École Polytechnique Fédérale de Lausanne

Modelling domestic energy load flexibility: Dishwasher usage habits and possible changes

Energy supply, economics and transition

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Contents

1 Introduction

To meet the EU environmental targets, the share of renewable energy in the electricity sector will have to increase to 35%.[1] Wind and solar energy, despite being fluctuating resources by nature, will be the main drive to a more environmentally friendly energy mix. A major challenge associated with this energy transition is the resilience of electricity networks to the variability of wind and solar energy production.

Future electricity systems will indeed face higher variability in scheduled power generation and without sufficient energy storage capacities, the demand would have to meet the supply at all times. However as shown by Figure 1, it is currently not the case: the electricity demand (in red) from the residential sector, which accounts for 35% of the total demand and 40% of the peak demand, does not overlap the PV generation curve in green.[2] An option for dealing with this challenge is to influence the electricity demand at short notice to significantly adapt shares of the electricity demand to the available renewable energy production. This method is known as Demand Side Management (DSM) and develops a more flexible energy demand.

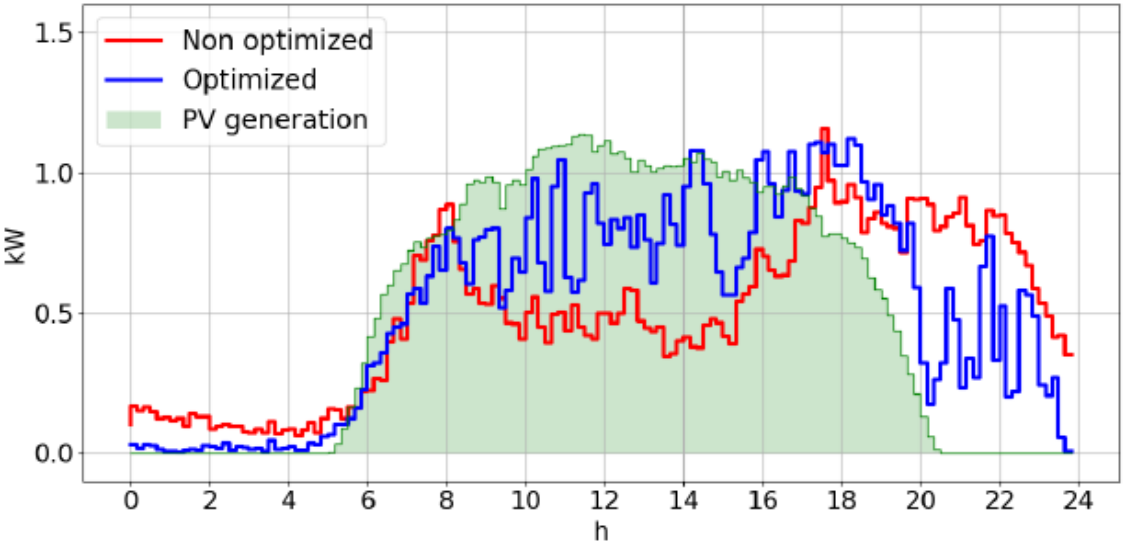


Figure 1: Residential electricity demand and PV generation as a function of the time of the day

In this study, we will develop a model for assessing the potential of residential Demand Side Management programs with the example of a dishwasher. In 2018, half of the households owned a dishwasher in the UK, which makes it a very common home appliance.[3]

[1] Jacopo Torriti. *"People's activities and residential electricity demand: A time use approach"*. University of Reading, Worshop. 2017

[2] Claudia Binder. *"The energy transition: An integrative analysis"*. EPFL lecture. 06/05/2020

[3] Arne Holst. *"UK households: ownership of dishwashers 1994-2018"*. Statista. 08/05/2020 https://www.statista.com/statistics/289151/household-dishwashing-in-the-uk/

Furthermore a EU study noted that the smart use of dishwashers, to be said the automatised operation of the device at optimal time, was widely accepted by users.[4] They also found that shifting the operation of dishwashers could save up to 90€ over a 12-year lifetime.

To understand the usage of dishwashers, a survey was created. The usage frequency for weekdays and weekends was modelled as well as the hourly demand curve. Based on those results, the average current cost of operation could be derived. The flexibility in operation was then modelled to determine the potential economical savings for the consumer. Finally the impact on the national scale of residential Demand Side Management for the dishwasher case study was addressed.

2 Methods

A survey was developed using the Qualtrics CoreXM platform[5] to gather qualitative and quantitative data regarding consumers' habits and preferences associated with dishwasher usage. The survey was made available in both English and French, in order to be accessible to a wider audience. A preview of the survey is available at `https://imperial.eu.qualtrics.com/jfe8/preview/SV_2gdUHWsTxZNrbXn`; it was open for responses from `2020-05-15T06:00:00Z` to `2020-05-17T10:00:00Z` and was distributed amongst friends and family of the authors through direct messages and social media posts.

Survey data were downloaded and analysed using MATLAB R2020a[6], Tableau Desktop[7] and Microsoft Excel[8]. Data files and code for analysis are available at `https://github.com/atdr/epfl-load-flexibility`.

3 Results

3.1 Survey results and model calibration

3.1.1 Number of runs per week

On average, the 40 survey respondents use their dishwasher 6 (5.4) times per week. This is split in 4 (3.5) runs during week days and 2 (1.8) during weekends. Figure 2 shows the responses in box plot with in red the median number of runs.

[4] Christof Timpe. *"Smart Domestic Appliances Supporting The System Integration of Renewable Energy"*. Öko-Institut. November 2009 `https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/smart-a_final_brochure.pdf`

[5] `https://www.qualtrics.com/uk/core-xm/survey-software/`

[6] `https://uk.mathworks.com/products/matlab.html`

[7] `https://www.tableau.com/products/desktop`

[8] `https://www.microsoft.com/en-us/microsoft-365/excel`

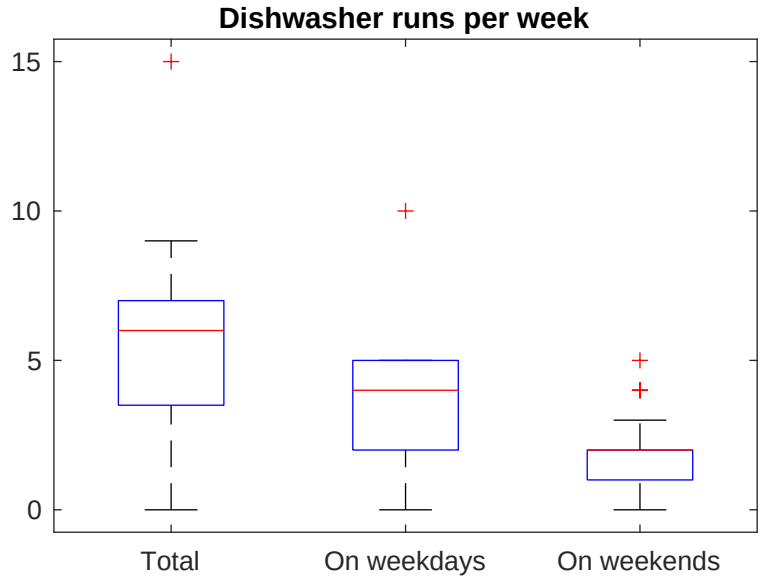


Figure 2: Number of dishwasher runs per week for sample population

Probability density functions were obtained for the number of dishwasher runs per week and a skew-normal function was fitted to the raw data. Figure 3 shows the distribution and the parameter of the skew-normal fit.

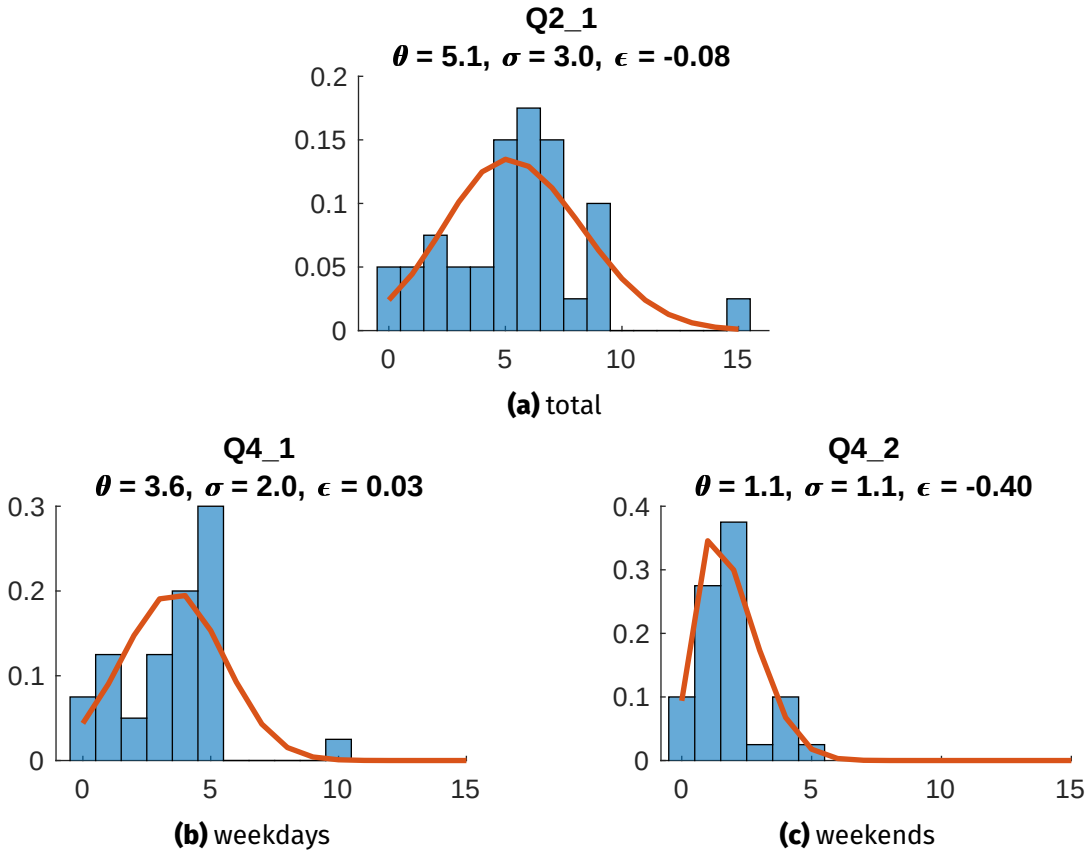


Figure 3: Probability density functions for number of dishwasher runs per week (histogram: raw data, line: skew-normal fit)

3.1.2 Average load curve

We asked consumer what is the most usual time for them to start their dishwasher, as well as what are the earlier and later times they usually operate their appliance. The question was asked independently for the weekdays and the weekends. If we assumed that all the survey respondents were to use their dishwasher all on the same day, despite some people using it less then 7 times per week, the hourly load curve for our population was determined.

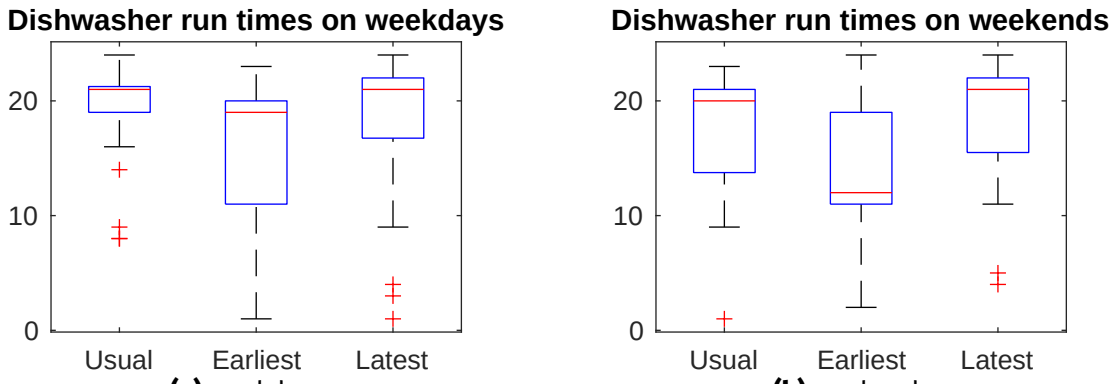
Weekdays On weekdays, the range of most common times to start the dishwasher is relatively small and corresponds to the evening and most likely after dinner. Figure 4a also shows the usage time is most likely to be advanced rather than postponed when the consumer does not consciously modify his habits. Moving forward the starting time to the afternoon could have a positive impact on the electricity grid since there is less demand and PV panels are highly productive (see fig. 1). In fig. 4a, several datapoints for the latest start time (those in the early morning) are considered outliers. This is because time data are recorded for hours in the range 0-24. By adjusting this range to e.g. 6-30, the early morning hours would be considered an extension of the evening and thus likely no longer outliers.

Figure 5a is the probability density as a function of the hour of the day. The peak indicates that for our sample population, almost 1/4 of the respondents start operating their dishwasher at 21:00. However the normal fit associated with our raw results informs us that the mean time of operation is actually 19:20.

Figure 6a shows data for the number of runs per day on weekdays. Although a skew-normal distribution was used to fit the raw data, the low skewness (ϵ = 0.03) indicates that a simple normal distribution would likely also have provided a good fit.

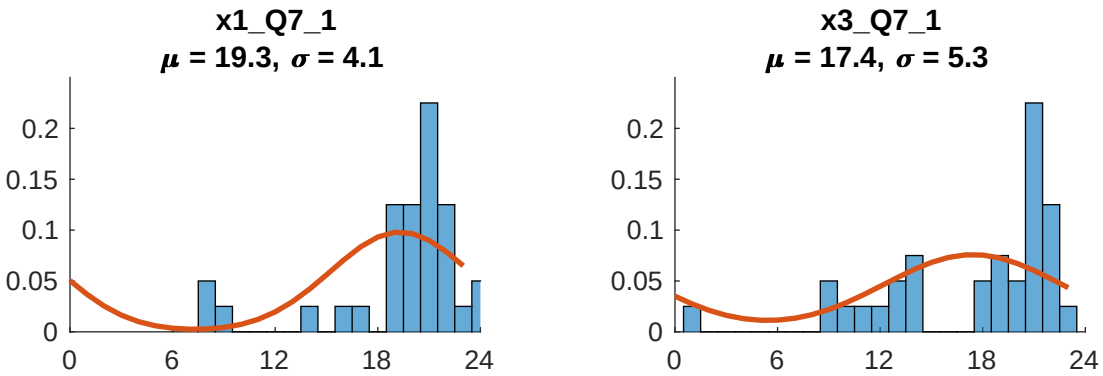
Figure 7a shows the adjusted load curve accounting for the number of dishwasher runs per day (using the median value from fig. 6a). Since the median number of runs per weekday is 0.8, the load curve is reduced. Notably, the peak in the adjusted load curve occurs before the evening peak in electricity price, suggesting that the adjusted load curve is not an accurate representation of the wider population behaviour captured in the electricity price data. Whilst geographic factors may contribute to this observation (since the electricity prices shown are for Switzerland, whilst most survey respondents were based in France and the UK), a more obvious explanation is that the normal fit of the start time data in fig. 5a does not capture the shape of the evening peak very well, thus giving an artificially-earlier peak.

Weekends On weekends, the range of most common time to start the dishwasher is wider than for weekdays. Figure 4b shows the usage time is even more likely than for weekdays to be advanced rather than postponed. Most people indeed indicated that they can usually move forward the start of their dishwasher to around 12:00 which corresponds to the off-peak electricity demand in the residential sector.



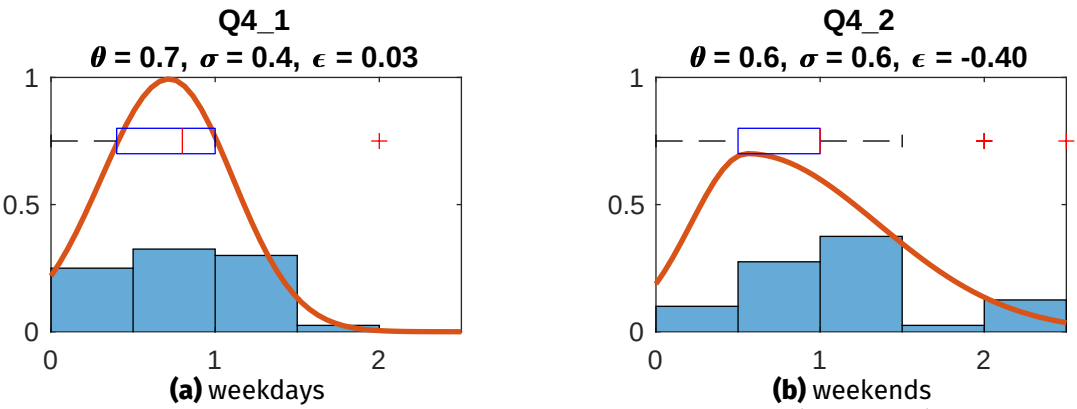
(a) weekdays **(b)** weekends

Figure 4: Box plot of dishwasher start time



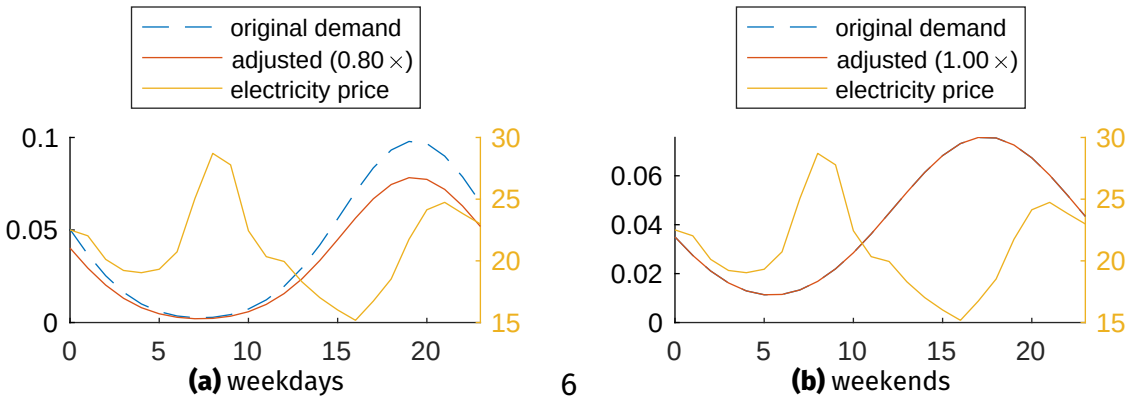
(a) weekdays **(b)** weekends

Figure 5: PDF for start time of the dishwasher (histogram: raw data, line: normal fit)



(a) weekdays **(b)** weekends

Figure 6: PDF for number of dishwasher runs per day, with raw data (histogram) and boxplot to illustrate goodness of fit



(a) weekdays **(b)** weekends

Figure 7: Load curve adjusted for median runs per day, with electricity price for comparison

Figure 5b is the probability density as a function of the hour of the day for the starting time during weekends. The peak at 21:00 is similar to that of weekdays. However, 1/4 of the respondents seem to operate their dishwasher when the electricity demand is lower, which points toward the fact that less incentives would be needed to invite people to operate their dishwasher during off-peak periods with high electricity generation from solar energy. But it must be kept in mind that the residential electricity demand as a function of the time of the day might be different on weekends compared to that displayed in fig. 1.

Figure 6b shows data for the number of runs per day on weekends, with a skew-normal fit of the raw data. The strong skewness (ϵ = -0.40 with $\epsilon \in [-1, 1]$) captures the not-insignificant number of responses reporting around 2 runs per day on weekends.

Figure 7b shows the adjusted load curve accounting for the number of dishwasher runs per day (using the median value from fig. 6b). Since the median number of runs per weekend day is 1.0, the load curve is unchanged.

3.1.3 Flexibility

Respondents were asked to express their willingness to have their dishwasher's typical start time adjusted automatically, both with and without financial incentive. This was treated qualitatively (figs. 8 and 9) before being quantified as the number of hours earlier or later than the usual start time that would be acceptable to the respondent. The financial incentive described was a discount on the price of the electricity, for which 2 randomly-selected discount values from the options 10 %, 20 %, 30 % and 40 % were presented to each respondent.

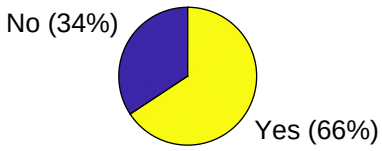


Figure 8: Qualitative willingness to accept demand shifting without remuneration

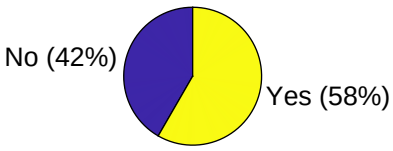


Figure 9: Qualitative willingness to accept demand shifting with remuneration

Figure 10 shows responses to flexibility questions. Since respondents were only presented with 2 out of a possible 4 discount levels, the number of responses to these questions is limited. A fit of these data based on the median responses (to reduce the influence of outliers) is presented in fig. 11.

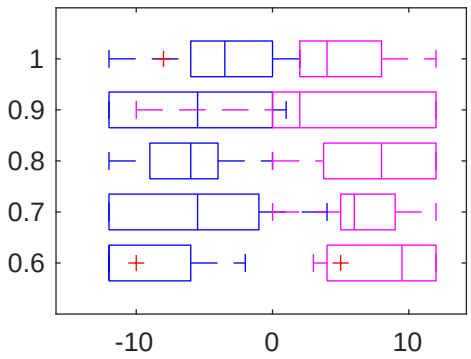


Figure 10: Boxplots for time flexibility relative to usual operating time (x axis) versus expected price multiplier (y axis). Blue: earliest acceptable time; magenta: latest acceptable time.

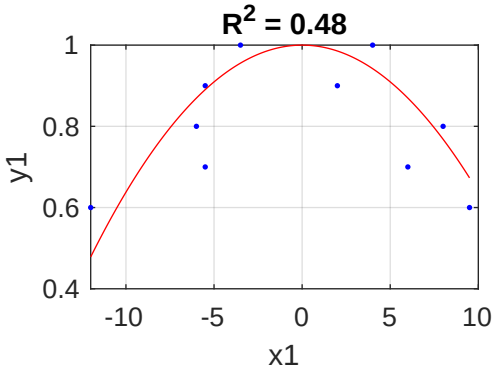


Figure 11: Second-order polynomial fit of the median responses for earliest/latest time. x1: time relative to usual operating time, y1: relative price level (e.g. 0.8 = 20% discount)

3.1.4 Current cost

To calculate the average yearly cost paid by the sample population to run their dishwasher, the hourly costs of electricity in €/MWh is assumed constant over the entire year.[9] From the raw responses for the most usual time for the start of the dishwasher, the average cost of electricity for this load is calculated as 22.44 €/MWh during the weekdays and 21.99 €/MWh during the weekends. During the year, we will assume there is 52 weeks and 52 weekends. Hence with an average number of runs of 3.5 during weekdays and 1.8 during weekends, over the year 182 runs take place on weekdays and 93.6 on weekends. Furthermore, the dishwasher is estimated to consume 190 kWh of electricity per year.[10] Hence the average yearly cost of operation of the dishwasher for the sample population was computed as 1167€.

[9] Claudia Binder. *"The energy transition: An integrative analysis"*. EPFL lecture. 06/05/2020

[10] Christof Timpe. *"Smart Domestic Appliances Supporting The System Integration of Renewable Energy"*. Öko-Institut. November 2009 https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/smart-a_final_brochure.pdf

3.2 Potential economic savings

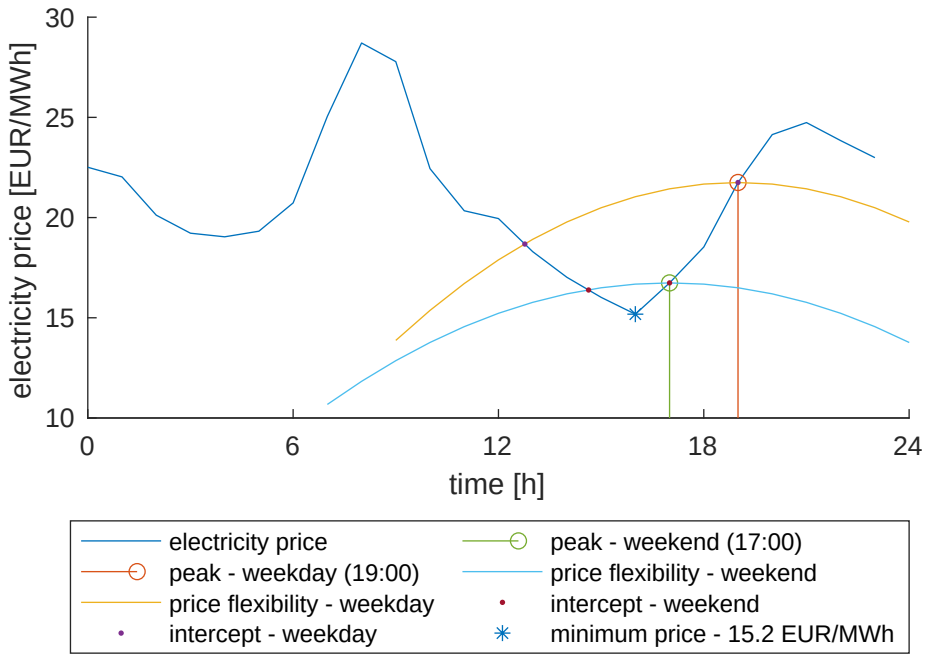


Figure 12: Hourly electricity price and price flexibility

Figure 12 shows the variations of electricity price through out the day. The peak periods indicated correspond to the maxima of the relevant demand curves. At each peak, the relative price flexibility curve (see fig. 11) is superimposed, scaled to the electricity price at the peak. This represents the maximum price acceptable to the consumer to shift their appliance's operation. Thus, when the electricity price curve is below the flexibility curve, this corresponds to a period acceptable to the consumer for the operation of their dishwasher to be shifted to. The intercept between the flexibility and price curves represents the furthermost possible point to which the operation can be shifted. However, the minimum of electricity price, which falls before the intercept, represents the optimal point for both the consumer and provider, since a low electricity price corresponds to relatively low demand and high supply.

3.2.1 Case study

The potential economic savings due to flexibility was illustrated by the study of a sample response to the survey. This person says to be using a dishwasher 7 times a week with 5 runs during weekdays and 2 runs during the weekend. On weekdays, the typical starting time of the dishwasher is 21:00 but it can be one hour earlier or one hour later. On weekends, the typical starting time remains 21:00 but it can start as early as 18:00. The latest starting time does not go

beyond 22:00. For the same electricity consumption, starting the dishwasher at 18:00 could reduce the cost by 25% compared to the standard operating time of 21:00. Hence without consciously modifying his habits, the consumer can reduce his electricity bill by purchasing energy when it is cheaper due to less demand, thus less strain on the production and distribution systems.

Furthermore, the respondent is willing to change his dishwasher usage habits to reduce the strain on the grid during peak hours, with and without financial incentives. With no financial incentives, the dishwasher owner would agree to voluntarily delay the start of his dishwasher 8 hours later then the usual starting time. He would however not be willing to start it earlier then his habits.

Figure 13 highlights the minimum discount acceptable for the user to change his habits by moving forward or delaying the operation of his dishwasher. The red dashed lines correspond to the usual earlier and later start times.

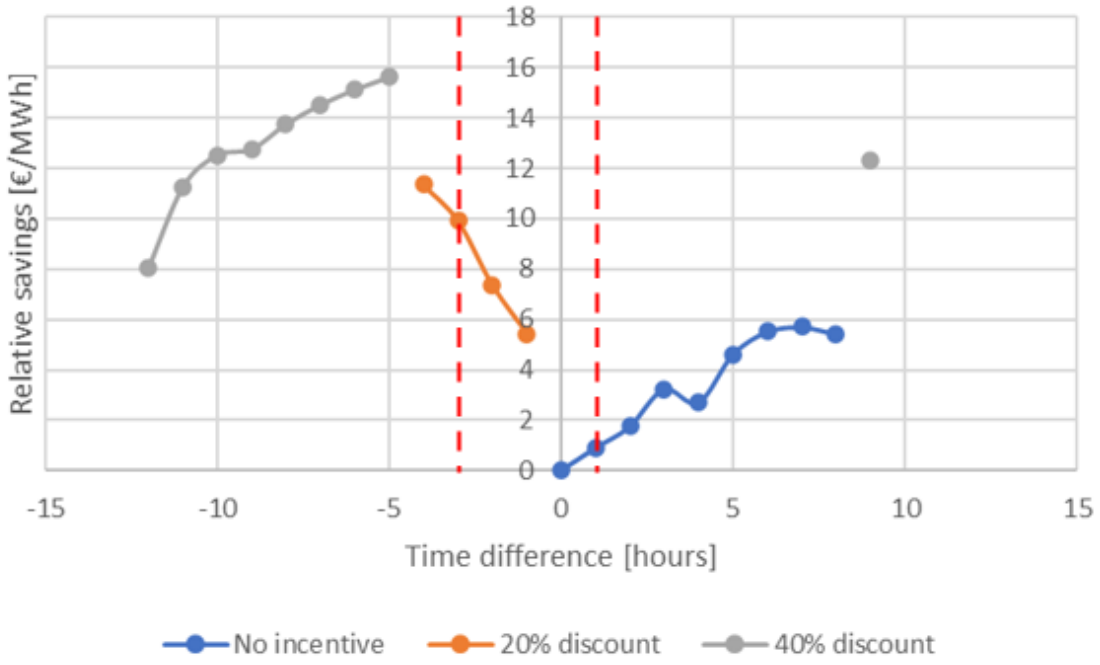


Figure 13: Savings based on consumer flexibility for minimum acceptable discount rate

In blue is what the consumer would do without financial incentive and we see that by changing his habits and delay the start of the dishwasher by 7 hours, he can save 23%. The consumer is willing to accept a 20% discount to operate up to 4 hours earlier, hence a higher discount rate for this area does not have to be offered by the electricity supplier. However, to operate the dishwasher more than 5 hours earlier than the usual time, the consumer is asking for a 40% discount. Hence if the supplier needed the consumer to operate his dishwasher during off-peak hours to reduce the strain on the electricity grid, a greater discount would have to be offered when the consumer has to change his usual time by more than 4 hours earlier. From a consumer point of view, the savings in €/MWH are maximized when the 40% discount rate is applied.

This case study shows that with his current flexibility, the consumer could

already reduce his electricity bill. However to influence greater his habits and increase his usage flexibility, discount rates must be applied as change incentives. Hence there is a potential to optimize the electricity demand for the dishwasher to match the variable supply from renewable energies by informing the consumer and offer discount rates to increase their flexibility.

4 Discussions

4.1 Impact at national level

Our analysis confirms the results from the EU Smart-A project that dishwashers contribute to electricity demand peak loads from domestic households in the evenings.[11] This means that a Demand Side Management could be effectively implemented to balance out the electricity system, since half of the population in the UK and most of Europe owns a dishwasher. Furthermore, dishwashers are appliances with technical constraints which fit the requirements for widespread smart operation. Compared to washing machines, the limitations of postponing the operation of a dishwasher are indeed much less relevant since no consumer action is required directly after the end of the dishwasher cycle.

A DSM program could thus promote the shifting of dishwasher operation into the night. Our research indeed shows that there is higher acceptance amongst consumers to shift the operation of dishwashers to night hours. This was highlighted by their willingness to delay the start of their dishwasher compared to the usual starting time. Our study also showed that consumers were quite flexible even without financial incentive. Hence as a first measure, electricity utilities could promote shifting dishwasher operation during the night by educating consumers to adjust part of their energy demand according to the availability of supply in the electricity system. This measure could already help alleviate strain on the electricity grid during peak loads.

Moreover it was found that financial incentives could increase the flexibility of the consumers' habits. Hence if the electricity supplier would like to shift the demand load of dishwashers to a particular time of the day to match the electricity generation, he could offer more attractive fares and discount rates for those time periods.

4.2 Challenges faced

Significant challenges around data collection, analysis and reporting were encountered throughout this project, some of which are briefly summarised below

- A small number of survey responses meant certain questions did not have sufficient data to draw significant conclusions (see for example fig. 10)

[11] Christof Timpe. *"Smart Domestic Appliances Supporting The System Integration of Renewable Energy"*. Öko-Institut. November 2009 https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/smart-a_final_brochure.pdf

- The time-series data collected were of the format 0-24, whereas dishwasher operation behaviour commonly extended after midnight (for which time was considered to reset from 0 again). This introduced subsequent difficulties in data processing

In addition, a number of assumptions and approximations were made, which could be revisited

- The duration of a dishwasher cycle was approximated to one hour to facilitate this study by keeping a constant electricity price throughout each dishwasher run.
- The electricity prices for one day were assumed to remain constant through out the year, which does not seem very realistic as the demand and the supply would vary between weekdays and weekends and between different seasonal periods. Hence to obtain more accurate results for the potential energy savings, the study could be conducted for typical time period by clustering the cost variations.

5 Conclusion

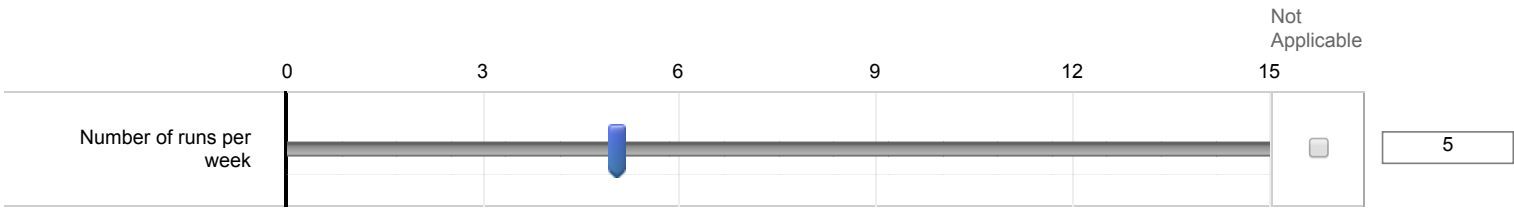
Adapting the load of dishwashers to meet the electricity supply is a promising Demand Side Management program. In this study, a survey was created to collect results about consumers' habits and flexibility regarding the usage of their dishwasher. It was found that the respondents mostly operate their dishwasher in the evening, which contributes to the peak load on the electricity system during this period and corresponds to higher electricity prices. Consumers are, as expected, more flexible during weekends and the load curve is more distributed during the day, thus reducing the strain of the electricity grid but also lowering the cost of operation of the appliance. Furthermore, the survey questioned the consumers on their willingness to change their dishwasher usage habits to reduce strain on the grid during peak hours. The dishwasher owners were found to accept that their appliance's operation is automatically adjusted. When their flexibility would be rewarded by a discount rate on their electricity bills, it was found that consumers' range of acceptable staring times increased with increasing discount rates. This shows that there is a potential to optimize the demand load over the whole day when best suited for the supplier. A major challenge of our future electricity system is indeed the variability of wind and solar energy production and it will be crucial to find means of influencing the demand to meet the supply at all times in the absence of sufficient energy storage capacities.

Appendix A Sample survey response

Following is a sample output from Qualtrics showing one survey response received.

Q1. In this survey we'd like to understand how you use dishwashers in your household!
Your responses will only be used for academic research.
PS: please try to answer based on your habits before the lock-down!

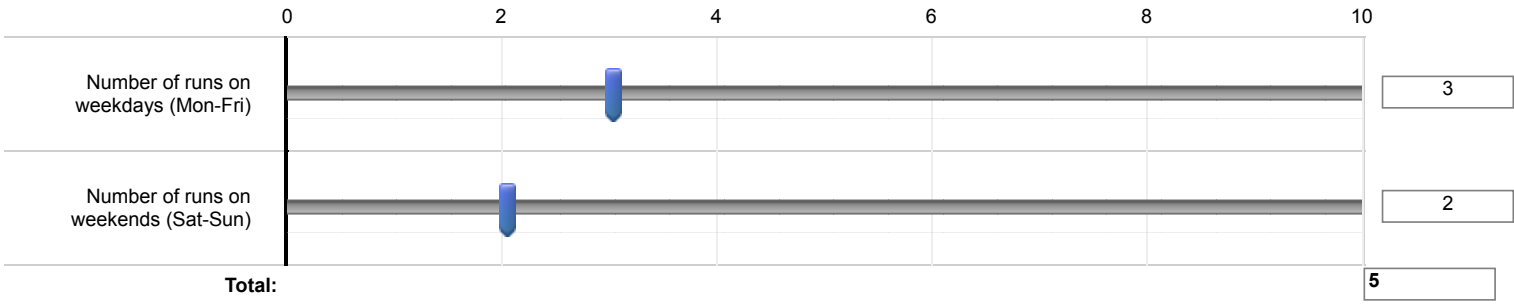
Q2. First, thinking about a typical week, about how many times on average do you run the dishwasher?



Q3. Please give further information: First, thinking about a typical week, about how many times on average do you run the dishwasher?

This question was not displayed to the respondent.

Q4. Great, so you typically run your dishwasher 5 times per week. How is this split between weekdays and weekends?



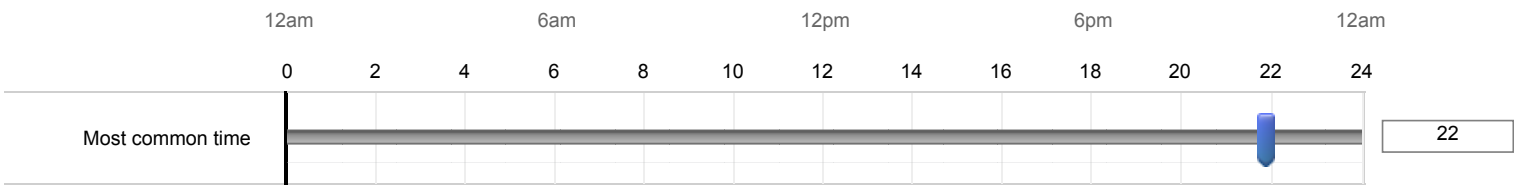
Q5.
Next, we'd like to understand how your dishwasher usage varies by time of day

Q21. [translation hack]

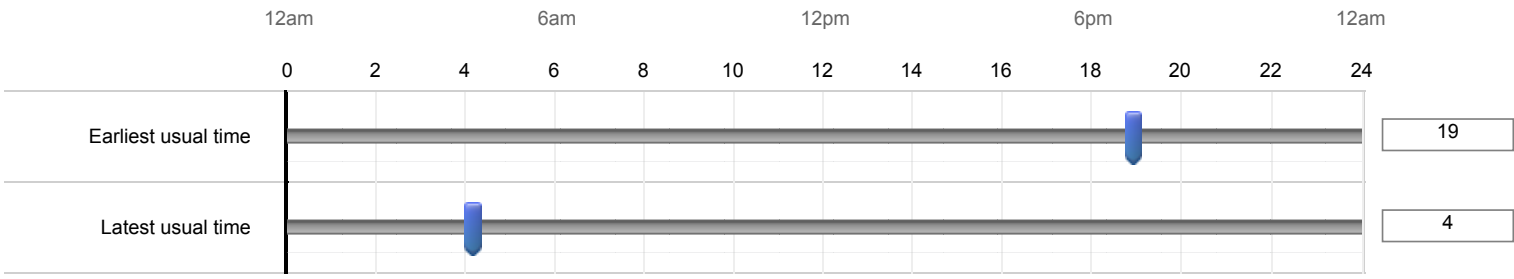
This question was not displayed to the respondent.

Q6. Please consider your dishwasher usage **on weekdays**

Q7. Typically what is the most common time you run your dishwasher on weekdays?



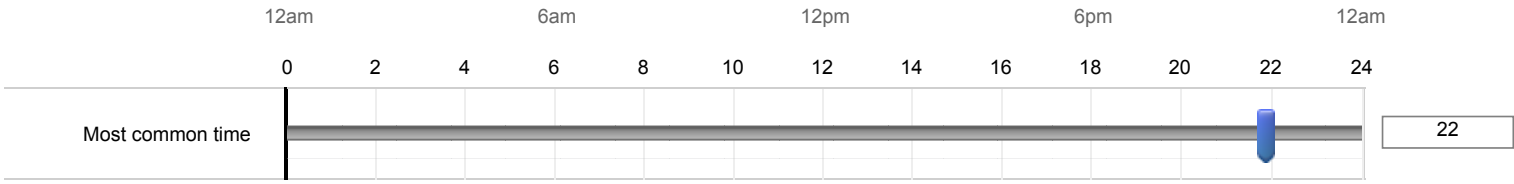
Q8. Thanks for telling us that you most frequently run the dishwasher at 22:00 on weekdays. Now we'd like to know how much this usual time varies



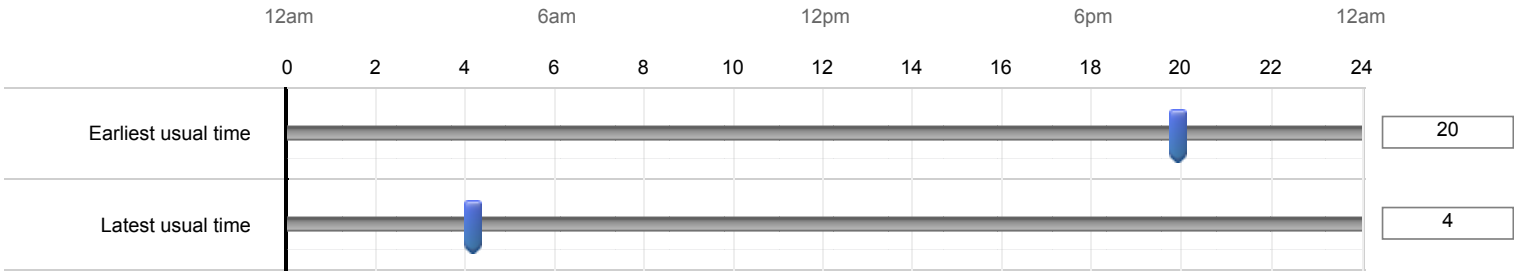
Q9. Great, so you've told us that on weekdays you usually run the dishwasher **between 19:00 and 4:00**, with the most common time being **22:00**.

Q6. Please consider your dishwasher usage **on weekends**

Q7. Typically what is the most common time you run your dishwasher on weekends?



Q8. Thanks for telling us that you most frequently run the dishwasher at 22:00 on weekends. Now we'd like to know how much this usual time varies



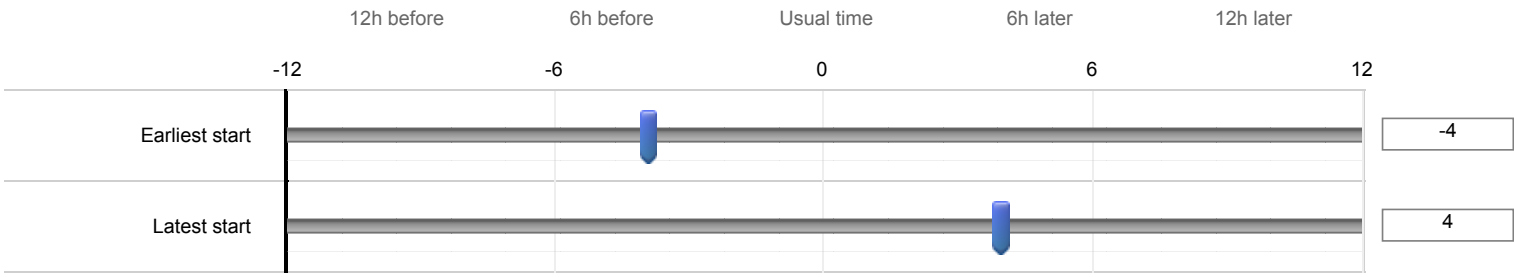
Q9. Great, so you've told us that on weekends you usually run the dishwasher **between 20:00 and 4:00**, with the most common time being **22:00**.

Q10. Next we'd like to ask you about how willing you might be to change your dishwasher usage habits. By changing when we use home appliances like dishwashers, we can shift their electrical demand to a different time of day, reducing strain on the grid during peak hours.

Q11. Would you be willing to let the time at which your dishwasher operates be automatically adjusted?

- (●) Yes
- ( ) No

Q12. How many hours **earlier or later than the usual start time** would you be willing to let your dishwasher operate?



Q13. **If at certain hours of the day there is a discount on your electricity bill**, would you be willing to let the time at which your dishwasher operates be automatically adjusted?

This question was not displayed to the respondent.

Q14. With a **% discount** on your electricity bill during certain hours of the day, how many hours **earlier or later than the usual start time** would you be willing to let your dishwasher operate?

This question was not displayed to the respondent.

Q14. With a **% discount** on your electricity bill during certain hours of the day, how many hours **earlier or later than the usual start time** would you be willing to let your dishwasher operate?

This question was not displayed to the respondent.

Q14. With a **30% discount** on your electricity bill during certain hours of the day, how many hours **earlier or later than the usual start time** would you be willing to let your dishwasher operate?

Q14. With a **40% discount** on your electricity bill during certain hours of the day, how many hours **earlier or later than the usual start time** would you be willing to let your dishwasher operate?

Location Data

Location: (49.442901611328, 1.1002960205078)

Source: GeoIP Estimation