INTEGRATED PLANNING OF DISTRIBUTION NETWORKS: INTERACTIONS BETWEEN LAND USE, TRANSPORT AND ELECTRIC VEHICLE CHARGING DEMAND

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ABSTRACT

This paper presents an agent-based simulation tool for integrated planning of distribution networks with high presence of electric vehicles (EVs). A simulation model, applied here to a case covering part of London, has been created with which various land use configurations and EV penetration levels can be tested. The energy demand of an EV fleet can thus be characterised and its interaction with land use, transport networks and charging infrastructure can be analysed providing insight in the impact on the electricity distribution network as well as possible ways to mitigate the negative effects.

INTRODUCTION

According to the United Nations, in 2014 more than half of the world's population (54%) lived in urban areas [1]. In the case of Europe, this figure increases to 73%, and with the projected rate of urbanisation, 82% of the population is expected to live in cities by 2050. Also, it is estimated that 75% of the final energy demand is currently used in cities with probably a similar proportion of CO_2 emissions [2]. These figures show the importance of the analysis of urban energy systems and the reduction of their environmental impacts.

To achieve these aims it is essential to understand the mechanisms of urbanisation and their influence on urban structures, people's mobility and on people's energy consumption behaviour [3]. Urbanisation, transport behaviour, energy demand, technology adoption, and the emergence of new energy services markets are all factors interrelated in a complex network which includes different social, technical, economic and environmental elements. In addition, in the next decades new technologies such as distributed generation, advanced district heating, electric vehicles and energy storage systems are expected to be part of future low carbon urban scenarios, increasing the level of complexity.

In this context, a multidisciplinary and holistic approach is necessary to design incentives to improve the city performance, allowing the deployment of future smart and sustainable cities. In this work an integrated urban energy systems model is developed to support the design and planning of distribution networks with a high presence of plug-in electric vehicles (PEVs), providing useful insights about the design of future energy networks with high levels of interrelated energy systems.

INTEGRATED URBAN ENERGY SYSTEMS

In this work it is envisioned that the integration of different energy systems can generate opportunities to improve the operational efficiency of the overall system. According to [4] there are potential co-benefits that include increased system reliability and performance, cost reductions and minimisation of environmental impacts. However, some challenges related with the vulnerability and resilience of interdependent networks have been noticed in the literature [5] and need to be addressed in future work. Analytically the many interrelationships between different sectors in an urban system are not easy to study with traditional methods and therefore it becomes necessary to develop advanced computational tools to support the decision of the stakeholders involved in the process of design and planning of these interrelated energy systems.

Some examples of energy systems integration that can be found in the literature are the following:

- **Land use and transport**: The developed models in this area explore the relationships between transportation networks and changes in land use with the correspondent change in economic activities. This is a very active research area with some published comprehensive reviews [6]-[8].
- **Land use, transport and energy:** These works include energy demand not only from the vehicles but also from stationary demand sources related with households and firms. Recent works in this group are the iTEAM project [9] and the SynCity tool kit [10].
- **Transport and power grids**: This research area deal with problems of energy management, networks design and planning, and energy markets [13] which crosses the traditional silos of energy and transport infrastructures. Here, the PEV with its distributed storage capacity represents a link between transport and power systems and it creates the opportunity for new grid services such as demand response, frequency regulation, etc. In previous works by the authors this topic has been addressed, in particular the analysis of the demand flexibility and the potential for grid services provision [11], [12].

Another important aspect that has been highlighted in recent literature is the need for the inclusion of social aspects in the analysis of urban energy systems processes from a bottom-up perspective [14], [15]. The analysis of this socio-technical system requires us to understand the relationship between energy technologies and users. It can be argued that any technological development is related with improvement in people's quality of life and therefore it will be shaped by social factors. These factors need not only to be included in an aggregated level, representing a group of the population with some similar characteristics and behaviour, but also they need to be included at the individual level.

In addition, decentralised energy system creates the need for a more disaggregated analysis, in which decisions of individuals can have a relevant impact in the aggregated system's behaviour. In this regard, if an integrated modelling approach is going to be developed, it needs to explicitly incorporate social behaviour and decision mechanisms at an individual level so interventions which affect specific behaviour or sub groups can be analysed. With this, the study of every stage of the decision processes involved in the operation and evolution of urban energy systems could be possible, and the system's behaviour could be generated from a bottom-up perspective. This is a complex phenomenon to be analysed in future research efforts that would require a deep exploration in the social and psychological aspects of urban energy technologies, and therefore a complete analysis of it is out of the scope of this papers. This work can be seen as an attempt to set up the framework in which these social aspects can be incorporated in the analysis of integrated urban energy systems, specifically looking at the impact on distribution networks.

Finally, the design and planning of future smart and sustainable cities is a challenging task that needs to account for the participation of different stakeholders (urban planners, architects, power networks operators, demand aggregators, consumers, etc.). In this context, the development of participatory and collaborative planning tools that integrate GIS functionalities with simulation models appears to be a sensible strategy. These tools can represent an important element in the support of those involved in the urban energy systems planning discussion [16], [17]. The model developed in this work has been tested previously in two workshops with architecture and urban planning schools at TU Berlin and London Metropolitan University to contribute in a multi-stakeholder context allowing for an iterative design process in which expert insights and scenario simulations feed each other to generate improved designs [18].

In this work an agent-based simulation model (ABSM) is proposed for the analysis of integrated urban energy systems in a multi-stakeholder environment. With this simulation tool different indicators such as energy demand, transport behaviour, etc. can be analysed holistically. The ABSM includes behavioural rules to represent agent's decision, in particular regarding the activities, transport and PEV charging processes. Specifically, the analysis is focused on the interactions between land use distribution, transport and PEV charging infrastructure, and the electricity demand.

METHODOLOGY

Based on a previous ABSM [11], a more detailed GIS-based representation of the city land use is incorporated with which the PEV ownership in the different regions of the urban area can be estimated.

The new ABSM implemented in this work uses a spatial city layout defined with the corresponding land use, area, density, household size, etc. The transport networks and the distribution nodes have been included in the spatial representation of the model as well.

A synthetic population of electric vehicle owners is generated and allocated according to the land use, density and car ownership distribution. The land use is also used to determine the location of agent activities. This population of agents uses the transport network to travel in order to accomplish the different activities, generating travel patterns with their corresponding energy consumption. Electric vehicle owners are modelled as agents who take their travel and charging decisions based on their parameters and states (working status, PEV's state of charge (SOC), charging infrastructure access, etc.). The agent's behavioural rules allow it to decide when and where to charge based on the availability of charging infrastructure. In this work, smart charging strategies are not considered.

Finally, the model creates a dynamic simulation, generating the power load profile disaggregated by different areas and by different agent types. The ABSM is then used to measure various outputs related with the transport and energy use. A simplified diagram of the model structure is shown in Figure 1. More information about the model can be found in [11].

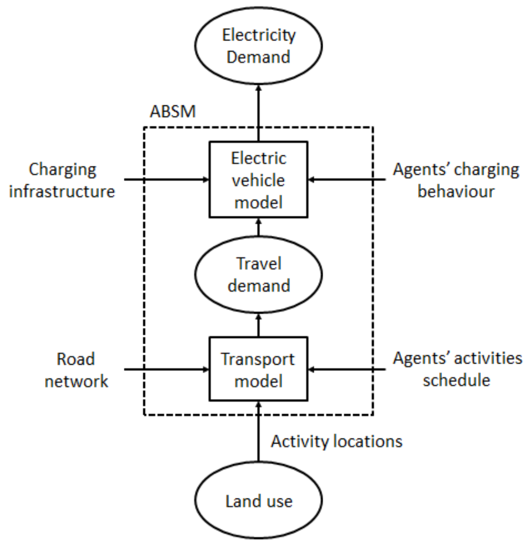

Figure 1. ABSM structure diagram.

SCENARIO DEFINITION

In this work, the methodology is tested using the Old Oak Common (OOC) site as a case study. The site lies in north-west London, UK, and has been proposed as a new smart neighbourhood development following new infrastructure investments that will significantly improve the connectivity with fast links to central London, Heathrow airport and other parts of England. As such the site is a prime candidate for new housing and commercial development which can become an example of a low-carbon urban area. The OOC site lies at the border of a few existing neighbourhoods in different boroughs (see Figure 2) and a successful analysis should take this environment and the dynamics between these areas into account. In this case study different options for land use are explored to inform the design of the OOC area.

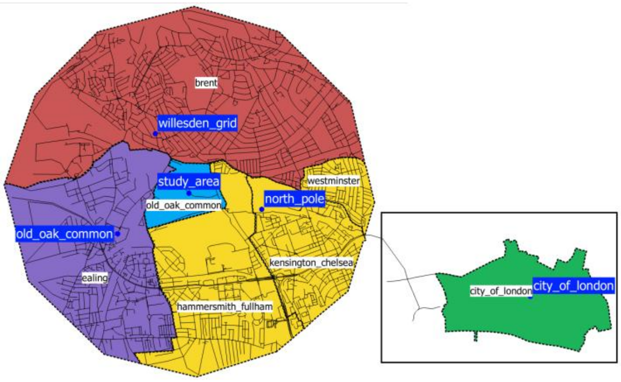

Figure 2. City layout with the OOC site in the centre of the circle (light blue) and main DN substations (blue dots).

The maps for the area are extracted from [19], and edited in the open source QGIS software [20]. To account for trips made to other parts of the city, the City of London borough is also included as an external area. In Figure 2 the city layout is shown with the OOC area in the centre (light blue colour). In this figure, the different colours represent the different areas linked with each of the distribution network (DN) main substations (blue dots). For an easier analysis, the OOC area is linked with a fictitious substation called "Study Area". Different possibilities for the land use for the study area are analysed (e.g. only residential, only industrial, etc.). For the surrounding boroughs, the land use is defined using the information available in [21] and simplified into four categories (Residential, Commercial, Industrial and Leisure). The final land use distribution used in the simulation is shown in Figure 3.

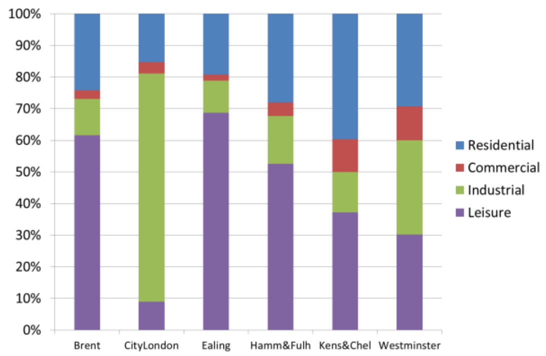

Figure 3. Borough land use distribution.

For the agent activities definition, two types of PEV owners are considered, namely "Worker" and "Non-Worker". The proportion of Worker agents is 61.8%, based on [22]. The activity schedule for each type of agent used in this work is shown in Table 1, using the notation presented in [11], and different PEV diffusion levels are considered (from 10% up to 50%). The rest of the scenario (e.g. electric vehicle, charging infrastructure, etc.), is defined in [11].

Table 1. Agent's activity schedule.

Activity Schedule {(ACT_j, MPT_j, SD_j, PD_j)}			
Worker	(work, 8, 1, 1.0)	*Non-Worker*	(work, 9, 1, 0.1)
	(shopping, 13, 0.5, 0.3)		(shopping, 11, 0.5, 0.8)
	(work, 15, 0.5, 1.0)		(work, 14, 1.0, 0.0)
	(home, 17, 1.0, 0.7)		(home, 13, 05, 0.8)
	(leisure, 18, 1.0, 0.3)		(leisure, 17, 1.5, 0.5)
	(home, 21, 1.0, 1.0)		(home, 21, 1.5, 1.0)

RESULTS AND DISCUSSIONS

The illustrative results are meant to make clear what kind of outcomes can be achieved and how they can be relevant for electricity distribution networks planning.

Transport and charging behaviour

Considering a PEV diffusion level of 10% (7,788 PEVs) for the simulation, the probability distribution of the travelled distance presented in Figure 4 shows that "Worker" agents travel longer distances than "Non-Worker" agents, as the former have to find a working place located mainly in the distant areas of City of London and Westminster (see Figure 2 and Figure 3).

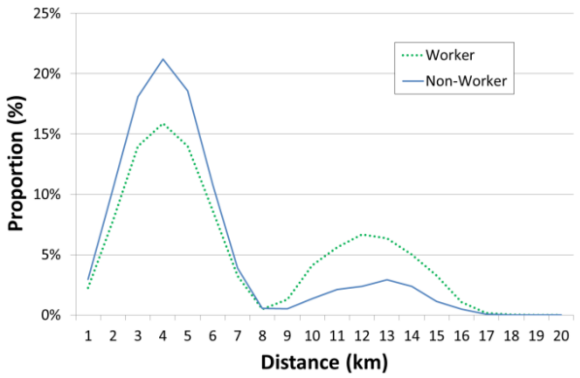

Figure 4. Travelled distance per trip per type of agent.

Regarding the charging behaviour, the simulation shows that with a higher access to residential charging points, the number of off-schedule charging events (which occur when the SOC is below a 30% threshold) declines. In the same way, with higher residential charging access, the duration of on-schedule charging events (which occur when the PEV reaches at an activity's destination with access to a charging point) decreases (see Figure 5).

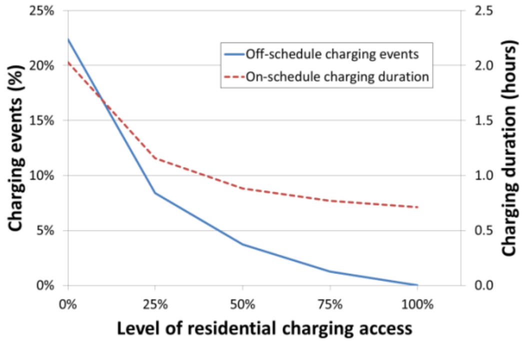

Figure 5. Charging behaviour indicators.

Electric vehicle charging demand

Figure 6 shows the variation in PEVs electricity demand in the "study area" substation when different land uses are defined for the OOC area. The most dissimilar profile corresponds to the industrial case in which the demand starts early with a peak around 09:00 when workers arrive and start charging their PEVs (in this case, no controlled charging strategy is considered). Figure 7 shows the electricity demand for each distribution network node (shown in Figure 2), including the study area (with mixed land use). It can be seen how the demand varies among the different areas and times of the day. For example, in the morning (around 9:00) a peak occurs in City of London due to workers who travelled from the rest of the city, reached their destination with charging access, and plugged-in their PEVs.

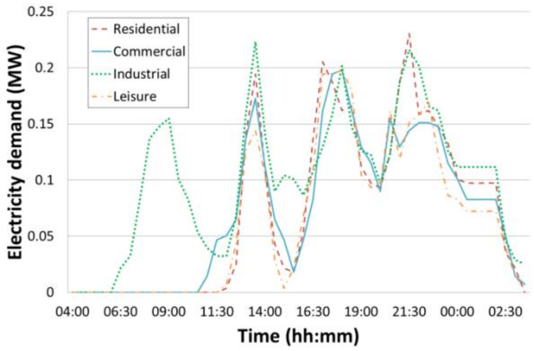

Figure 6. Electricity demand of PEV in the study area for different land use.

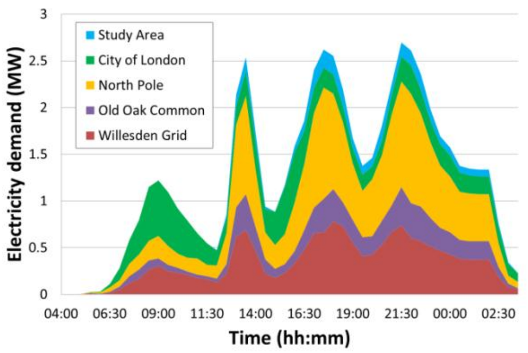

Figure 7. Electricity demand of PEV by substation.

On the other hand, afternoon and evening peaks are mostly affected from people going back to residential areas (North Pole substation). Finally, Figure 8 shows the effect of higher levels of PEV diffusion in the electricity demand. In this case the OOC area land is defined as totally mixed (i.e. equal proportion for residential, commercial, industrial and leisure). The results show a non-linear increment of the demand and a sharpening of the peaks when more PEVs are considered in the area.

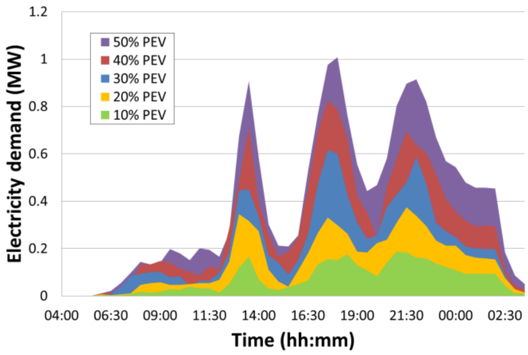

Figure 8. PEV power load in the study area (with mixed land use) for different level of PEV diffusion.

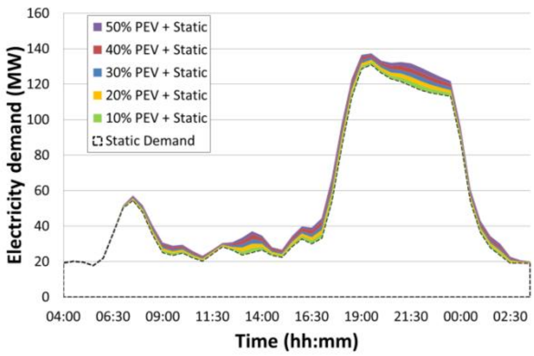

Figure 9. PEV and residential electricity demand.

Interaction with static demand

Finally, in order to analyse the interaction between the mobile demand and the static demand related with the residential sector, the static electricity profiles were estimated for each of the boroughs using the *Electricity Demand profile* generator developed by the University of Strathclyde [23]. The demographic data and the annual electricity consumption were extracted from [21] and modified according to each borough's simulated area. The cumulative PEV demand and the estimated static demand for the whole area are shown in Figure 9 for different levels of PEV diffusion. According to these results, high levels of PEV diffusion could have an impact at this level of distribution networks. In the case of 50% of diffusion, the total energy related with the PEVs represents an 11% of the static demand, and in terms of power, at some moments of the day (around 13:30) it can represent up to 47% of the static demand. At the peak demand (around 19:30), however, the PEV power load represents an increment of only 5%.

CONCLUSIONS AND FURTHER WORK

This work presents a support tool for distribution networks planning with a high presence of plug-in electric vehicles. The developed model allows the simulation and analysis of the interaction between a set of heterogeneous individuals (drivers) and a technological network (transport and charging infrastructure). The results of this work demonstrate the flexibility and adequacy of this bottom-up tool for the integrated analysis of urban energy systems to evaluate the impact of various land use and EV diffusion scenarios.

Further work could be done in order to get a deeper understanding of the influence of agent activities and charging access on the energy demand. Also, a more realistic and detailed representation of the distribution network and static demand is needed in order to assess the possible impact of PEVs. Finally, smart charging strategies can be applied using the results of this work in order to reduce those impacts, and other energy vectors could be added into the analysis such as heat and water to include higher levels of interdependencies.

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