

ELECTRIC VEHICLES FOR POWER SYSTEM FLEXIBILITY

Mr. Eamon Keane

PhD Candidate

UCD

Dr. Damian Flynn

Senior Lecturer

UCD

Abstract

Electric vehicles (EVs) have the potential to be a significant source of flexibility for power systems with high penetrations of renewables. In this paper, travel diaries from a national travel survey are used to create EV driving profiles from which two charging scenarios are developed. These charging profiles are then integrated into a 2020 unit commitment of the Irish power system to determine the costs to the system of charging EVs. The results show that uncontrolled charging of EVs after their last driving trip in the evening can be more expensive than uncontrolled charging throughout the day due to a higher peak in demand at 6 pm. The change in the operation of storage plant between scenarios indicates that allowing EVs to be flexibly charged would benefit the power system. The importance of extending the model from hourly to sub-hourly resolution is then discussed.

1. Introduction

Electric Vehicles (EVs) have the potential to be one of the most dynamic domestic loads on the power grid, and how this load is managed is a pertinent question for transmission system operators (TSOs). Electricity supply and demand must be continuously matched, with reserve required to cover unexpected variations in demand and outages of generation plant. Systems with high penetrations of renewables also require increased flexibility to meet changes in net load (load minus renewable generation) [1]. Net load changes are traditionally met by conventional generators, however in the future this will lead to increased cycling which can increase system costs against a background of less conventional generation on line [2]. This paper investigates how the charging of EVs influences these costs and how smart charging can be employed to mitigate them. The driving behaviour of EVs is described in section 2, the unit commitment methodology in section 3, results are presented in section 4 followed by a discussion on extending the model in section 5 and conclusions in section 6.

2. Driving Behaviour

Data from the National Travel Survey (NTS) in Ireland was used for determining the travel behaviour of EVs. In the NTS, households were selected from the Quarterly National Household Survey in the fourth quarter of 2009 and asked for details of their travel for a 24-hour period. For each trip during the specified day the start time, end time, distance travelled, day of week and mode of travel were recorded.

From the 17,000 trips in the database, the data was narrowed down to the 11,000 where the main mode of travel was by car. The distribution of trip distances for these is shown in Figure 1. The 95% of journeys below 50 km were chosen as those most likely to be undertaken by an EV given its limited range. From these trips a weekly driving profile for 1,000 individual EVs was developed by assigning a random trip diary to each EV for each day of the week. EVs were assumed to have a 24 kWh battery and require 0.2 kWh/km travelled and to charge at 3.7 kW [3, 4]. Figure 2 shows the weekly driving pattern which emerges. The twin peaks of driving during weekdays and the difference in driving between weekends and weekdays are clearly visible.

From these driving trips, two base charging patterns were developed: an uncontrolled charging scenario where EVs charge whenever parked (universal charging) and a scenario where EVs charge after their last trip of the day. The resulting charging profiles are shown in Figure 3. For the universal charging scenario, there is a sharp ramp in charging demand in the morning as people plug in upon arrival at work (it is assumed everyone has access to workplace charging). In the evening time centred on 6 pm there is a peak in both the universal and last trip scenarios. Almost all EVs are fully charged by midnight in the case of universal charging, while for the last trip scenario, charging continues into the early hours of the morning. There will be variability in the charging demand across the year and heating demand can raise charging requirements although these results serve to benchmark the charging pattern which emerges from the NTS data.

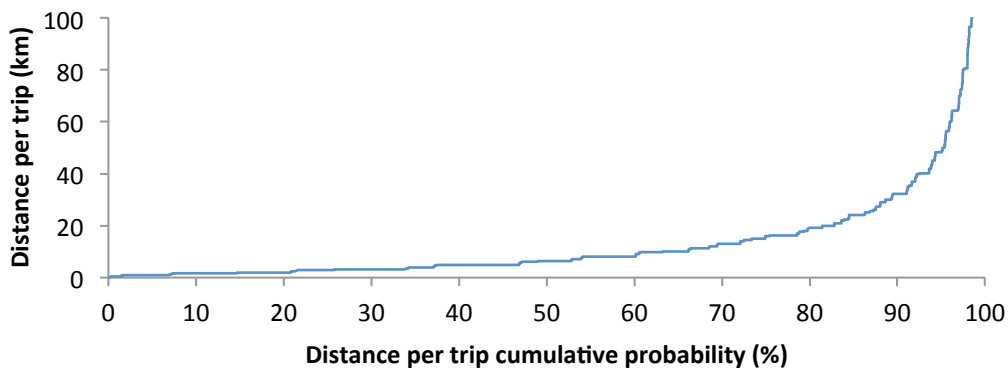


Figure 1: Distance per driving trip

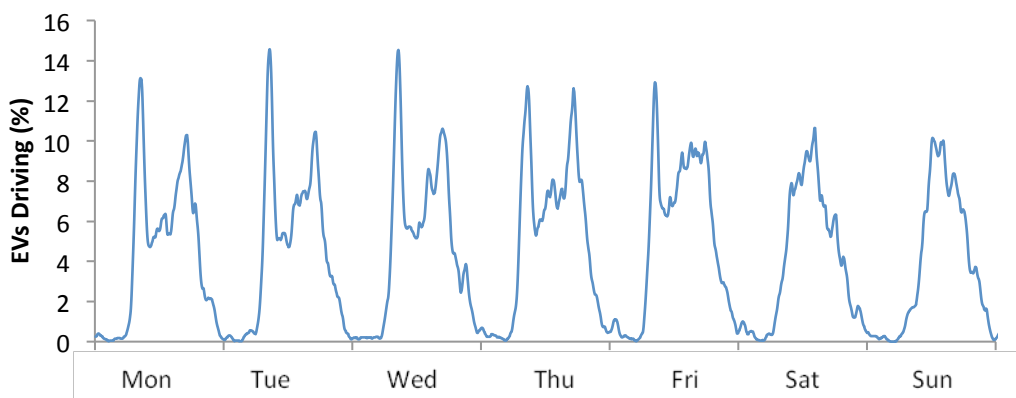


Figure 2: EVs Driving (hourly average)

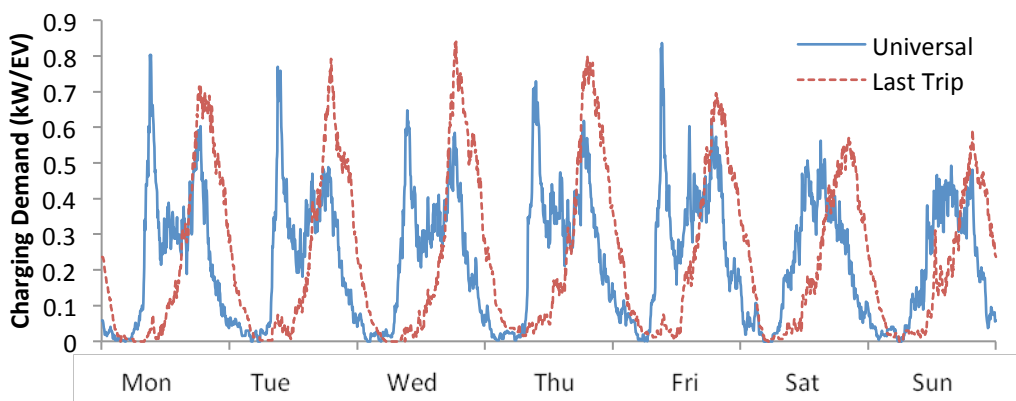


Figure 3: EV Charging Profiles

3. Unit Commitment Methodology

The unit commitment (UC) framework is described in detail elsewhere [2, 5] but the constraints and equations relevant to storage devices including EVs are shown here. The system assumes 1 GW of interconnection between Great Britain and Ireland, and assumes a 7.5 GW peak of Irish demand in 2020. For wind and demand, 2009 profiles are scaled up to 2020 with wind accounting for 40% of energy in 2020. The charging profiles from Figure 3 are used to represent the charging of a 10% fleet penetration of EVs [4]. A maximum system non synchronous penetration (wind + storage demand) of 75% of demand was assumed. The pumped storage facility at Turlough Hill was included which has a rated capacity of 292 MW and storage capacity of 1,590 MWh.

The goal of the model is to minimize power system cost (equation 1) which consists of startup costs, production costs and carbon costs subject to a range of technical constraints with those relating to storage shown in constraints 2-13. The model implements rolling optimisation each 3 hours over a 36 hour time horizon.

Indices/Sets

| | |
|------------|--|
| t, T | Time step, set of time steps |
| g, G | Unit, set of units |
| sto, STO | Storage unit, set of storage units |
| l, L | Segment of the piecewise linearization of the variable cost function, set of all segments of the piecewise linearization of the variable cost function |

Parameters

| | |
|--|--|
| $D(t)$ | System demand (MW) at time t |
| $w(t)$ | Wind power output (MW) |
| R_{wind} | Additional spinning reserve requirement due to wind |
| $\overline{P}_g, \overline{P}_{sto}$ | Maximum capacity for unit g , storage unit sto |
| $\underline{P}_g, \underline{P}_{sto}$ | Minimum capacity for unit g , storage unit sto |
| α | Maximum amount of wind power (% of demand) which can be online at time t |
| min_units | Minimum number of units required to be online for all t |
| r_g^{max}, r_{sto}^{max} | Maximum amount of spinning reserve (MW) which can be provided by unit g , or storage unit sto |
| NL_g | No load heat rate for unit g (GJ/h) |
| NT_g | Number of segments in the linearized fuel consumption curve for unit g |
| T_{lg} | Upper limit (MW) of segment l in the linearized fuel consumption curve of unit g |
| UT_g, DT_g | Minimum up time, down time for unit g |
| \overline{T} | Number of hours in the planning period |
| T_g^{cold} | Number of hours unit g must be offline, beyond its minimum downtime, before it is considered to be in a cold state |
| cc_g, hc_g | Cold, hot start-up cost for unit g |
| h_g^{up} | Number of hours unit g has been online at start of planning period (h) |
| h_g^{down} | Number of hours unit g has been offline at start of planning period (h) |
| $ramp_g^{up}$ | Maximum upward ramp rate for unit g (MW/h) |
| $ramp_g^{down}$ | Maximum downward ramp rate for unit g (MW/h) |
| $start_fuel_g^{hot}$ | Fuel consumed (GJ) when unit g undergoes a hot start |
| $start_fuel_g^{cold}$ | Fuel consumed (GJ) when unit g undergoes a cold start |
| \overline{C}_{sto} | Maximum charging level (MW) of storage unit sto |
| \underline{C}_{sto} | Minimum charging level (MW) of storage unit sto |
| $content_{sto}^{max}$ | Maximum energy storage capacity (MWh) of storage unit sto |
| eff_{sto} | Charging efficiency of storage unit sto |
| f_g | Fuel price (€/GJ) for unit g |
| cf_g | Carbon released by unit g (tonnes/GJ) |
| cp | Carbon price (€/tonne) |

**Binary
Variables**

| | |
|----------------------|---|
| $v_g(t), v_{sto}(t)$ | Equal to 1 when unit g , storage unit sto , is online/pumping at time t |
| $s_g(t)$ | Equal to 1 when unit g starts up at time t |
| $z_g(t)$ | Equal to 1 when unit g shuts down at time t |
| $x_{sto}(t)$ | Equal to 1 when storage unit sto is charging at time t |

**Positive
Variables**

| | |
|----------------------|---|
| $c_g^p(t)$ | Production cost for unit g at time t |
| $c_g^s(t)$ | Start-up fuel cost for unit g at time t |
| $c_g^c(t)$ | Carbon cost for unit g at time t |
| $p_g(t)$ | Output (MW) of unit g at time t |
| $p_{sto}(t)$ | Output (MW) of storage unit sto at time t |
| $w_{cur}(t)$ | Curtailed wind power (MW) at time t |
| $r_g(t), r_{sto}(t)$ | Spinning reserve (MW) provided by unit g , storage unit sto , at time t |
| $R(t)$ | Spinning reserve requirement (MW) at time t |
| $\delta_l(g, t)$ | Power produced in segment l of the linearized fuel consumption curve of unit g at time t (MW) |
| $content_{sto}(t)$ | Stored energy in storage unit sto at time t (MWh) |
| $charge_{sto}(t)$ | Charging level of storage unit sto at time t (MW) |

Constraint 2 balances supply and demand, constraint 3 sets the spinning reserve target equal to the largest infeed on the system plus a portion due to the wind production at that hour. Constraint 4 ensures that spinning reserve target is met (the largest unit does not contribute reserve). Constraint 5 ensures that the wind penetration cannot exceed a certain percentage of demand in a given time period. Constraints 6-13 determine the operation of the storage units.

$$\text{Minimize } \sum_{t \in T} \sum_{g \in G} c_g^p(t) + c_g^s(t) + c_g^c(t) \quad (1)$$

Subject to:

$$\sum_{g \in G} p_g(t) + \sum_{sto \in STO} p_{sto}(t) + w(t) - w_{cur}(t) = D(t) + \sum_{sto \in STO} charge_{sto}(t), \forall t \in T \quad (2)$$

$$R(t) \geq p_g(t) + R_{wind} - w_{cur}(t) - \sum_{sto} charge_{sto}(t), \forall t \in T \quad (3)$$

$$\sum_{g \in G} r_g(t) = R(t), \forall t \in T, g \in G \quad (4)$$

$$w(t) - w_{cur}(t) \leq \alpha \cdot D(t), \forall t \in T \quad (5)$$

$$content_{sto}(t) \leq content_{sto}^{max}(t) \quad (6)$$

$$content_{sto}(t) \geq content_{sto}^{min}(t) \quad (7)$$

$$content_{sto}(t) = content_{sto}(t-1) + charge_{sto}(t) * eff_{sto} - p_{sto}(t) \quad (8)$$

$$p_{sto}(t) + r_{sto}(t) \leq \overline{P}_{sto} * v_{sto}(t) \quad (9)$$

$$p_{sto}(t) \geq \underline{P}_{sto} * v_{sto}(t) \quad (10)$$

$$charge_{sto}(t) \leq \overline{C}_{sto} * x_{sto}(t) \quad (11)$$

$$charge_{sto}(t) \geq \underline{C}_{sto} * x_{sto}(t) \quad (12)$$

$$x_{sto}(t) + v_{sto}(t) \leq 1 \quad (13)$$

4. Results

The model was run at an hourly resolution for the month of January 2020 without EVs (base scenario) and for each of the two EV scenarios. The fuel prices used are shown in Table 1.

Table 1: Fuel Prices

| | €/GJ |
|--------------|-------|
| Baseload Gas | 6.98 |
| Midmerit Gas | 7.22 |
| Coal | 2.90 |
| Peat | 3.33 |
| Distillate | 15.10 |

The total cost for the base case scenario was €86.55 million while it was €87.36 m for the universal charging scenario and €87.68 m for the last trip scenario. This translates to an average system cost of €4.04/EV for the month for the universal scenario and €5.66/EV for the last trip scenario. The difference in cost is due to the higher charging requirement of EVs after the last trip around 6 pm (Figure 3) which is when the system marginal price is on average higher.

The start costs and number of unit starts across the month are shown in Table 2. The last trip scenario, by maintaining load higher in the early hours of the morning, has slightly fewer unit starts than the base case scenario although these are larger units with more expensive start costs. Maintaining a higher night-time load in the last trip scenario also led to 9% less wind curtailment (constraint 5 due to the limit on wind as a percentage of demand) compared to the base case. The least cost scenario for the universal scenario involves more unit starts than the base case. Future work will consider cycling costs which were not considered here and may alter this result [2].

Table 2: Start costs and number of starts

| | Base | Universal | Last Trip |
|------------------|---------|-----------|-----------|
| Start Cost (€) | 726,445 | 813,708 | 821,608 |
| Number of starts | 143 | 153 | 141 |

The operation of the pumped storage plant compared to the base scenario is shown in Figure 4 for the full month. The two cases are noticeably different in that in one scenario the storage may be charging while storage is discharged in the other scenario. The sensitivity of the operation of this pumping unit to changes in the demand profile indicates that if smart charging of EVs was assumed, the charging profile could be significantly altered compared to the two dumb charging patterns used in this paper.

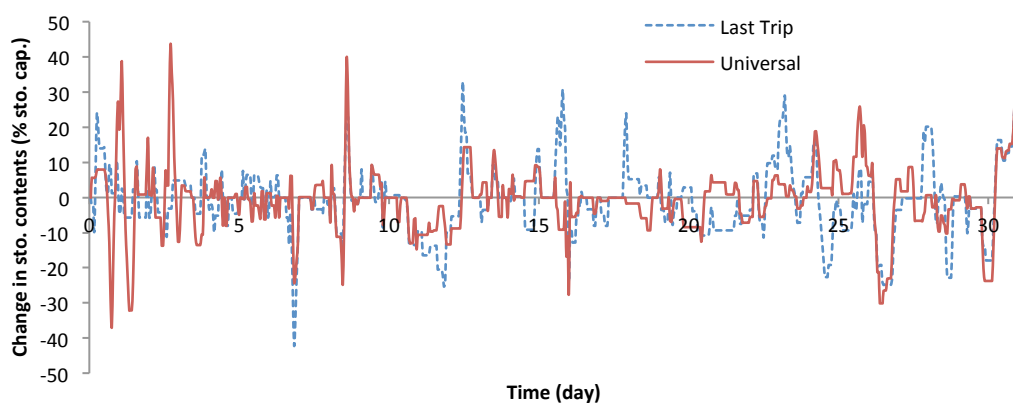


Figure 4: Change in storage reservoir contents relative to base scenario

5. Future Work

The results presented here focused on an hourly resolution of the UC model using two representative 'dumb' charging scenarios which can increase power system costs. Future work will focus on smart charging at shorter timescales. The effect on unit starts and system costs for the dumb scenarios will be compared against a smart charging scenario with the

objective of minimizing user cost/ramping burden/cycling costs, which can optimize EV charging across the day.

Previous renewable integration studies focus on an hourly timestep, while it has been shown that the effect of intra-hourly net load ramps can be a significant driver of the behaviour of storage devices such as EVs [5]. Intra-hourly ramps are higher than averaged hourly ramps and insufficient on-line ramping capability may lead to altered UC and economic dispatch decisions [6]. Most generators have startup times of several hours and also have ramping limits. These ramping limits can be binding at 15 minute resolution but may not be seen when ramps are averaged over an hour. The EV charging demand is also noticeably different at the 15 minute timeframe compared to the hourly timeframe, as shown in Figure 5 for a weekday.

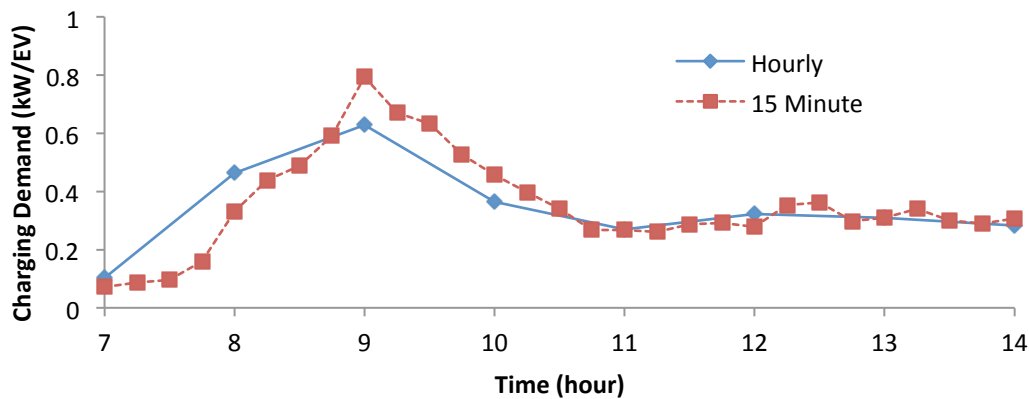


Figure 5: Difference in ramping of EV demand between hourly and 15-minute charging intervals

The degree to which EVs can provide flexibility depends on how many vehicles are not yet fully charged. EVs may still provide services by discharging energy from their batteries, however this entails a high battery degradation cost and the hardware required to do so is not installed on most current EVs. Consequently, only modulation of charging levels will be considered to provide grid services, which still enables EV charging load to be shaped up or down as appropriate. Figure 6 shows that for the universal charging scenario, nearly all EVs are charged by midnight each day. This limits the value EVs may provide during the night by responding to wind forecast errors and also increasing the baseload demand or ramping capability. From the system’s perspective there is value in not charging EVs as soon as possible to retain flexibility and ramping capability throughout night time period and during daytime hours to a lesser extent.

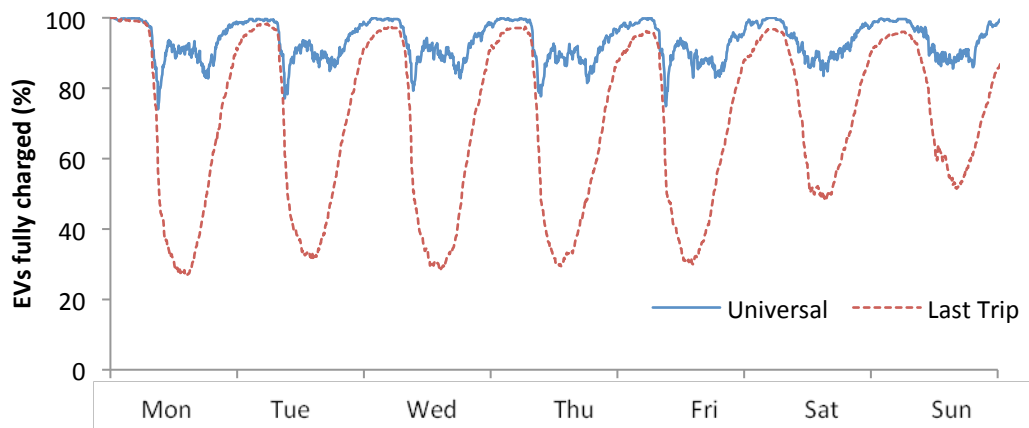


Figure 6: Proportion of EVs which are fully charged

6. Conclusions

In this paper charging profiles of EVs were developed from a national travel survey and provided as input to a unit commitment model of the Irish power system in 2020. The results show differences in EV charging costs, number of unit starts, startup costs and operation of storage plant depending on the charging scenario. The results suggest that the flexible operation of EVs would result in substantially different charging profiles and the inclusion of cycling costs could additionally alter the charging profiles. The importance of operating at sub-hourly timescales was discussed and will be implemented in future work.

References

- [1] N. Troy, *et al.*, "Base-Load Cycling on a System With Significant Wind Penetration," *IEEE Transactions on Power Systems*, vol. 25, pp. 1088-1097, 2010.
 - [2] N. Troy, *et al.*, "Unit commitment with dynamic cycling costs," *IEEE Transactions on Power Systems*, *in press*.
 - [3] J. Kiviluoma and P. Meibom, "Methodology for modelling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles," *Energy*, vol. 36, pp. 1758-1767, 2011.
 - [4] E. Keane and D. Flynn, "Potential for electric vehicles to provide power system reserve," in *IEEE PES Innovative Smart Grid Technologies*, 2012.
 - [5] N. Troy, *et al.*, "The importance of sub-hourly modeling with a high penetration of wind generation," *Proc. IEEE Power and energy society general meeting 2012 (forthcoming)*, 2012.
 - [6] E. Lannoye, *et al.*, "Evaluation of Power System Flexibility," *IEEE Transactions on Power Systems*, vol. 27, pp. 922-931, 2012.
-