Electric Vehicles as Storage Devices for Supply-Demand Management

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Abstract
The use of electric vehicles as storage devices is investigated, with a view to improving the supply/demand matching of electrical networks. Consideration is given to making this supplementary function compatible with the primary function as a means of transport. Case studies showed that, where solar energy is the primary energy source, daytime charging, combined with evening/overnight regeneration, provides the optimum matching. Large car parks, close to the place of work, would be used for charging. Conversely, for wind energy, charging is generally best carried out overnight. This would therefore be performed largely in residential areas. Network reinforcement would include extra transformers for MV feeders to car parks, and higher capacity LV feeders in residential areas.

I. INTRODUCTION

The future of energy use is characterised by a number of problems, two of which are depletion of fossil fuel reserves, and carbon dioxide emissions from those fuels. Transport, in particular, is almost totally dependent on petroleum oil derivatives [1]. A number of renewable energy technologies are being developed, both for general application and for transport. Electric vehicles are an example of the latter, and offer the potential to overcome some of the limitations of renewable energy in general, as will be described.

Electric vehicles are one of a number of sustainable technologies being developed for transport. Others include –

- Hydrogen powered vehicles, usually incorporating fuel cells, but internal combustion engines are also being developed [2].
- Synthetic organic fuels produced from atmospheric carbon dioxide and water. These could be used in existing vehicles with little or no modification [3].
- Biofuels. These could be used in existing vehicles with little or no modification [4].

Electric vehicles, hydrogen and synthetic fuels all require a large input of electrical energy. Therefore, these types of transport will have a significant impact on fossil fuel depletion and carbon dioxide emissions only if the electricity is derived from a sustainable carbon-neutral primary source. For this reason, this paper considers the use of electric vehicles in conjunction with renewable sources of energy.

Many of the renewable sources of energy – particularly solar and wind – have highly variable availability, which is not generally well matched to variations in demand. In order to determine the requirements and options for supply-demand matching in the future based on renewable energy, the current situation (based on fossil fuels) is first considered. Variations in availability do not generally apply, and supply-demand matching is therefore load-led. The demand for energy varies throughout each day, due to patterns of use by customers. This daily cycle varies throughout the year, due to seasonal variations in particular demands, e.g., space heating results in a higher demand in winter. This variation in load is conventionally met by a combination of base load (coal-fired steam turbines, which operate at high efficiency and constant (or slowly varying) output) and peak load (gas turbines, which operate at lower efficiency, but can run up to maximum power in a short time) [5].

II. MODELLING OF SUPPLY-DEMAND MATCHING PROVIDED BY ELECTRIC VEHICLES

In order to evaluate the effects of different types of variability of both supply and demand, two sources – solar and wind – are considered, along with geographic locations, where heating and air conditioning are the primary demands. Thus four case studies were investigated for supply/demand matching.

- Solar energy, primary demand – space heating
- Solar energy, primary demand – air conditioning
- Wind energy, primary demand – space heating
- Wind energy, primary demand – air conditioning

In each case, the daily heating/cooling load for typical residential and commercial buildings were calculated using EnergyPlus™ [6], for the season of highest demand. In order to compare the demands of residential and commercial premises, buildings typical of small businesses were chosen, so that the load per building would be similar to that for a residential building. The heating/cooling demand was based on the "solair" temperature, the set inside temperature, and the schedules for use of these different types of building. These were aggregated, using C++ software, to give the average heating/cooling load per building. Statistical routines were incorporated into this program, to estimate other loads – lighting, appliances, etc – taking diversity into account. The renewable energy source was scaled such that the energy generated over the selected day approximately equalled the daily demand.

Based on the results of these case studies, two further case studies examined the requirements for reinforcement of the medium and low voltage distribution networks.

A. Solar energy, primary demand – space heating

The location chosen was New York (latitude: 41ºN). This is in a transition climatic zone, where heating is required in winter and air conditioning in summer. January was selected as the month with the maximum demand for space heating. The heating demand is shown for January 15th in Figure 1, for both residential and commercial buildings. An aggregate is also shown based on a mix of 2/3 residential buildings and 1/3 commercial buildings.

The total load (not including EVs) per building is shown in Figure 2, together with solar generation based on 36 m^2 of south-facing optimally tilted panels (operating at 15 % efficiency) per building (not necessarily located on the building). The resulting surplus/deficit is also shown.

The period of energy surplus occurs from 9:00 am to approx. 4:00 pm. During this period, the batteries of electric vehicles could be charged from the grid. As this is during the working day (Mon to Fri), cars would be parked at the place of work, or in municipal car parks nearby. Both the morning and evening rush hour periods are during times of deficit. As many cars are not available for grid support at these times, alternative sources of stored energy would be required. The deficit continues into the evening, and stored energy from the EV batteries would be required for grid support – via the users' domestic charging point. However, sufficient charge would have to remain after this, for the user to drive to work the next morning. Therefore, daytime charging (9:00 am to 5:00 pm) would have to provide sufficient energy for the drive home after work, grid support overnight, and the drive to work the next morning. Scaling of the charging system would need to based on these requirements.

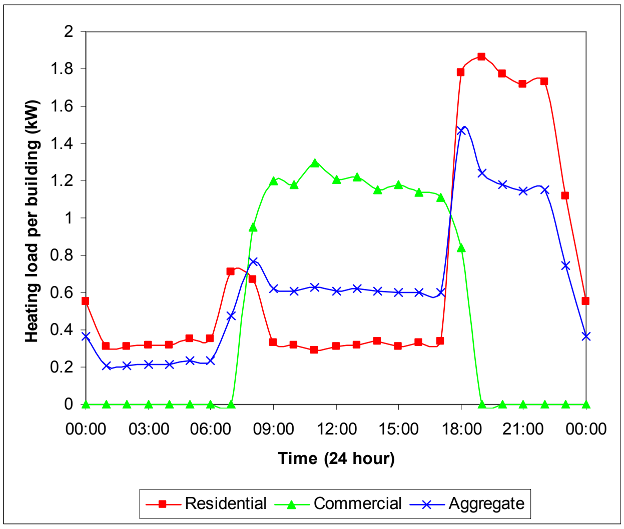

Figure 1. Daily heating demand for residential and commercial buildings in New York, January 15th.

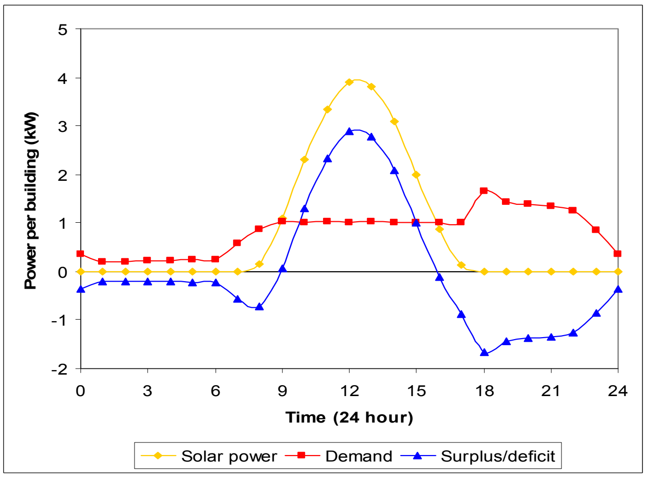

Figure 2. Solar power, load demand and surplus/deficit for New York, January 15th.

The capacity of the distribution network needs to be determined for two locations – commercial centres and residential areas. In commercial areas, the peak charging load during the hours of daylight combines with the peak demand during working hours in the nearby buildings. This results in a high demand for power to be brought in by the distribution network. However, given the concentrated location of EV charging centres (and some commercial loads), much of the required upgrading would be in the form of medium voltage feeders connecting directly to these load centres, with low voltage distribution being largely on-site. This would be less disruptive than upgrading the (more dispersed) low voltage network. Building integrated PV, on commercial buildings, or as canopies over car parks/charging centres, could provide some of the load, and reduce the requirements on the distribution network.

In residential areas, the highest demand is in the evening. During the winter, solar availability is low at this time of the day, so on-site generation is negligible. In the early evening, many vehicles are travelling home from work, and are thus unavailable for grid support. Later in the evening, when these vehicles have reached home, they are available to meet local demand, thus reducing the power import via the distribution network.

Based on all of these considerations, the highest demand on the network is in the early evening. As the existing network is already scaled to meet this demand, and both on-site generation and EVs would be absent at this time, relatively little upgrading should be necessary.

B. Solar energy, primary demand – air conditioning

The location chosen was Shanghai (latitude: 31ºN). This is also in a transition climatic zone, where heating is required in winter and air conditioning in summer. August was selected as the month with the maximum demand for air conditioning. The cooling demand is shown for August 15th in Figure 3, for both residential and commercial buildings. An aggregate is also shown based on a mix of 2/3 residential buildings and 1/3 commercial buildings.

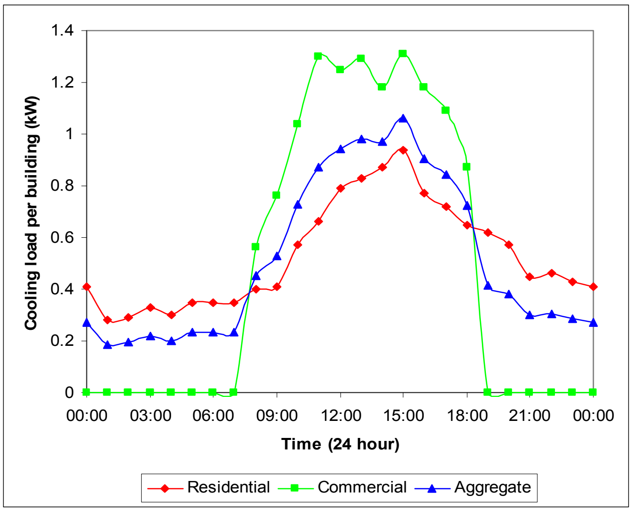

Figure 3. Daily heating demand for residential and commercial buildings in Shanghai, August 15th.

The total load (not including EVs) per building is shown Figure 4, together with solar generation based on 18 m^2 of south-facing optimally tilted panels per building. The resulting surplus/deficit is also shown. Compared to Case Study *A*, there is greater matching of supply and demand (as is generally the case where air conditioning is a major component of demand). As a result, both the surplus and deficit are lower. However, they occur at the same times of the day – surplus during the middle of the day, and deficit in the evening. The availability of EVs for grid support would also follow a similar pattern – being largely unavailable during the morning and evening rush hours.

The requirements for upgrading the distribution network will be similar to those in Case Study *A*, but on a lower scale. The locations in both studies – New York and Shanghai – are in transition climates, where space heating and air conditioning are required. In each case, the requirements for the distribution network are highest in winter, when space heating is the primary demand. Therefore, scaling of the necessary upgrading of the network should be based on the requirements at this time of the year.

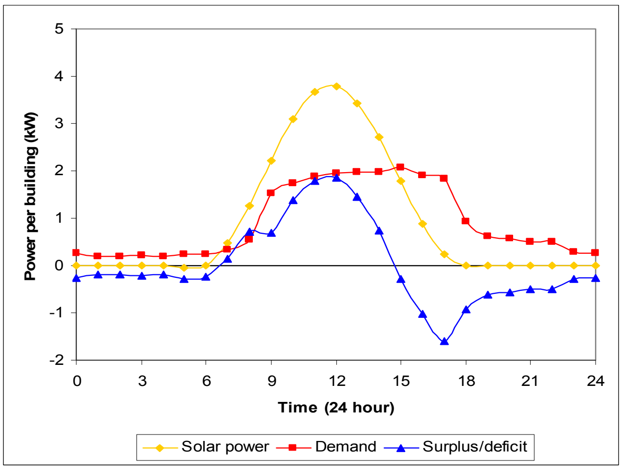

Figure 4. Solar power, load demand and surplus/deficit for Shanghai, August 15th.

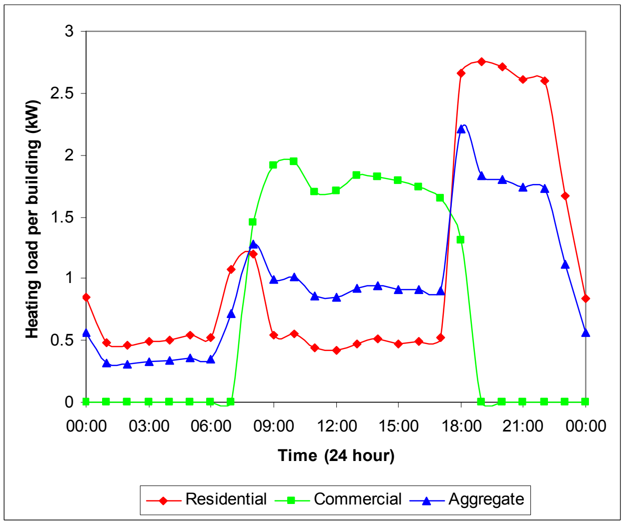

Figure 5. Daily heating demand for residential and commercial buildings in Montreal, January 16th.

C. Wind energy, primary demand – space heating

The location chosen was Montreal (latitude: 45ºN). This is in a cold climatic zone, where heating is the major demand. January was selected as the month with the maximum demand for space heating. The heating demand is shown for January 16th in Figure 5, for both residential and commercial buildings. An aggregate is also shown based on a mix of 2/3 residential buildings and 1/3 commercial buildings.

The total load (not including EVs) per building is shown in Figure 6, together with wind generation based on 2.7 kW (rated power at windspeed 10 m/s) per building. For this day, the periods of maximum deficit occur during the morning and evening rush hours, when many vehicles will be in use, and hence not available for regeneration. Although some of the deficit is due to low wind speeds at these times of this particular day, a large part (especially in the evening) is due to high demand. Thus deficits at these times of the day could be expected to be fairly frequent. Therefore, an alternative form of storage will be required to cover these periods.

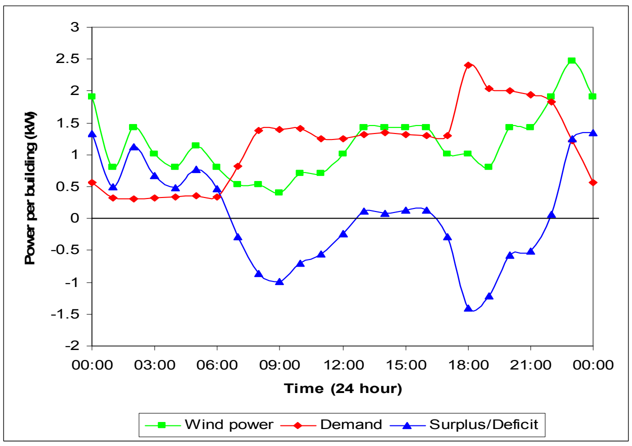

Figure 6. Wind power, load demand and surplus/deficit for Montreal, January 16th.

Considering this day and other days, where the daily variations in wind speed/power are different (results not shown), there are periods of both surplus and deficit during both the working day and overnight. Thus both charging and regeneration functions will be required at the company/municipal car parks, and similarly both functions will be required at residential facilities.

As most of the wind power is assumed to be generated by large wind farms outside the city, this will be fed to load centres via the (transmission and) distribution network.

The greatest demand on a given distribution feeder will be when charging of EVs coincides with a peak for other demands. This applies both to large central car parks, fed directly by MV feeders, and residential areas, where the network includes LV distribution. The anticipated demand on the network will be greater than the current demand, and will determine the need for network reinforcement.

D. Wind energy, primary demand – air conditioning

The location chosen was Lisbon (latitude: 39ºN).). This is in a moderately warm climatic zone, where cooling is the significant demand in summer. August was selected as the month with the maximum demand for air conditioning. The cooling demand is shown for August 16th in Figure 7, for both residential and commercial buildings. An aggregate is also shown based on a mix of 2/3 residential buildings and 1/3 commercial buildings.

The total load (not including EVs) per building is shown Figure 8, together with wind generation based on 2 kW (rated power at 10 m/s) per building. On this particular day, the wind power is highest during the period from 9:00 am to 6:00 pm. Despite this, the high demand during the working day results in an energy deficit over this period. Conversely, there is an energy surplus during the early morning and evening/overnight, despite the lower wind power. Thus the cycle of surplus and deficit is determined largely by demand, even when the wind supply curve would suggest the opposite, and can be regarded as typical of most days at this location.

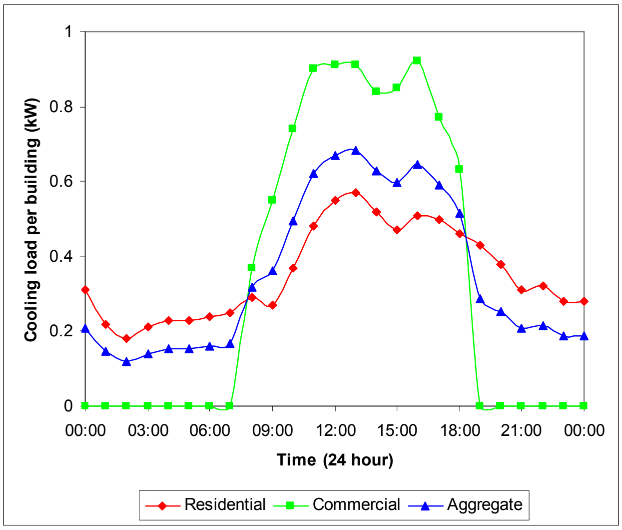

Figure 7. Daily heating demand for residential and commercial buildings in Lisbon, August 16th.

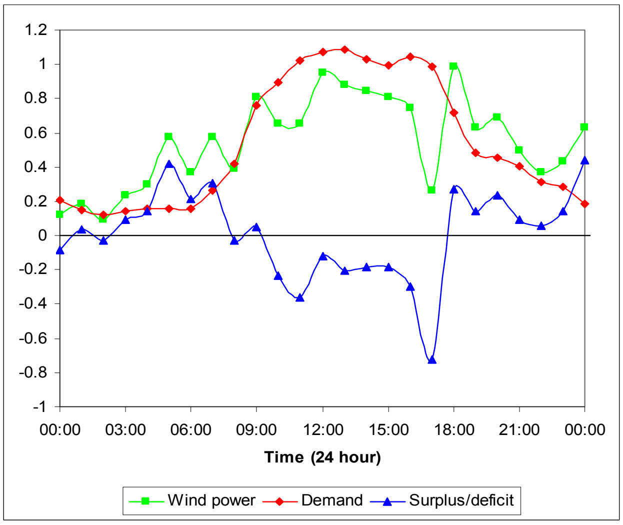

Figure 8. Wind power, load demand and surplus/deficit for Lisbon, Ausust 16th.

Based on this, central car parks would be used largely for regeneration, and charging points in residential areas largely for charging. As was the case for Montreal, the bulk of the wind power is assumed to be generated by large wind farms outside the city. Regeneration could provide for some of the demand in nearby premises – offices, etc – reducing the power required to be transferred from elsewhere. An MV spur from an existing line to the transformer supplying the car park would probably be sufficient for the required power transfer. Charging in residential areas would add to the demand due to pre-existing domestic loads, and reinforcement of the MV and LV networks may be necessary.

E. Solar energy – reinforcement of the medium voltage network

Based on case studies *A* (New York) and *B* (Shanghai), it can be seen that, when solar energy is the largest primary energy source, the most significant increase in power transfer requirement is for daytime charging at central car parks. This requires a dedicated MV feeder to be connected from the existing network to a transformer feeding the LV distribution within the car park.

An ERACS model of a car park (located in Shanghai) with an MV feeder was investigated. The car park had charging points for 1000 cars, and was supplied by an on-site 10 kV /380(220) V transformer. The transformer plus charging units were considered as a single load connected at various points to the 10 kV feeder, shown in Figure 9. The feeder was (initially) supplied by two 35/10 kV 20 MVA transformers with on-load tap changing (OLTC).

In the first model, only pre-existing loads in (largely commercial) buildings were connected, to act as a baseline for further studies. In the second model, a car park was added at busbar 10. A third transformer was added to provide the required power. In the third model, an additional car park was added at busbar 6.

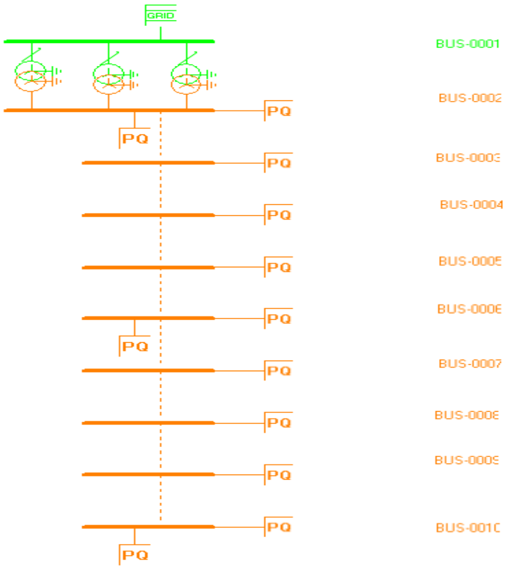

Figure 9. ERACS model of a 10 kV feeder, supplied by 35/10 kV 20 MVA transformers.

As seen in Figure 10, operation of the OLTC ensures that the voltage remains within limits for all points along the line, for all of the loading conditions investigated. Thus the reinforcement required on the existing network (i.e., apart from the feeder to the car park) consists of the extra 35/10 kV transformer.

F. Wind energy – reinforcement of the low voltage network

As seen in case studies *C* (Montreal) and *D* (Lisbon), where wind power is the main form of primary energy, the most significant increase in power transfer requirement is for evening/overnight charging at residential charging points. This may require reinforcement of the LV networks in such areas, and this may then require reinforcement of the MV feeders supplying these networks.

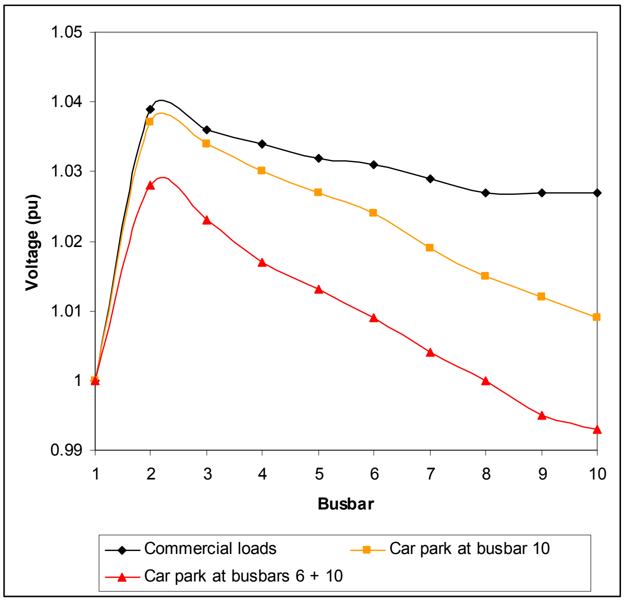

Figure 10. Voltage drop along 10 kV feeder, for baseline and additional loading due to EV car parks.

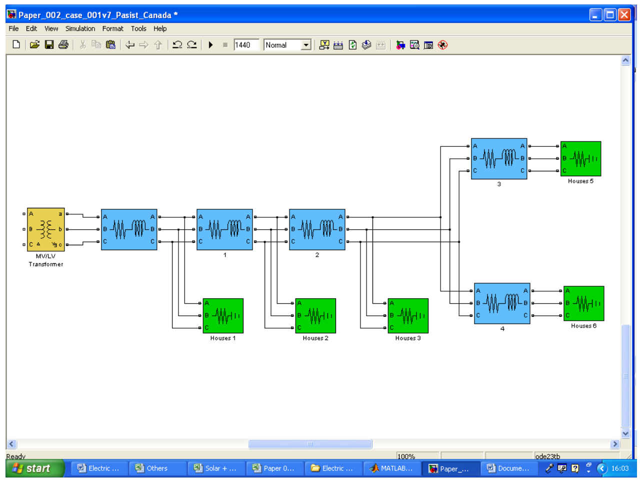

Figure 11. Simplified representation of the LV section of the network, showing cables sections and groups of houses. EVs were connected in parallel with some or all of these groups.

A Matlab Simulink model of the MV/LV network in a residential area was investigated, with EVs connected at various positions. A simplified diagram of the LV section of the network is shown in Figure 11. Approx. 200 houses were connected to the LV network, each drawing a load of 1.3 kW. One hundred EVs were connected to this network, each drawing 2.5 kW, representing 50 % penetration.

In the first run, the vehicles were distributed equally among the houses (i.e. approx. 50 % at each block), representing the case where each house has a driveway/garage, and a EVs may be connected at any of these locations. As seen in Figure 12, the voltage drop is acceptable along all points of the feeder.

In the second run, higher density housing was assumed, where houses do not have individual driveways/garages. In this case, the cars are parked at a local car park, in which charging points are installed.

In order to consider the most demanding case, it is further assumed that this is a pre-existing car park, located close to the far end of the feeder from the transformer. As seen in Figure 12, the voltage at the car park is unacceptably low (point shown as red triangle), and network reinforcement (higher capacity cables) would be required in this case.

IV. CONCLUSIONS AND FUTURE WORK

The case studies considered in this paper show that the daily cycle of supply and demand, and hence surplus/deficit, depends largely on the nature of the primary energy source. In the case of solar energy, the daily cycle of solar availability is more pronounced than the cycle in demand. In order to maximises use of high solar availability in the daytime, charging is carried out at central (workplace) car parks. The extra power transfer incurred does not cause excessive voltage drops on the MV feeders, but extra transformers may be required to increase the capacity of the network.

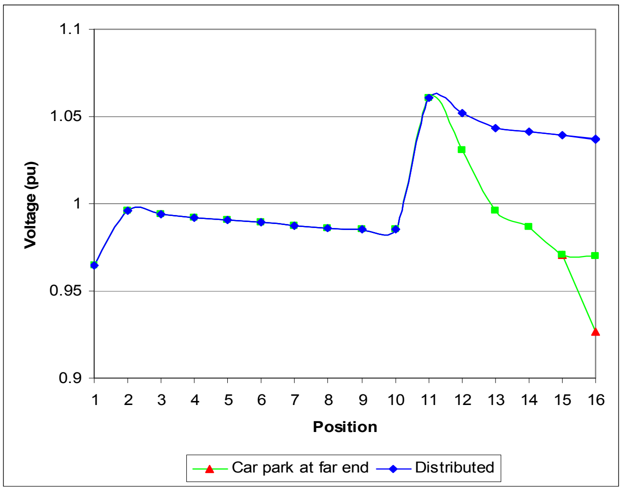

Figure 12. Voltage along the MV and LV feeder, for 50 % penetration.

Where wind is the dominant energy source, there is less of a daily cycle in availability, and the cycle in demand is of greater importance. Generally, low pre-existing demand at night favours charging at this time, which would therefore be done largely at residential charging points. The need for reinforcement will depend on the detailed distribution of charging points.

In this work, a single source of primary energy has been used in each case study, in order to identify the supply/demand balance resulting from characteristic variations in availability. More realistically, a combination of energy sources would be used. In particular, significant use of hydro-electricity would make available a large storage capacity, which could be used to improve supply/demand matching. However, where most of the energy comes from one type of source, the characteristics observed in these case studies would still apply.

The vehicles considered in the case studies are assumed to be privately-owned cars, which are parked (in a car park) during the day, and (at home) during the evening/night, with relatively short periods of use as transport. However, many commercial and public transport vehicles (lorries, buses, etc) are in use for most of the working day, and perhaps well into the evening. Although smaller in number, the distance travelled per vehicle means that they would represent a significant fraction of total transport demand. Electric vehicles in these categories would be unavailable for network support for most of the time, and during the time they are connected, the priority would be recharging for the next day, allowing little flexibility for supply/demand matching.

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