Capacity Assessment of Residential Demand Response Mechanisms

Simone Pagliuca
Department of Electrical Engineering, Eindhoven University of Technology
simone.pagliuca@gmail.com

Ioannis Lampropoulos
Department of Electrical Engineering, Eindhoven University of Technology
i.lampropoulos@tue.nl

Matteo Bonicolini
Department of Computer Science, Bologna University
bonicol2@cs.unibo.it

Barry Rawn
Department of Electrical Engineering, Delft University of Technology
b.g.rawn@tudelft.nl

Madeleine Gibescu
Department of Electrical Engineering, Delft University of Technology
m.gibescu@tudelft.nl

Wil L. Kling
Department of Electrical Engineering, Eindhoven University of Technology
w.l.kling@tue.nl

***Abstract* - The power system design was mainly based on developing the supply side (supply follows the demand) and minor attention was given in controlling the demand side. During the effort to accommodate larger shares of renewable energy sources, while maintaining the power balance and ensuring the reliability of the power system, the implementation of demand response mechanisms may provide considerable options to reshape the supply of electrical energy. This study presents a new approach for modelling flexible loads and aims to create further knowledge on the potentials of residential demand response concepts. Specific types of loads were modelled as finite states machines, based on behavioural and technical constraints. Then, the available capacity for demand response actions was quantified based on Monte Carlo simulations, and normalised aggregate load profiles are provided for electric vehicles and four typical domestic appliances.**

***Index Terms* - Residential Demand Response, Modelling Domestic Appliances, Electric Vehicles, Aggregation of Flexible Loads, Virtual Power Plant, Ancillary Services.**

I. INTRODUCTION

The incorporation of renewable energy generators in the power system complicates the operation and planning phases due to their less-predictable and intermittent output. In an electrical power system where large scale energy storage solutions are not available, regulating units perform control actions to maintain a momentary power balance between generation and load [1]. Currently, most of the operating reserves are provided by fossil-fuelled generators. However, as our society moves away from fossil-fuelled generation, part of the flexible generation capacity that is available today will be replaced by intermittent renewable energy sources in the future. In this context, all available resources for balancing purposes should be considered, and it is expected that the demand side will also adjust to the supply side. Residential Demand Response can play an important role in the effort to achieve an efficient and reliable power system with high penetration of renewable energy sources.

A. *Purpose and Outline of the Paper*

The contributions of this paper are:

- Analysis of residential loads' characteristics and constraints, and evaluation of demand response capabilities of four specific domestic load elements, and electric vehicles.
- Reconstruction of the aggregate load profile for certain types of domestic appliances and electric vehicles.
- Assessment of the flexibility of the aggregate demand, through modelling and simulations, while taking into account user behaviour (and needs) and devices operational characteristics.

Due to the underlying behaviour of the users, which is dominant in the micro-level (electricity end-use), the available capacity that residential demand response mechanisms can offer vary significantly during the day. However, by employing the Monte Carlo method, the available capacity can be estimated, based on simulation results for different aggregation levels (number of devices under the control area). This paper ends with a proposal for utilising these results in a uniform way for further power system studies of residential demand response mechanisms.

II. FLEXIBLE LOADS MODELLING

A. *Background*

Decentralized power generation is gaining significance in liberalized electricity markets and small size electricity consumers become also potential producers (prosumers). Aggregated under an eligible market entity, and connected through information and communication technologies (ICT), prosumers might be able to compete with conventional technologies in markets for ancillary services. Although on an individual basis, consumers' electricity use is relatively small, the aggregate demand for energy consists of a large portion of the system load. Furthermore, in many developed countries, the residential sector is the largest contributor to seasonal peak demand. Thus, Residential Demand Response (RDR) is a resource that can be exploited in many system applications, such as the provision of secondary reserves [6]. However, due to its dispersed nature it is difficult to be utilised as a uniform resource, in terms of controllability and capacity. Nevertheless, recent advances in ICT open new opportunities for the development of residential demand response mechanisms.

B. Approach

The approach followed in this study, to assess the potential of residential demand response, was through modelling and simulation. RDR exploits a resource already latently present in the system. However, its utilisation should require little or no user intervention during planning and operation, while both the users and system's requirements are respected. Until now, there have been many different perspectives in academia and industry of how to transform this vision into practical applications. Usually, large aggregation and coordinated operation of such devices is assumed, and then directed at a specific problem. However, the intrinsic device characteristics and users' requirements complicate the implementation of demand response schemes. In literature, many different demand response options provided by domestic appliances can be identified. In [2] the authors discuss two options, which are smart-timing (delay of the full appliance's cycle), and interruptions of appliance's cycle. The first option is limited by consumer involvement and is not considered in this paper. The second option considers interruptions of appliances (which are already in operation) for short time periods. If kept under certain limits these interruptions do not compromise significantly the quality of service and require minimum user intervention. The latter option is considered in this paper.

C. Software architecture

Information from electricity utilities about domestic electricity consumption usually consists of aggregated data over many households, without knowledge about the events in the micro level (inside the households).

In order to assess the available capacity for residential demand response actions, a discrete-event probabilistic (Monte Carlo) model was developed, which simulates aggregate load-shifting actions, triggered by an external operator. Four different types of domestic appliances (Refrigerators, Freezers, Washing Machines and Dish Washers) suitable for demand response applications, plus Electric Vehicles (EVs) were modelled as finite state machines. The finite states represent a deterministic power demand over a specific time period equal to 15 minutes. A load shifting action, as implemented in the model, involves two sections; an aggregate load reduction and a sub-sequent energy recovery.

The model consists of two parts which are further discussed in the next sections; a generator of load profiles, and a control mechanism to actuate the load (to perform load-shifting actions). Initially, the model generates load profiles for large numbers of residential loads, and allocates them in a data structure. These aggregate load profiles are illustrated in Fig. 4. Then, a control strategy is applied with the objective to minimise energy imbalance within a Program Time Unit (PTU; electricity trading time unit, equal to 15 minutes in the Netherlands). This means that the projected energy imbalance (per PTU) consists of the input for the controller to decide if and which loads have to switch off at each time step.

Each simulated entity is represented in the data structure (maintaining track of the changes) by four relevant parameters; i.e. type of the device, power consumption level, state of the device, and time available for interruption. The state of the device reflects the status of a device which is in operation and the possibilities for interruption. These discrete states where defined for time intervals of fifteen minutes. Each device can be interrupted at a specific moment during a cycle, based on technical constraints, and the available time of interruption is defined by the user. In this study some rational assumptions were made; for electric vehicles the maximum interruption time was assumed equal to one hour, while for the other domestic appliances an interruption time equal to fifteen minutes was assumed. The developed simulator has been named AB@CUS, its code has been written using C programming language and is conformed to the ANSI C89 and POSIX 2001 standards.

D. Load profiles generator

The aggregate residential load is reconstructed based on two variables, the load profiles illustrated in Fig. 1, and start-up probabilities of the loads' cycles as discussed and utilised in [2]-[5]. The results obtained from the load profile generator are presented in Fig. 4 together with the available capacity that these devices can offer to the grid, The available capacity for demand response actions was quantified through simulations, and is further discussed in the next section.

'Cold appliances' (e.g. refrigerators and freezers) were modelled as duty cycle loads with a constant power demand of ~0 W/140 W when the compressor is off/on, an active time of 15 minutes, and a period of 45 minutes [2]. The compressors' start-up probabilities were assumed to be evenly distributed during the day, which results in a constant aggregate power demand from 'cold' appliances. Furthermore, it was assumed that the compressor can be interrupted at any instant while is active.

The aggregate load pattern of 'wet appliances' (e.g. washing machines and dish washers) is mainly determined by user behaviour since their start-up times, and modes of operation are defined by the user.

For 'wet' appliances, it was decided to interrupt the load-cycle just before the phase of heating the water (i.e. at 00:15 for washing machines, and at 1:15 for dish washers, according to Fig. 1). The reason for this design choice is to minimise thermal losses. An interruption of the washing cycle after the water has been heated would require more energy to compensate for thermal losses during this interruption.

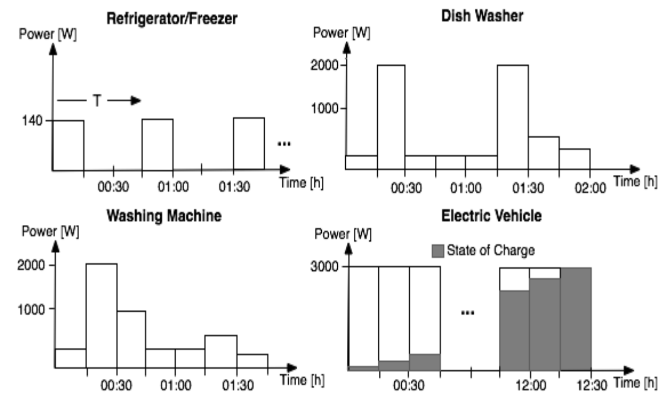

Fig. 1. Load profiles, and states of the investigated residential loads.

Charging profiles for EVs were constructed based on statistical data about mobility and transport in the Netherlands [3], as utilised in [4], [5]. The parameters used to reconstruct the load of electric vehicles are: user groups, arrival and departure time, distance driven during the trip, vehicle location, and energy used in the trip. Constant nominal charging power of 3 [kW] was assumed for all vehicles. Two different scenarios were developed: one only for domestic charging and one including charging also at the working environment. The reason behind this choice is that commuters (people who drive to work and back) consist of a characteristic category of drivers [5]. The interruption of a charging process is allowed with the constraint that the State of Charge (SoC) of the vehicle's battery is above 85%. This threshold was set to avoid the situation that a charging process is interrupted while the charge within the vehicle's battery is relatively low, and this constraint is related to the driving range and consumer acceptance.

When looking at the load profile per household calculated for different levels of aggregation (Fig. 2) it is clear how the power demand from individual households is characterized by high irregularity, both in amplitude and frequency. However, aggregation of loads mitigates such phenomena. The diversity among different households' energy requirements are resulting mostly from variations at the micro level (i.e. individuals behaviours and needs, users schedules, etc.). When a large number of devices are under investigation, the law of large numbers, which guarantees stable long-term results for random events, becomes applicable. Monte Carlo simulations show that this assumption is valid for large numbers (>10.000) of households/devices and the results are illustrated in the load profile of Fig. 2 in [W] per averaged household.

E. Load shifting actions

Taking into account different aspects, such as devices' technical constraints, or users' requirements and acceptance, the capabilities and constraints of shifting these types of loads were analysed. In this study the focus is on short interruptions of the appliances' cycles. Intermittent operation of residential loads, if kept under certain limits, will most probably remain unnoticed by most of the users. In addition, since no further user interaction is required, it creates room for remote control applications by a third entity. Such an entity could aggregate (contract) large amounts of residential customers, and then coordinate them in real-time for the provision of ancillary services. As a general principle for the load shifting options considered, the service quality of the appliance must be always within acceptable limits. This topic is addressed by defining the maximum interruption time for each device. Furthermore, for EVs a physical constraint is imposed by the state of charge of the vehicles' batteries.

The developed control strategy is discrete and acts using information about the current PTU and the next PTU. The desired operating set-points are based on meeting the projected energy imbalance per PTU. The algorithm checks the availability of devices in the database, and if adequate resources are available, the aggregate load performs a constant gradient/slope ramp to meet these set-points. If resources are limited then the maximum available ramp is performed.

The full deployment of the aggregate resource was assumed to be possible within a time period of fifteen minutes; a faster response is likely possible. The true capabilities of such resources can only be assessed by accounting for specific ICT requirements (time response, delay times etc.) at a level of detail deemed out of scope for this study.

III. RESULTS

Assessing flexibility of aggregated loads is a difficult task mainly for two reasons; availability is linked to user behaviour which is subject to both personal and contextual aspects, and its level of response differs depending on whether fast or slow reaction is required. In this work, the problem of user behaviour is addressed by performing Monte Carlo simulations that draws samples randomly from a population with proper statistical properties (e.g. devices' start-up probabilities). The issue of response time is addressed by choosing a particular application for study. The maximum load-reduction available in a 15 minute period was simulated to assess the capacity of residential demand response. Since the states of the devices change continuously throughout the day (user behaviour), the simulation experiment is repeated at

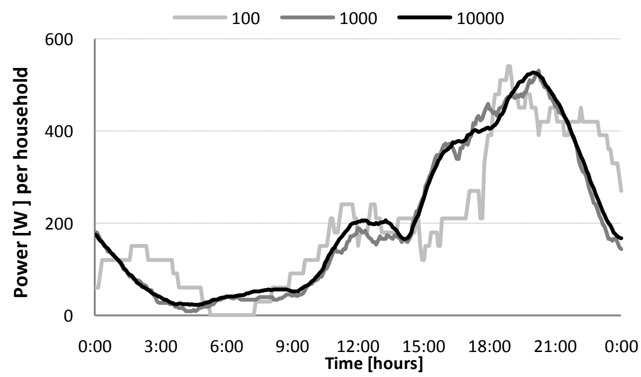

Fig. 2. Household demand power on a "per household" basis at different levels of aggregation.

different hours of the day to assess the variation on the available capacity due to the varying availability of the devices (modelled based on probabilities of start-up). As a result, flexibility can be assessed in terms of available capacity for aggregate load reduction as a function of time (during a day).

A. Maximum available ramps and energy recovery

Every deviation in the load (in this case a load-reduction with a ramp shape) is accompanied by an action of energy recovery when the load resumes its operation (from the point it was interrupted). The size and duration of this energy recovery will vary depending on the type of appliance used to perform the ramp and on the finite state of the device when its cycle was interrupted. In figure 3 the energy recovery for all investigated devices is depicted (normalised by the size of the load reduction (A)).

'Cold appliances' are characterized by a duty cycle operation. When a large number of devices are considered, the number of compressors running is almost constant in every PTU. Thus, under aggregation 'cold' appliances can serve the grid in a similar way to energy storage devices. Storing heat (delaying the compressor) or cold (prolonging the cooling process) inside the insulated compartment, these devices can provide the system with a relatively fast and flexible demand response resource. Delaying/prolonging the cooling process for fifteen minutes the temperature inside the container increases/decreases approximately ±1.5°C [2]. The energy can be recovered at any subsequent time interval, restoring the ideal temperature boundaries inside the container, and an example of an aggregate load shifting action is illustrated in Fig. 3.a. The capacity of this virtual battery is dependent on the number of 'smart' devices connected to the grid. Even though 'cold appliances' are characterized by a relatively low power demand, the possibility of delaying the compressor start-up in every cycle makes them a very flexible resource for the provision of ancillary services (e.g. provision of operating reserves).

The analysis on 'Wet appliances', Dish Washers (DW) and Washing Machines (WM), revealed that these resources have the least potentials, in terms of flexibility, when compared to the other investigated devices in this study. The energy recovery period for these devices is relatively long (up to 2 hours) and unpredictable, mainly due to their load profile which is characterised by many steps with different power demand levels. Thus, even though these devices might be able to offer considerable resources to distribution system operators for localised management or peak shaving, their characteristics make them difficult to be controlled in an aggregated way within short time frames.

Simulation results show that electric vehicles have the greatest potential, among all the investigated devices, in terms of available capacity (high power demand), controllability (long charging processes with respect to single-phase domestic charging), and shifting capabilities (duration of interruption). The energy recovery, illustrated in Fig. 3, is characterised by a long duration mainly due to the maximum duration of interruption value which was assumed equal to one hour and allows room for reshaping the energy recovery. In real life applications, even longer interruption times can be involved during night hours, accompanied by incentives such as low price tariffs. Nevertheless, even when the requirements of the batteries (SoC>85% to allow interruption of the charging process), and the users' requirements (driving patterns and vehicles' availability based on statistical transport data for the Netherlands) are taken into account, then electric vehicles are considered as the most suitable loads (compared to domestic loads) for utilization within demand response programs.

B. Normalised available capacity on a per-device basis

In this study, the term flexibility reflects aspects related to available capacity as a function of time. Since devices' availability during the day follow a characteristic pattern which originates from user behaviour, then some conclusions can be drawn about available capacity based on the probabilistic start-up distributions utilised as input. Starting from an analysis of the maximum available amplitude of the load reduction (A) at different hours of the day a capacity factor (CF) can be defined to capture the available capacity dimensions of the aggregate load.

The net capacity factor of a power plant is often referred as the ratio of the actual output of a power plant over a period of time and its nominal output. All power plants have capacity factors that vary depending on resource, technology, and purpose.

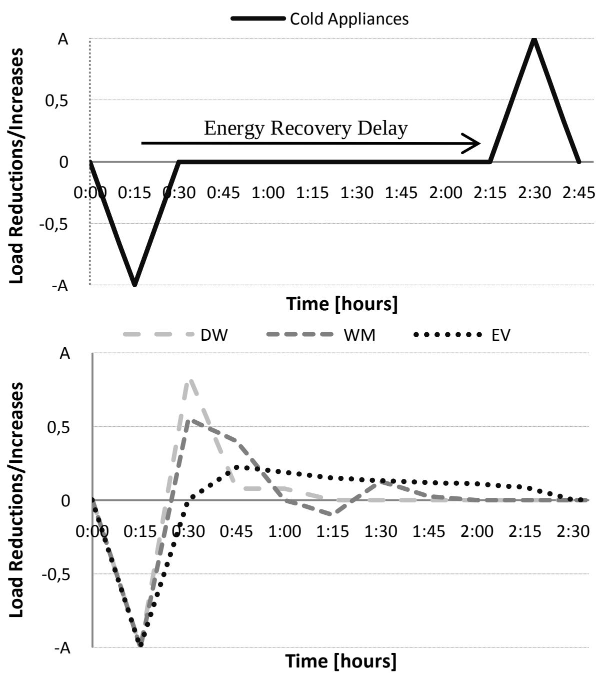

Fig. 3. Load reduction and subsequent energy recovery. A is the amplitude of the load reduction in watts [W] for a) Cold appliances; b) Electric vehicles.

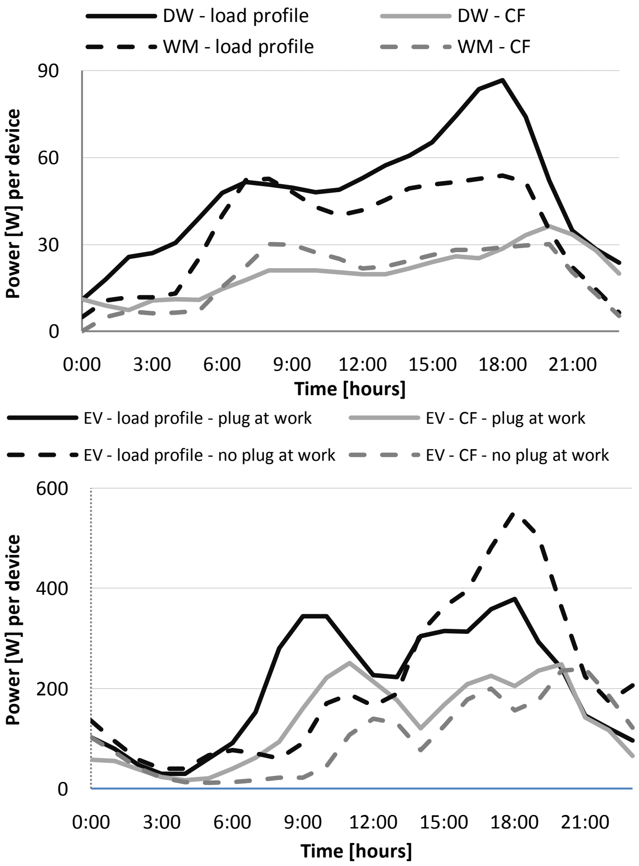

Fig. 4. Load profile on a per-device basis (W per-device) and capacity factor (available capacity for load reduction in a 15 min basis – A) . For a) 'Wet appliances'; b) Electric Vehicles

A virtual power plant, composed of residential loads, has constraints related to end-user behaviour and performs only load-shifting actions. It contains no generation units in its portfolio, thus the requirements are different to those of a conventional power plant.

For such a plant, the capacity factor will depend on the start-up probabilities and the capabilities and constraints of the particular devices (e.g. maximum available time for interruption, demand profiles, etc.).

A direct relationship between start-up probabilities and available capacity was identified through simulation for all investigated devices, and a capacity factor was estimated for each one. The capacity factor represents the maximum load reduction per device in a 15 min basis that can be actually actuated given the constraints. This load reduction is accompanied by a recovery period whose implications were discussed in the previous paragraph.

Simulations results show that 'cold appliances', due to their duty-cycle nature, are characterised by a constant capacity factor equal to ~46 W per unit.

Simulation results for all the other investigated loads show that the available capacity will vary with time, as illustrated in figure 4. Even in peak hours the capacity factor of 'wet appliances' is quite low (~30 W per device). Finally, electric vehicles are characterised by a capacity factor that ranges from 30-40 W per unit during the early hours of the day, when most of the vehicles are fully charged, to 250 W per unit during evening when most of the vehicles are plugged at the households' connection. Surprisingly, although the demand for charging power during evening hours is significantly higher for the scenario of charging only at home, the available capacity is almost equal to the scenario where a plug is available also at the work environment. In the first scenario vehicles are getting re-charged only when the drivers return at home and the SoC is relatively low, thus performing only one long charging process instead of two shorter ones during. For how the model constraints are implemented, load shifts are possible only if the SoC is above a certain threshold. If more than one charging process is created for the same trip (e.g. in the case that a plug is available also close to the work environment), this threshold can be passed more than once during the day offering more flexibility to the grid.

C. *Discussion and Analysis*

Aggregation of even a few thousands households makes residential demand response uniform enough to consider it as a system resource. It differs from operating conventional reserves from a single large unit because its available capacity can not be set and scheduled, but instead varies during the day. However, even with the simple and non-intrusive intervention approach of applying a short-interruption, it is considered a significant resource in terms of capacity.

Furthermore, how this aggregated flexibility can be applied is a question subjected to market design, user acceptance, related costs and other factors. Residential customers are not electricity professionals, but they could in principle still participate in dynamic pricing environments, under aggregation. A legal entity that makes contracts with large number of customers and represents them in markets could provide ancillary services to the system [6]. Still, more research is needed in this field which emerged following the liberalisation of electricity markets (from centralised to de-centralised decision making) and environmental concerns and policies. The purpose of this paper is not to conclude in economic terms about the operation of regulating power plants, but to illustrate and quantify, in terms of available capacity, the flexibility of these devices. In a previous work [6], the model was utilised to evaluate the capabilities of residential loads to provide secondary reserves. Residential demand response was assessed for the case study of the Netherlands, and verified to be a significant resource in terms of capacity [6]. Indeed, considering only a fraction of the total households participating in demand response, it is comparable to a power plant of ~580 MW during peak afternoon hours. The simulation scenarios revealed two potential applications, the utilization of residential demand response to cope with contingencies, and to follow stochastic generation from renewable energy sources.

The effect of performing load-shifting actions is similar to that of utilising energy storage devices. However load-shifting is not only capacity constrained (in terms of energy and power), like batteries, but is also time-constrained. After a reduction in the load, the energy has to be recovered within a certain time period. In this study only load-reduction actions were considered. However, apart from the load reduction process, load-shifting actions also involve an energy recovery process. At some moment the control on the devices has to be released, the operation is resumed and the energy recovery process is initiated. This can be resembled with a load-increase action, where the dispatcher gradually releases controllable loads to increase the aggregate demand. Thus, the available capacity for ramp-down actions is related to the actions taken in the past. Ideally, flexible domestic loads under aggregation could supply wave-shaped load functions (regulation up and down in sequence). This resembles the behaviour of an aggregated battery that is getting charged and discharged periodically.

In this study, the input for the model was consisted of average probabilistic distributions of use for every device, but in a practical application this could be computed locally and in a decentralized way. In a real life application this information can be generated from meters in the household level, then processed in a decentralised way, and transferred to the upper levels (e.g. to the system operator) in reduced forms. It would be ideal if future energy management systems can be trained on the actual requirements of each prosumer, based on historical data, and optimise the operation of residential loads according to the needs of both the user, the devices and the system.

The complexity of optimising processes and planning decisions might increase exponentially when a large number of flexible loads are aggregated. Scheduling algorithms will be required to couple information such as weather forecasts and expected load consumption from seconds to days and to plan resources accordingly. However power systems show properties that are very similar to communication networks. Both are constrained by capacity and congestion issues. The Quality of Service (QoS) is a collection of technologies, used in ICT, which allows applications to request and receive predictable service levels in terms of data throughput capacity (bandwidth), latency variations (jitter), and delay. Algorithms used for QoS, such as fair queuing and load balancing, could be adapted to optimise the power system operation.

IV. Conclusion

This paper has quantified the available capacity for residential demand response actions when large number of units are aggregated and given specific constraints related to user behaviour and technical aspects. Individual customers have limited capacity thus aggregation is needed, but at the same time aggregation of resources reduces uncertainty since variations in power demand from individual customers are cancelled out with each other.

This study attempted to provide a more realistic capacity assessment of residential demand response by focusing on specific types of loads. Simulation results show that 'cold appliances' can be characterised as very flexible resources despite their relatively low power demand. They can be operated, under aggregation, in a way similar to battery storage, since they are not characterised by any time constraints like the other investigated devices. 'Wet appliances' can be characterised as the least performing resource for short-term load-shifting actions, both in terms of flexibility and available capacity. Their characteristics (behavioural and technical) make them more suitable for shifting the whole cycle, and they deserve a dedicated and more comprehensive study. Electric vehicles perform well both in terms of capacity and flexibility due to their relatively large batteries and power intensive charging processes. Aggregation of a sufficient number of customers reduces uncertainty enough to consider an equivalent normalised load profile and available capacity for specific residential loads.

Acknowledgment

This work is supported by the E-PRICE project (Price-based Control of Electrical Power Systems) funded by the European Commission's Seventh Framework Program. All information on AB@CUS and its source code can be found at: http://bonko.xen.prgmr.com/~abacus/wiki/doku.php?id=Start

References

[1] ENTSOE, *"Operation Handbook, Policy 1: Load-Frequency Control and Performance"*, European Network of Transmission System Operators, Technical Report, 19 March 2009.

[2] R. Stamminger, and H. Jungbecker, *"Smart use of domestic appliances in renewable energy systems",* in Proc. of the 5th International Conference on Energy Efficiency in Domestic Appliances and Lighting, Berlin, pg. 92-96, 2009.

[3] Mobility research of the Netherlands 2008 (Mobiliteitsonderzoek Nederland 2007), Ministry of Transport, Public Works and Water Management (Rijkswaterstaat Ministerie van Verkeer en Waterstaat), 1 april 2008 (In Dutch). Available: http://www.rijkswaterstaat.nl/

[4] I. Lampropoulos, E. Veldman, W.L. Kling, M. Gibescu, and J.G. Slootweg, "*Electric vehicles integration within low voltage electricity networks and possibilities for distribution energy loss reduction*," in Proc. Innovation for Sustainable Production (i-SUP), Sustainable Energy Conf. (3), pp. 74-78, 2010.

[5] I. Lampropoulos, G.M.A. Vanalme, and W.L. Kling, "*A methodology for modelling the behaviour of electricity prosumers within the smart grid*," in Proc. of IEEE PES Conference on Innovative Smart Grid Technologies Europe, October 11-13, 2010, Gothenburg, Sweden.

[6] I. Lampropoulos, J. Frunt, S. Pagliuca, W.W de Boer W.L. Kling, 2011. *"Evaluation and assessment on balancing resources,"* 8th International Conference on the European Energy Market, Zagreb, Croatia, 25-27 May 2011.