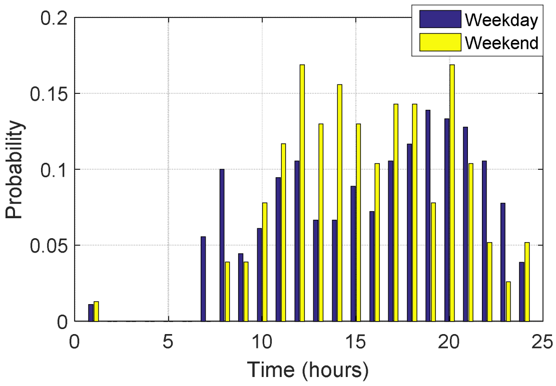
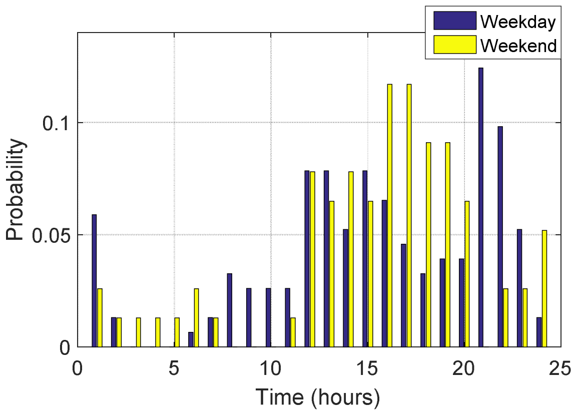
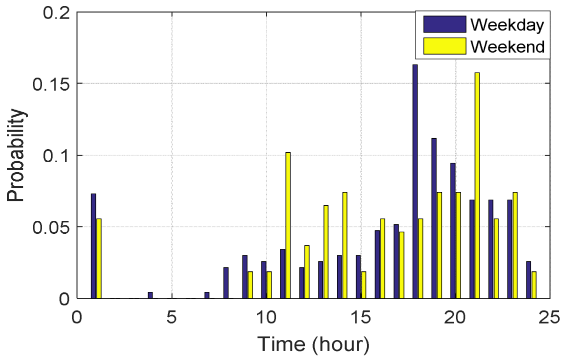


a) Cloth Washing Machine



b) Dryer



c) Dish washer

Fig. 5 The probability of starting to use appliances at each hour of weekday and weekend average day is presented for a) cloth washing machine, b) dryer and c) dish washers

V. Flexibility Model

In flexibility or demand response modelling the first important task is to model the base line or the reference load profile. Once the probability of use-start of washing machine and drying machine is computed, we can then synthetically reconstruct the 24-hour consumption profile of a single household using single washing machine and single dryer one-time average consumption profiles and following the developed method as outlined in Fig. 1. Brief description of the reconstructing process of average household level washing machine related power consumption is presented in Fig. 6. The comparison of an average household consumption reconstructed as described above and the average of real-measurements are presented in Fig. 7. This approach is capable of calculating the aggregated effect or the average household consumption profiles since the probability data and single-use consumption profiles comprise information such as the different wash and dry programs and the variation on the use of these appliances among group of households.

In order to quantify the DR potential and to study the rebound effect of DR programs, a Matlab script is written, which uses only the average one use profile of a washing machine (Fig. 4) and the probability of start profile in Fig. 5. The main principle of the flexibility modelling method is that the shifting potential in the consumption of washing machine and dryers shall essentially be estimated from the shifting of the probability of use profile as illustrated in Fig. 1. This approach preserves the probable availability of a washing machine which will start operating at the time when shifting is required in the distribution system.

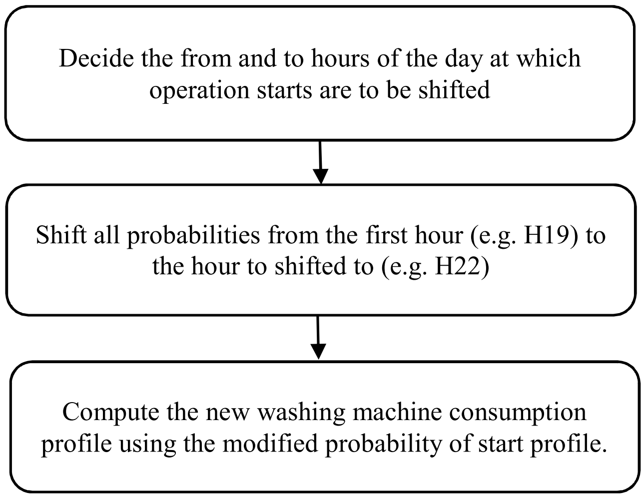


Fig. 6 Quantifying DR potential

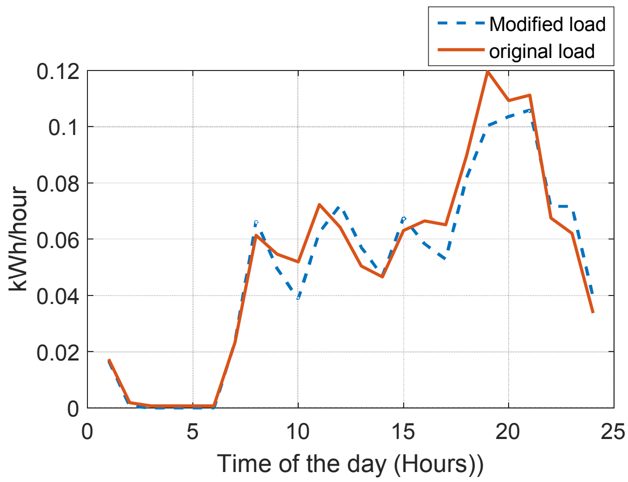


Fig. 7 Comparison of original cloth washing machine related consumption and the profile generated using the method in Fig. 1.

Using the average single-use profiles of the appliances and the probability of start values, one can write a script to calculate the aggregated flexibility potential of atomic loads without the concerns with the variability in the type of appliances and the differences in appliance use pattern. Flexibility potential, in this study, refers to the amount of power one can reduce from the system by shifting the would-be operations of appliances to different times of the day. The script can also be used to calculate the rebound effect for the implemented shifting operation. An example shifting operation of cloth washing machines from hour 20 to hour 21 and for 100 households is plotted in Fig. 8.

A delay in washing activity would most likely result in a delay in drying activity. Hence, it gives much sense to combine washing and drying related consumption as a combined resource of demand response and their respective rebound effects. Nevertheless, the drying activity can also be delayed independently from the washing activity.

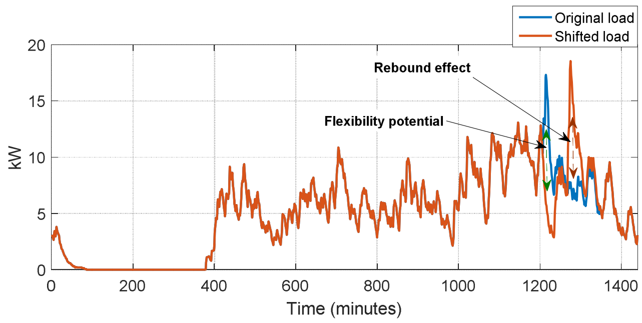


Fig. 8 Impact of shifting cloth washing activities from hour 20:00-20:15 to hour 21:00-21:15 for 100 households

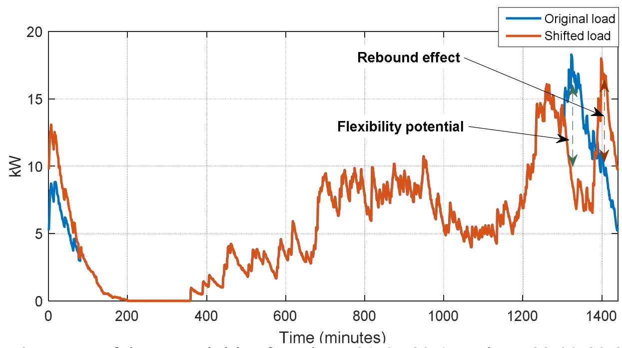


Fig. 9 Impact of dryers activities from hour 21:45-22:15 to hour 23:00-23:30 for 100 households

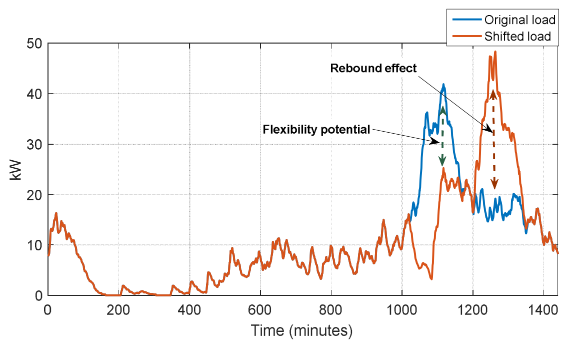


Fig. 10 Impact of shifting dish washer activities from hour 17:00-17:59 to hour 20:00-20:59 for 100 households

TABLE III. FLEXIBILITY POTENTIAL FOR 100 HOUSEHOLDS WHERE ALL OF THEM HAVE AT LEAST ONE TIME APPLIANCE USE AT THE PARTICULAR DAY

	Time shifted (from-to)	**Flexibility potential (kW)**
Cloth Washing machines	20:00-20:15 to 21:00-21:15	11.45
Dryers	21:45-22:15 to 23:00-23:30	9.28
Dishwashers	17:00-17:59 to 20:00-20:59	16.7

Certain shifting times are selected for the individual appliances to show case their flexibility potential as it is plotted in Figs 8 to 10. Table III presents the kW flexibility aggregated potential from the individual atomic loads in 100 households. Nevertheless, the appropriate time for shifting can be selected by reviewing the impact on the total load as the total load peak is the main driver. In this analysis, when a shifting operation occurs from 20:00-20:15 to 21:00-21:15 it effectively means all the probable atomic load use-starts in the first period are shifted to the second period. Practically this happens when the probabilities of the first period are shifted to the second period.

VI. DISCUSSIONS

This paper essentially present a method to quantify the flexibility potential of shiftable non-interruptible appliances. In effect the presented method will inform stakeholders how much power (kW) they can reduce by shifting the potential operation of the appliances. The activation of such flexibility resources, on the other hand, requires its own in-depth investigation as it may depend on the availability of communication channels to both customers and appliance, the willingness of customers, the market arrangement and the smartness of the appliances. Also, smart activation of the resources shall be executed to avoid rebound effects; for example, by distributing the shifting of group of appliances over time than executing all resources at once. The rebound effect mainly arises from an increase in consumption due to the superimposing of shifted appliances on top of the already operating appliances. Hence, rather than spreading the shifting of the appliances overtime, one need to observe the probabilities of start operation for the next hours to decide the appropriate hour to shift to.

When flexibility potential of aggregated loads in a distribution network is calculated, careful consideration of the interdependencies of the individual activities within the house is needed. For example, a delay in washing activity would most likely result in a delay in drying activity. Hence, it gives much sense to combine washing and drying related consumption as a combined flexibility resource and also for their rebound effect analysis. Nevertheless, the drying activity can be delayed independently from the washing activity.

The average number of wash cycles in an average European household is calculated to be 3.8 washes per week based on the 2011 figures [10]. The flexibility model for atomic loads is provided for an average single appliance (say cloth washing machine) with one operation per day. Let us say 100 households

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are connected in a distribution network and 70 of them conduct in average 1.2 times washing activity in a particular day, then the probability of start values for cloth washing machines need to be multiplied by 1.2. Then after, the flexibility potential of the 70 households at any particular time of the day can be calculated leaving the rest of the 30 households with zero flexibility.

The presented method for shiftable loads can be used by aggregators to forecast or estimate the flexibility potential (in kW) which they can get from group of households at any time of the day. These estimations help them in their participation to the power market. The method can also be used by a DSO preparing to incentivize the shifting of atomic loads from peak-hours to other hours. The presented method in general enables the estimation of flexibility potential one can get from shiftable atomic loads. The application areas can be short and long term planning of the network (e.g. distribution network planning) involving the participation of flexibility resources.

VII. Conclusion

The flexibility potential of aggregation of household shiftable appliances mainly depends on the power rating of the appliance and the coincidence for the appliance to operate at the same time in different households. Although the rebound effects show higher peaks for the appliance consumption, being the integral part of the total household, the overall effect will level out the total load by shaving the peak. The computed flexibility potentials encompass the variability in program selection of the specific atomic loads such as cloth washing machines, dryers and dishwashers. The presented data driven method of flexibility modelling involves data mining of existing measurements to extract important characteristics of the appliance use such as probability of use-start and average single-use consumption profiles.

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