QUANTIFYING DISPLACED CARBON DIOXIDE EMISSIONS FROM ELECTRIC VEHICLES IN IRELAND

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ABSTRACT

Under EU Directive 2009/28/EC on Renewable Energy each Member State is mandated to ensure that 10% of transport energy (excluding aviation and marine transport) comes from renewable sources by 2020. The Irish Government intends to achieve this target with a number of policies including an increase in the use of biofuels in transport by 3% by 2010 and ensuring that 10% of all vehicles in the transport fleet are powered by electricity by 2020. Electric vehicles (EVs) do not emit exhaust fumes in the same manner as traditional internal combustion engine (ICE) vehicles. The optimal benefits of EVs can only be truly achieved if EVs are deployed effectively, so that exhaust pipe gaseous emissions are not fully displaced to the electricity sector. This paper examines the potential contributions that Plug in Hybrid Electric Vehicles can make in reducing carbon dioxide. The paper presents the results of the generation expansion model for Northern Ireland and the Republic of Ireland built using the dynamic programming based long term generation expansion planning tool called the Wien Automatic System Planning IV tool. The model optimizes power dispatch using hourly electricity demand curves for each year up to 2020, while incorporating generator characteristics and certain operational requirements such as energy not served and loss of load probability while satisfying constraints on environmental emissions, fuel availability and generator operational and maintenance costs. In order to simulate the effect of PHEV, two distinct charging scenarios are applied based on a peak tariff and an off peak tariff. The importance and influence of the charging regime on the amount of energy used and gaseous emissions displaced is determined and briefly discussed.

Keywords: electric vehicles, transport system, power system, modelling, smarter travel, gaseous emissions

1 INTRODUCTION

Internationally the drive is on to deploy electric vehicles (EV), especially as the new mode of private vehicular transport in urban areas. As society is concentrated at urban and suburban centers with average weekly travel distances of approximately 50 miles or 80 kilometers this is an opportunity to apply a technology with certain limitations and constraints [1]. There are a number of economic and environmental benefits to the introduction of EV including reduced oil consumption and dependency, new research and development (R&D) and associated job opportunities, a reduction in greenhouse gas (GHG) emissions, a reduction in localized noise levels and a reduction in localized air pollution from other pollutants such as particulate matter (PM_{10}). These pollutants are linked to global warming, localized air pollution and deterioration in the quality of human health. The International Energy Agency (IEA) studied the effects of a strong policy of decarbonization in transport and estimated that the introduction of new vehicle technologies and fuels including some modal shifting in passenger and freight transport has the potential to generate a 40% reduction in CO_2 emissions [2]. Reference [3] provides a detailed review of over 40 studies carried out in the USA to examine the effects of EVs on well-to-wheel emissions. Other recent articles study potential GHG emissions reductions from EVs include References [4 - 10].

The United States of America (USA), Japan, China and a number of other countries have targeted EVs as part of their future policy plans to reduce GHG emissions. For example in the European Union (EU) each Member State is mandated to ensure that 10% of transport energy (excluding aviation and marine transport) comes from renewable sources by 2020 [10]. The Irish Government intends to achieve this target with a number of policies including an increase in the use of 3% biofuels in transport by 2010 and ensuring that 10% of all vehicles in the transport fleet are powered by electricity by 2020 [11].

In this paper the potential contribution that Plug in Hybrid Electric Vehicles (PHEV), can make in reducing CO_2, when driving in all electric mode is quantified. A model to study the generation expansion for Northern Ireland and the Republic of Ireland up to 2025 was built by the authors employing the dynamic programming (DP) based capacity generation expansion planning tool called Wien Automatic Planning System IV (WASP-IV), which was created by the International Atomic Energy Agency (IAEA) [12]. The importance and influence of the charging regimes on energy used and displaced gaseous emissions is determined and discussed.

2 METHODOLOGY

The methodology employed is traditional long term generation expansion planning (GEP) [13]. WASP-IV is commonly used for electricity planning in monopoly electricity markets [14]. In a monopoly market the primary objective of a utility is to meet electricity demand within a 'reasonable' loss of load probability (LOLP) or energy not served (ENS[1]) at a minimum cost, whereas in a liberalized electricity market the aim is to meet demand at a reduced ENS and wholesale electricity price [15]. However, all things being equal supply should always meet demand at the least cost.

The generation expansion model for Ireland and Northern Ireland is built using WASP-IV, which uses three main optimization techniques to find the most optimal portfolio mix for a power system within user defined constraints. Probabilistic estimation is applied to determine system production costs, ENS costs and reliability. Linear programming finds the optimal portfolio mix, which satisfies exogenous constraints on environmental emissions, fuel availability and electricity generation by some plants. The alternative expansion plans are optimized using dynamic programming (DP).

WASP-IV consists of seven modular programmes coded in Fortran with a windows based graphics user interface to input and manipulate data, as shown in Figure 1.

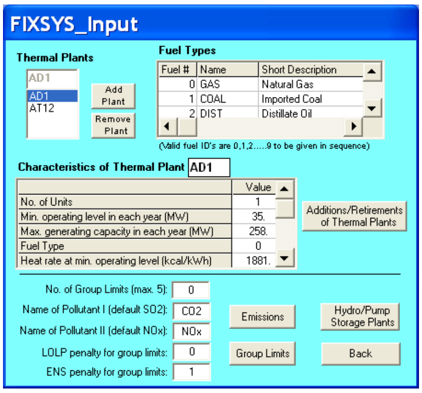

Figure 1. FIXSYS Input Screen in WASP-IV

The seven modular programmes are:

1. Load system (LOADSY), which predicts peak loads and load duration curves (LDC) for the system,
2. Fixed system (FIXSYSY), which describes the existing plant, all future firm additions and all firm retirements,
3. Variable system (VARSYS), which details the candidate plants available to expand the portfolio mix,
4. Configuration generator (CONGEN), produces all possible year to year alternative combinations of expansion configurations,
5. Merge and simulate (MERSIM), merges the system and calculates the production costs, ENS and system reliability denoted by LOLP for each configuration,
6. Dynamic programming optimization (DYNPRO), establishes the optimal expansion plan based on the input data,
7. Report writer of WASP-IVin a batched environment (REPROBAT), summarizes the input data, results of the study and cash flow requirements of the optimal expansion plan.

WASP-IV can determine the optimal GEP for a power system over a period of 30 years, within the system planning constraints, based on total minimum discounted system costs [16]. Each potential series of generators added to the power system, which meets the power system constraints are weighted using a present value cost function. The cost (objective) function is based on Equation (1).

$$B_j = \sum_{t=1}^{T} [\bar{I}_{j,t} - \bar{S}_{j,t} + \bar{L}_{j,t} + \bar{F}_{j,t} + \bar{M}_{j,t} + \bar{O}_{j,t}] \quad \text{Equation (1)}$$

where B_j is the objective function of the expansion plan j, I_j are the capital investment costs

[1] Energy not served (ENS) or expected unserved energy is the expected amount of energy not delivered each year because of scarcities in generating capacities and or shortage in energy supplies.

of expansion plan j, S_j are the salvage value of investment costs of the expansion plan j, F_j are the fuel costs of expansion plan j, L_j are the fuel inventory costs of the expansion plan j, M_j are the non-fuel operation and maintenance costs of the expansion plan j, O_i is the cost of ENS of the expansion plan j, during the time, t in years 1, 2, 3, ……., T, where T is the planning period. The horizontal bar represents discounted values to a reference year or base year at a given discount i. The optimal expansion plan is defined by minimizing B_j to all j. As WASP-IV uses DP the analysis based on Bellman's Principle of Optimality requires a start point to determine the all the possible alternative expansion plans in power system [16]. If $[K_t]$ is a vector containing all the generating units in operation in year t for a given expansion plan, then $[K_t]$ must satisfy Equation (2).

$$[K_t]=[K_{t-1}]+[A_t]-[R_t]+[U_t] \qquad \text{Equation (2)}$$

where $[A_t]$ equals a vector of committed additions of units in year t, $[R_t]$ equals a vector of committed retirements of units in year t and $[U_t]$ equals a vector of candidate units added to the system in year t. The installed capacity must lie between the maximum and minimum reserve margins, above the peak demand $D_{t,p}$ in the critical period, p of the year and is defined by the following constraint set-out in Equation (3).

$$(1+a_t)D_{t,p} \geq P\,(K_{t,p}) \geq (1+b_t)D_{t,p} \qquad \text{Equation (3)}$$

In WASP-IV the system reliability is configured using LOLP. The LOLP index is calculated for each period of the year and each hydro-condition in the same period weighted by the hydro-condition probabilities and the average annual LOLP. The generation of each plant during each period is determined using the optimal dispatch policy in WASP-IV, which is based on the availability of plants and units, maintenance of plants and units, spinning reserve (SR[2]) requirements and other exogenous constraints such as environmental emissions, fuel usage and or availability of certain plants as described in Equation (4)

$$\sum_{i \in I_j} COEF_{ij} \times G_i \leq Lim_j \qquad \text{Equation (4)}$$

where G_i is the generation by plant i, $COEF_{ij}$ is per unit emission or per unit fuel usage and so forth by i plant in the group limited by j.

[2] Spinning reserve (SR) as defined in Reference [17] is the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power.

3 TEST SYSTEM

The test system is the all island grid (AIG) of the Republic of Ireland and Northern Ireland, which has an existing installed dispatchable capacity of 9,742MW, approximately 5,842MW of which is gas fired. Currently in the AIG there is an installed wind power capacity of circa 1,533MW. There is a 275kV double circuit interconnector and two standby 110kV lines between Northern Ireland and the Republic of Ireland. The AIG is linked to the Great Britain (BG) grid via the Moyle 500MW high voltage direct current (HVDC). In addition, there is also EirGrid's 500MW HVDC East West interconnector (EWIC), which runs from Rush, County Dublin to Barkby Beach, North Wales, which is at an advanced stage of planning and expected to commence operation in 2012. Thus the AIG can be treated as one synchronous system. The baseline model data was collected from published information from the single wholesale electricity market operator (SEMO), the transmission system operators[3] (TSO) and the regulators[4] for Northern Ireland and in the Republic of Ireland and all island market modeling project and the all island grid (AIG) study [19 - 25].

3.1 Scenario Approach

For each year up to 2025 two distinct charging scenarios are applied based on a peak tariff and an off peak tariff in order to simulate the effect of PHEV on the power system. Figure 2 shows the flowchart approach used to examine the impacts of the two PHEV load profiles on the power system.

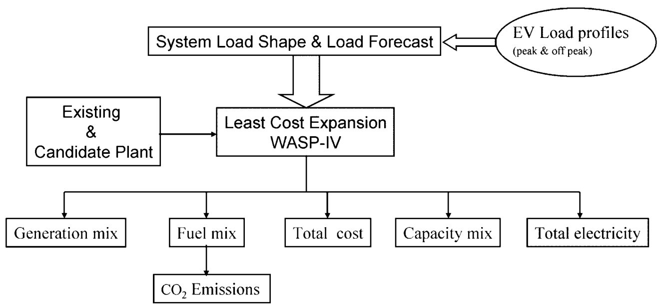

Figure 2. WASP-IV GEP & CO2 Flowchart

The number of PHEVs charging is per annum is estimated using the results of the 'Car Stock' model [26]. Figure 1 provides a graph of the growth in PHEVs for the passenger car fleet in the Republic of Ireland only, from 2010 to 2025 inclusive as

[3] EirGrid plc is TSO in the Republic of Ireland and the TSO in Northern Ireland is called the System Operator for Northern Ireland (SONI).
[4] the Commission for Energy Regulation (CER) and the Northern Ireland Authority for Utility Regulation (NIAUR).

estimated by 'Car Stock'. For the purpose of this model a 10% (i.e. 262,068) PHEV target is achieved in 2020.

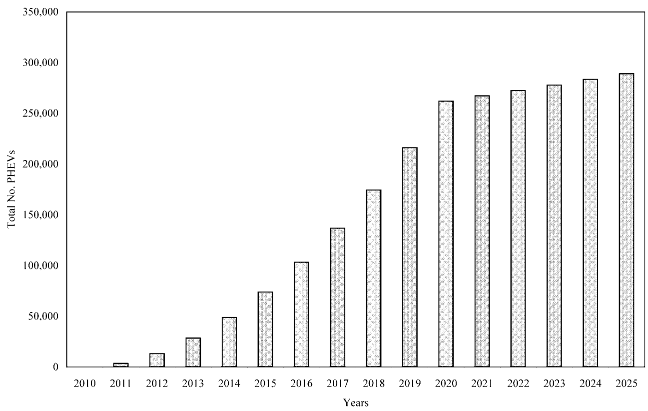

Figure 3. PHEV Numbers from 2010 to 2025

As the alternating current (AC) electrical energy from the grid is converted to direct current (DC) in the EVs battery pack there will be power losses associated with stationary loads in the charging process such as communications controls and the battery/engine cooling system [27]. Reference [28] assumed 88% conversion efficiency from AC to DC. Thus more power is actually required to full charge the EV.

For this study it is assumed that charging will take place mostly at the EV owners' home at level 1 charging using a 3.3kW charger, which includes the conversion efficiency factor over 8 hours with 'trickle' charging of the battery to reach a full state of charge (SOC). Table 1 gives an indication of the power demand and charging options for a domestic charge in Ireland based on the existing grid circuitry.

Table 1. Domestic Charging & Power

Level (Mode)	Type	Electrical	Resulting Charge	Time to Charge	Power
1	Standard (Domestic)	230V 16A 1 or 3 phase	100%	6 to 8 hours	3kW to 10kW

Applying the same methodology used in the 'EV Car Stock' model plug-to-battery energy losses of 88% conversion efficiency were used [29]. In order to determine the additional energy used and the amount of CO_2 produced by the power system, WASP-IV is ran without the load of the PHEVs and with the load of the PHEVs for both the peak and off peak charging regimes.

3.2 Baseline Data

In the test system power dispatch is optimized using hourly electricity demand curves over an entire year (i.e. 8,760 hours) for each year up to 2025. The baseline year is 2009. Figure 4 shows the load duration curve for 2009. A conservative growth of 1.15% per annum in electricity demand is taken up to 2025. This data was inputted into WASP-IV using PRELOAD2 [30].

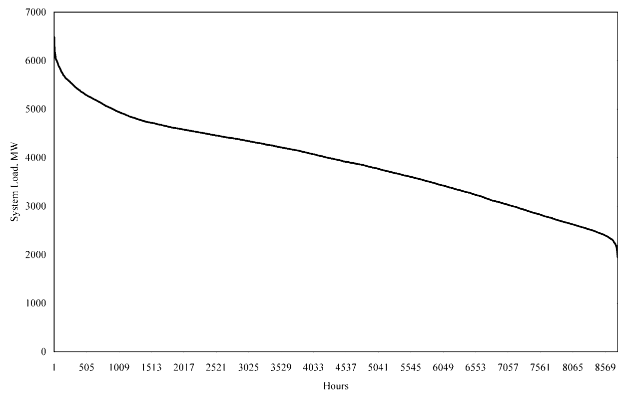

Figure 4. Load Duration Curve for Base Year

Peak charging is assumed to occur during peak electricity usage, which is typically between 12pm and 8pm each day. Off peak charging is assumed to occur during the period of lowest electricity demand, typically between 12am and 7am. This is usually referred to as the night-time valley. A trickle charge approach was applied over the eight hours. The details for the minimum load level, fixed operations and maintenance (O&M) costs, variable O&M costs, forced outage rates, net heat rate at minimum load, fuel costs, carbon costs and average incremental heat rate for each unit were collected from References [19 – 25].

Wind power generation in this study is established in WASP-IV as a 'fictitous' run-of-hydro unit. The installed wind power capacity for each year was linearly extrapolated starting with 1,533MW of installed wind capacity in 2009 and 6000MW in 2020. The Republic of Ireland has a target of generating 40% electricity from renewable energy sources (RES), which is expected to come predominantly from wind power by 2020 [31]. Northern Ireland currently has a renewable target of 12% electricity production from indigenous sources by 2012. A revised target of 42% power from RES, mostly from off-shore wind power, by 2020 is currently under consultation. Northern Ireland currently has a renewable target of 12% electricity production from indigenous sources by 2012. A revised target of 42% power from RES, mostly from off-shore wind power, by 2020 is currently under consultation [32, 33 and 34]. All the dispatchable plant inputted into WASP-IV are listed in Table 2.

Table 2. Dispatchable Plant in AIG

Plant	ID x no. units	Net Capacity, MW	Fuel type
Aghada	AD x 1	258	Gas
Aghada	AT x 3	90	Gas
Aghada	ADC x1	432	Gas
Ballylumford ST	B1 x 3	170	Gas
Ballylumford CCGT	B2 x 3	170	Gas
Ballylumford GT	B3 x 2	58	Gas
Ballylumford CCGT	B10 x 1	97	Gas
Cahir OCGT	CH1 x 1	98	Gas
Cuilleann OCGT	CL1 x 1	98	Gas
Coolkeragh	CO1 x 1	53	Oil
Coolkeragh CCGT	CO2 x 1	402	Gas
Dublin Bay	DB1 x 1	403	Gas
Dublin Waste to Energy	DW1 x 1	72	Waste
East West Interconnector	EWIC	500	-
Edenderry	ED1 x 1	117.6	Peat
Edenderry OCGT	ED2 x 1	111	Gas
Great Island	GIA x 2	54	Gas
Great Island	GIB x 1	108	Gas
Huntstown	HNI x 1	343	Gas
Huntstown	HN2 x 1	401	Gas
Kilroot	KC x 2	29	Oil
Kilroot	KO1 x 2	40	Oil
Kilroot	KO2 x 1	400	Gas
Lough Ree Power	LR4 x 1	91	Peat
Marina	MRT x 1	85	Gas
Meath Waste to Energy	MW x 1	17	Waste
Moyle Interconnector	MI x 1	450	-
Moneypoint	MP x 3	282.5	Coal
Nore Power	NP x 1	98	Gas
North Wall	NW1 x 1	163	Oil
North Wall	NW2 x 1	104	Gas
Poolbeg	PBC x 1	463	Gas
Rhode Island	RP1 x 2	52	Gas
Sealrock	SK X 2	80.5	Gas
Tarbert	TB1 x 2	54	Oil
Tarbert	TB3 x 2	241	Oil
Tawnaghmore	TP x 2	52	Gas
Tynagh	TY x 1	384	Gas
West Offaly	WO x 1	137	Gas
Whitegate	WG x1	445	Gas
Ardnacrusha Hydro	AA x 4	21.5	Water
Erne Hydro	ER x 4	16.25	Water
Lee Hydro	LE x 4	9	Water
Liffey Hydro	LI x 4	9.5	Water
Turlough Hill	TH x 4	73	Water

The fuel prices are given in Table 3 and are the average of the prices used in the AIG study [35].

Table 3. Fuel Costs

Fuel type	Cost, €/GJ
Gas OCGT	5.91
Gas CCGT	6.46
Coal	1.75
Peat	3.71
Wind	2.78
Hydro	0

Finally, note that the SR was left at the default value of 10% in WASP-IV for this study.

4 RESULTS & ANALYSIS

Figure 5 shows the graph of total energy with and without PHEV charging from 2010 to 2025. Both peak and off-peak charging modes use in effect approximately the same amount of total energy per annum. As can be seen from the graph the total amount of energy produced increases as would be expected as the number of PHEVs charging increases. PHEV charging accounts for approximately 1,184GWh of additional energy in electricity in 2020. This result is comparable with earlier research by the authors [1 and 29]. 1,073GWh of additional energy in electricity in 2020 or around 93ktoe, of which 42% is renewable, which equates to 97.65ktoe when the 2.5 weighting is applied in accordance with Directive 2009/28/EC. Therefore PHEVs could contribute 1.68% to the 10% renewable energy in transport target in the Republic of Ireland.

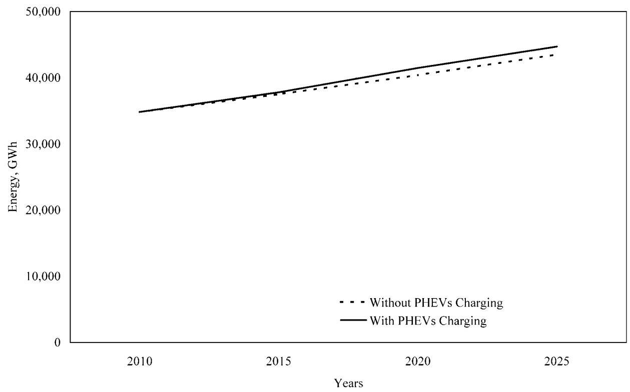

Figure 5. Total Energy with & without PHEV Charging

Figure 6 shows the graph of total CO_2 emitted without PHEV charging, with PHEV off peak and with PHEV peak charging from 2010 to 2025. As can be seen from the graph the amount of CO_2 produced without PHEV charging is the lowest, as would be expected. The amount of CO_2 emissions also decreases year on due to the increase in installed wind. The PHEV peak charging generates more CO_2 emissions than the off peak charging as less efficient peaking and mid-merit thermal generators are used. This model has not taken into account the stochastic nature of wind power on the system, which may result in increased CO_2 emissions due to cycling[5] and part loading of thermal generators [36]. The analysis is also limited because the impacts of using surplus wind on the AIG system to charge PHEV was not included.

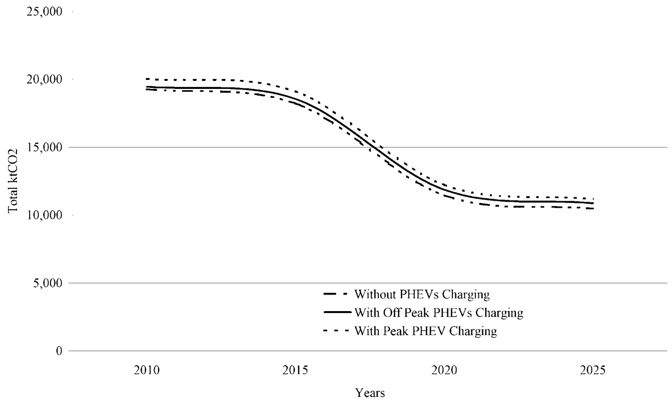

Figure 6. Total Systems CO_2 Emissions per Scenario

The difference in CO_2 emissions between the baseline case, without PHEVs charging and with PHEVs charging for both the peak and off peak scenarios is 598ktCO_2 and 375ktCO_2, respectively in 2020. If the Car Stock model CO_2 savings in ICE reductions of 504ktCO_2 is included, then the overall net reduction in CO_2 emissions is a reduction of 129ktCO_2 for the off peak scenario but an increase of 94ktCO_2 for the peak scenario. Thus WASP-IV indicates that peak charging increases CO_2 emissions. Therefore off peak charging has more overall transport and power systems benefits in terms of CO_2 emissions reductions and contributes 0.95% to the Republic of Ireland’s 20% reduction in non-emissions trading scheme (Non-ETS) emissions by 2020 relative to 2005 [37].

5 SUMMARY & CONCLUSION

This paper has presented the results of a first pass at examining the impacts of PHEV charging on the AIG using the WASP-IV long term GEP model. The analysis indicates that off peak charging during the night-time valley is the most efficient with the lowest increase in CO_2 emissions. This is because the base load plants are used. The model revealed that PHEVs have the potential to contribute 1.68% to the 10% renewable energy in transport target in the Republic of Ireland. The model also shows that off peak PHEV charging has more overall transport and power systems benefits in terms of CO_2 emissions reductions and contributes .95% to the Republic of Ireland’s 20% reduction in non-emissions trading scheme (Non-ETS) emissions by 2020 relative to 2005.

The next phase of this research is to build a PLEXOS[6] model to improve the understanding of the affects of PHEV charging on Ireland’s single electricity market electricity market, called the SEM.

[5] Cycling is the operation of thermal generation units at varying load levels, low load levels or in a start/stop manner and has cost implications for operation and maintenance of thermal plant.

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