THE IMPACT OF PLUG-IN ELECTRIC VEHICLES ON LONG RANGE DEMAND FORECASTS OF DISTRIBUTION NETWORKS – ETHEKWINI CASE STUDY

Author & presenter: G. Brand B.Eng – Senior Consultant at NETGroup S.A.
Co-author: J. Roesch B.Eng – Senior Consultant at NETGroup S.A.

1. Introduction

The current market penetration of plug-in electric vehicles (PEVs) is limited. However, the market for PEVs is expected to grow rapidly with increased concern about the environment, advances in technology and, as electricity is one of the least expensive transportation fuels, the cost of energy [i].

Due to the high energy capacity of PEVs, significant deployment will potentially introduce substantial demands on power distribution networks.

This paper suggests a model for the inclusion of PEV loads in long range (15-25 years) spatial demand forecasts and tests the impact of the introduction of PEVs on the metropolitan distribution network of eThekwini. As a result a view is obtained on the extent to which capacity of existing and planned plant will be affected in a typical urban network within the South African context under various PEV market penetration scenarios.

This is an area of significant interest to a number of stakeholders - from PEV fabricators and distributors through to the electricity supply industry that will in effect fuel these vehicles.

2. Study Objective

A major question faced by electric distribution utilities is whether the current and currently planned network will cope with the introduction of PEVs and what network reinforcement will be required.

The objective of this study is to utilise an existing long range (20 years) load forecast that was created in absence of recognition of PEV load contributions and to apply a PEV load forecast model to this forecast. Baseline forecast results are then compared to baseline plus PEV forecast results to assess the impact on existing and planned network capacity.

3. PEV Forecast Model

A PEV load forecast model differs somewhat from conventional forecast models in that it is significantly influenced by changes in both consumer adoption as well as technology shifts.

Variables that influence the proposed PEV model are:

- PEV market penetration
- Vehicle efficiency
- Current and forecasted charge capacity of batteries
- Current and forecasted charging rates of batteries and residential chargers
- Distances travelled by PEVs (utilisation behaviour)
- Consumer charging behaviour (time of day)
- Home charging vs. charge at office vs. public parking charging vs. top-up-and-go charging stations

Vehicle Efficiency

For the purpose of this study an efficiency of 5.44km/kWh (similar to the Nissan Leaf)[iii] is assumed for all electric vehicles throughout the study.

Charge capacity forecast

Over the next five to ten years, battery and electric drive train components are expected to improve significantly. Between 2017 and 2020, with expected technology advances (primarily in batteries), PEVs can be expected to become mainstream[i].

When comparing battery technology the two most important factors to consider are energy density and cost. In today's automotive market technology is continuously improving and it can be expected that batteries will continue to become smaller (Wh/L) and lighter (Wh/kg). Based on the chemistry used, theoretical maximums indicate potential ceiling values of the various chemistries.

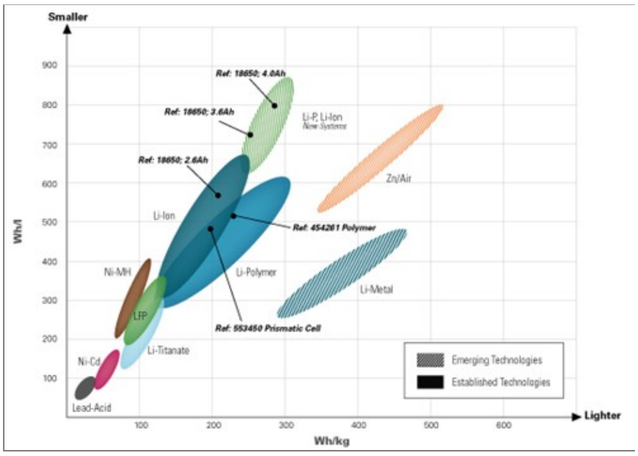

Figure 1 Energy densities for battery chemistries [ICCNexergy]

Evident from the graph above is that technologies like Lead Acid, Ni-Cad and Ni-MH have already reached maturity and that additional advances aren't expected. Currently Li-Ion and Li-Polymer holds the most promise for energy density increases in the next couple of years. What can also be seen is that the established technologies can potentially reach a maximum density of 300Wh/kg. Emerging technologies are expected to breach the 300Wh/kg barrier.

Historic energy density (Wh/kg) data for Li-Ion batteries shows that density has increased at an average rate of 6% during the last 20 years while costs have come down[ii]. Applying the same rate of increase, established technology will continue to improve over the next 10 years until the theoretical ceilings are reached.

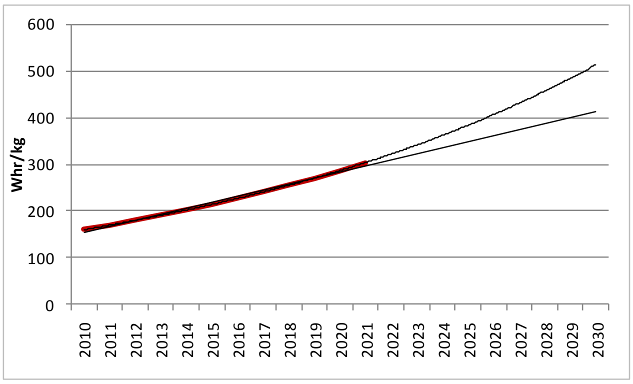

Figure 2 Battery energy density forecast

Assuming that today's emerging battery technologies will become mainstream contenders and will be ready for use when the 300Wh/kg ceiling is reached the future energy density can be between 420 and 520Wh/kg when extrapolating the data using linear and exponential methods. The implication is that PEVs of the near future will be able to travel between 2.6 and 3.2 times further than what they are capable of today.

PEV Utilisation Behaviour

For the metropolitan study area under consideration, an average daily commute of 50km per day is applied which is consistent with US based commuter studies for metropolitan areas [i].

For all years of the study a travel distance distribution density peak at 50km is assumed, but deviation is gradually increased towards year 20 of the forecast to simulate extended vehicle use due to increased battery capacity and charging rates.

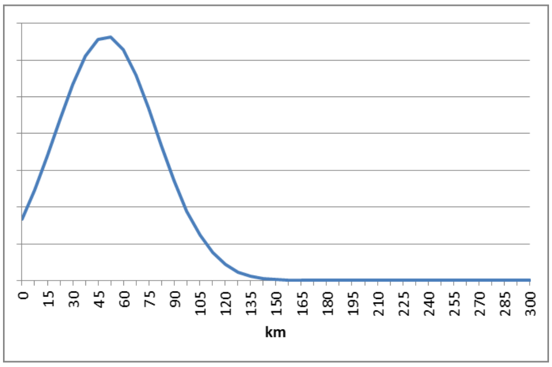

Figure 3 Travel distance distribution density 2010

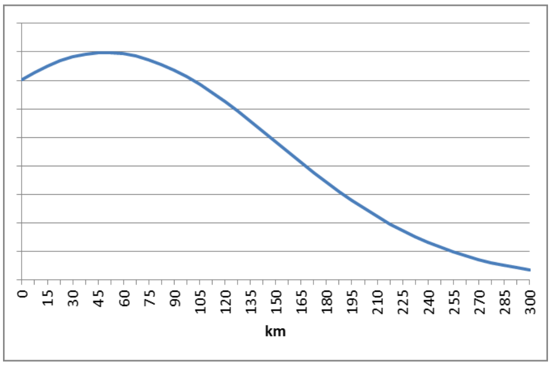

Figure 4 Travel distance distribution density 2030

These are admittedly rather clumsy assumptions and research and survey data in this area could improve forecast accuracy.

Charging profile

This paper assumes a linear charging characteristic for residential charging equipment.

The current study is limited in assuming that all charging will take place at home. The development of charging stations at public parking areas and places of work as well as high transfer rate top-up-and-go charging stations, expected to be established in residential and commercial areas, are not considered. This might be acceptable for study purposes as survey and vehicle use data suggest that 80% to 90% of charging will occur at night [i].

Two home charging scenarios are considered – uncontrolled charging and time-of-use charging.

Uncontrolled charging:

Uncontrolled charging assumes that PEV owners plug in and recharge their vehicles as soon as they arrive home and the vehicles remain connected until fully charged.

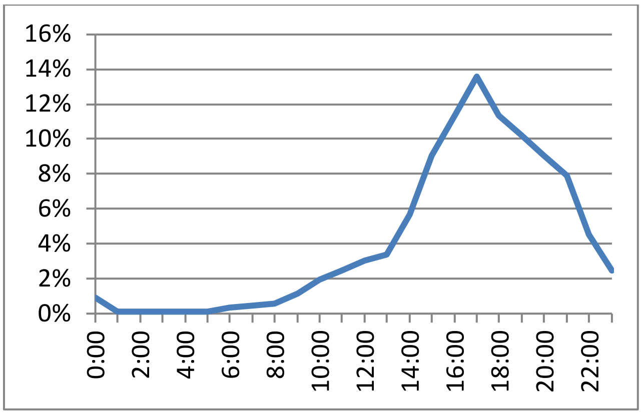

Figure 5 Average home arrival times [iii]

Applying current and forecasted recharge requirements (kWh), transfer capability (kVA) and battery capacities to the home arrival time profile, expected after diversity average load profiles can be inferred. Year by year the profiles differ in magnitude and shape due to extended traveling distances (from higher capacity batteries) and improved charge transfer technology and rates (the study assumes that domestic charge currents grow from 20A in base year to 125A in 2029).

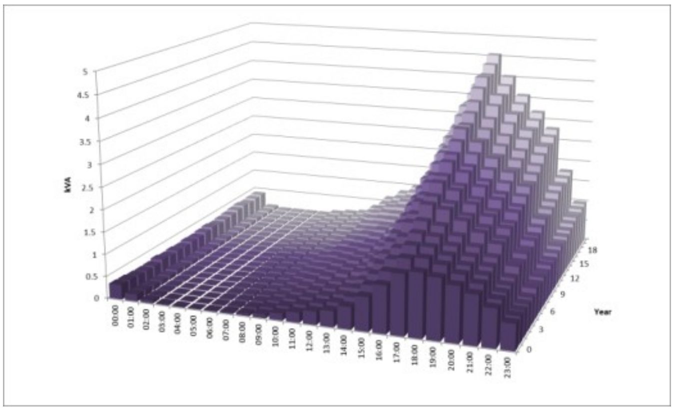

Figure 6 Uncontrolled charging profiles

For the uncontrolled scenario charging profiles peak at 1.4kVA per vehicle in base year and 4.55kVA in year 20 of the forecast.

Time of use tariff charging:

The time of use (ToU) charging scenario assumes that PEV owners will be on a residential time of use tariff with an off-peak window commencing at 22:00 and that the majority of vehicles will start charging during this window. In the ToU charging scenario, 80% of vehicles would start charging as soon as off-peak rates start applying, while the remaining 20% would still charge in an uncontrolled manner. This creates a significant peak effect on the off-peak ToU commencement interval. This peak is exacerbated by the expected improvements in battery capacity and battery charge rates over course of the study period.

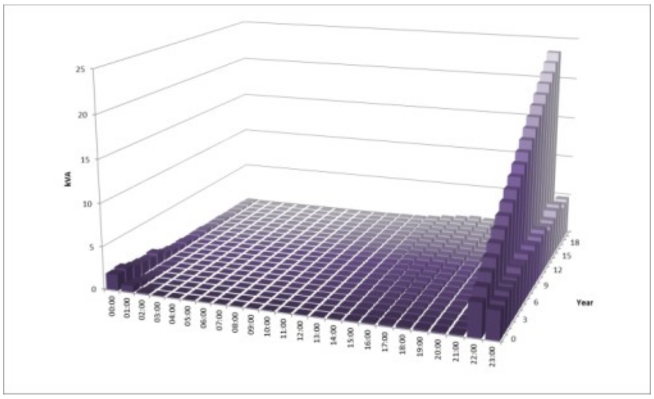

Figure 7 Time of Use charging profiles

For the time of use scenario charging profiles peak at 3.85kVA per vehicle in base year and 23.35kVA in year 20 of the forecast.

Other study assumptions:

- Charger efficiency: 0.9
- Charger power factor: 0.95
- Battery effective capacity: 80%

Study Scenarios

Baseline Scenario: Demand forecast as per most likely scenario of the 2009/2010 eThekwini master plan load forecast. The current study assumes that this forecast is still valid and provides a reasonable view on expected load levels and planned network capacity and configuration.

EPRI Medium Scenario: Baseline forecast plus effect of medium scenario of EPRI PEV market penetration forecast [iii].

EPRI High Scenario: Baseline forecast plus effect of high scenario of EPRI PEV market penetration forecast [iii].

For purposes of PEV population estimates in the study area, EPRI forecasted values for PEV market penetration in the United States are utilised and assumed to be reflective of adoption levels within the study area.

This study assumes heterogeneous adoption of PEVs throughout the vehicle population. It does not take clustering behaviour of consumers into account. It should be expected that specific residential areas will show higher or lower penetration levels due to clustering. To model this, the standard deviation of the load profiles will need to be increased. The effect of this will be that capacity requirements will increase, but energy dispensed (i.e. sales) will remain as per the current forecast. A detailed study of the clustering and derivation of suggested cluster factors are beyond the scope of the current study.

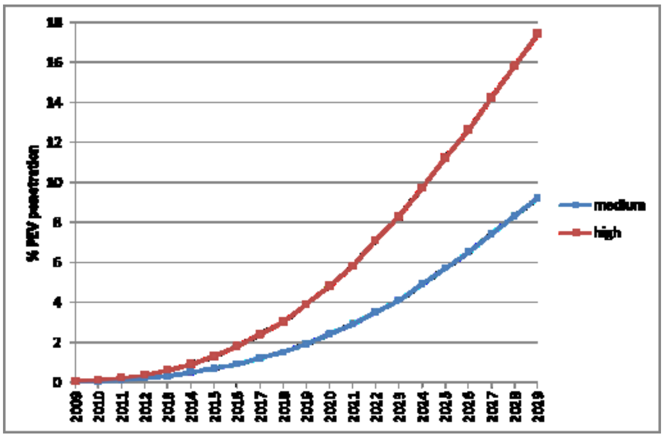

Figure 8 PEV Market penetration (% of vehicle population)

Study Area

The selected study area is based on the load forecast study area of a 2009/2010 eThekwini Metropolitan Municipality electrical distribution network master plan (utilised with the kind permission of eThekwini). The forecast period of this study was 2009-2029.

The study area covers an area of about 70km by 40km down the KwaZulu-Natal coast around the city of Durban, South Africa.

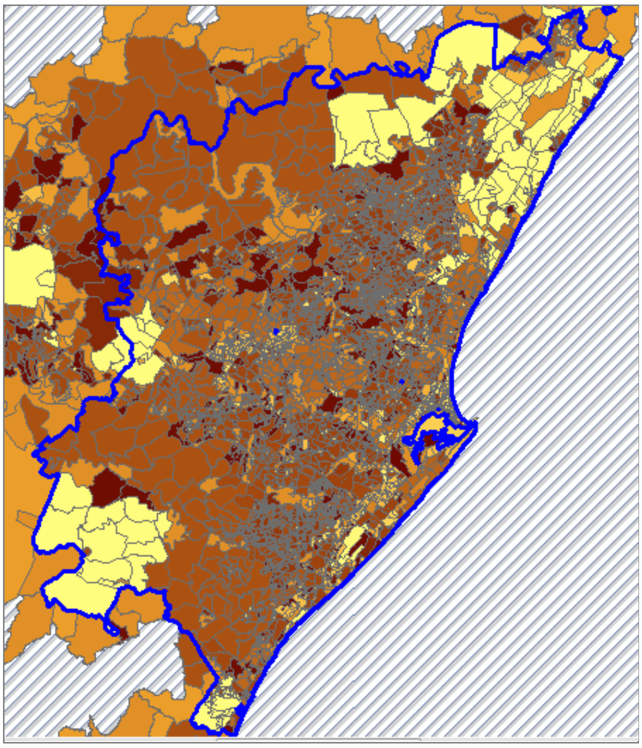

Figure 9 eThekwini study area

Current and forecasted vehicle populations for the study area are obtained from a 2011 transportation study of the eThekwini Transport Authority[iv].

4. Forecast Results

Total Load Impact

The impact of **uncontrolled charging** on the total network load is limited within the span of the study period. A 7% and 14% increase is obtained from the EPRI medium and EPRI high scenarios respectively.

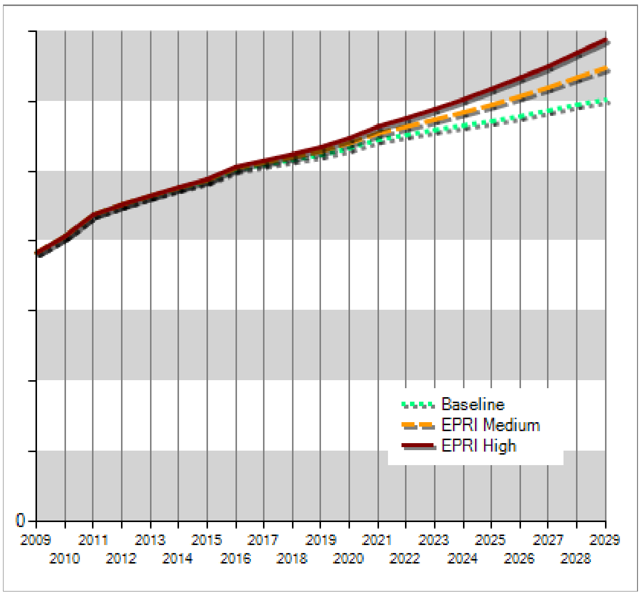

Figure 10 Uncontrolled scenario total load forecast

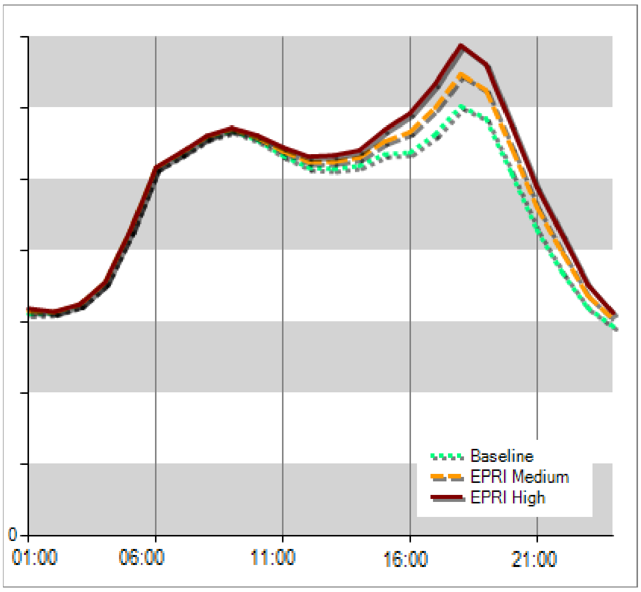

Figure 11 Uncontrolled scenario total load profile (2029)

Despite the demand spike introduced by ToU behaviour, the **ToU scenario** has no impact on the baseline forecast until 2027 when the EPRI High scenario starts increasing total supply requirements substantially. This would suggest that in the short to medium term, residential time of use tariffs might be sufficient to control PEV demand.

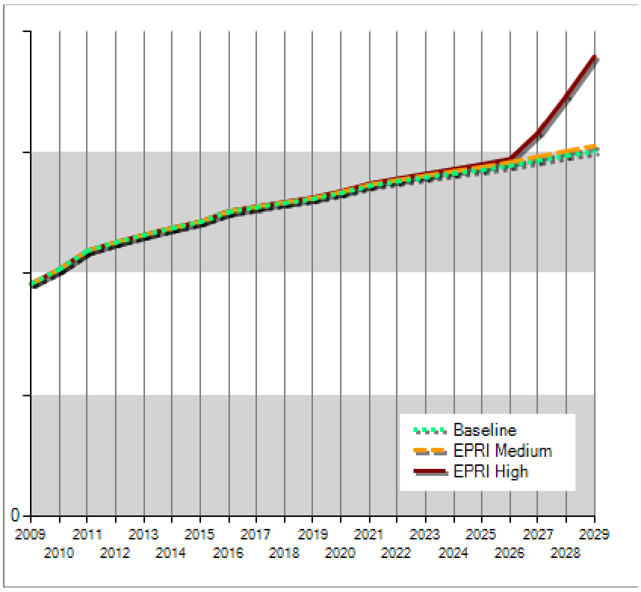

Figure 12 ToU scenario total load forecast

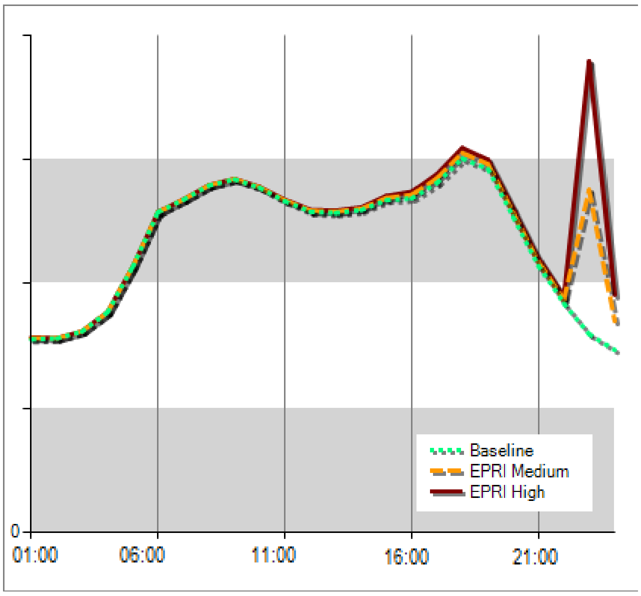

Figure 13 ToU scenario total load profile (2029)

Impact on Distribution Substations

The study area is supplied by 153 substations where the primary side voltages range between 33kV and 275kV.

Comparing results from the baseline with the uncontrolled charging model reveals that for the EPRI Medium PEV scenario, 8 substations exist where firm capacity is exceeded. This figure rises to 23 substations in the EPRI High scenario.

Voltage	Number of substations	Firm capacity exceeded	
		EPRI Medium	EPRI High
275kV	8	1	1
132kV	100	7	22
33kV	45	0	0
Total	**153**	**8**	**23**

Evaluating the 23 substations where firm capacity is not maintained reveals that for 19 of them the problem can be addressed by simply shifting load to adjacent substations or implementing planned extensions earlier.

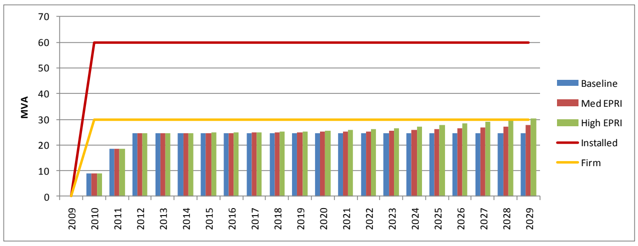

Figure 14: Example where additional load can be shifted to adjacent substations

In only 4 of the substations the additional PEV load growth is substantial enough that it will require the current proposed network expansion plan to be revised.

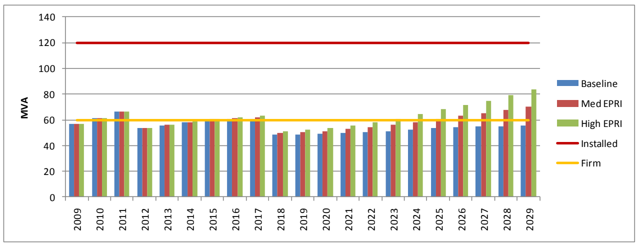

Figure 15: Example where Network Expansion plan needs revision to accommodate load growth

In the uncontrolled load forecast the additional PEV load added doesn't cause any of the substations' installed capacity to be exceeded.

Impact on Medium Voltage Network

In the **uncontrolled scenario**, significant impact on the peak demand can be seen on many MV distribution load zones from 2020 onwards. Of concern is the observation that in these cases the saturation load of the load zone is often exceeded by 20% - 40% towards the end of the study period as illustrated in the example zone in Figure 16.

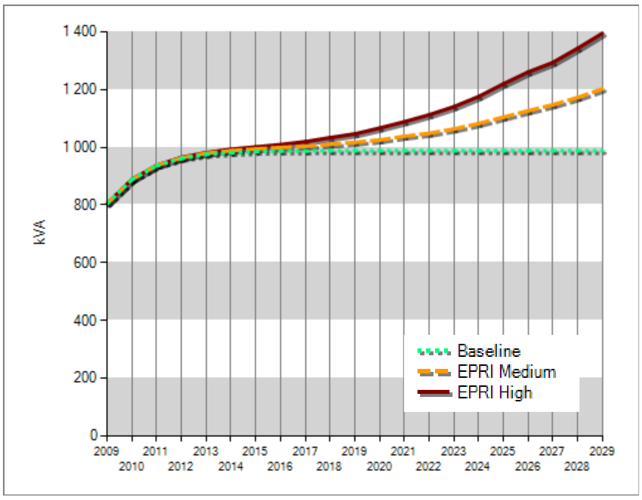

Figure 16 Uncontrolled MV load forecast example

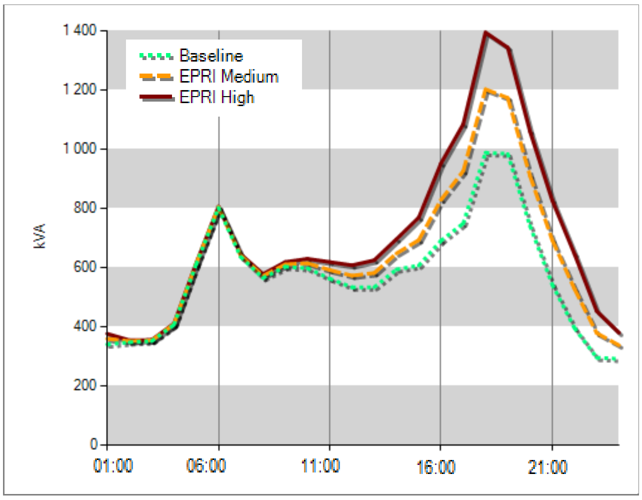

Figure 17 Uncontrolled MV load 2029 profile sample

However, as pointed out in Figure 18, ample opportunity exists for the utility to shift PEV overnight charging load to the valleys in a **controlled charging environment**. This would probably require separate charging connections together with utilisation of smart meters to control the load.

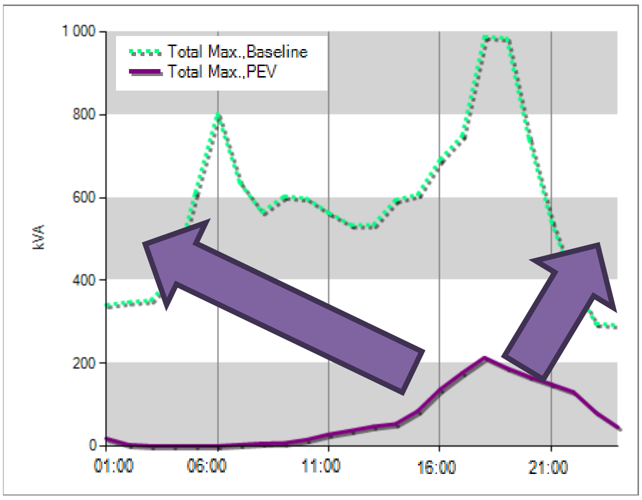

Figure 18 Baseline load profile vs PEV component (2029) example

In the **ToU scenario** the impact of PEV load is much more pronounced and manifests as a peak at a much earlier stage than is seen at total network level. This leads us to question the viability of residential time of use tariffs to control PEV load at an MV level.

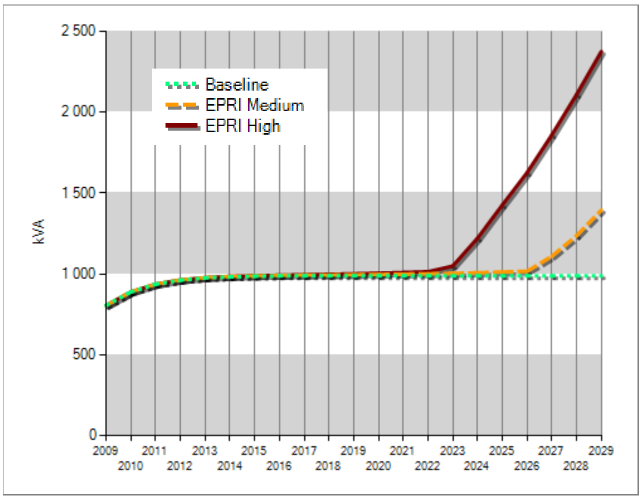

Figure 19 ToU MV load forecast example

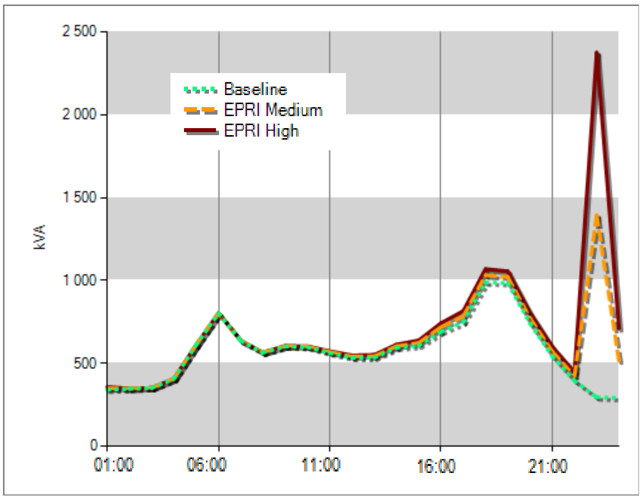

Figure 20 ToU MV load 2029 profile sample

PEV Saturation Load

It should be noted that the current study only addresses a 20 year forecast window. It is clear that by year 20 the PEV loads have not reached saturation in any of the forecast scenarios. While the impact of PEVs on the study area's network appears manageable over 20 years, cognisance should be taken of the fact that it is primarily limited by a 10%-18% penetration level as per Figure 8. The EPRI PEV market penetration forecast appears to be in the "innovator" dominated stage of a Bass model[v]. With maturing of technology and imitators entering the market the rate of adoption is expected to increase.

Whether electric vehicles will achieve a 100% adoption level might be debateable, but a 40 year view will yield substantially higher PEV demand forecasts than a 20 year view.

5. Conclusion

The impact of supplying additional PEV loads over the next 20 years seems negotiable at distribution network substation level where the utility currently has a long term master plan in place to cater for normal load growth. This is partly due to the fact that PEV penetration levels are expected to increase slowly - only 4% expected during the next 10 years. Between year 10 and 20 we do however see a 14% increase and it is during this time that loading levels at certain substations become problematic.

Design criteria for electrical equipment and associated networks are based on standard equipment sizes when planning leading to substation capacity expansion in discrete blocks. This coarse granularity helps to limit the number of substations where the network expansion and strengthening plan needs to be revised in order to accommodate the new growth.

On the other hand, results from this study indicate that the effect of PEV loads at MV network level poses a serious risk to constrained networks where limited spare capacity is available. In addition, clustering could result in higher than average adoption concentrations in small supply areas, further exacerbating the effect on MV network capacity.

From the difference observed between the uncontrolled charging scenario and time of use charging scenario at a total system level it appears that the time of use tariff option offers benefits to the utility to increase its load factor during the short to medium term without impacting on total demand. But this benefit is negated when the PEV charging load, driven by technology improvements and increased levels of PEV adoption, increases to become the new utility system peak.

The benefit of time of use charging at MV level attenuates sooner than at total network level as MV circuits are saturated and overloaded much earlier in the forecast. For these reasons there is merit to consider controlled charging options by means of smart metering solutions paired with smart tariffs over a time of use approach.

The ability of distribution utilities to meet charging requirements in a financially sustainable manner might be dependent on the extent to which customer adoption is going to be clustered and how utilities adapt service offerings to provide intelligent charging offerings on acceptable timing and cost terms[vi].

Residential design ADMD values and expected consumer consumption profile changes will need to be re-evaluated where significant PEV penetration is be expected.

[i] Plug In, Turn On, and Load Up, E. Ungar, K. Fell, IEEE Power & Energy Magazine May/June 2011
[ii] http://batteryuniversity.com/learn/article/battery_statistics
[iii] Transportation Electrification: A Technology Overview, 2011 Report, EPRI
[iv] Study to Determine the Present and Future Spatial Distribution of Population, Employed Residents, Workplace Employment and Vehicle Ownership for the eThekwini Metropolitan Area, eThekwini Transport Authority, January 2011
[v] A new product growth model for consumer durables, F. Bass, 1969
[vi] Electric Vehicles: Holy Grail or Fool's Gold, P. Mohseni, R.G. Stevie