electricity market; SEMO, single electricity market operator; SNSP, system non-synchronous penetration; SMP, system marginal price; TSO, transmission system operator; UR, utility regulator; V2G, vehicle to grid.

* Corresponding author. Address: Queen's University Belfast, School of Mechanical & Aerospace Engineering, Ashby Building, Stranmillis Road, Belfast BT9 5AH, Ireland. Tel. + 44 028 9097 4492; fax + 44 028 9097 4148.
E-mail address: a.foley@qub.ac.uk (A. Foley).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.06.052

directives. The overarching EU target is to reduce GHG emissions to 20% below 1990 levels, to improve energy efficiency by 20% and to ensure 20% of the EU's gross final energy consumption comes from renewable energy sources, all by 2020, the so-called '20–20–20 by 2020 target' [6]. Final energy includes heating and cooling, electricity generation and transport. For sectors (including transport) outside of emissions trading (Non-ETS sectors) the EU target is to achieve a 10% reduction by 2020 relative to 2005. Under EU Decision 2009/406/EC on effort sharing with regard to the EU Non-ETS emissions reduction, Ireland's target is to achieve a 20% reduction by 2020 relative to 2005 [7].

In response Ireland has set National targets for renewable energy to deliver the 16% renewable energy target, namely to achieve 40% electricity, 12% heat and 10% transport from renewable energy sources by 2020 [8,9]. In Ireland in late 2008 the Irish Government set a target that 10% of all vehicles in its transport fleet be powered by electricity by 2020 [10]. Ironically, Foley et al. [10] summarise global Electric Vehicle (EV) targets by country and provides an EV technology roadmap from the automotive industry and concludes that by 2020 it is unlikely that these national EV targets will be achieved simple due to a lack of EVs [11]. Ignoring the fact that it is unlikely EVs will be manufactured in sufficient numbers globally to meet international policy targets. The Irish government, like many other countries, still expects that EVs will make a sizeable contribution to meeting their targets for energy efficiency, renewable energy and Non-ETS GHG emissions reduction [12]. This paper investigates this expectation, because the electrification of 10% of the transport fleet in the Republic of Ireland will have impacts on the power system and electricity market in Ireland. The single wholesale electricity market (SEM) in Ireland is managed by the Single Electricity Market Operator (SEMO) on behalf of EirGrid plc. EirGrid is the licensed independent electricity Transmission System Operator (TSO) and market operator in the Republic of Ireland. EirGrid is also owner of the System Operator for Northern Ireland (SONI Ltd.), which is the licensed TSO and market operator in Northern Ireland. In order to investigate the impacts of EVs in Ireland we model the SEM with and without EVs focusing on changes in costs, power plant dispatch and the contribution to Ireland's renewable energy and Non-ETS emissions reduction targets. We also develop two separate charging profiles, (i) peak and (ii) off-peak, to illustrate the effects of charging profile on the results. Section 2 reviews previous research in this field. Section 3 describes the methodology used and introduces the model used in this analysis. Section 4 presents the results from the research and Section 5 concludes the paper with a discussion of the results.

2. Literature review

2.1. Interactions between EVs and power systems

The main impact associated with EV charging is the additional electrical load and the related changes or movement in transport-related energy and GHG emissions from the exhaust pipe or tailgate to the power system. For example, Doucette and McCulloch [13] determined the CO_2 emissions for a Battery Electric Vehicle (BEV) and Plug-in Hybrid Electric Vehicle (PHEV) and compared their results to the published CO_2 emissions values for a conventional 2010 Ford Focus. They concluded that countries with CO_2 intensive generation portfolios would not benefit fully from transport electrification. Kiviluoma and Meibom [14] investigated 'dumb' and 'smart' EV charging in a future power system in Finland using a model called WILMAR,[1] which optimises unit commitment and calculated that smart charging was more beneficial than uncontrolled. Juul and Meibom [15] used Balmorel with a transport model extension to study the interactions of the power system and the transport system. They found that the introduction of V2G technology increased power system flexibility and facilitated large increases in wind power. Juul and Meibom [16] also examined the optimal configuration and operation of the integrated power and road transport system in Northern Europe and established that PHEVs reduce power system investment and operational costs by €6.2 billion or 3% of total system costs and that the introduction vehicle to grid (V2G) only resulted in small additional systems cost savings of €18 million.

In Kristoffersen et al. [17] the findings of a linear regression model, which minimised charging and discharging costs subject to constraints in the Nordpool electricity market was presented. In their model an aggregator managed the electricity market participation of the EV fleet and optimised EV charging and discharging, given fleet driving patterns and the variations in the spot price of electricity. They showed that EVs provide flexibility within the day but only limited flexibility from day to day when driving patterns are fixed. Another study by Mathiesen et al. [18] examined a complete renewable energy system, which included transport, in 2015, 2030 and 2050. This analysis revealed that GHG mitigation strategies although considered costly have many benefits for example socio-economic (e.g. employment and increased exports), energy savings, renewable energy and efficient energy technology deployment such as EVs. Peterson et al. [19] examined the economics of using the batteries in EVs to store off-peak electricity to meet peak demand in three electricity markets and determined that the potential financial gain from energy arbitrage to EV owners in the absence of incentives was insufficient to be attractive to car owners. This study is unlike others, which have investigated the impact of EVs on the power system, because the model developed uses an actual real life day-to-day working wholesale electricity market software tool, called PLEXOS for power systems (PLEXOS) [20], which schedules, dispatches and trades wholesale electricity in the SEM. PLEXOS is a power systems modelling tool used for electricity market modelling and planning worldwide. PLEXOS is a commercially available proprietary software but is provided by Energy Exemplar free for non-commercial research to academic institutions. PLEXOS has been used by SEMO and both energy regulators in Ireland as the market model since 2007. Therefore PLEXOS is a well-proven, robust model and suitable to examine the impacts of EVs on the SEM.

2.2. Other PLEXOS studies

In Foley et al. [21] PLEXOS is compared to other similar power systems software. A number of research studies have been undertaken using PLEXOS. Denny [22] investigated the economics of tidal energy in the SEM and calculated that for tidal generation to produce positive net benefit capital costs would need to be less than €510,000/MW. Deane et al. [23] modelled the economic impacts of 500 MW of installed wave power in the SEM, where the wave energy generated displaces and equivalent amount wind energy (equivalent to 555 MW wind power). The analysis shows that in general the inclusion of wave energy has a negligible effect on wholesale electricity prices, reduces total system cost in Ireland and can increase CO_2 emissions on the island of Ireland under certain carbon price assumptions. Another study by Tuohy et al. [24] analysed peat power production in Ireland. It was found that carbon pricing affected the merit order[2] of generators and that the considerably high cycling cost of baseload units negated the

[1] WILMAR = Wind Integration in the Liberalised MArkets was developed by Risø National Laboratory, Denmark with a number of other partners as part of a European fifth framework project.

[2] Merit-order is the order in which power plants are instructed to dispatch electricity to meet the load demand.