Swarm demand response: virtual storage by small consumers

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22 August 2018

Abstract

Energy storage and load shifting (demand response, DR) are options for coping with the rising share of intermittent renewable generation to reduce environmental damage from electricity. While the potential for further DR in the industrial sector might be limited, Swarm DR (sDR) based on shifting small loads in the residential sector by only a tiny interval of minutes, smartly coordinated could have significant potential, especially if its operation is delegated or automated. We develop a sDR model, quantify it and integrate it in to the electricity systems context. We show that optimally managed sDR is equivalent to an optimally operated conventional storage with a capacity of several GW, strongly dependent on the season. Assuming sDR can be implemented with low costs it is a scalable alternative to expensive battery storage. Furthermore, we find no evidence that an ideally coordinated sDR may pose any threat to system stability.

Keywords: Demand response, electricity storage

1. Introduction

Energy storage and load shifting (demand response, DR) are options for coping with the rising share of intermittent renewable generation to reduce environmental damage from electricity. So far DR is interpreted as technology applicable to heavy industry by shifting few large loads. Beyond these firms, the potential is expected to be limited as market prices will hardly motivate companies to dispense with immediate electricity consumption. But Swarm DR, shifting a lot of small loads by only a tiny interval of minutes, smartly coordinated, could have significant potential.

sDR might be implemented by electrical devices that have been enabled to delay or interrupt operation according to preferences and a highly resolved price signals. In this case it can be expected that a high share of load could be shifted by a short time of 5-10 minutes while a small share might be shifted by longer time e.g. 30-60 minutes without any costs or inconveniences. If, after this indifference time has elapsed, a price signal succeeds in finding sufficient successors who are also willing to shift load, a chain of short load shifts can be build up that is equivalent to long term storage.

As sDR enabling is only a simple extension of the controlling logic of many devices sDR storage equivalent will be cheap compared to conventional storage. But is sDR also technically equivalent to conventional storage? Even if the ideal technological, market design and communication conditions were met there is still the question if sufficient successors can be found at any time to avoid an interruption of the chain of shifts. In the best case this might result in an inability to shift load but it could also cause large generation jumps that endanger system stability. The inability to find successors might also result in additional generation capacity that would not be required with conventional storage, limiting the economic potential of sDR.

We analyse the efficiency and continuity in a model. sDR is modeled as storage with dynamic capacity constraints for each interval considered. The capacity constraint is dynamic as a small share of the load can be expected to be shiftable for longer periods while a larger share might be shifted for only short periods. In contrast to conventional storage storing into the past (pulling consumption ahead) is also admissible.

This sDR model is then integrated into a highly resolved (10 Minutes) total cost minimizing energy system model including a set of generation technologies with operation costs and investment. In detail one of the multi period storages is defined for every 10 minute interval. So a large set of overlapping storages is available. This model is quantified with looping 24 hour average load profiles in the winter and the summer (for the UK 2040, National Grid scenario) and solar generation. For comparison virtual storage levels have then been derived as the aggregated difference between generation and load. This virtual storage is compared to a conventional storage with capacity calibrated to the maximum of the virtual DR.

Virtual sDR storage is equivalent to conventional storage in terms of conventional generation and the costs. So both can be considered as substitutes. There is no evidence of sudden sDR-spikes. Prices are in principle able to ‘find’ sufficient shifters. Thus the analysis justifies modelling of sDR as conventional storage and provides a rule of thumb for its storage capacity. This simplifies modelling sDR in large models.

The analysis has shown that under ideal conditions sDR is equivalent to several GW of conventional storage at lower costs. The equivalence strongly depends on load profiles and renewable capacities. The robustness of the results has been improved by using load profiles generated with the load profile generator of DESSTINEE[1] for scenarios of 2040 and sDR applied to the residential sector differentiated by end use categories separately.

2. DR technology

DR refers to the changes in electricity consumption patterns of end-use customers in response to time-varying electricity prices or incentive payments from aggregators to improve the reliability and provide flexibility to power system.

DR involves the consumer's reaction to electrical scarcity indicators - for example, a highly dynamic price. This can be achieved through active energy management with price monitoring and participation on the electricity markets, as practiced by energy-intensive industrial sectors. However, the implementation of DR for the industrial sector is presumed to be more demanding than for the residential sector, because of optimized production processes, constraints of the production process, required production targets, inventory restrictions etc.

By contrast, in the household sector, the money-saving potential compared to the costs of obtaining information and deciding is low. Thus, a response to the price signal must be delegated. This can be done through automation or delegation of the response to an aggregator. Chase et al. 2017[2] come to the same conclusion that “automation and direct load control often act as enablers to response.”

For this purpose, it is necessary to articulate the preferences regarding the commissioning of devices that are not directly controlled by the consumer and to transfer them to a decision-making body, which can bundle these decisions avoid high transaction costs. If articulation succeeds without much effort, then electromobility research[3] shows that a significant proportion of consumers are willing to participate in such a concept.

We will denote this kind of load shifting in the residential sector as costless demand response. Typical electric appliances that are suitable for this include HVAC (heating, ventilation and air conditioning), refrigerators, dishwashers, clothes dryers and washing machines. The steps necessary to implement the idea might not be that far from reality, as a closer look on a control panel of a contemporary washing machine shows (figure 1). A bit further away from reality is however the communication infrastructure that transmits the market or switching signals. However, the internet of things is an active field of research and might be implemented even without a direct motivation of the electricity sector.

[1] T. Bossmann and I. Staffell, 2016. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy, 90(20), 1317–1333.
[2] Page 49 in Adam Chase, Rob Gross, Phil Heptonstall, Malte Jansen, Michael Kenefick, Bryony Parrish, Paul Robson, 2017: "REALISING THE POTENTIAL OF DEMAND-SIDE RESPONSE TO 2025", Summary report, Department for Business, Energy & Industrial Strategy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/657144/DSR_Summary_Report.pdf
[3] Geske, J., Schumann, D., 2018: “Willing to participate in vehicle-to-grid (V2G)? Why not!”, Energy Policy, Volume 120, Pages 392-401, https://doi.org/10.1016/j.enpol.2018.05.004.

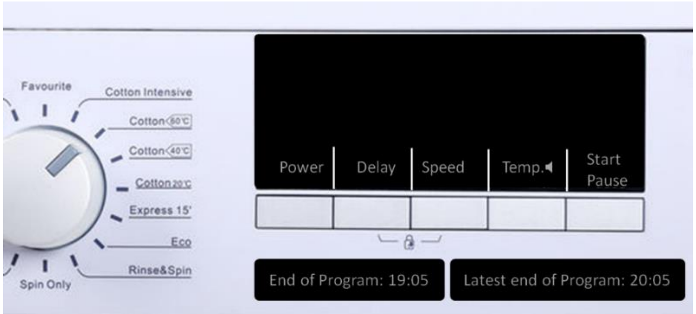

Figure 1: control panel of a contemporary washing machine amended by two program timing displays. The first one shows the time that the program would be finished, if started at once and the second one offers the option to choose the 'latest end of the program'. Consider that a delay of the start of the program is already standard. Here an hour delay of the program is accepted by the user enabling a significant shift of load.

A further intuitive example of the potential of sDR in the residential sector is presented in table 1. Issi and Kaplan, 2018[4] document for an example household the usage of electrical appliances with their energy consumption over several months. They consider the suitability of appliances for DR in terms of a highly aggregated triple time electricity tariff (day, demand, night). This however implies hours of load shifting. Therefore they come to the conclusion that only washing machine, dishwasher and iron may be deferrable - only 15% of the total power consumption in a month.

Device	**Mode**	**Duration**	**Energy per run [kWh]**	**Usage Density**	**Average Consumption Monthly [Wh]**	**Costlessly shiftable?**	**Energy [Wh]**
Refrigerator		24 h	782	All time	23469	Yes	23469
Washing machine	30 Grad	1 h	286	1 per week	8005	Yes	8005
	40 Grad	1 h	650	1 per week			
	40 Grad Synth	2 h	1064	1 per week			
Dishwasher	55 Grad Econ.	3 h	871	6 per month	5231	Yes	5231
	65 Grad Power	56 min	1125	2 per month	2250		2250
Oven	150 Grad	50 min	933	1 per week	16363	No	0
	180 Grad	1 h 2 min	1052	3 per week			
Iron		38 min	486	1 per week	1945	No	0
Hair dryer		43 min	1263	1 per week	5055	No	0
Kettle	0.5 L	1 min 53 sec	66	2 per week	6864	No	0
	1 L	3 min 17 sec	104	6 per week			
	1.5 L	4 min 30 sec	155	1 per week			
Range hood	Level 1	34 min	41	2 per week	1091	No	0
	Level 2	18 min	24	1 per week			
	Level 3	21 min	32	5 per week			
Toast		13 min	209	14 per month	2932	No	0
Printer	Printing	7 min 53 sec	44	16 per month	2858	No	0
	Stand By	23 h 52 min	3				
TV	Weekday	4 h 17 min	245	22 per month	8413	No	0
	Weekend	6 h 33 min	376	8 per month			
PC	On power	2 h 14 min	387	everyday	14946	No	0
	Stand By	21 h 4 6min	110				
Total					99422		38955
							39%

Table 1: Usage density and power consumption of household appliances for November 2016.

[4] Fatih Issi and Orhan Kaplan, 2018:"The Determination of Load Profiles and Power Consumptions of Home Appliances", Energies 2018, 11, 607; doi:10.3390/en11030607

We have amended table 1 by two columns indicating which devices may be suitable for costless shifting of only few minutes up to an hour. With this estimate 40% of electric appliances in the residential sector could be shiftable, while e.g. lighting is not considered to be a shiftable demand.

In the next section we will develop an economic modelling framework of load shifting that clarifies the idea of costless DR and offers the opportunity to model this kind of demand response on an aggregate level, to quantify it and to introduce it into the electricity system context.

3. A model of 'costless' demand response

A household comprises several electricity consuming devices e.g. electric appliances, heating and cooling appliances or also electric vehicles. In our example (Figure 1) devices are preferred to be used altogether at t_0. The start of using a device may be delayed due to load shifting. For each device an indifference threshold interval is defined. Costs are incurred, and then increase gradually, only if the start of the device is delayed by more than this threshold. In figure 2 devices $\tau_1 - \tau_6$ have been ordered according the threshold. The threshold of τ_1 is zero (e.g. lighting; any delay is costly) and the threshold of τ_6 is highest (e.g. dish washer; a delay of an hour or two may have no cost).

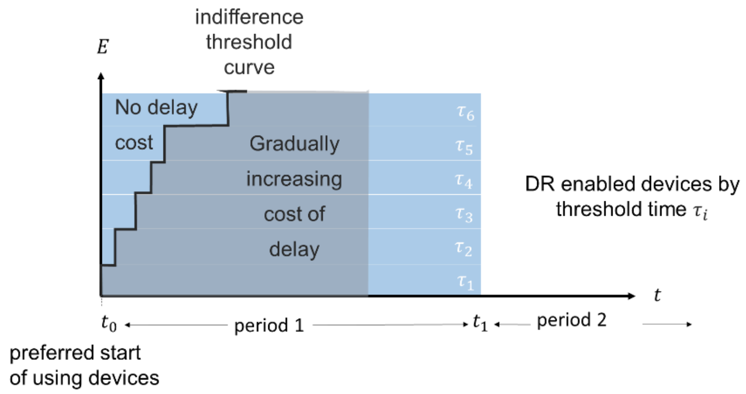

Figure 2: DR and cost of delay

In the example presented in figure 3 the start of devices $\tau_4 - \tau_6$ is delayed by Δt. The threshold of devices τ_4 and τ_5 is exceeded thus this shift incurs a cost for each device, dependent on the length of the period the device exceeds the threshold and the device itself. In contrast there is no cost of delaying the start of device τ_6 by the same amount of time.

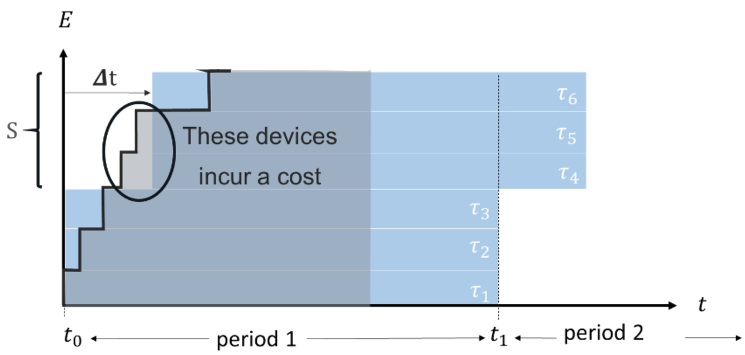

Figure 3: DR and cost of delay

In our analysis we assume that time tolerance of delaying or postponing the start of electric devices without cost can be exploited to shift load. This shifting load from one period to another is interpreted as storage of electricity. The according storage has a dynamic capacity depending on the load and the distribution of the delays across the devices. That means intuitively that a 'huge' load can be shifted for short time while only small load can be shifted for a long time. This intuition will now be formalized as a storage model with dynamic capacities.

The indifference thresholds of electric devices are modelled as a distribution f of the load L at t_0 over the thresholds Δ. $f(t_0, t)$ is the share of the load of all devices initially planned to be used at t_0 that is maximal (costlessly) shiftable to t, but not any further. Devices may be delayed maximally by Δ^{max} periods. The distribution fulfils

$$\sum_{\Delta=-\Delta^{max}}^{\Delta^{max}} f(t_0, t_0 + \Delta) = 1 \quad (1)$$

f constrains the load shifting plan s. $s(t_0, t)$ describes, which load will be shifted from t_0 to t. To frame the idea of the previous section the sequential structure has to be considered: e.g. a device delayed by (a maximum of) 5 periods is not available for shifting load by 4 periods only. But if the device is not used for the delay of 5 periods, then it is indeed available for shifting four periods only. In other words, unused capacity for transfer to more distant periods is available for a transfer to any less distant period.

Let us develop the idea stepwise along an example: assume the maximal shifting interval was $\Delta^{max}=3$. So, consumption may be pulled ahead maximally to period $t_0 - 3$. The available capacity is $f(t_0, -3)L_{t_0}$, therefore the energy that is directly pulled ahead to $t_0 - 3$, $s(t_0, t_0 - 3)$ is constrained by

$$f(t_0, -3)L_{t_0} \geq s(t_0, t_0 - 3) \geq 0$$

The storage capacity that is not required for shifting load from t_0 to $t_0 - 3$ is available for shifting to period $t_0 - 2$ that is:

$$available\ for\ period\ t_0 - 2 = f(t_0, -3)L_{t_0} - s(t_0, t_0 - 3)$$

Thus energy that can be shifted directly to $t_0 - 2$ is bounded by

$$\underbrace{f(t_0, -2)L_{t_0}}_{capacity\ for\ t'=-2} + \underbrace{f(t_0, -3)L_{t_0} - s(t_0, t_0 - 3)}_{unused\ capacity\ in\ t'=-3} \geq s(t_0, t_0 - 2) \geq 0$$

Stepping further ahead the amount of energy that can be pulled ahead to $t_0 - 1$ is

$$\underbrace{f(t_0, -1)L_{t_0}}_{capacity\ for\ t'=-1} + \underbrace{f(t_0, -2)L_{t_0} + f(t_0, -3)L_{t_0} - s(t_0, t_0 - 3) - s(t_0, t_0 - 2)}_{unused\ capacity\ in\ t'=-2} \geq s(t_0, t_0 - 1) \geq 0$$

This can be combined to the conditions of storage capacities:

$$\sum_{\Delta'=-\Delta^{max}}^{\Delta} \left[f(t_0, \Delta')L_{t_0} - s(t_0, t_0 + \Delta')\right] \geq 0\ \forall t_0, \Delta = -\Delta^{max}, \ldots, -1 \quad (2)$$

$$\sum_{\Delta'=\Delta}^{\Delta^{max}} \left[f(t_0, \Delta')L_{t_0} - s(t_0, t_0 + \Delta')\right] \geq 0\ \forall t_0, \Delta = 1, \ldots, \Delta^{max}$$

$$s(t_0, t_0 + \Delta) \geq 0 \quad (3)$$

We have thus formulated constraints for the storage program that captures the idea of load shifting as long as it is 'costless'. How this storage is applied economically in a real world setting will be analysed in section 5. To do so in the next section shiftable load L_{t_0} and the distribution f will be quantified.

4. 'Costless' shiftable load

It is basically difficult to classify loads as costlessly shiftable. As mentioned in the introduction, however, it is plausible that production and business have been process-optimized and thus offer little leeway for a cost-neutral load shift. This does not mean that it cannot be profitable to reshape production processes to cost-effectively adjust the temporal electricity demand profile to electricity prices. Since only the costless load shift will be considered here, neither the loads of the industrial sector nor the commercial sector will be considered for a short-term shift.

Instead, it is assumed that load that is related to the household can be shifted. This includes electrical applications in which the end of the use up to one hour is irrelevant (e.g. refrigerator, washing machine, dishwasher, but also a laptop that uses its own batteries) and the use of heat storage to bridge the load shift (electric heaters, night storage heating and air conditioners). Even electric vehicles with full V2G integration, could be used for DR. By contrast, less suitable are e.g. lighting, hotplates and water heaters. To say it again, we assume that all devices can be operated according to the consumer's request by articulating his preferences without load shifting.

In section 2, the share of electrical appliances well suited to shift load has been estimated as 40%. This share is now estimated space heating, cooling and water heating. While boilers as heat storages would be suited for load shifting, instantaneous operating water heaters are not. We assume that in the future hot water will be produced by water heaters and therefore will not be available for load shifting. In contrast, space heating and cooling units are used assumed to be used with a high share of 70%. These load-shifting shares are summarized in table 2.

Shiftable load component	Participation rate
Appliance	40%
Water	0%
Heating	70%
Cooling	70%

Table 2: Assumptions on the share of participation in load shifting

With these shares it is now possible to determine a weighted mean of annual end use load profiles. This weighted mean represents the shiftable load with season-specific and diurnal cycles. For this purpose, hourly end-use profiles of the household sector were simulated with the load profile generator DESSTINEE based on annual projections of National Grid for the UK in 2040[5]. National Grid's long-term projections of the annual composition of load (table 3) shows a strong increase in electricity demand for space heating and a sharp decline in demand from appliances.

UK Residential Demand	2015	2020	2030	2040
Space heating	73,309	90,724	164,682	201,182
Water heating	28,197	20,401	29,506	20,329
Cooling	477	529	551	569
Appliances	271,038	286,344	208,055	171,882

Table 3: long term trends in annual residential electricity demand. 2015 actual values and projections; National Grid Future Energy Scenarios for the UK

[5] The data have been conditioned in I. Staffell and S. Pfenninger, 2018: "The increasing impact of weather on electricity supply and demand". Energy, 145, 65–78.

Two simulated 24h winter and summer profiles are shown in figures 4 and 5. The average load is 20 GW in winter, with a minimum load of 16 GW (80% of the average load) in the early morning (5 am) and a maximum of 27 GW (135% of the average load) at 8pm. In summer, the average load halves to 10 GW, with a minimum load of 7 GW (70% of the daily average load) and a maximum of 14 GW (140% of the daily average load).

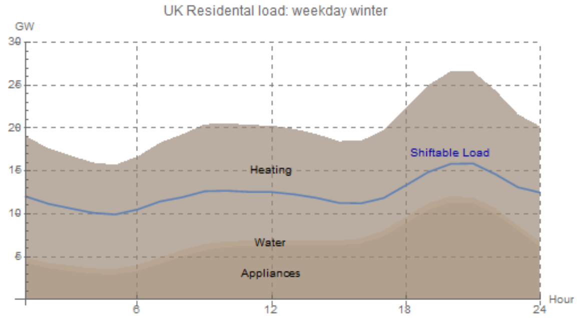

Figure 4: Simulated UK residential load by end use on a weekday winter; shiftable load (blue curve) as weighted mix.

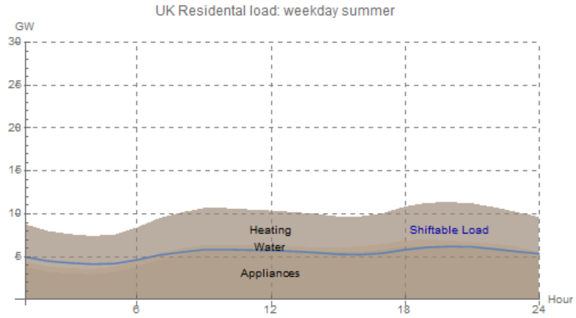

Figure 5: Simulated UK residential load by end use on a weekday summer; shiftable load (blue curve) as weighted mix.

The weighted (components of table 1) average of these load profiles is a profile of shiftable loads (blue curve in figures 4 and 5). The high share of space heat (70%) and the low share of appliances, modulates the shiftable load with a high seasonal variability and a low diurnal variance. The average of the shiftable load is 5 GW in summer and 12 GW in winter. Thus, in the summer only low storage potentials are available, while in winter the potential is more than twice as high. This limits the ability of the DR to store solar energy in the summer but provides greater reserves for the storage of wind. The low daily variability prevents the emergence of bottlenecks.

5. 'Costless' demand response in the electricity system

With these shiftable load profiles, the relation of sDR to a conventional storage was examined under realistic conditions in system context. The modelling of sDR in section 3 has not immediately clarified whether an optimally operated sDR behaves in the same way as an optimally operated conventional storage. It is straightforward to construct a case where a difference between both concepts becomes obvious: if shiftable load is close to zero for Δ^{max} periods DR is 'unable' to transfer energy across this bottleneck. Fortunately, it was shown in the previous section that shiftable load almost constant within a day such that this bottleneck effect is not realistic. However, it still remains unclear how sDR and conventional storage could be compared and what conventional storage capacity might be equivalent to DR parameters. Unfortunately the impact of the constraints (2) is difficult to analyse analytically. Therefore the DR model will be embedded into an electricity system model and analysed numerically in a realistic setting.

In detail we describe an electricity system model with conventional storage and with DR. Both models depend on characteristic parameters such as storage capacity and Δ^{max} (DR). We would like to find a relation between both parameters to compare the technologies. To derive this relation we first define the electricity system models with both storage technologies.

The electricity system is modelled as linear variable cost minimizing optimization problem. The generation of each of I conventional generation technologies is x_i. Variable cost costs of generation are the total of all technologies over all periods considered. The goal is to minimize total system costs over the generation level respectively storage:

$$\sum_t c_{var} x_t \tag{4}$$

For each technology a capacity k_i is given. k_i constraints generation x_{it}

$$k \geq x_t \geq 0 \tag{5}$$

With conventional storage, conventional generation x_t exceed load L_t and storage s_t

$$x_t \geq L_t + s_t \tag{6}$$

Storage is limited by storage capacity $\overline{S}$. Stored energy evolves according

$$\overline{S} \geq S_{t+1} = S_t + s_t \geq 0 \tag{7}$$

With demand response the resource constraint includes storage plan $s_{t,t'}$ with transfer of energy from t to t'

$$x_t + \sum_{t'} s_{t',t} \geq L_t + \sum_{t'} s_{t,t'} \tag{8}$$

Capacity constraints of load shifting have been derived in (2). The conventional storage model consists of the minimization of (4) with respect to x_t and s_t constrained by (5), (6) and (7). While the solution of the DR model is derived by minimizing (4) with respect to x_t and $s_{t,t'}$ constrained by (5), (6), (8), (2) and (3).

The standard way of modelling electricity supply stacks with few technologies has a drawback in the case of costless storage. Assume a cost minimizing generation profile with storage has been found. Now choose two consecutive periods where the same technology is used to satisfy marginal load. Any tiny transfer of load between these two periods that does not change the marginal load serving technology in both periods will also be cost minimizing. Thus the storage solution is not uniquely defined. The set of solutions is greater the larger the capacities of the technologies are. With a not uniquely defined solution it is impossible to compare storage concepts. To reduce this effect we artificially increase the number of technologies, such that the indeterminacy tolerance shrinks.

In detail we assume that generation is made up of I technologies, each with a capacity of only 1 GW. Total capacity (and hence I) was chosen to satisfy the winter peak demand. Variable costs c_i^{var} of technology i were then derived from an exponential supply curve estimated for the scenario ENTSOE Vision 3 scenario 2030 UK and the cumulated capacity

$$c_i^{var} = C'\left(\sum_{j=1}^{i} k_j\right) \tag{9}$$

The supply curve is parameterized as

$$C'(L) = e^{3.83+1.45\ 10^{-5}L} \tag{10}$$

For both models, annual sectoral load profiles have also been generated with DESSTINEE based on National Grid's annual projections for 2040 in the UK. These loads have been added and a solar generation profile with 10 GW peak generation has been subtracted. Non shiftable load was finally obtained by subtracting shiftable load (section 4). Out of the annual profile, the same summer and one winter 24-hour profiles were selected as for the determination of shiftable load in section 4.

All profiles were then interpolated to obtain 24x6 values for every 10-minute interval. To model a meaningful storage operation, these days were looped, so that the energy stored at the end of the day is also available at the beginning of each day. This procedure imitates a longer period with the same conditions. A longer period was not modelled directly to limit the complexity of solving the DR problem. The resulting profiles are shown in figures 6 and 7.

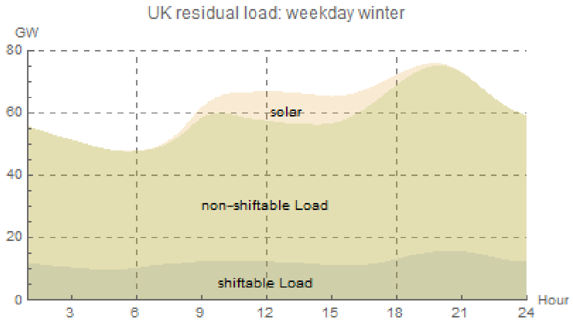

Figure 6: 24-hour winter profiles of shiftable and notshiftable load, and solar generation (10GW Peak).

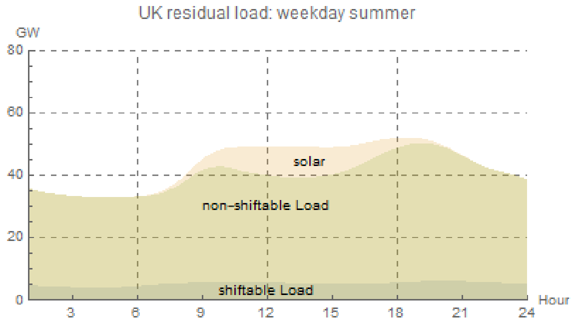

Figure 7: 24-hour summer profiles of shiftable and notshiftable load, and solar generation (10GW Peak).

To determine the distribution function f - characterizing the DR - it is assumed that the longer a load is shifted, the fewer devices are available. We formalize this idea, under the additional assumption that the distribution is symmetric through the triangular discrete distribution conditional on the maximal shiftable interval Δ^{max}

$$f(\Delta|\Delta^{max}) = \begin{cases} \dfrac{\Delta^{max} - |\Delta| + 10}{\Delta^{max}\left(1 + \dfrac{\Delta^{max}}{10}\right)} & \Delta^{max} \geq |\Delta| > 0 \\ 0 & else \end{cases} \tag{11}$$

For $\Delta^{max} = 60$ f is presented in figure 8. Only 2x2% of the load is shiftable by 60 minutes.

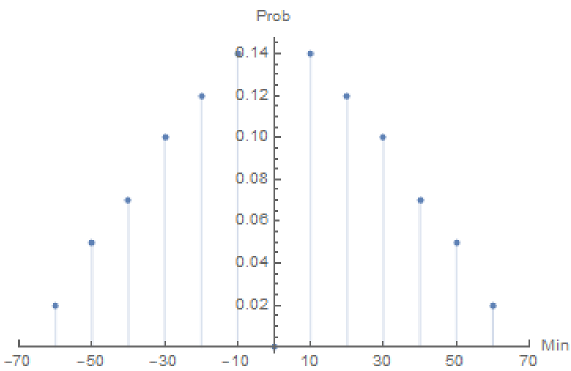

Figure 8: Discrete distribution of max available sifting load. E.g. 14% of the devices are no longer shiftable than +10 min.

The following heuristic is used to map the DR to a conventional storage design: First the generation level x_t^{DR} of the DR model is derived. With this generation level a virtual storage can be defined as

$$S_t^{virt} = S_{t-1}^{virt} + x_t^{DR} - L_t \tag{12}$$

and aggregated to the energy S_t^{virt}. The storage capacity of the virtual storage $\overline{S}^{virt}$ is then defined as

$$\overline{S}^{virt} = \max_t S_t^{virt} \tag{13}$$

This virtual storage $\overline{S}^{virt}$ capacity was then used as storage capacity of the conventional storage capacity $\overline{S}$.

Under these conditions, DR and the conventional storage problem have been solved. Two metrics (table 4) show a very small difference between the generation in winter and in summer, such that it is reasonable to claim $x_t^{DR} \approx x_t^{CON}$. In this sense the virtual storage capacity heuristic has successfully established a mapping between the parameters of the DR model and the storage capacity.

Metric		**Winter**	**Summer**
Relative mean average difference	$\sum_t \lvert x_t^{DR} - x_t^{CON} \rvert / \sum_t x_t^{CON}$	0.0035	0.0044
Maximum relative difference	$\max_t \lvert x_t^{DR} - x_t^{CON} \rvert / \frac{1}{T} \sum_t x_t^{CON}$	0.0127	0.0076

Table 4: differences in generation profiles

This mapping was then used to determine equivalent storage capacities for several values of Δ^{max}. The results are shown in table 5. It turns out, as expected, that equivalent storage capacities of the DR have approximately the same seasonal ratios as the shiftable load and therefore have the same high seasonality. Extending the maximal shifting interval by 30 min increased the storage potential by 2 GWh in winter and 1GWh in summer. Compared with the costs of a Li-Ion battery (ambitious targets are for 100€/kWh) this amount of sDR could replace an investment of 400-900 Mio€.

Maximal shifting interval Δ^{max}	**Storage capacity equivalent [GWh]**	
	winter	**summer**
$\pm 30\ min$	4	2
$\pm 60\ min$	6	3
$\pm 90\ min$	9	4

Table 5: equivalent conventional storage capacity

6. Conclusion

We have shown how to interpret Demand Response in the residential sector, how to model and quantify it. Under realistic conditions DR equals a conventional storage with seasonally variable storage capacity between 2 and 9 GWh. Thus, DR might replace expensive conventional storage (batteries) or enable countries without a natural storage potential (hydro) to store energy. DR enabled by information and communication technology could provide flexibility for the power system with high shares of renewables.

However, there are still challenges to tackle. For example, from the engineering perspective the reliability of this kind of control system might be questioned as demand elasticity of consumers is difficult to quantify in price-based DR and relies on real-time communication. This means that sDR may be perceived as “unreliable” and "failures” may occur.

At least the analysis does not show any evidence that under ideal market coordination a sudden DR-spike might emerge. Thus, a case when all shifted fridges switch on as prices go down is unrealistic. Prices are in principle able to ‘find’ successive shifters to smooth load shifting in a welfare enhancing way. In that sense a swarm of imperceptible demand shifts directed by market signals behaves like a gigantic storage unit, unknown to any of the participants.