Electric Vehicles as Storage Devices for Supply-Demand Management

David Johnston*, Edward Bentley, Mahinsasa Narayana, Tianxiang Jiang, Pasist Suwanapingkarl, Ghanim Putrus
School of Computing, Engineering and Information Sciences, Northumbria University
Ellison Building, Ellison Place, Newcastle upon Tyne, NE1 8ST
+44 (0)191 227 4737
david.johnston@unn.ac.uk

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. Typical daily load curves are shown for the United Kingdom in Figure 1 [5]. 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) [6].

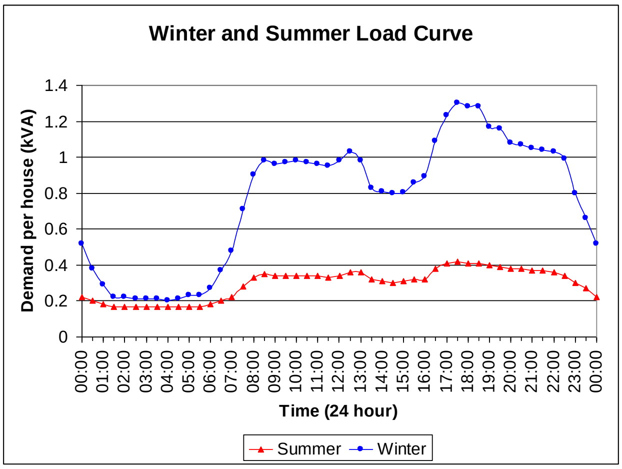

Figure 1. Daily load curves for winter and summer for the UK.

II. REQUIREMENTS FOR SUPPLY-DEMAND MATCHING

The following issues need to be considered.

A. Variability in availability of particular renewable energy resources

A number of renewable energy resources have both predictable (generally cyclic) and random variations. The random variations are usually localised in a small area, and thus average out over the area covered by a typical electricity grid. Thus only the cyclic variations need to be considered for supply-demand matching purposes over large areas. However, localised random variations may

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have significant effects on the power flow, and hence voltage, etc, in specific parts of the network.

The time variation of solar energy sources consists largely of two cycles – a pronounced daily cycle, which is subject to seasonal cyclic variations.

Wind energy does not generally have a significant daily variation, but there may be a large seasonal variation, depending on local climate.

Hydro-electricity has inherent storage, which can compensate for variation in river flow, rainfall, etc. Wave energy has similar variability to wind, i.e., largely seasonal. Tidal energy has an approximately twice daily cycle, which is phase-locked to the moon. Where tidal energy forms a significant component of total supply, this cycle would need to be considered in supply-demand matching.

B. Variability in demand

Variations in demand include both daily and seasonal variations, and a weekly variation – due to different lifestyle patterns between the working week and the weekend. A major component of energy demand for buildings is for heating or cooling (air conditioning) [7]. Demand, and cyclic variations therein, will therefore be dependent on climate at the location in question.

- In cold climates, the primary energy demand is for space heating. The daily cycle has a maximum overnight, and this is most pronounced in winter.
- Conversely, in hot climates, air conditioning is the major demand. The highest daily demand is in mid afternoon, with this being most accentuated during summer.
- In certain regions, e.g., the mid latitudes of the United States and China, there is demand for heating in winter and air conditioning in summer. As a result, the daily cyclic demand is largely reversed between these two seasons.

C. Options for supply-demand matching

In order to ensure that sufficient power is available at all times, based on a mixture of renewable and conventional energy, a number of strategies can be adopted, often in combination.

- The generating capacity can be oversized, such that the power output exceeds demand, except under the most unfavourable circumstances. However, this results a large surplus capacity under more typical operating conditions, which is uneconomical.
- Greater use can be made of the generators which provide peak load. However, this includes gas turbines, which are less efficient and have higher fuels costs. This could result in higher overall generation costs [6].
- Energy storage systems can be used to store electrical energy, when there is a surplus in availability, and return this energy to the grid, when availability is low and/or there is high demand. Existing systems for implementing this include pumped hydro-electric storage [2, 4]. Electric vehicles could provide a similar function, if present in sufficient numbers in the future.

In determining the requirements for storage systems, both power and energy capacity must be considered. For instance, a peak demand which must be met by current and future systems is the surge in use of kitchen appliances, e.g., kettles, in the intervals during sports events or popular films. The peak power is very high, but the period over which it occurs is short, so the total energy is relatively small. Conversely, winter space heating demand, which contributes a large fraction of the evening peak, as shown in Figure 1, lasts for a number of hours, and thus constitutes a larger total energy. Any energy storage system must be able to meet both these requirements.

D. Compatibility of transport and energy-storage functions

In considering electric vehicles as a means of electrical energy storage, a number of factors must be taken into account.

- When the vehicles are in use as transport, they are not available for either absorbing or supplying electrical energy. This situation will occur (during the working week) at the morning and evening rush hours (approx. 7:00 to 9:00 a.m. and 5:00 to 7:00 p.m. respectively).
- When the vehicles are in use as transport, they consume energy, which is therefore not available for subsequent regeneration to the grid. As a result, they are net consumers of electrical energy. Thus they have more potential for absorbing surplus power/energy than for making up a deficit.
- In the periods immediately prior to their use as transport, the users' priority for electric vehicles will be that they are fully (or at least sufficiently) charged for the journey ahead. This will limit their availability for regeneration onto the grid.
- The vehicles will be parked at different types of location at different times of the day. This may be related to daily variations in energy supply and demand. For instance, where solar energy is the primary form of supply, there is an energy surplus during the middle of the day, and a deficit during the remaining hours. During the working week, cars will be parked close to the owner's place of work in the daytime (energy surplus), and at their home during the night (energy deficit).

In order to use the storage capacity of electric vehicles to contribute to supply/demand matching, a number of measures can be adopted, based on the factors above.

- Additional forms of storage – such as pumped hydro-electric storage – can be used, during the periods when many of the vehicles will be in use, and thus unavailable for grid support. In many countries, the capacity of existing or future reservoirs for energy storage is limited. By concentrating their use within the times when electric vehicles are unavailable, the required energy storage capacity is reduced, and may then be within the limits of the resources available.

- The primary function of a charging station (charging versus regeneration) should be dependent on its type of location. This would be related to the time during which it would generally be in use, and how this relates to the energy surplus/deficit at that time. For instance, corporate or municipal car parks providing spaces for vehicles, while their owners are at work, would be used predominantly during the working day. In cases where solar energy is the main source of supply, there will be a surplus during this period. On this basis, charging stations at such car parks should be primarily for charging of vehicle batteries. Conversely, residential charging stations would be used largely during the evening and night, when there is an energy deficit. These stations should therefore be used primarily for regeneration. Favourable export tariffs could act as an incentive for vehicle owners to provide this service.
- Given the owners' requirement to use their vehicles to drive to work, an owner-settable over-ride should be provided, preventing energy from being drawn from the vehicle battery, for the purpose of regeneration, during the early morning period. This could include the option to charge the battery during this period. Where the type of renewable energy has low availability at this time, resulting in a deficit, owners would miss favourable export tariffs and pay unfavourable import tariffs. (Exemptions could be made for emergency workers and vehicles on 24 hour call.)

E. Requirements for the distribution network

Consideration must also be given to the locations of the generating systems, EV charging points and loads. The distance between these will be an important factor in determining the capacity requirements of the distribution network (and, in some cases, the transmission network). Some of the renewable technologies being developed (notably solar photovoltaic panels) are suitable for on-site generation, possibly including building integration [8]. As the energy generation system is close to the point of use, this reduces the energy which must be transferred via the distribution network (although peak transfer requirements may still be high in the case of poor temporal matching of supply and demand).

As electric vehicles may be charging from, or discharging to the network, they may add to the existing requirements, or improve local supply/demand matching, which reduces the need for power to be supplied from elsewhere. In determining the required capacity of the distribution network, the daily and seasonal cycles of supply, demand and EV use must be considered, and the capacity is then based on the maximum required power transfer during the cycle. For instance, if the optimum time for EV charging is overnight, when most vehicles will be at the users' homes, and the level of on-site generation (or its availability) is low, then the capacity of the distribution network in residential areas will be based on the peak of the sum of domestic and EV charging demand.

III. 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™ [9], 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 2, 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 3, 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.

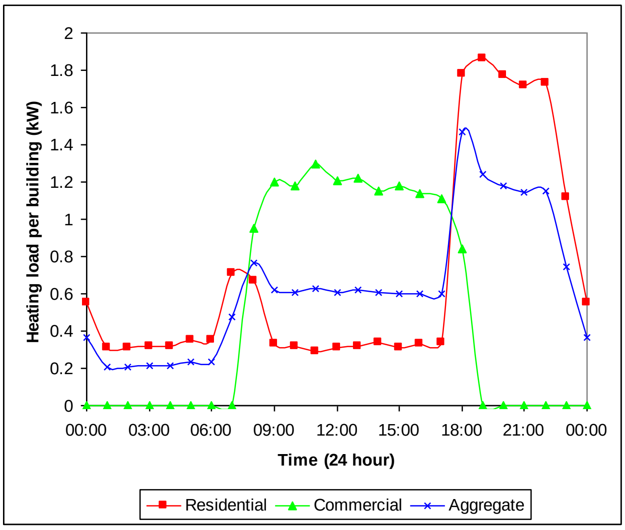

Figure 2. Daily heating demand for residential and commercial buildings in New York, January 15th.

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.

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

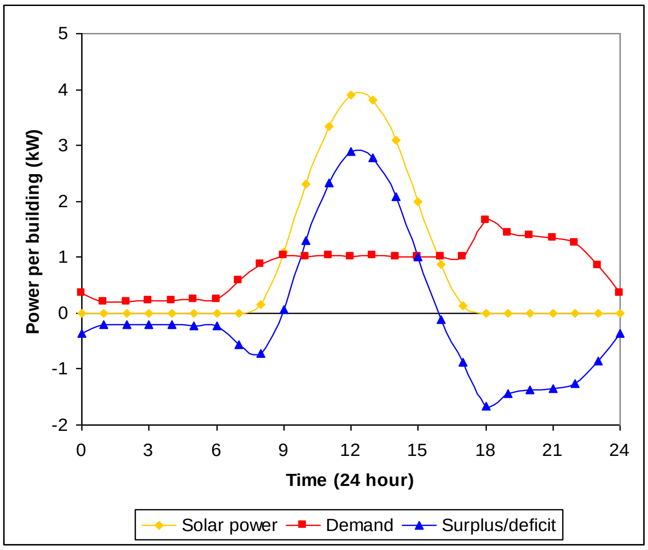

Figure 3. Solar power, load demand and surplus/deficit for New York, January 15th.

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 4, 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.

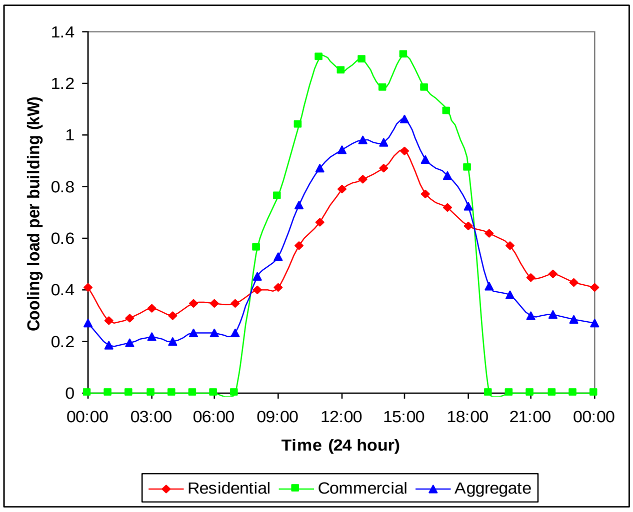

Figure 4. Daily heating demand for residential and commercial buildings in Shanghai, August 15th.

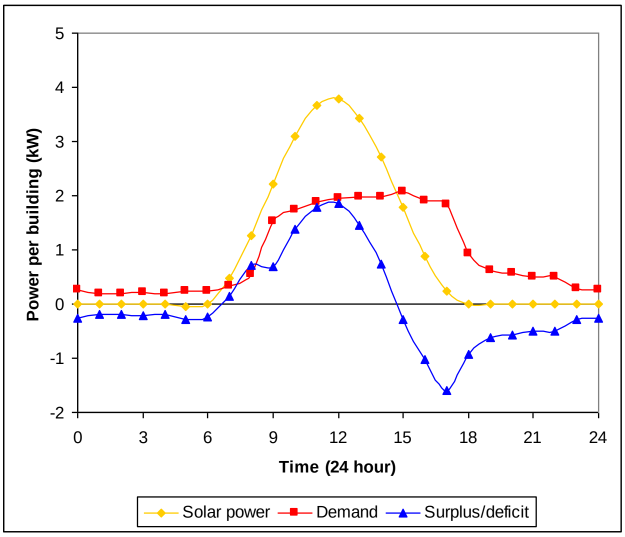

Figure 5. Solar power, load demand and surplus/deficit for Shanghai, August 15th.

The total load (not including EVs) per building is shown Figure 5, 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.

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 6, 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 7, 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

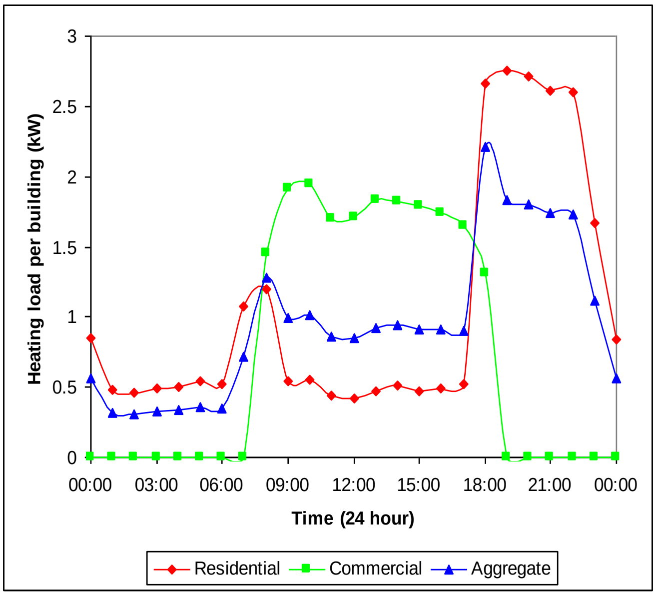

Figure 6. Daily heating demand for residential and commercial buildings in Montreal, January 16th.

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.

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.

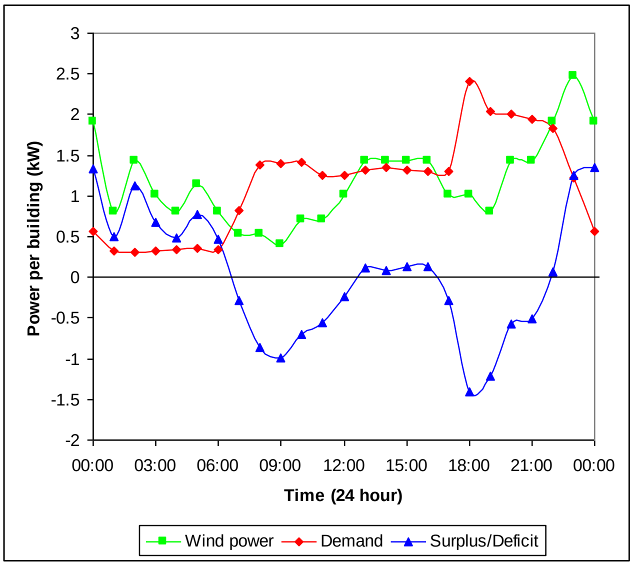

Figure 7. Wind power, load demand and surplus/deficit for Montreal, January 16th.

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 8, 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 9, 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.

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.

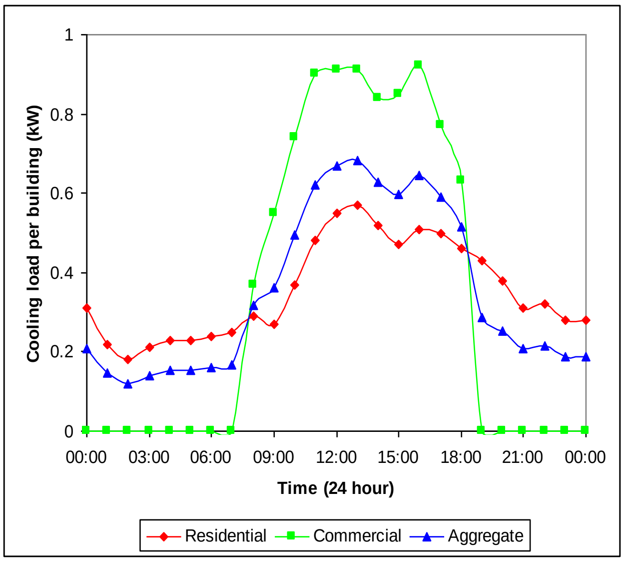

Figure 8. Daily heating demand for residential and commercial buildings in Lisbon, August 16th.

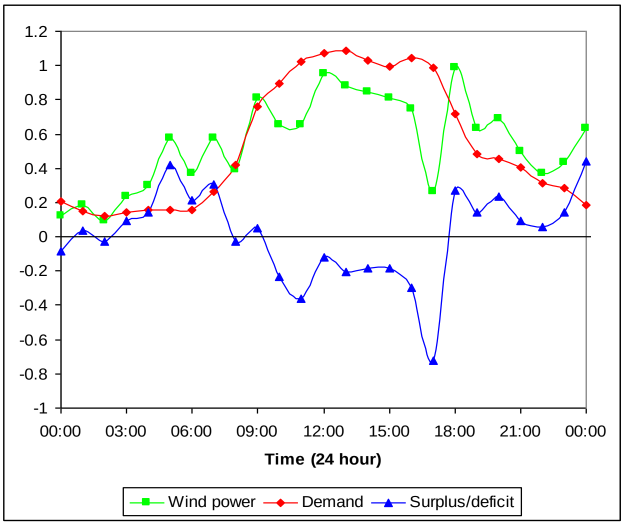

Figure 9. Wind power, load demand and surplus/deficit for Lisbon, Ausust 16th.

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 10. The feeder was (initially) supplied by two 35/10 kV 20 MVA transformers with on-load tap changing (OLTC).

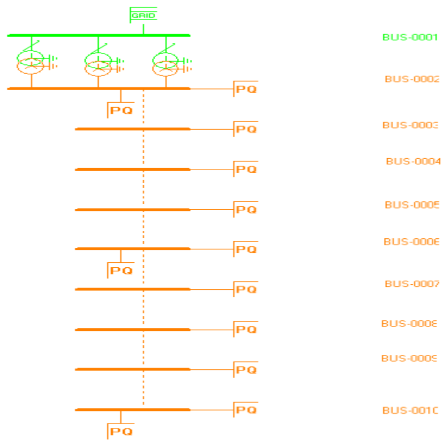

Figure 10. ERACS model of a 10 kV feeder, supplied by 35/10 kV 20 MVA transformers.

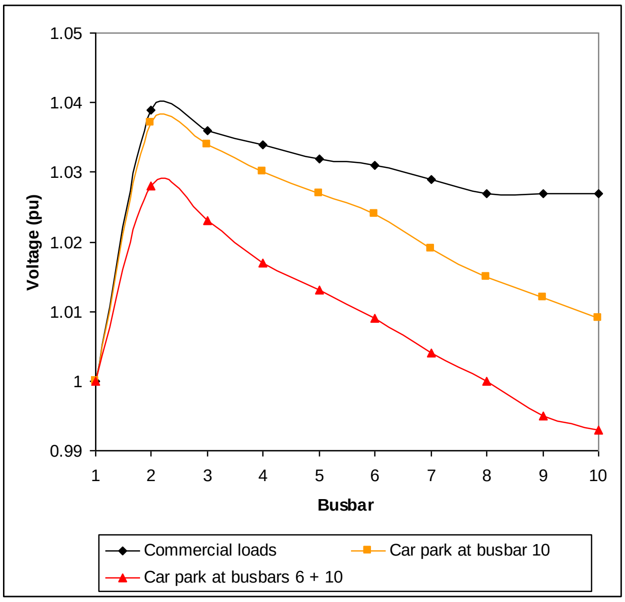

Figure 11. Voltage drop along 10 kV feeder, for baseline and additional loading due to EV car parks.

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. As seen in Figure 11, 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.

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 12. 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 13, 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.

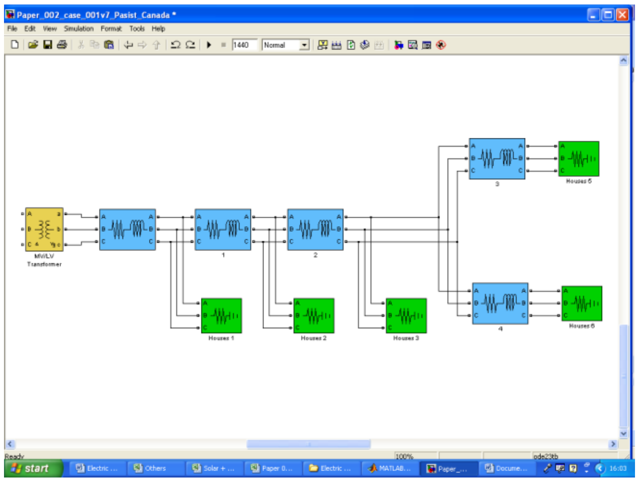

Figure 12. Simplified representation of the LV section of the network, showing cables sections and groups of houses. EVs were connected in parallel with some or all of these groups.

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 13, 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.

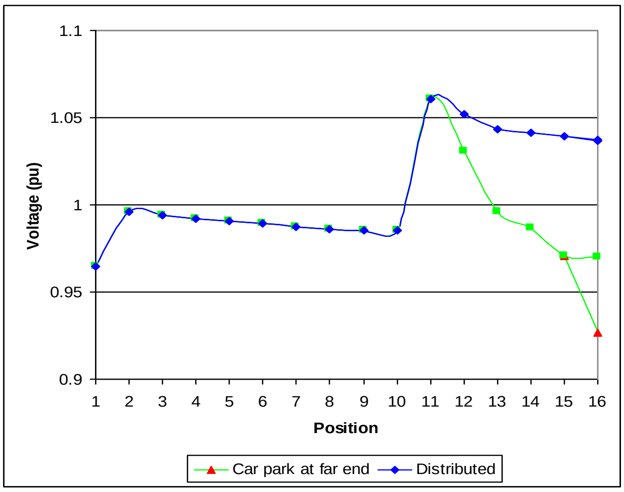

Figure 13. Voltage along the MV and LV feeder, for 50 % penetration.

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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