INVESTIGATION OF THE IMPACT OF FLEXIBLE LOADS' PARTICIPATION IN ELECTRICITY MARKETS

Dimitrios PAPADASKALOPOULOS
Imperial College London – UK
d.papadaskalopoulos08@imperial.ac.uk

Goran STRBAC
Imperial College London – UK
g.strbac@imperial.ac.uk

ABSTRACT

Realization of the significant demand flexibility potential in deregulated power systems requires its integration in electricity markets. In previous work, the authors developed a novel market mechanism enabling flexible demand participation in the market setting without requiring flexible loads to submit their operational characteristics to a central entity, in order to avoid the associated communication, computational and privacy limitations. In this paper, case studies in the context of the UK system are carried out in order to quantify, analyze and compare the impact of flexible loads' market participation on system demand, prices, generation costs, demand payments and wind curtailment. The examined flexible demand technologies include electric vehicles with smart charging capability, electric heat pumps accompanied by heat storage for space heating and wet appliances with deferrable cycle operation, due to their significant penetration and flexibility potential.

INTRODUCTION

Environmental and energy security concerns have paved the way for the electrification of the transport and heat sectors, expected to introduce a significant amount of new electrical demand, accompanied by significant generation and network costs to support it. In the same time however, technological developments have enabled the wide penetration of flexible loads, exhibiting an ability to reschedule users' demand requirements in time through different types of storage [1].

Suitable deployment of this flexibility could yield significant technical, economic and environmental benefits for the users of such flexible loads and the power system as a whole. In the emerged deregulated environment, the realization of this demand flexibility potential necessitates its integration in electricity markets. This paradigm change requires suitable modifications in traditional, one-sided markets which were designed to treat demand as a fixed, inflexible forecasted load [2].

Market integration of the demand side through traditional centralized market mechanisms requires flexible loads to submit their operational characteristics to the market operator, who clears the market through a central optimization problem. Under significant demand participation, the communicational and computational scalability of such mechanisms is at least questionable, while they are likely to raise privacy concerns.

A second approach involves dynamic pricing schemes, enabling loads' participation without the requirement to reveal their properties to a central entity, but by individually responding to fixed time-variable prices. However, such schemes fail to realize the actual value of demand flexibility, since prices are not influenced by demand response close to real-time; without accounting for this feedback of demand on prices, inefficient or infeasible market outcomes occur [2].

In [3], the authors proposed, analyzed and tested a novel day-ahead pool market mechanism combining the solution optimality of centralized mechanisms with the decentralized demand participation structure of dynamic pricing schemes. Based on mathematical decomposition principles, the mechanism involves a two-level iterative algorithm. At the local level, flexible loads determine their optimal response to a set of trial prices in order to minimize their energy payments, given their operational constraints. At the global level, the market operator updates the trial prices in an effort to achieve a market outcome satisfying system constraints and objectives.

In this paper, case studies in the context of the UK system are carried out in order to quantify, analyze and compare the impact of flexible loads' market participation through the mechanism proposed in [3]. The examined flexible demand technologies include *electric vehicles (EV) with smart charging capability*, *electric heat pumps (EHP) accompanied by heat storage for space heating* and *wet appliances (WA) with deferrable cycle operation*, due to their significant penetration and flexibility potential in the UK and beyond.

CASE STUDIES FRAMEWORK

The market mechanism proposed in [3] has been applied to a simulation model of the UK power system. Due to the rather low projected penetration of flexible demand in the next decade, the year 2025 is selected as the setting of the case studies, for which projections concerning conventional generation and inflexible demand characteristics are drawn from [3]-[4]. The case studies refer to a typical day of the winter season. While different scenarios are examined for the electrification of the transport and heat sectors, the penetration of WA in the system is assumed fixed to the 2025 projected levels, since their operation is already based on electricity consumption. Detailed operation models of the examined flexible demand technologies are presented in [3].

Regarding EV, fully electric light- to medium- size vehicles are considered, each carrying out two journeys per day and connected to the grid while parked at users' home. Original data about UK driving patterns was taken from [5]. When operated inflexibly, EV are assumed to start charging immediately after being connected to the grid until are fully charged. Their flexibility potential is associated with the smart charging capability, enabling them to charge any time they are connected to the grid.

Concerning EHP, air-source heat pumps space-heating domestic buildings are assumed; the thermal behavior of such buildings is modeled through the *EnergyPlus energy simulation software* [6]. When operated inflexibly, the electrical power consumption of the EHP follows the thermal power consumption of the space heating load. Their flexibility potential is related to the incorporation of a heat storage component decoupling the absorption of electricity by EHP from the actual heat consumption.

Regarding WA, three different types -dishwashers, washing machines and integrated washer/dryers- are considered, operating in domestic buildings and executing one operational cycle per day. When operated inflexibly, their cycle starts immediately after the users load and activate them. Their flexibility potential is associated with time-delay functionality, enabling them to defer the execution of their cycle from the time the users activate the appliance within a latest termination time pre-set by the users [7].

The following sections explore the effects of demand flexibility on system demand and price profiles, generation costs, demand payments and wind curtailment with respect to a *Base scenario*, where the three considered demand technologies do not exhibit flexibility and the whole system demand is inflexible.

FUNDAMENTAL IMPACTS OF DEMAND FLEXIBILITY

Flexible loads reschedule their demand from high-priced (peak) hours to low-priced (off-peak) hours in order to minimize their payments. This shift results in a *flattening effect on the system demand (and price) profile*, with peaks' reduction and valleys' filling, which is translated to an improvement of the system demand's load factor.

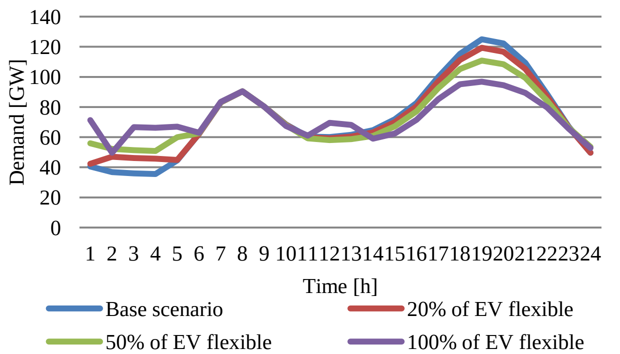

Fig. 1: Impact of different EV flexibility scenarios on system demand (100% EV/EHP penetration, no wind generation)

This effect is enhanced as the percentage of EV, EHP and WA exhibiting flexibility is increased. This is illustrated in Fig. 1 for a case of 100% penetration of EV and EHP (100% of light- to medium-size vehicles are EV and 100% of domestic buildings are space-heated by EHP), no wind generation in the system and different percentages of EV exhibiting flexibility. *This flattening effect is also enhanced as the individual flexibility extent of each flexible load becomes more significant*. This is illustrated in Fig. 2 for a case with flexibility deployment in EHP and different energy capacities of the heat storage component in each building (expressed as % of the daily heat energy demand in the respective building).

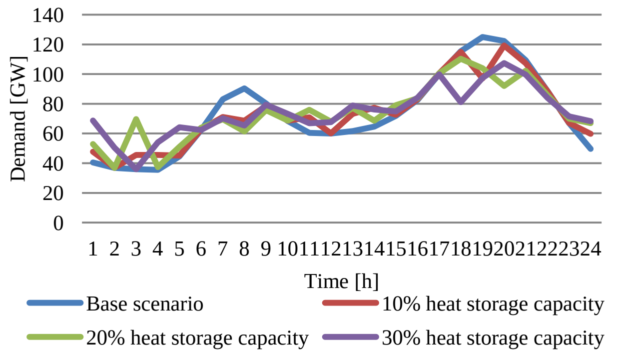

Fig. 2: Impact of different EHP flexibility scenarios on system demand (100% EV/EHP penetration, 100% of EHP exhibiting flexibility, no wind generation)

Since the hourly marginal cost of the generation side increases with the hourly demand, the flattening effect on the demand profile yields *significant savings in system generation costs*. The migration of flexible demand away from peak hours leads to *a significant demand peak reduction and an even larger price peak reduction*, due to the disproportionately high generation costs of peaking plants. *EV, EHP and WA demand payments are very significantly lower when they exhibit flexibility* since they can shift their demand towards hours with much lower prices. Demand flexibility results in *considerable payment savings for inflexible demand* as well since: i) inflexible demand is generally higher during hours that flexible loads yield price reductions (peak hours) and lower during hours that flexible loads yield price increases (off-peak hours) and ii) price reductions during peak hours are larger than price increases during off-peak hours due to the disproportionately high generation costs of peaking plants.

As shown in Table 1, these beneficial effects are increased with an enhanced demand flexibility, with the only exemption associated with the correlation between the flexible demand payments and the percentage of flexible loads; as the latter increases, flexible loads' payments are reduced since prices during off-peak hours (towards which they migrate) are increased.

Table 1: Impact of different EV flexibility scenarios on system indices, in % reduction with respect to Base scenario (100% EV/EHP penetration, no wind generation)

	20% of EV flexible	50% of EV flexible	100% of EV flexible
Generation costs	5.87%	12.09%	20.17%
Demand peak	4.52%	11.29%	22.59%
Price peak	68.50%	71.83%	75.60%
Flexible demand payments	79.88%	77.92%	74.82%
Inflexible demand payments	25.86%	28.30%	31.52%

COMPARISON OF IMPACTS OF DIFFERENT FLEXIBLE DEMAND TECHNOLOGIES

This section compares the impacts of the three examined flexible demand technologies when each is deployed separately and exhibits an assumed maximum flexibility extent [3]. Fig. 3 and Table 2 indicate that *flexible EV generally yield the most significant demand flattening effect and the highest benefits in terms of generation costs and inflexible demand payments savings, demand and price peak reductions, and they experience the highest own payments savings*. This trend can be attributed to: a) the *relative demand flexibility extent* of the three considered technologies, as well as b) their *demand patterns in the case they are operated inflexibly*.

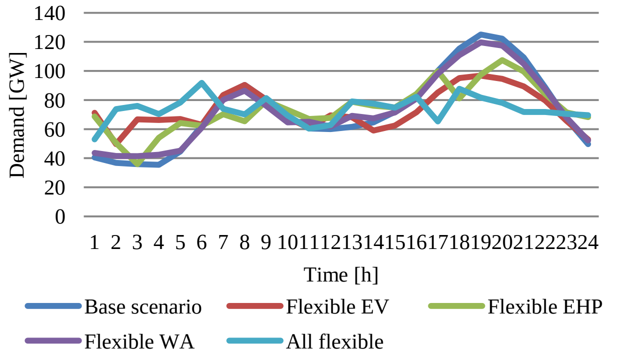

Fig. 3: Impact of flexible demand technologies on system demand (100% EV/EHP penetration, no wind generation)

Flexible EV generally exhibit the highest flexibility due to the significant energy and power capacities of their batteries (with respect to their modest driving energy requirements) and their low energy losses. Flexible EHP exhibit the highest energy consumption due to the energy intensity of space heating loads and -in contrast with EV and WA- are connected to the grid throughout the day. However, their flexibility is limited by the practical space availability restrictions constraining the maximum plausible energy capacity of their heat storage and the considerable energy losses of the latter. Finally, flexible WA can shift the whole amount of their energy demand and the WA energy requirements at the period between their activation and the initiation of their cycle are generally negligible. However, their flexibility is limited by the fact that the time window over which they can obtain their required energy is constrained by the strict maximum cycle deferability set by their users and their relatively small energy intensity.
Apart from their flexibility extent, the % benefits yielded by the three technologies depend on their demand patterns in the case they are operated inflexibly. Under inflexible operation, the total electrical demand of EV is much more concentrated in the expensive peak afternoon/evening hours of the day due to the users' driving patterns and the assumed home charging scenario. This effect enhances the relative benefits of flexibility deployment in EV with respect to EHP and WA.

Table 2: Impact of flexible demand technologies on system indices in % reduction with respect to Base scenario (100% EV/EHP penetration, no wind generation)

	Flexible WA	Flexible EHP	Flexible EV	All flexible
Generation costs	6.32%	14.77%	20.17%	24.28%
Demand peak	4.29%	14.06%	22.59%	26.57%
Price peak	68.26%	72.77%	75.60%	76.91%
Flexible demand payments	52.32%	43.96%	74.82%	51.12%
Inflexible demand payments	27.41%	30.88%	31.52%	32.32%

IMPACTS UNDER DIFFERENT SCENARIOS OF TRANSPORT AND HEAT SECTORS' ELECTRIFICATION

Fig. 4 depicts the system demand for different scenarios regarding the penetration of EV and EHP when all demand technologies are operated inflexibly. As the EV and EHP penetration increases, their inflexible operation yields disproportionally higher increase in demand peaks with respect to the increase in total energy consumption and enlarges the demand (and price) differentials between peak and off-peak periods, due to the temporal patterns of vehicles' and heating systems' use by the consumers.

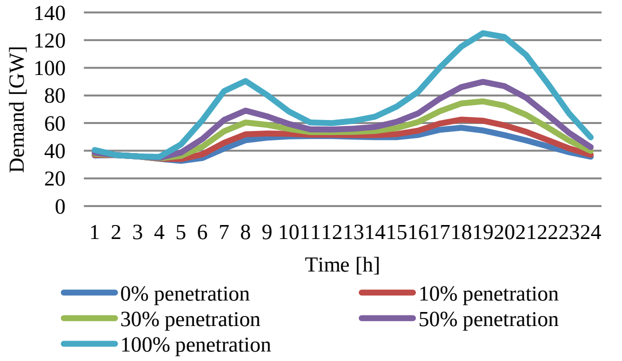

Fig. 4: System demand under inflexible demand operation and different EV/EHP penetration scenarios

Fig. 5 and 6 illustrate generation cost savings and demand peak reductions respectively for the demand flexibility scenarios of the previous section, different EV/EHP penetration scenarios and no wind generation, and reveal the *increased value of demand flexibility under an extensive electrification of transport and heat sectors*.
The effect of inflexible EV and EHP operation on demand peaks discussed above, in combination with the effect of the disproportionately high generation costs of peaking plants justifies the increase of generation costs' and flexible demand payments' savings in each demand flexibility scenario as the EV/EHP penetration increases.
Demand peak reductions are also enhanced as the EV/EHP penetration increases under flexibility deployment in EV and EHP, as the inflexible operation of those technologies contributes to the demand peak in the Base scenario. The % demand peak reduction under flexibility deployment in WA decreases with an increasing EV/EHP penetration since the WA number is constant in the different EV/EHP penetration scenarios.

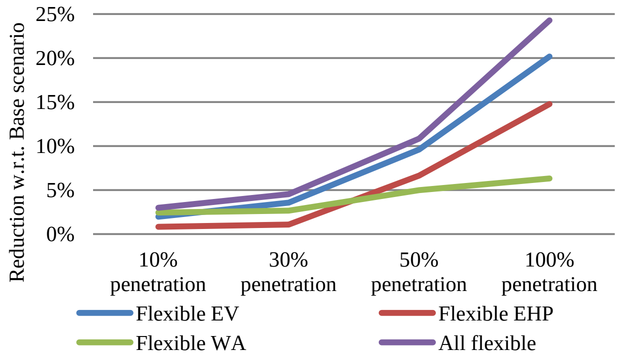

Fig. 5: Impact of different demand flexibility scenarios on generation costs under different EV/EHP penetration scenarios

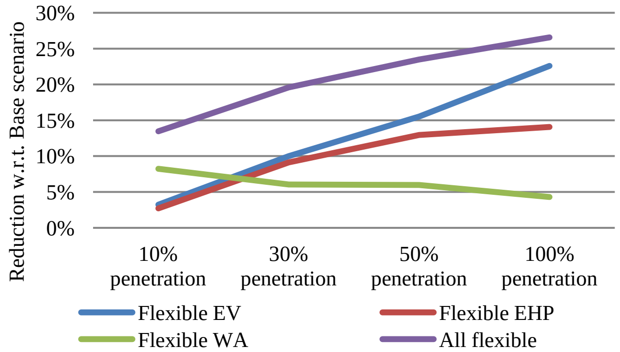

Fig. 6: Impact of different demand flexibility scenarios on demand peak under different EV/EHP penetration scenarios

IMPACTS UNDER DIFFERENT WIND GENERATION SCENARIOS

A case with 100% EV/EHP penetration, a 35GW wind generation capacity and three different scenarios for the wind generation output profile, is examined; all three scenarios exhibit equal daily wind energy productions but dissimilar wind output patterns (Fig. 7).

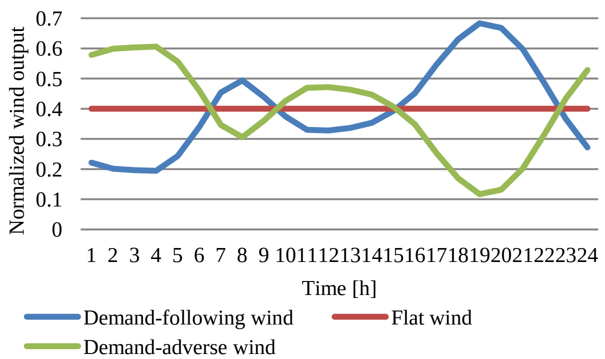

Fig. 7: Assumed wind generation's daily output scenarios

In a similar fashion with an increasing EV/EHP penetration, *a wind generation profile exhibiting a larger pattern deviation with respect to the system demand* results in higher net demand (and price) peaks and -in combination with the disproportionately high generation costs of peaking plants- *increases the value of demand flexibility in terms of generation costs and flexible demand payments savings*, as shown in Fig. 8.

In hours when the sum of wind and must-run generation is higher than the system demand, the excess wind generation is curtailed and the price gets equal to zero. Since zero-priced hours naturally attract flexible demand, *the amount of wind energy curtailed is reduced by the deployment of demand flexibility*, as illustrated in Fig. 9.

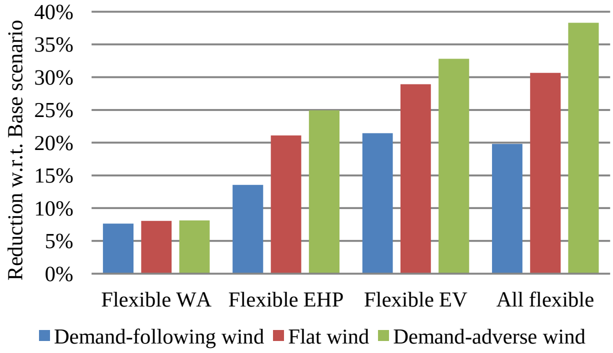

Fig. 8: Impact of different demand flexibility scenarios on generation costs for different wind generation output scenarios

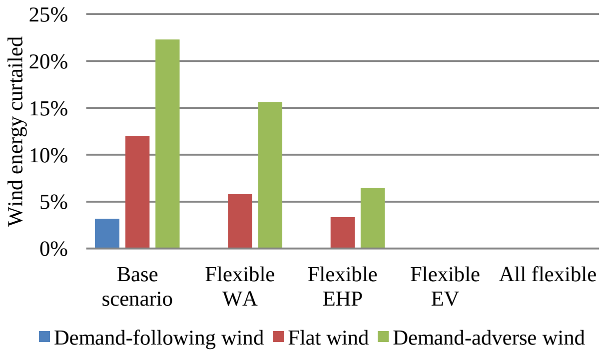

Fig. 9: Impact of different demand flexibility scenarios on wind energy curtailed for different wind generation output scenarios

REFERENCES

[1] G. Strbac, 2008, "Demand side management: Benefits and challenges", *Energy Policy*, Vol.36, No.12, 4419-4426

[2] D.S. Kirschen, 2003, "Demand-Side View of Electricity Markets", *IEEE Trans. Power Syst.*, Vol. 18, No.2, 520-527

[3] D. Papadaskalopoulos, 2013, *A Mechanism for Decentralized Participation of Flexible Demand in Electricity Markets*, Ph.D. Dissertation, Imperial College London

[4] *National Grid*, U.K., www.nationalgrid.com/uk

[5] *2008 National Travel Survey*, U.K. Department for Transport, www.dft.gov.uk

[6] *EnergyPlus Energy Simulation Software*, U.S. Department of Energy, www.apps1.eere.energy.gov

[7] R. Stamminger, 2009, *Synergy Potential of Smart Domestic Appliances in Renewable Energy Systems*, University of Bonn, Shaker Verlag, Aachen, Germany