SCENARIO-BASED MODELLING OF RESIDENTIAL ENERGY DEMAND UNCERTAINTY USING ACTIVITY-BASED APPROACH

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Overview

Driven by the need to decarbonise, the energy sector is undergoing a shift towards greater reliance on renewable sources as well as use of local generation and storage capabilities. This ongoing shift towards use of renewable energy sources has made energy supply volatile, due to dependence on inherently dynamic phenomena, such as wind or sunlight (Abrell et al., 2019). This volatility in supply is nowadays compounded with uncertainty concerning the demand, due to variation in activity participation and the consequent requirements for energy. As for the localised energy solutions, these range from local generation (such as roof-mounted photovoltaic panels) as well as local storage, including based on electric vehicles (V2G). In an ideal scenario, local generation and storage is matched with the local demand, both spatially and temporarily, reducing the need for transmission. In practice, such conditions are rarely met by themselves, creating the need for transmission or, in the extreme circumstances, imbalance and infrastructure overload. However, incentivisation strategies, in the form of demand side response (DSR) strategies or flexible storage (e.g. batteries) can provide a means for correcting such imbalances, especially at local levels.

What this implies is the need for high resolution demand prediction that can provide a detailed account of the expected demand, alongside the associated uncertainty (Tascikaraoglu et al., 2014). Whilst modelling of energy demand profile is a well-established practice, both at an aggregate and disaggregate level, quantification of the associated uncertainty is undertaken less frequently. Even less explored is the ability to quantify sources of uncertainty in demand (e.g. is it due to stochasticity in activity-travel behaviour or due to heterogeneity in the link between such behaviour and energy consumption) at a disaggregate level and under various scenarios. However, such insights are critical to management at both strategic (ensuring suitable infrastructure capacity) as well as day-to-day operations, such as network balancing where strategies explicitly accounting for uncertainty can be applied to particular scenarios (robust optimisation). Towards this end, the present paper proposes an approach for quantification of uncertainty in energy demand using the activity-based approach as applied in a variety of scenarios, including varying levels of electric vehicle adoption, prevalence of work from home or sociodemographic composition. In addition, we show how coordination in activities can lead to a reduction in uncertainty, establishing the upper bounds on effectiveness of such approach in uncertainty reduction.

Methods

At the core of the study lies activity-based agent residential energy demand simulator developed as part of the Integrated Development of Low-carbon Energy Systems. The demand simulator consists of three components: population synthesiser, activity synthesiser and energy demand model. Population synthesiser is responsible for creating a suitable representation of the desired population, either via direct draws from real population (e.g. census) or by artificially synthesising population data with desirable attributes. The activity synthesiser component relies on a multiple discrete-continuous extreme value (MDCEV) model that produces allocation of time to several in-home, out-of-home and virtual activities (Rovira et al., 2022), whilst scheduling is undertaken using a set of discrete choice models. The synthesiser is calibrated using the UK Time Use Survey 2014-15 (Gershuny & Sullivan, 2017). The final component of the simulator is activity-based energy demand model (Pawlak et al., 2021) based on a log-linear regression framework calibrated using data from the UK (Grunewald & Diakonova, 2018).

The demand simulator can produce point estimates of the expected energy demand, based on the mean values of the input parameters and input covariates. However, an even more useful feature from the standpoint of the present research is the capability to provide confidence intervals surrounding such estimates and derived from accounting for three main types of uncertainties: a) covariates that are fundamentally stochastic and exogenous to the consumers, e.g. weather b) covariates endogenous to the consumers, e.g. variations in activity-travel behaviour; c) uncertainty resulting from stochastic nature of the parameters' of the modelling components. We term the 'a', 'b' and 'c' uncertainties, 'exogenous', 'behavioural' and 'model', respectively. The end output of such analysis is therefore an energy demand profile for a particular surrounded by a number of confidence intervals that represents the aforementioned sources of uncertainty. This approach provides a means of not only assessing the magnitude of uncertainty in local demand, but also trace back its source and, in turn, provide an indication concerning effectiveness of mechanisms directed at reducing such uncertainty, e.g. improved forecasting or design of behavioural incentives, e.g. activity coordination or shifting electric vehicle charging schedule.

To demonstrate how this approach can provide workable insights into demand management strategies, we present three scenarios for which we predict the associated expected demand alongside the various uncertainties. In the first scenario, we show how coordination in work from home activities can reduce the associated behavioural uncertainty, as previously hinted in the context of application of the earlier version of the simulator in the context of understanding implications of Covid-19 lockdowns (Trask et al., 2021) under joint scenarios of work-from-home proliferation and electric vehicle ownership. In the second scenario, we show how the uncertainty can be reduced by an increased proliferation of vehicle-to-grid (V2G) capable electric vehicles, especially if accompanies by appropriate pricing schemes. In the third scenario, we show how improved forecasting (across any or all of the model components) can result in a reduction of model uncertainty. For all the aforementioned scenarios, we provide a proxy valuation of such reductions in uncertainty of the demand by comparing it against the costs of battery-based storage that would be required to buffer against such uncertainties.

Results

The initial results are derived from application of the aforementioned methodology in the context of modelling the impacts of work-from-home (WFH) policies during the Covid-19 lockdown in the UK. The simulation based on artificially synthesised 4,200 households revealed that coordination among agents in participation in work-from-home can contribute towards reduced uncertainty in the demand as behavioural patterns become more certain, despite the possibility of net consumption in the area increasing. We thus prove the value of coordination between agents in participation in activities. In addition, through comparison of the results to price of storage, we are able to quantify the size of potentially available incentive budget that could be utilised to reach the desired activity pattern. Arguably, if such budget exceeds value of required incentives to induce suitable coordination, the findings could pave the way towards another mechanism for improving sustainability of the energy system operation under demand and supply volatility. Our ongoing analysis is looking at the remaining scenarios, where we expect to quantify reduction in demand uncertainty under various EV adoption rates and pricing regimes. Lastly, our results are expected to shed light on the value of improved forecasting, in light of proliferation of forecasting methodologies for both exogenous inputs to our models (e.g. weather forecasting) as well as behavioural and energy demand forecasting.

Conclusions

The energy systems are required to rapidly decarbonise, the pathway towards which leads inescapably through volatile supply in the form of renewable energy sources. However, the physics and engineering underpinning the energy grids require a fine balance between the supply and demand, on a continuous basis. Consequently, reduction of uncertainty in demand becomes a paramount consideration, given the otherwise unattainable buffer (storage, fast generation) costs. Towards this end, the paper contributes with presenting a simulation-based methodology for quantifying uncertainties alongside tracing back its source. Through exploration of three scenarios, the paper shows ways in which uncertainties in demand can be reduced, via consumer coordination, EV adoption and pricing strategies as well as improved forecasting overall. In addition, by providing proxy valuations of such uncertainty reductions, the analysis contributes towards devising novel economic tools for achieving more sustainable, i.e. balanced energy systems, that can better accommodate volatility in the clean energy generation.

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