META-ANALYSIS OF THE RESULTS OF EUROPEAN SMART GRID PROJECTS TO QUANTIFY RESIDENTIAL FLEXIBILITY

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ABSTRACT

To quantify the flexibility potential that can realistically be expected to be available at residential consumers, the results of several smart grid pilots have been analysed, categorized and compared based on the observed level of flexibility. A range of actual flexibility potential of residential load is specified, which provides grid and system operators with realistic handles to take demand side management into account in power system planning.

INTRODUCTION

The increasing penetration of heat pumps (HPs) and electric vehicles (EVs) along with a growing amount of distributed generation leads to more variable power flows with potentially higher peaks. The greater intermittency and less predictable power flows pose issues for planning and operation of future electricity networks [1]. Implementing demand side management (DSM) schemes can help cope with the effect of these changes, e.g. by enabling (local) balancing of supply and demand or provision of ancillary services for grid support. The future impact of DSM schemes on grid loading will depend on the chosen operational structure and can either in- or decrease the need for grid investments and is therefore important to take into account in the planning and design of networks [2].
To enable the future use of DSM it is important to obtain a more quantitative insight into the flexibility potential that can realistically be expected to be available at residential consumers. To assess this flexibility potential, a meta-analysis of the results of several European smart grid pilots was carried out. The different results were categorized and compared on the observed level of flexibility. First, the assessed smart grid pilots will be briefly introduced, after which we will discuss the assessment of the observed flexibility. A quantitative comparison of the results will be presented and consideration is given to what extent these results can be generalized.

SMART GRID PILOTS

Several (inter)national pilots study the possibilities and consequences of DSM by activating the flexibility in electricity use of residential consumers. To quantify the residential flexibility potential, results of seven smart grid pilots carried out in different countries were categorized and analysed.
The assessed pilots are Couperus [3], E-DeMa [4], Your Energy Moment (YEM) [5], LINEAR [1], Low Carbon London (LCL) [6], PowerMatching City (PMC) [7] and Smart Charging Enexis (ScE) [8] and are geographically depicted in Fig. 1. These pilots all investigated the response of residential consumers or smart appliances to some form of (price) incentives, but used different techniques to unlock the flexibility and focused on different flexible appliances.

ASSESSMENT OF FLEXIBILITY POTENTIAL

To allow for a proper comparison of results, first a common definition of flexibility was determined based on the definitions used in the pilots. All pilots describe flexibility as a function of either power or energy use. In general, two measures of flexibility can be discerned: on the one hand there is the automated appliance flexibility potential, on the other hand the real-life load shifting behaviour. The appliance flexibility potential is

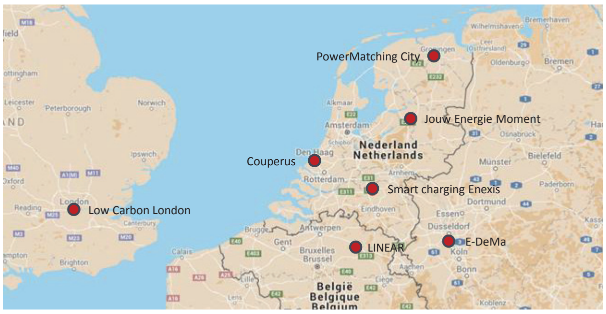

Fig. 1. Location of seven pilots addressing flexibility.

mainly applicable to devices with the possibility to store energy using a buffer. Flexibility is then defined as the power in- or decrease that would have been available, by using the buffer limits. Load shifting presents a group of users with an incentive to shift loads and the amount of flexibility is quantified by comparing the difference in load level with a reference case. The appliance flexibility potential generally shows a larger change in power than the load shifting. In this paper the amount of flexibility is defined by a possible average change in power, per time of day, per household.
Next, the pilot results are categorized by type of investigated appliance and quantitatively compared based on the measured flexibility.

OBSERVED LEVELS OF FLEXIBILITY

The reported pilot results can be divided into four different categories. Some pilots regarded only the total household load and did not discern between different appliances, whereas other pilots focused more specifically on either wet appliances, HPs, micro combined-heat-and-power (μCHP), EVs, or a combination of these.

Aggregated household load

Both the E-DeMa and the LCL pilots focused on the flexibility in the total household load. Results are presented as a change in household load and do not differentiate between appliances providing flexibility. Both pilots provided consumers with two different Time of Use (ToU) tariffs, illustrated in Table 1 (colour gradient from light to dark indicates the price level from low to high).

Table 1 Time of use tariffs used in the E-DeMa and LCL pilots.

		Time of day												
E-DeMa	2-tariff													
	5-tariff													
LCL	SF	Low/high price events depend on generation												
	CM													

The reported demand response averages from both pilots are given in Table 2.

Table 2 Reported level of demand response from E-DeMa and LCL pilots.

LCL		*E-DeMa*	
SF	CM	2-tariff	5-tariff
+50W	+20W	+40W	+90W
-30W	-50W	n.a.	-110W

To allow for a proper comparison, the results of E-DeMa (given in percentages in [4]) have been recalculated to values in watts by linking it to the electricity use of an average German household [9]. Both pilots show the same trend (increasing load during low prices and decreasing load during high prices) and are in the same order of magnitude. E-DeMa yields higher results overall, despite the lower price differences in the tariffs. This could be explained by E-DeMa providing consumers with more time to adapt to the pricing schemes and adjust their behaviour to shift loads to low pricing periods. LCL only used the Constraint Management (CM) pricing scheme on some days in the program, while E-DeMa continuously used the same pricing scheme.

Wet appliances

Wet appliances are seen as typical postponable devices, users can postpone the time of use of these appliances without investing major effort [1]. The LINEAR and the YEM pilots studied the flexibility of wet appliances. YEM used a dynamic tariff (real time pricing) to activate flexibility; LINEAR used a flexibility fee: awarding users with 1 euro for every 40 hours of flexibility (postponing operation) provided. In Fig. 2 the reported in- and decrease in wet appliance usage in both pilots are plotted relative to an averaged usage profile from [10]. YEM reported a 31% decrease and 18% increase in washing machine demand during respectively high and low price moments. To allow for a comparison of results here the overall level of flexibility is assumed to be similar for all wet appliances, which results in a -50 W and +30 W flexibility that could be sustained for approximately 6 hours. The depicted results from the LINEAR project are the maximum in- or decrease that can be sustained for 30 minutes. The power increase and decrease that can be

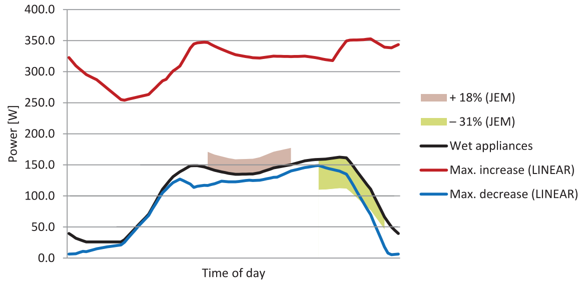

Fig. 2 Report results of LINEAR and YEM plotted relative to an average load curve for wet appliances

sustained for 6 hours on a weekday equal approximately 20 to 35 Watt increase at night and in the afternoon and 20 to 40 Watt decrease in the evening. Comparing these results to E-DeMa and LCL suggests that the flexibility currently available in household load is provided by wet appliances.

Differences between LINEAR and YEM show that a flexibility fee is more effective to cause consumers to use the appliances' smart function, which lets the appliance determine the best period to schedule its program. The smart scheduling of appliances is found to cause more total energy to be shifted towards low power consumption and low price periods than manual response to price signals. The larger decrease of power in the YEM pilot can be attributed to the high pricing during peak hours, effectively penalizing people for using power during peak hours and providing an extra incentive to shift load besides only rewarding usage during off-peak hours.

Table 3 Pilot characteristics regarding space heating

	Couperus	*PMC*	
Appliance	HP	HP	µCHP
Power	1 kW$_e$	1.1 kW$_e$	1 kW$_e$
Buffer	ΔT = ± 0.2°C room temp.	210 L hot water	
Heating	Space heating	Space heating + tap water	

Heating

The Couperus and PMC pilots investigated the flexibility of space heating. Couperus focused on (hybrid) HPs, whereas PMC additionally included µCHPs. Both pilots used a market principle combined with an automated response by the tested appliances. To provide flexibility the pilots either allowed the indoor temperature to slightly rise or drop, or used a hot water buffer. Differences in the characteristics are summarized in Table 3.

Couperus describes flexibility as the total power of the HPs, minus those that cannot be turned on or off [3]. For a period lasting from September until March they found on average 20.6 kW of power of the HPs to be flexible, without influencing indoor comfort. Dividing by the 127 HPs this amounts to 160 W of flexible power per HP on average. In PMC flexibility is described as a maximum increase or decrease of power based on the effect of the price on the actual power consumption [11]. On average this results in +67% / -48% flexible power as a percentage of average HP power and +101% / -54% for the µCHPs. In absolute terms for the HP this is a 150 W and 160 W maximum for weekdays and weekend days respectively, and for the µCHP respectively 325 W and 275 W.

To compare the results of both pilots Fig. 3 shows the flexibility response from PMC [11] together with the flexibility found in Couperus plotted relative to the average load in the PMC. The Couperus results have been distributed symmetrically around the average load, as on average the same amount of upward and downward flexibility was observed. Couperus shows more overall flexibility, which can be explained by the way flexibility is calculated in both pilots. In Couperus this is defined by the total HP power that can be turned on or off, in PMC it is based on the effect of the price on the load during each hour. On average a 1 kW_e HP, with a buffer of 200 L or ±0.2°C, provides an increase flexibility of +30 to +120 W, and a possible decrease of power of -20 to -90 W. Furthermore the size of the buffer is of major influence on the amount of available flexibility.

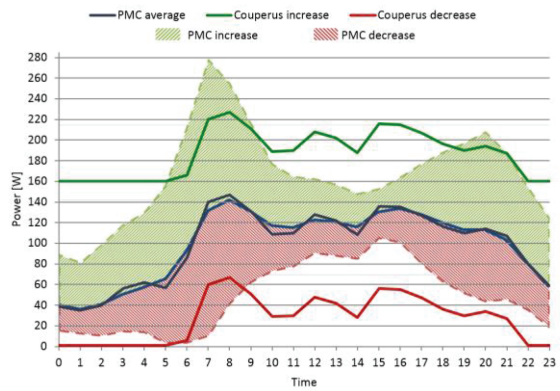

Fig. 3 Combined results of PMC and Couperus.

Electric vehicles

LINEAR, PMC, and ScE investigated the flexibility of EVs. LINEAR and ScE used actual EVs to test users' behaviour, PMC used a mobility research (called OViN) done by the Dutch CBS. The flexibility of the EVs was analysed by determining the possible deviation from the normal charging behaviour (i.e. instantly start charging at maximum power when connected) based on the departure time of the car. Parameters influencing the flexibility of EVs are: charging power, battery capacity, the distance that is driven, and behaviour of the user of the EV. LINEAR represented flexibility as the available in- or decrease of power, combined with duration [1]. PMC showed flexibility as a possible change in current loading pattern. ScE showed flexibility by simulating the overloading of a transformer when increasing numbers of EVs are introduced and subsequently comparing the case with and without smart charging the EVs.

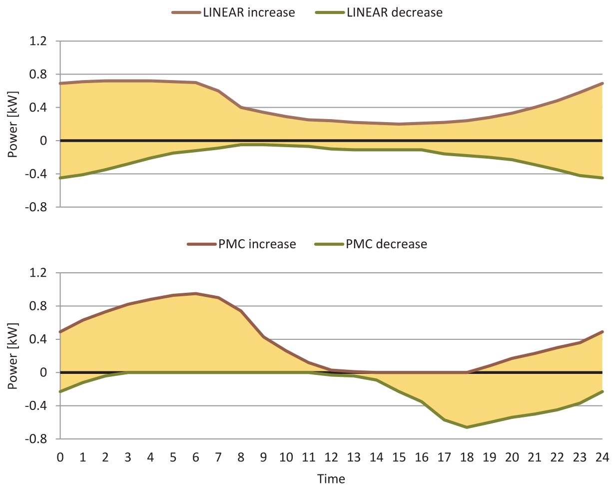

Fig. 4 Possible increase and decrease of power for EVs from the LINEAR and PMC pilots

In Fig. 4 the possible increase and decrease of power for both LINEAR and PMC are shown. The maximum power increase is calculated when power consumption is as early as possible, i.e. EVs start charging immediately once plugged in. The maximum decrease of power is based on the situation that power is consumed as late as possible, i.e. the charging process is delayed as long as possible while ensuring the EV is fully charged before departure. Fig. 4 shows that LINEAR and PMC show approximately the same amount of total flexibility (energy per day), i.e. the areas between the curves are approximately equal for both pilots (15.1 vs. 14.6 kWh). Both pilots show the bulk of flexibility during the evening and night, and the minimum of flexibility available at noon. A high level of flexibility during evening and night was also observed in ScE, although here flexibility was also available during the day as (controllable) charging spots were provided at work. The differences between LINEAR and PMC may be explained by the charging power, because PMC had a larger charging power, EVs can charge faster, and therefore the peak in power consumption occurs earlier, and provides more flexibility to decrease loads. This also causes the latest moment of charging to be later, as the EVs can charge faster, providing a higher possible increase in power. The largest increase of power usage is available early in the morning (around 6:00) and is +0.7 to +0.9 kW on average per EV. The largest decrease of power usage is available in the late afternoon/early evening (around 19:00) and is an average -0.2 to -0.6 kW per EV. At midnight both increase and decrease of power is possible: -0.3 to -0.5 and +0.6 to +0.7 kW per EV.

Total flexibility

Finally the individual categories were aggregated to achieve the total flexibility potential as a possible change in power, per time of day, for an average household. This is illustrated by the profile in Fig. 5 for a household owning both a HP and an EV. The 'average load' curve in the figure is built up by adding the average HP and EV profiles from PMC to an average profile of an average Dutch household [12]. The flexibility is visualized by adding the reported minimum and maximum flexibility values for all flexible appliances together to construct a total minimum and maximum flexibility profile. This represents the range in which flexibility can be realistically expected to be available.

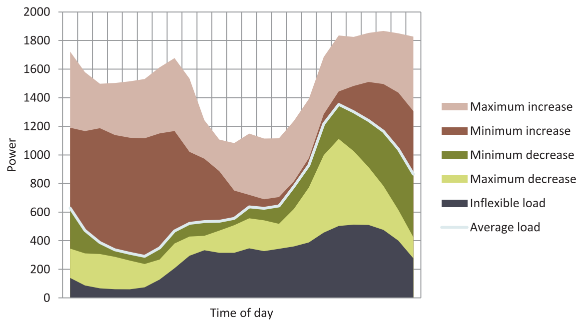

Fig. 5 Flexibility potential per time of day for an average Dutch household

CONCLUSION

The meta-analysis of various smart grid pilot results showed various similarities, but also some differences in measured flexibilities. Wet appliances appear to account for the flexibility currently available in household load, which is quite limited on average in terms of change in power. Moreover a large spread in responsiveness between different consumers was observed in the pilots. HPs can provide a substantial amount of flexibility at a relatively reliable level, especially during circumstances in which only a small part of total aggregated HP power is required. EVs show the largest potential, although more rigorous testing with a larger vehicle fleet would be required to more accurately quantify the actual obtainable amount of flexibility.

All pilots investigated used price incentives as the way to activate flexibility. But pricing can be used in different ways, resulting in different effects. Using smart appliances causes more response to varying prices and hence provides more flexibility than manual response. Applying a flexibility fee (i.e. compensating users per hour that they allow their appliance operation to be postponed) leads to a larger amount of smart scheduling, and hence provides more overall flexibility than time of use pricing. In turn, time of use pricing is more effective for peak load reduction. Also, it was observed that more load is shifted if consumers are given more time to adjust to pricing schemes.

The specified range of the actual flexibility potential of residential load is based on actual measured consumer responses and as such provides grid and system operators realistic handles to take DSM into account in long term power system planning.

REFERENCES

[1] R. D'hulst, W. Labeeuw, B. Beusen, S. Claessens, G. Deconinck, and K. Vanthournout, "Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium," *Appl. Energy*, vol. 155, pp. 79–90, 2015.

[2] E. Veldman and R. A. Verzijlbergh, "Distribution grid impacts of smart electric vehicle charging from different perspectives," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 333–342, 2015.

[3] O. van Pruissen, K. Kok, and A. Eisma, "Simultaneous Imbalance Reduction and Peak Shaving Using a Field Operational Virtual Power Plant with Heat Pumps," in *23rd International Conference on Electricity Distribution*, 2015, no. June, p. 1258.

[4] H. J. Belitz, S. Winter, and C. Rehtanz, "Load shifting of the households in the E-Energy project E-DeMa," in *2013 IEEE PowerTech*, 2013.

[5] C. B. A. Kobus, E. A. M. Klaassen, R. Mugge, and J. P. L. Schoormans, "A real-life assessment on the effect of smart appliances for shifting households' electricity demand," *Appl. Energy*, vol. 147, pp. 335–343, 2015.

[6] J. Schofield, R. Carmichael, S. Tindemans, M. Woolf, M. Bilton, and G. Strbac, "Residential consumer responsiveness to time-varying pricing," 2014.

[7] F. Bliek, A. Van Den Noort, B. Roossien, R. Kamphuis, J. De Wit, J. Van Der Velde, and M. Eijgelaar, "PowerMatching City, a living lab smart grid demonstration," *IEEE PES Innov. Smart Grid Technol. Conf. Eur. ISGT Eur.*, pp. 1–8, 2010.

[8] B. M. J. Vonk, D. a. M. Geldtmeijer, and J. G. Slootweg, "Analysis of electric vehicles measurements," *2013 48th Int. Univ. Power Eng. Conf.*, pp. 1–6, Sep. 2013.

[9] Westnetz, "dl-Lastprofile-WWE," 2015 [online] http://www.westnetz.de/web/cms/de/1772992/westnetz/netzstrom/ .

[10] R. Stamminger, "Synergy Potential of Smart Appliances," 2008.

[11] DNV GL, "PowerMatching Final Report," 2015.

[12] NEDU, "Verbruiksprofielen elektriciteit 2014", [online] http://nedu.nl/portfolio/verbruiksprofielen .