# Clustering Direct Load Control Appliances in the Context of Demand Response Programs in Energy Communities

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**Abstract:** The demand response program explained in this article is designed to be implemented in communities seeking to achieve a self-sustaining system, namely through renewable energy such as photovoltaic energy. This article, through concepts such as prosumer and clustering, aims to make the most efficient management of the resources provided by the energy community. The developed demand response clusters the different consumers who have the same type of consumption throughout the day. That is, it brings together those whose behavior of the respective loads resemble each other and can be viewed from the perspective of an individual load or even clustered with one or more loads. The study comprises three villages with different numbers of consumers and charges, where, through their participation, it is estimated that there are reductions in electricity bills and, for those who collaborated for the study, it is attributed a remuneration according to their performance.

*Keywords:* Clustering, Demand Response, Energy Communities, Prosumer, Renewables, Smart Grids.

## NOMENCLATURE

**Acronyms**
**AC** - Air Conditioner
**WH** - Water Heater
**FH** - Fan Heater
**WM** - Washing Machine
**DW** - Dishwasher
**DR** - Demand Response
**IL** - Initial Load
**PV** - Photovoltaic
**RE** - Renewable Energy
**SG** - Smart Grid
**Parameters**
**K** - Number of allowed clusters
**Variables**
$P_a(t)$ - Consumption of the Appliance **a**
$P_{pv}(p)$ - Scheduled power from PV unit **p**
$T_a(t)$ - Total consumption related to appliance **a**
$P_{extSup}(s)$- Scheduled power from External Suppliers **s**
$P_{TR}(a)$ **-** Scheduled power reduction from appliance **a**
$P_{NSP}$ **-** Scheduled power non-supplied power
**Indexes**
**a** - Appliances (WH, AC, FH, WM, DW)
**i** - (1,2,3,4,5)

## 1. INTRODUCTION

In everyday life, the implementation of renewable energy (RE) in communities has been a critical factor, namely in the context of sustainable electrical systems as well as to produce clean energy. However, only the implementation of RE is not enough for a community to achieve a self-sustaining state. Thus, it is essential to implement mechanisms that enable a community that has local RE to make the most of energy management. This is called the energy community.

A crucial concept that enables the development of a sustainable electricity system is the demand response (DR), where the scope is to efficiently manage the energy resources of a given energy community to meet its socio-economic needs (Asadinejad *et al.*, 2018). In other words, this concept provides management flexibility, allowing it to accommodate discrepancies arising from energy resources (Kim *et al.*, 2011; Faria, Spínola and Vale, 2018). However, the effectiveness of this program strongly depends on the input of consumers from their energy community. Within these consumers, some can produce their energy through RE, such as solar energy. Depending on photovoltaic (PV) production and consumption, they can meet their energy needs by sharing their excesses with the community itself. Thus, they have a duality, that of a consumer and producer, which is currently referred to as a "prosumer" (Abrishambaf, Faria and Vale, 2018; Park *et al.*, 2019). However, the implementation of a DR program first needs an update to the power grid to monitor both its output and the consumption of the community concerned. In other words, it needs an electrical system that can establish two-way communication as well as overseeing the different stages in which the energy itself is subjected to the smart grids (SG). Given the context of this paper, SG makes the integration of RE into the network itself more efficient and secure (Estrella, Belgioioso and Grammatico, 2019).

This article is the continuation of paper (Faria, Barreto and Vale, 2020), where it, concerning the previous one, contains new information from two more energy communities that benefit from RE from PV panels. The innovative contributions introduce clustering methods to the method: each consumer has, for each appliance, a consumption pattern, which, when it is verified that different types of equipment of several consumers have similar patterns, cluster them into one, to ease the implementation of consumption reductions. An optimization to schedule the different equipment of different consumers by consumption pattern throughout the day is applied. Section 1 is the introduction. Section 2 shows the flowchart of the methodology discussed and explains the different phases of the proposed model. Section 3 describes in detail the case-study. Section 4 includes the results and section 5 presents the main conclusions of work developed.

## 2. APPLIANCE CLUSTERING APPROACH

This section serves to reveal and explain in detail the proposed method of this article. Figure 1 illustrates the different phases of the proposed method by the authors as well as generally describes the various steps.

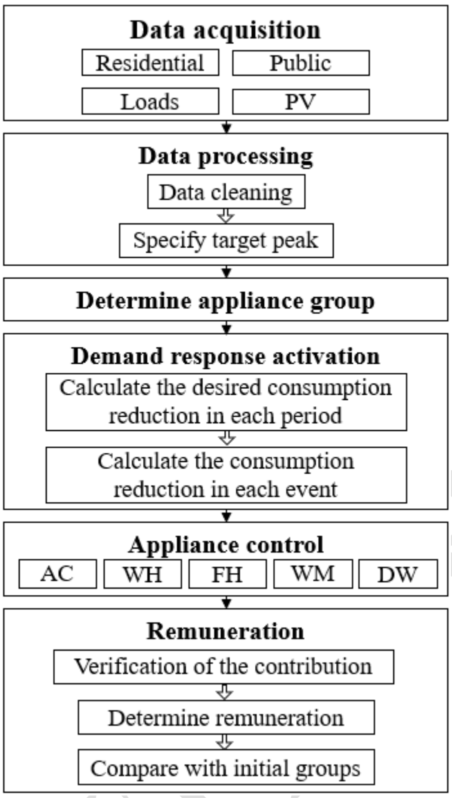

Fig. 1. Proposed Methodology.

The first step of this method, Data acquisition, is to collect the data of load consumption, PV production and tariffs of public buildings and residences, in periods of 15 minutes, where at the end of the day there are 96 periods.

As for the Data processing stage, it has 2 phases, where the first phase consists of verifying and correcting the data provided by the participants that do not fit with the others in each period. That is, in periods where there are very high values of equipment consumption and photovoltaic production compared to other periods, they are replaced by a value that is determined by the average daily consumption or production. With this, it becomes possible to use the received data, where then, for period **t**, it joins the different consumptions of each equipment of the **n** consumers, thus acquiring the total power consumed by the community in the respective apparatus, as in (1). Later, by having the total power consumed of the **N** types of equipment, it is possible to obtain, for period **t**, initial load (IL) of the energy community in question, as shown in (2). Thus, with these equations, it is possible to acquire a better notion of the behavior of the community itself, facilitating its analysis.

$$T_a(t) = \sum_{x=1}^{n} P_{a(x)}(t) \tag{1}$$

$$IL(t) = \sum_{x=1}^{N} T_{a(x)}(t) \tag{2}$$

As for the second phase, Specify target peak, this, by analyzing the consumption of the community in question, aims to determine a target peak where reductions in equipment will be applied.

As for the third step, it consists of grouping, over the 96 periods, the different equipment of different consumers by consumption pattern, through the k-means clustering method. The algorithm k-means is defined by the total variation within a cluster as the sum of the squares of Euclidean distance between a point and the center of the cluster, attributing the object to the nearest **k** cluster. Each **k** cluster is represented by an updated centroid in following iterations of the algorithm – an average of all objects in the respective cluster. Initially, to find the more adequate **k** cluster, a range of clusters is studied in order to compare with each other. In this specific case, the clustering method was used to find groups of appliances, which can be from different consumers, with equivalent load profiles to remunerate them equally and fairly when participating in DR events. So, each group has a specific remuneration value and could be formed by different types of appliances.

Regarding DR activation phase, optimal scheduling was applied according to previous works by the authors (Silva, Faria and Vale, 2019). The objective function is presented in Equation 3 assigning a cost to each parameter. The goal is to minimize operation costs by the perspective of the community manager. In this way, several constraints are applied to find the balance between consumption and production, having the flexibility provided by the consumers means available.

$$MinOF = \sum_{p=1}^{P} P_{pv(p)} C_{pv(p)} + \sum_{s=1}^{S} P_{extSup(s)} C_{extSup(s)} + \sum_{a=1}^{A} P_{TR(a)} C_{TR(a)} + P_{NSP} C_{NSP} \tag{3}$$

The amount of reduction from each appliance relies on the DR program applied. Considering an Incentive-based program, namely curtailment, the total consumption from appliance **a** was considered as upper bound for $P_{TR}$. Concerning the constraints for a generation: $P_{pv}$ and $P_{extSup}$ have an upper bound (capacity) and a lower bound (zero). The total amount to be used by each generation technology is also restricted. As for the Appliance control stage, it is used to implement, in each period, the reductions resulting from the optimization, in the appropriate equipment of the respective consumer. Finally, the Remuneration stage, the first phase, is to determine which consumers made equipment reductions at the time of order. In the second phase, considering the total reduction made by the community and the total reduction of each consumer, it is possible to obtain the respective portion of the contribution. Thus, the remuneration of each contributor is obtained through the contribution portion and the total gain of the PV panels.

The motivation for the proposed methodology relies on the need to improve demand response events accuracy and effectiveness. Normally, in the previous works, appliances were activated for consumption reduction regarding each type of appliance; all the air conditioning devices, for example, were activated at the same time. However, it may happen that, according to the period of the day, for a specific consumer, one air conditioning device may have the same or similar consumption profile as a washing machine, for example, so they should be grouped as they are similar, and activated for demand reduction at the same time. Such groups are provided by a clustering approach. Then, the community manager can compare the results of using the groups by type with the groups formed by the clustering approach.

## 3. CASE STUDY

This section highlights the different case studies designed to test the methodology developed. For the study of these case studies, it was used three village electrical networks located in Portugal. Village A and C are in the northern region of Portugal. However, the former is in the interior while the latter is in the center of the former. In both locations, throughout the year, they have good sun exposure with little cloudiness and humidity. In the case of village B, it is near the center region of Portugal, also has good sun exposure, and has a dry climate and little cloudiness. Table 1 summarizes the information of the respective Portuguese villages, indicating the number of PV panels and the amount of different equipment for each type of consumer, where R represents the residences while P represents the public buildings. Otherwise, this table shows the amount of variety of appliances in each village as well as the number of residences and public buildings. In the case of village C, there are no public buildings, as shown in the table. As can be seen from this table, public buildings only have equipment such as air conditioning (AC) and fan heaters (FH), while residences, depending on the village, have water heaters (WH), washing machines (WM), dishwashing machines (DW) and AC.

**Table 1. Information of the villages.**

| | A | | B | | C |
|---|---|---|---|---|---|
| | R | P | R | P | R |
| **#PV** | 4 | 3 | - | 4 | 4 |
| **#AC** | 40 | 21 | - | 7 | 4 |
| **#WH** | 9 | - | 10 | - | 10 |
| **#FH** | - | 4 | - | 24 | - |
| **#WM** | 7 | - | 7 | - | 3 |
| **#DW** | 14 | - | - | - | - |
| **#Type of Appliances** | 5 | | 4 | | 3 |
| **#Consumers** | 23 | 4 | 12 | 4 | 13 |

Figure 2 serves to illustrate the behavior of each of the villages, highlighting, in kW, the respective total consumption of the equipment, and also the production of the PV panels over the 96 periods. Through these graphs, it is also possible to see which equipment each village has made available for the study, where village A, B, and C contain, respectively, 5, 4 and 3 equipment. Graphs a), b), ..., and f) represent, respectively, AC, WH, WM, FH, DW and, finally, the PV production of the respective village.

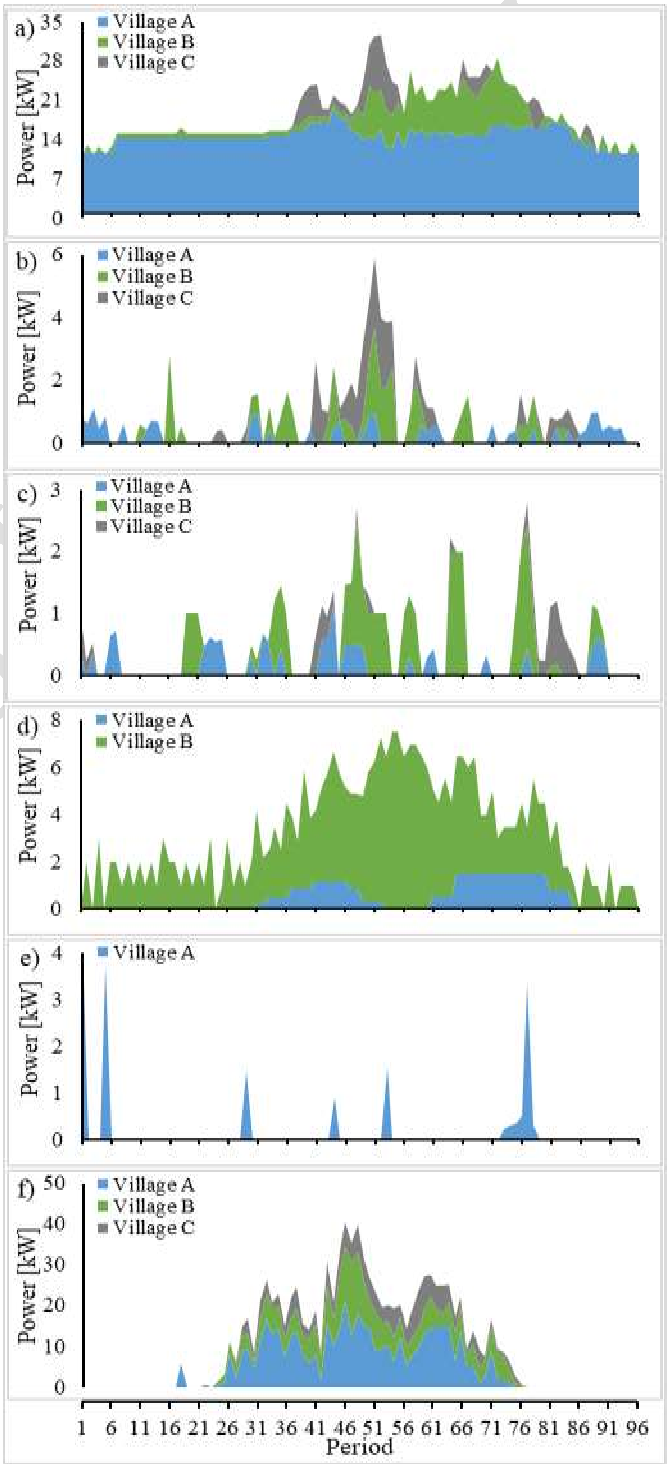

Fig. 2. Consumption of the appliances in each village.

## 4. RESULTS

This section will serve to demonstrate the results of the methodology covered in the case studies explained previously in the previous section, as well as a brief analysis of them. All figures presented in this section contain the letters a), b) and c), which respectively represent villages A, B, and C.

### *4.1 Clustering*

This subsection includes the results from clustering in each of its three villages. It is made clustering for K between 3 and 7 in each village to demonstrate optimization performance. Where K represents the permitted number of clusters that the respective community can divide, that is, for K=3, divide each of the communities into 3 clusters, and so on, up to K=7, in which case it fragments communities in 7 clusters.

Figure 3 illustrates the resulting clustering for the different K mentioned above, where gray shows the number of types of devices that each cluster has in its respective K, and in orange is the total consumption of each of the clusters, in kW.

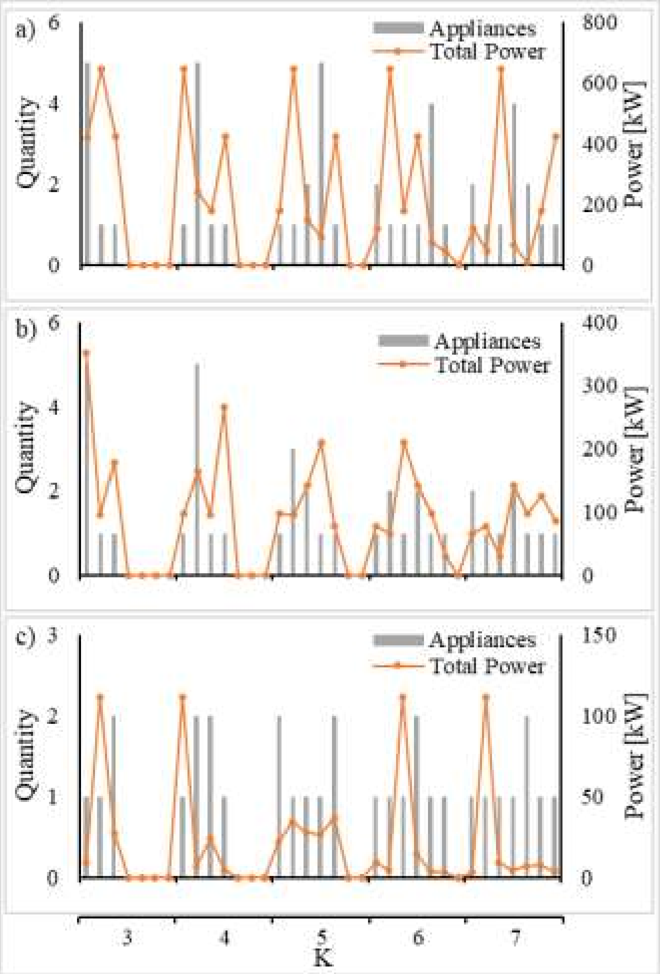

Fig. 3. Clustering of appliances in each village.

In the first graph, it is possible to verify that there are always two clusters that have both the same type of consumption as well as the same amount of type of appliances, in each K. The appearance of these two clusters in different Ks may mean that they are always composed of the same consumption profiles or, otherwise, it means that they are composed of a single element that stands out from the others. As for the other clusters, we can see that as the K increases, they always vary, fragmenting into other clusters with differing consumptions. As for the second graph as the K increases, can be seen that there are clusters that can distribute their consumption with the new clusters, but it is also noted that there are clusters that maintain their consumption, which means that they either consist of a single element or a set having the same or very similar consumption profile. Third graph resembles the first graph only because it has a cluster that appears in all K except for K=5, i.e., this cluster contains more than one element. However, for K=5, it is possible to verify that the cluster is fragmented, sharing with others its consumption. After clustering for different K, and taking into account the different types of equipment each village has, it turns out that the ideal would be to use K with a value equal to the amount of equipment variety per village, that is, K=5 for village A, K=4 for village B, and K=3 for village C. Thus, Figure 4 to illustrates the respective cluster consumption averages for the respective K.

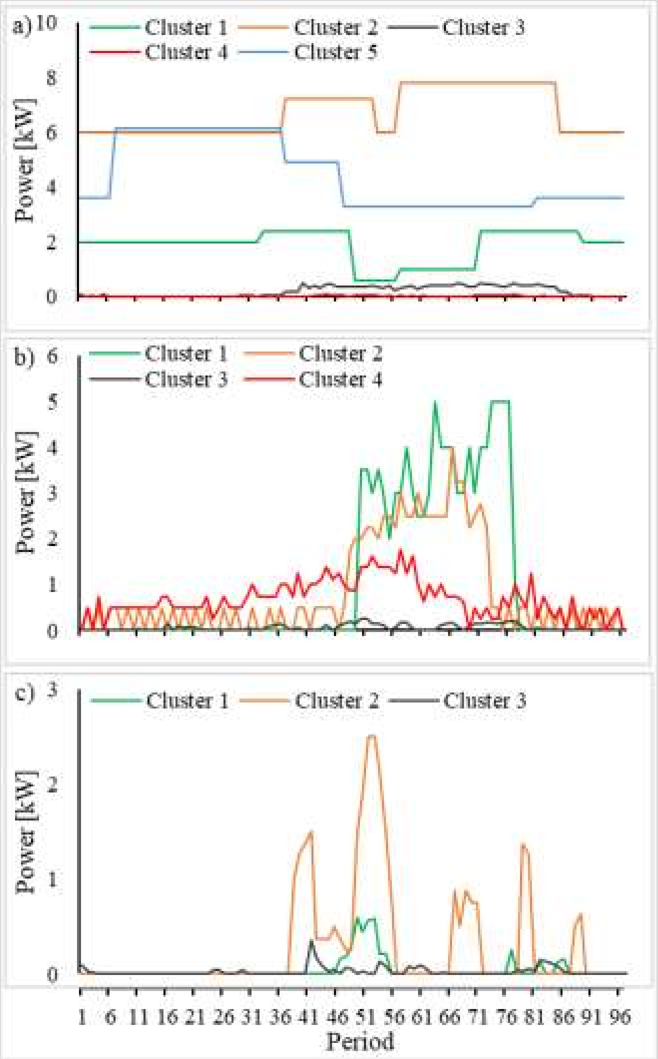

Fig. 4. The centroid of each cluster, in each village.

In this paper, the most enumerated clusters are those which, per period, have a lower average total consumption than the less populated clusters, i.e., over the periods, the fact that a cluster has several members makes average tend to be lower than a cluster with fewer. There are other factors to consider, such as whether in a populated cluster all consumers have the same magnitude of consumption, i.e., if they have similar load behavior over time, they also have the same consumption. Thus, the average will be strongly influenced by the different profiles of the members' consumption as well as by the number of elements. In the first graph, clusters 1, 2, and 5 show, throughout the day, a high average consumption, which means that these clusters can only consist of one element. While clusters 3 and 4 are the most enumerated, because the average consumption is very low, especially in the fourth cluster, where the average over the periods is almost zero. As for the second graph, cluster 1, in relation to the others, has a higher average consumption, indicating, in a way, that it is formed by only one element that alone acted during the afternoon of the particular day. Clusters 2 and 4 also have their highest averages in the middle of the afternoon, but you can see that they have a specific pattern for the rest of the day. Finally, cluster 3, this one has the most members, so it has a low average throughout the day. Finally, the third graph shows that cluster 2 has, in specific periods, high average consumption values, which means that this cluster contains elements with the same type of equipment and magnitude of consumption. The first cluster has similarities with the second. However, they do not have the same magnitude of consumption, i.e., the average consumption of the first is lower than the second. Finally, the third cluster 3 has the most elements, hence having a very low average consumption compared to the other clusters.

### *4.2 Schedule*

This subsection demonstrate how the villages behave with the optimization. Figure 5 illustrates the result of the implementation of the proposed method in each of the villages. In light of the above, what should be highlighted with these graphs is the impact that optimization has had on the total initial consumption of the respective community (SIL), emphasizing the total final consumption of the respective community (SFL) and the Grid. As for SRL, this represents total rigid load, i.e., the consumptions where there is no control. The flexible load, SFlex, represents the consumption of all equipment related to this study, that is, it has control. For SPV, this represents the total production of the PV panels in the community. Returning to the SFL and the Grid, the first one represents SIL with the reductions of the respective devices, while the second represents the SIL with the respective reductions in the equipment together with a part or even of the whole SPV, in order to mitigate the consumption of the loads that could not be reduced with optimization. In other words, given the context of the project, the Grid can only decrease to the value of the SRL because from this one, it has no control. However, in cases where it is found that the SPV is not used in its entirety, this means that there is excess PV production that represents monetary benefits.

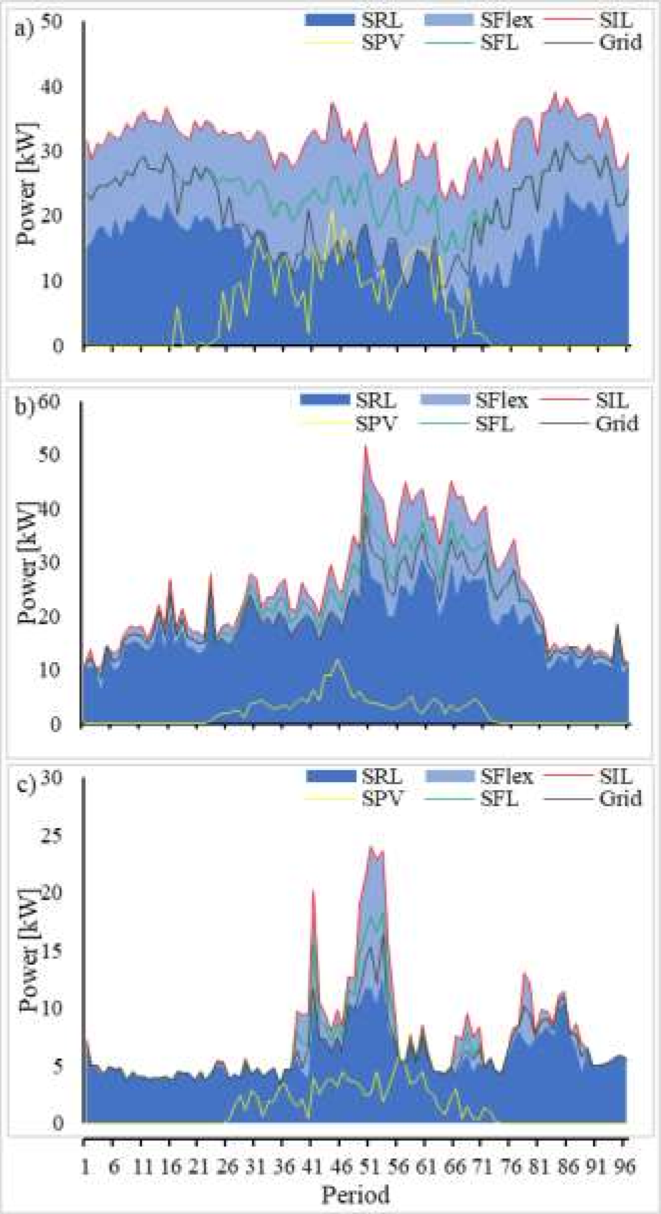

Fig. 5. Initial and Final consumption in each village.

### *4.3 Analysis*

Considering the methodology explained in Section 2, each cluster is assigned a cost of applying the DR according to the number of elements. The cluster with the most members is the one with the lowest DR cost and the one with the least members has the highest DR cost. If there are clusters with the same number of elements, the lowest DR cost is assigned to the one with the highest average consumption at the end of the day. Figure 6 presents the reductions made in the equipment in each of the respective clusters, where the graphs represent, respectively, the optimizations for K = 5, K = 4 and K = 3. In the first graph, we can see that, of the five clusters, the fourth cluster was the only one to make reductions in all types of equipment, in which, taking into account the methodology explained, we can conclude that this is the cluster that has the most elements.

This cluster encompasses most or even all residential consumers, as there are reductions in all equipment associated with homes, as well as one or more public buildings, due to reductions in FH.

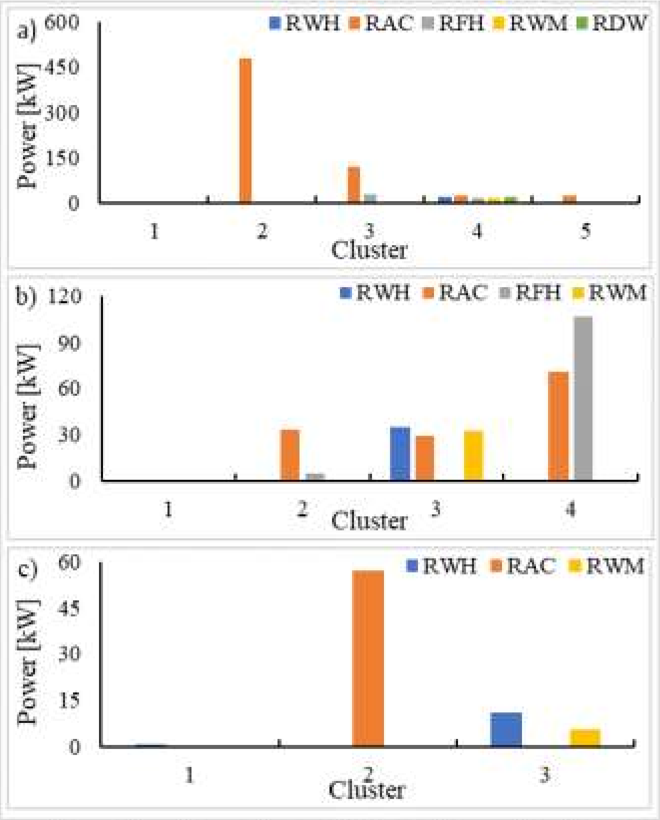

Fig. 6. Equipment consumption reduction in each village.

As for the other clusters, these, given the magnitude of the reductions, are only made up of public buildings, as seen in clusters 2 and 3. In the case of cluster 5, as having a very low AC reduction can mean, which is a single element cluster, which makes it have a very high DR cost value.

As for the second graph, in this case, the cluster with the most elements is cluster three because it has made reductions in various equipment, in which, considering the respective community, we can conclude that it encompasses both types of consumers. Considering the community in question, clusters 2 and 4 are only made up of elements with FH and AC, i.e., public buildings, where the fourth cluster represents the second-largest cluster, as it has a reduction in well-equipped equipment higher than cluster 2.

Finally, the third graph, this has reductions in all clusters, although in the cluster 1 the reduction is very low, which indicates that this has the highest cost of DR. As for the other clusters, the third is the most listed, only because it has reductions in two types of equipment. However, cluster number 2 has the greatest reduction. Another point to note is that in the first two graphs, cluster 1 has no values because it has the highest DR cost, so no reductions were made.

## 5. CONCLUSIONS

The work presented in this paper is based on the concept of energy community, where it attempts to achieve a state of self-sustainability through the aid of a DR program that efficiently manages consumption and PV production from the respective community. The proposed method takes advantage of the excess of RE produced by the PV panels installed in the participant's buildings, in order to distribute it evenly among the contributors. The developed DR program focuses on grouping different consumer devices by consumption patterns, regardless of the magnitude of consumption, to optimize the community's energy management. Participants, by contributing to the study by applying reductions in the appropriate equipment at the time of their request, are compensated according to their performance through reductions in their electricity bills.

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