Key Performance Indicators to Support the Participation in Demand Response Programs: A Testing Framework for End Users

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Abstract: With the new challenges and complexity in power electricity management, demand response programs can be a way to reduce stress and strengthen power grids. However, as demand response implies end users to intentionally change their consuming patterns to adapt to grids needs, some decision-making support tools are necessary. The present paper proposes an energy management and controlling tool to assist electricity end users to make their decision to change consumption pattern in a DR scenario while using key performance indicators. The tool was tested using a group of 20 end users and showed a consistent result throughout all the elements in the sample.

Keywords: System Management, Monitoring, Key Performance Indicators, KPI, Demand Response

1. INTRODUCTION

Nowadays, the growing demand, environmental concerns and protection needs, the increase in renewable energy generation and in distributed generation brought more complexity and difficulties to the already challenged power management (Faria et al. 2019). One of these new topics, already well know and much commented, is distributed generation which come, not only as an necessity for increasing renewable generation, but also as a solution to reduce losses, costs and inefficiencies (Mezouar, El Afia, & Chiheb, 2016).

The predominant conventional power grid, usually focussed on big centralized power plants generating energy to a large group of passive consumers, is changing to adapt to the new reality/complexity created, and this new model is the well-known Smart Grid. Smart grid is defined by (2016) as "a generation, transmission and distribution system equipped with a two-way communication system controlled by the grid operator". In that way, one of Smart Grid's purpose is to reduce stress and strengthen the power grid. One way to do that is by balancing supply and demand and avoid overload the power grid through Demand Response (DR) programs. In order to do that, some decision-making support system have been created to help evaluating performance and giving feedback. However, key performance indicators (KPI) can lead to a faster and more focused analysis, they provide on time information and are very graphical, which leads to faster analysis and decision making and lower margin for error or miss understanding.

KPI are the most relevant variables to be measured in order to assess the success of a strategy or a management process, which means, the effectivity to reach the expected goals.

In that context, a managing and controlling tool is proposed in the present paper to help evaluating end users' performance and facilitate the decision-making process. The creation and testing of an energy management and controlling tool was thought to assist electricity end users to make their decision to change consumption pattern in a DR scenario while using a simple, visual and effective method, KPI.

This paper is organized in five sections. The first one is the introduction, followed by a concise literature review; section 3 presents the methodology, section 4 results and discussion and, finally, section 5 presents the conclusions of this study.

2. LITERATURE REVIEW

Demand response is defined by Albadi and El-Saadany (2008) as the changes performed by end-user electricity consumers that occur as consequence of changes in electricity prices over time or as the decrease in electricity consumption as a result of incentive payments. Which means, end users intentionally changing their consumption patter (time, instantaneous demand or total consumption). There are three general actions (Albadi & El-Saadany, 2008):

1. Reduction of electricity consumption during peak time while keeping same consumption during off peak periods:
   a. Prices during peak time are higher;
   b. Implies temporary reduction of comfort.
2. Shifting demand from peak to off-peak periods:
   a. There is no loss of comfort;
   b. For residential customers, there is no cost in the action.
3. Generating completely or partially their own energy:
   a. None or little change in previous consume pattern.

Based on that, consumers can reduce their comfort, which can be associated with a gain that compensate the comfort loss; shift their demand, which is associated with a change in habits/routine/schedule; or starting to generate their own energy, (total or partially) which means some investment and conditions (structure, geography, among others) that may not be available. Furthermore, as DR is an intentional change that consumers make in their own behaviour in order to reduce electricity use, and considering that this change can happen in different ways, it is necessary some measurements to analyse the results of the DR program, i.e. how the consumers are willing to change their behaviour.

In order to help final consumers to make better-informed changes in their pattern to balance demand and supply, reduce the stress of the grid and reduce their own costs, a set of KPI was created to work as an energy management and controlling tool. KPI are a visual/graphic tool that allow clear and fast asses to information, reduce the time and increase the number and effectivity of responses. KPI have already been used in some projects to assess energy efficiency in smart grid scenarios (Fadhel Khelifa & Jelassi, 2016; Hussain, Gabbar, Musharavati, & Pokharel, 2013; May, Taisch, & Kelly, 2013; Rasam, Hanif, Samad, & Hadi, 2013; Sanz et al., 2015) and it is proven to be a reliable approach that provides decision support to stakeholders. However, the cited authors do not evaluate the type of response action chosen by the consumers and some of them just present and explain the KPI method without testing it with any group of real consumers.

Considering that the goal of this research was to create and test a managing and controlling tool for end users to make their decision to change consumption pattern in a DR scenario, analyse their predominant type of change and test it with a group of real end-users was fundamental for the success of this research.

3. METHODOLOGY

This work is a continuity of (Silva et al. (2019) research on how aggregation can influence the final remuneration of the resources associated with virtual power player. In such work, the consumers are aggregated according to their actual participation in Demand response events so it is possible to achieve a number of tariff groups for the remuneration of the demand reduction provided.

The goal of the proposed methodology in the present paper is to create and test an energy management and controlling tool to assist electricity end users to make their decision to change consumption pattern in a DR scenario with the support of a selected KPI group. In order to build and test the tool, data from 20 consumers were taken. The data comes from a Virtual Power Player and all 20 elements from the sample are only consumers (do not generate energy) of Incentive-based Demand Response Program. That means the only response actions available are to reduce electricity consumption or to shift the original demand. Furthermore, it used two periods of analysis, the first one corresponds to the consumption before DR implementation and the second one, after implementation.

Considering the interactions between this research and (Silva, Faria and Vale, 2019), Figure 1 presents the overview of the proposed methodology.

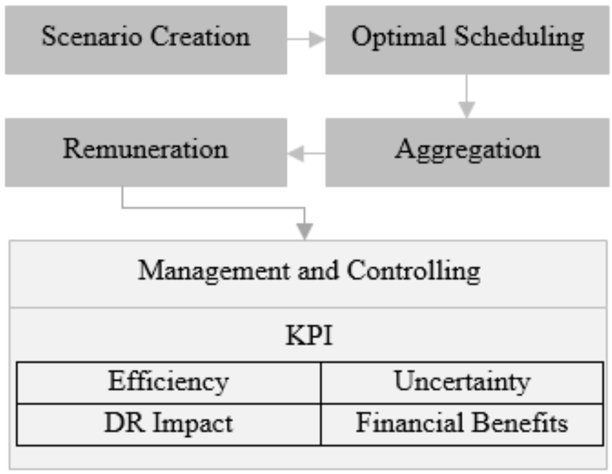

Fig. 1. Overview on proposed methodology

For the KPI, as it intends to measure the performance of each demand response goal, show if the current strategy is bringing the expected results and access how the variables are evolving through time, a set of 12 KPI distributed in four groups of interest were created. They are organized as in Table 1.

Table 1. KPI per interest group

Interest Group	KPI
Efficiency	Total Energy Consumption Maximum Consumption per Period Maximum Daily Consumption Peak Load Duration
DR Impact	Change in Total Consumption Change in Consumption during Peak Periods Change in Consumption during Off-Peak Periods Customer Response Action
Uncertainty	Power Deviation
Financial Benefits	Self-Elasticity Self-Elasticity – Negative % Correlation Between Cost and Demand

Each KPI is described in the following sub-sections. Some were previously used and can be found in (Fadhel & Jelassi, 2016; Thanos et al., 2013)

2.1 Efficiency

KPI from efficiency group are related to attend customer's necessities and to describe demand critical aspects.

The first KPI, Total Energy Consumption, represents the energy consumed during a period of time and can be expressed by equation 1.

$$E = \int_{t_i}^{t_f} e_i(t)\partial t \quad (1)$$

where
E – energy consumption
e_i (t) – power delivered
t_i – inicial time period
t_f – final time period

Maximum Consumption per Period corresponds to the maximum consumption during each period of the day. It calculates the peak demand and returns a visual representation of its curve. This KPI is represented by equation 2.

$$MaxConp = Max\,[e_i] \quad (2)$$

Its goal is to help the end consumer to understand its pattern and to make decisions to shift the demand to periods with smaller energy costs.

The third KPI, Maximum Daily Consumption, correspond to the daily load energy consumption and can be expressed as

$$MaxCond = Max\left[\int_{t_i}^{t_f} e_i(t)\partial t\right] \quad (3)$$

considering the time interval of a day.

The last one, Peak Load Duration, gives an overview of the duration of the peak consumption for a customer. To calculate this KPI it is used a statistic analysis based on the peak consumption and the load behaviour. This KPI can be represented as in equation 4.

$$PeakDur = \{RefLoad_{t_i}\} \quad (4)$$

where

$RefLoad_{t_i}$ - correspond to the load consumption during each time interval t_i.

2.2 DR Impact

DR Impact measures end users changes due to demand response programs. In this group of interest, the before consumption is measured before DR implementations and after consumptions is measured after its implementation.

The first KPI of the second group is Change in Total Consumption and can be defined as the change considering the periods before (orig.consumption) and after (new.consumption) implementation.

$$\frac{orig.consumption - new.consumption}{orig.consumption} \quad (5)$$

The second, Change in Consumption during Peak Periods corresponds to the consumption between 8:00 hours and 22:00 hours, considering the periods before (orig.peak.consumption) and after (new.peak.consumption) implementation.

$$\frac{orig.peak.consumption - new.peak.consumption}{orig.peak.consumption} \quad (6)$$

And Change in Consumption during Off-Peak Periods correspond to all periods that were excluded in the previous KPI, also analysing periods before (orig.offpeak.consumption) and after (new.offpeak.consumption) implementation.

$$\frac{orig.offpeak.consumption - new.offpeak.consumption}{orig.offpeak.consumption} \quad (7)$$

The last KPI in DR Impact group is Customer Response Action, which measures the change in consumption per period comparing the periods before and after DR implementation and return the more frequent behaviour of each consumer, comfort loss (decrease in total energy consumption) or demand shift (decrease in energy consumption during a period of the day with no or minimal change in consumption considering the entire day).

2.3 Uncertainty

This group has only one KPI, which is Power Deviation and represents the error or variability in customer demand during a day. Smaller values indicate smother load curve and smaller uncertainty.

$$\sigma_p = \frac{1}{t_f - t_i}\sqrt{\int (p(t) - \bar{p})^2 \partial t} \quad (8)$$

where
p(t) – power consumption during period of time t
$\bar{p}$ - average power consumption during the period ($t_f - t_i$)

2.4 Financial Benefits

The last group measures the gain and the cost-demand dependency.

The first KPI, Self-Elasticity, represents end users demand sensitivity to changes in electricity price.

$$Self\ Elasticity = \frac{\delta e}{\delta p} \quad (9)$$

where

δe - demand change
δp price change

Considering that consumption should decrease as the electricity cost increase and increase or remain constant as the cost decrease the Self-Elasticity should always be a negative value. However, during the analysis it was noticed that the majority of self-elasticity values were positive, meaning that demand is not strongly influenced by changes in price. In order to re-evaluate this fact a new KPI was introduced, Self-Elasticity – Negative %, which measures the amount of demand and cost variation that respect that premise.

The Correlation Between Cost and Demand correspond to the correlation coefficient between cost and before DR demand, cost and after DR demand and cost and measured change in demand. The results for each of these KPI that was obtained during the test analysis can be found in section 4.

4. RESULTS AND DISCUSSION

A sample composed by 20 consumers were subjected to the management and controlling tool with all the 12 KPI presented in section 3. The sample data were collected with a time interval of 15 minutes and, for the analysis, were used four time frames, Weekdays (WD), Saturday (Sat), Sunday (Sun) and Whole Week (WW), this difference is due to costs variability, as during Sundays there is no difference in electricity price through the day, and on Saturdays this variability is less frequent than the one during weekdays.

Furthermore, all of the sample elements are domestic consumers who does generate neither part nor total electricity they consume. It was considered the prices and time periods used in (Silva et al., 2019) and it was, also, considered two periods, one before (January/2018) and one after (February/2018) implementation, for comparison. When analysing change in patters, the first 3 days of January were ignored, so both periods would have the same length and start in the same weekday. Fig. 2 presents the main information generated after analysis, which is used to create the visual feedback for end-users. It is an example of the summary provided for each KPI with necessary information to analyse the DR performance for each consumer. Fig. 3 presents the result for KPI change in consumption patter for customer C1.

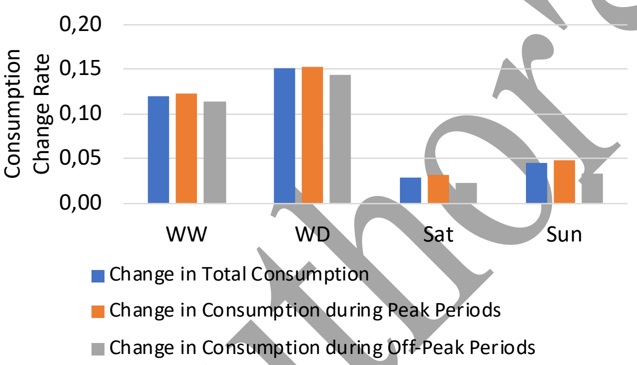

Fig. 3. DR impact - C1 Change in Consumption

Not only C1 customer, but all consumers presented a positive change due to DR impact, which means that all customers intentionally changed their consumption patter. However, in all cases their response was, predominantly, due to a loss in comfort and not a shift in demand. Another aspect that should be noticed is that the electricity consumption presented a decrease during both periods, peak (when the DR system send signals to the consumer to reduce their demand) and during off-peak periods (when the reduction was not necessary). To better understand that, a deeper analysis will be necessary.

Fig. 4 presents the correlation between cost and demand for C8 and C15. The Financial Benefit KPI didn't show a strong correlation between demand and electricity price, in fact, the Self-Elasticity, which should be a negative value, is majority positive for all changes in electricity price. Which means that, for the 20 customers analysed in this test, the decrease in electricity consumption is not a result of an increase in price.

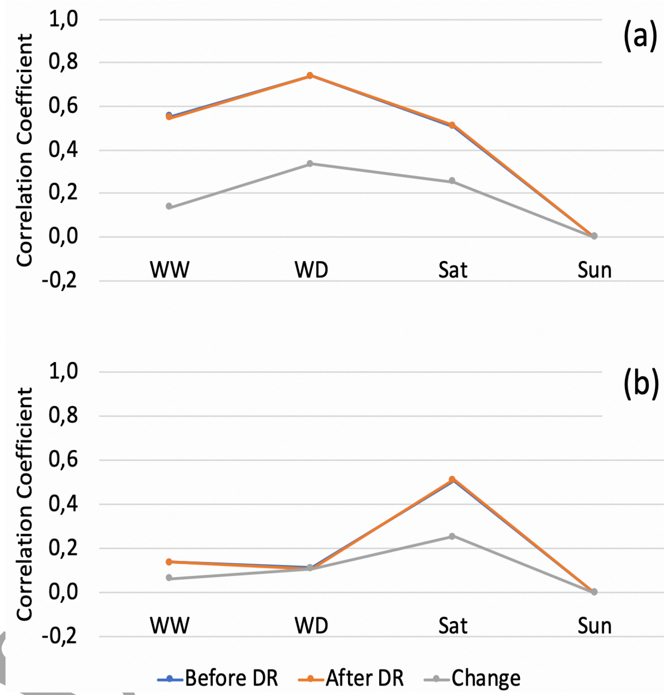

Fig. 4. Financial Benefit – (a) C8 and (b) C15 Change in Consumption

However, all sample elements have an almost zero correlation coefficient on Sundays, which was expected as there is no variation in price during this period. Another interesting result is that the correlation coefficient before DR implementation and after DR implementation are very similar, which causes an overlap in the graphics of Fig. 4.

Fig. 5 presents the uncertainty result for C1. For customer C1 and for all other elements in the sample, uncertainty also presented a decrease, which means a smoother demand curve, even on Sundays.

Finally, Fig. 6, Fig. 7 e Fig. 8 presents the global results for a hypothetical energy community composed by the 20 consumers. Fig. 6 correspond to the DR impact, Fig. 7 to the correlation between demand and cost and Fig. 8 to the power variation in the community.

From the community results, one can notice that the difference in uncertainty before and after is much smaller than the one presented in Fig. 5, which means that some consumers continue to have an accentuated peak demand even after DR implementation. That would be expected as the decrease in consumption occurred during peak and off-peak periods.

Based on that, KPI showed a consistent result throughout the sample and presented itself as a reliable way to analyse end users' performance in a DR system and also to indicate/highlight when results or consumers' behaviour do not correspond to previously established assumptions.

	EFFICIENCY		DR IMPACT	UNCERTAINTY		C1
	Total Energy Consumption		Change in Total Consumption	Power Deviation		
	Before DR	After DR		Before DR	After DR	
WW	50366,7366	44297,3197	0,12	9,6620	9,3687	
WD	36996,8877	31426,7436	0,15	9,5385	9,2883	
Sat	6702,7578	6504,3986	0,03	10,0357	9,6950	
Sun	6667,0910	6366,1774	0,05	9,9755	9,4467	
	Maximum Consumption per Time Period (ti)		Change in Consumption during Peak Periods	FINANCIAL BENEFITS		
				Self Elasticity		Total Cost Reduction
	Before DR	After DR		Before DR	After DR	
WW	29,6538	29,6227	0,12	64,22946104	51,40819796	270,33 €
WD	29,6538	29,6227	0,15	57,67429238	48,2170039	256,09 €
Sat	29,5761	29,6227	0,03	6,555168655	3,191194062	6,60 €
Sun	29,1203	28,6243	0,05	0	0	7,64 €
	Maximum Daily Consumption		Change in Consumption during Off-Peak Periods	Self Elasticity - Negative%		Maximum Cost Reduction (ti)
	Before DR	After DR		Before DR	After DR	
WW	1705,4408	1661,1502	0,11	28,24%	37,93%	0,0078 €
WD	1667,1953	1659,2749	0,14	31,30%	39,00%	0,0050 €
Sat	1705,4408	1661,1502	0,02	6,25%	31,25%	0,0069 €
Sun	1702,6150	1647,2533	0,03	-	-	0,0078 €
	Peak Load Duration (ti)		Customer Response Action	Correlation Between Cost and Demand		
	Before DR	After DR		Before DR	After DR	Change
WW	55	55	Comfort Reduction	0,552096443	0,54659554	0,136550574
WD	55	55	Comfort Reduction	0,738037883	0,738186522	0,334572895
Sat	55	55	Comfort Reduction	0,509087405	0,511916704	0,253500602
Sun	55	55	Comfort Reduction	-3,47322E-16	1,16403E-15	6,54493E-16

	EFFICIENCY		DR IMPACT	UNCERTAINTY		C8
	Total Energy Consumption		Change in Total Consumption	Power Deviation		
	Before DR	After DR		Before DR	After DR	
WW	98036,2465	86222,4406	0,12	18,8066	18,2356	
WD	72012,5276	61170,5303	0,15	18,5662	18,0791	
Sat	13046,5712	12660,4753	0,03	19,5340	18,8708	
Sun	12977,1477	12391,4349	0,05	19,4168	18,3875	
	Maximum Consumption per Time Period (ti)		Change in Consumption during Peak Periods	FINANCIAL BENEFITS		
				Self Elasticity		Total Cost Reduction
	Before DR	After DR		Before DR	After DR	
WW	57,7195	57,6590	0,12	125,0193224	100,0633974	526,19 €
WD	57,7195	57,6590	0,15	112,2600259	93,85190329	498,47 €
Sat	57,5684	57,6590	0,03	12,75929652	6,2114941	12,84 €
Sun	56,6813	55,7157	0,04	0	0	14,88 €
	Maximum Daily Consumption		Change in Consumption during Off-Peak Periods	Self Elasticity - Negative%		Maximum Cost Reduction (ti)
	Before DR	After DR		Before DR	After DR	
WW	3319,5523	3233,3428	0,11	28,24%	37,93%	0,0152 €
WD	3245,1095	3229,6927	0,14	31,30%	39,00%	0,0097 €
Sat	3319,5523	3233,3428	0,02	6,25%	31,25%	0,0134 €
Sun	3314,0519	3206,2934	0,03			0,0152 €
	Peak Load Duration (ti)		Customer Response Action	Correlation Between Cost and Demand		
	Before DR	After DR		Before DR	After DR	Change
WW	55	55	Comfort Reduction	0,552096443	0,54659554	0,136550574
WD	55	55	Comfort Reduction	0,738037883	0,738186522	0,334572895
Sat	55	55	Comfort Reduction	0,509087405	0,511916704	0,253500603
Sun	55	55	Comfort Reduction	9,33226E-16	-2,45862E-16	4,52523E-16

	EFFICIENCY		DR IMPACT	UNCERTAINTY		C15
	Total Energy Consumption		Change in Total Consumption	Power Deviation		
	Before DR	After DR		Before DR	After DR	
WW	13693,3255	12043,2186	0,12	2,6268	2,5471	
WD	10058,4326	8544,0642	0,15	2,5933	2,5252	
Sat	1822,2948	1768,3665	0,03	2,7284	2,6358	
Sun	1812,5980	1730,7879	0,05	2,7121	2,5683	
	Maximum Consumption per Time Period (ti)		Change in Consumption during Peak Periods	FINANCIAL BENEFITS		
				Self Elasticity		Total Cost Reduction
	Before DR	After DR		Before DR	After DR	
WW	8,0620	8,0536	0,11	-0,663107661	-0,931288327	54,14 €
WD	8,0620	8,0536	0,15	-2,44527708	-1,798885911	50,27 €
Sat	8,0409	8,0536	0,02	1,782169418	0,867597583	1,79 €
Sun	7,9170	7,7822	0,03	0	0	2,08 €
	Maximum Daily Consumption		Change in Consumption during Off-Peak Periods	Self Elasticity - Negative%		Maximum Cost Reduction (ti)
	Before DR	After DR		Before DR	After DR	
WW	463,6623	451,6209	0,10	43,51%	39,66%	0,0021 €
WD	453,2644	451,1110	0,14	48,70%	41,00%	0,0014 €
Sat	463,6623	451,6209	0,01	6,25%	31,25%	0,0019 €
Sun	462,8940	447,8427	0,02			0,0021 €
	Peak Load Duration (ti)		Customer Response Action	Correlation Between Cost and Demand		
	Before DR	After DR		Before DR	After DR	Change
WW	55	55	Comfort Reduction	0,137125289	0,13989491	0,065141503
WD	55	55	Comfort Reduction	0,113667165	0,108778595	0,11092992
Sat	55	55	Comfort Reduction	0,509087405	0,511916704	0,253500603
Sun	55	55	Comfort Reduction	1,75488E-16	-1,24533E-15	-2,80178E-16

Fig. 2. Summary of the information provided for each KPI

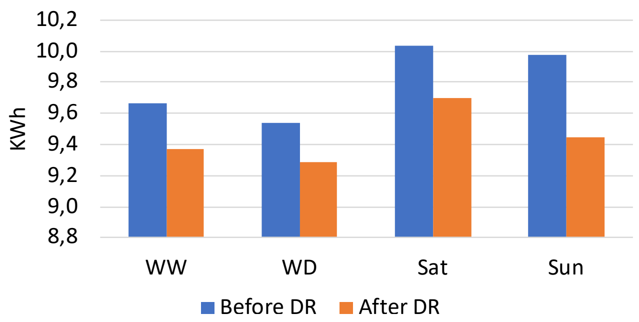

Fig. 5. Uncertainty – C1 Power Deviation

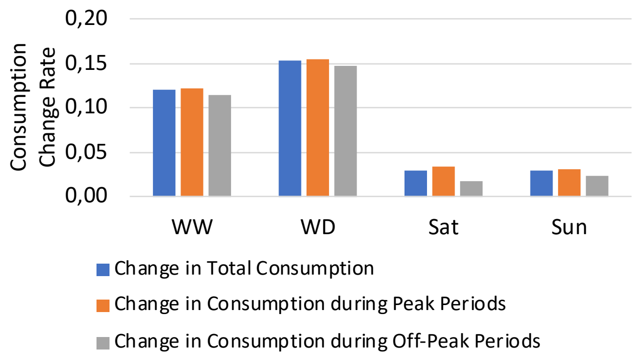

Fig. 6. DR impact - Community Change in Consumption

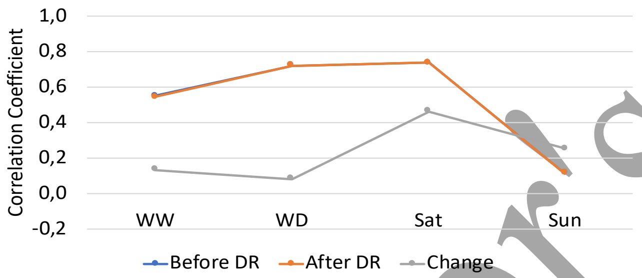

Fig. 7. Financial Benefit – Community Change in Consumption

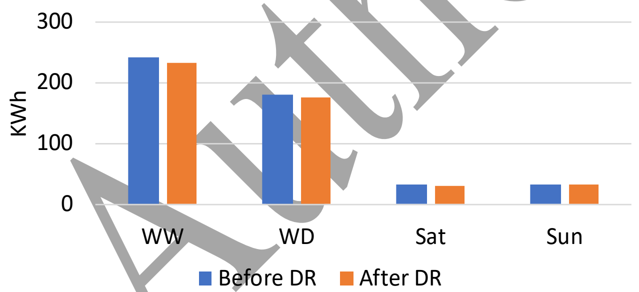

Fig. 8. Uncertainty – Community Power Deviation

5. CONCLUSION

The goal of this study was to create and test an energy management and controlling tool to assist electricity end users to make their decision to change consumption pattern in a DR scenario while using key performance indicators. The tool was tested using a group of 20 end users and showed a consistent result throughout all the elements in the sample. However, a deeper analysis is necessary to better understand the price-demand behaviour and its influence in persuading consumers to change their behaviour in order to adapt the Financial Benefit KPI group.

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