Flexible Load Management: How DSOs can benefit from energy efficiency plugs for hot water management

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Abstract

Residential electric hot water heaters (EWHs) have the potential to deliver significant benefits to the end-user as well as the distribution system operators (DSO). This paper provides evidence that a coordinated number of connected EWH can provide peak shaving services to the DSO. This peak shaving potential can result in the deferral of costly physical upgrades to the physical distribution infrastructure. The paper uses real data obtained from a pilot project consisting of a group of connected EWH operated by Klugit Energy and E-REDES, the Portuguese DSO, to demonstrate the potential economic benefits of using a coordinated group of connected EWH as non-wires alternatives to upgrading a specific MV/LV Secondary Substation. The paper finds that installing 70 connected EWH in a system of 384 consumers can reduce periods where the transformer exceeds 95% of the peak load by 66%. The economic analysis showed that the economic benefit of installing a given number Klugit devices is positive. These results can lead to lower electricity tariffs for the consumer, through a more efficient investment. Results show that the Klugit device can be an efficient and cost-effective way to reduce residential peak loads.

1 Introduction

1.1 Background

In order to rapidly reduce the greenhouse gas emissions from the global economy, a concerted effort is required to decarbonise the electricity sector and then replace other energy carriers with electricity [1]. While this electrification of final energy use can provide challenges in sectors such as high temperature heat or long-distance, heavy-duty transport, electrification of final energy use in the residential sector is possible. Electrification of residential energy use is crucial as accounts for 26% of final energy use within the European Union in 2018 [2]. Water heating accounts for approximately 14.8% of residential energy use but electricity for water heating only accounts for 3%. The other 12% is largely from gas or oil and petroleum products [3]. This shows the potential for reducing emissions by electrifying residential hot water heating. Using electricity to supply household water demand is proven technology which has been used for many years [4].

The application of Information and Communication Technologies (ICT) devices to electric hot water heaters (EWH) can increase the efficiency of the EWH and allow the EWH to deliver various services to the customer as well as the distribution system operator (DSO) [5]. A major service that these connected EWH can provide DSO's is reducing the peak electricity demand through coordinated demand shifting [6]. By switching off the EWH at certain periods, the peak load can be reduced. Thus, aggregating a number of connected EWHs can have the potential to deliver significant peak load reductions.

By reducing the peak load experienced by a secondary substation, expenditure on physical infrastructure investments can be delayed while still providing reliable, efficient and safe electricity to the end-users. Therefore, connected EWH can reduce emissions associated with residential hot water demand and provide important grid services to the DSO. These connected EWH can act as non-wires alternatives to infrastructure upgrades if the economic assessment is carried out.

1.2 Literature review

The potential of connected EWHs to reduce peak loads has been studied in the existing literature. A dynamic programming approach to estimate the peak shaving potential of 73 EWHs was carried out by [6]. Results show that EWHs can provide peak shaving services while respecting user comfort requirements. The authors recommend that a local control point is added to improve end-user satisfaction.

A study investigating the peak-shaving as well as frequency response potential of EWHs is conducted by [5]. The authors find that it may be economically lucrative for end-users to participate in peak shaving and frequency services. The potential flexibility of an EWH to benefit end-users in a Portuguese context was investigated by [7]. The authors found that the EWH can reduce the electricity costs for a consumer however the authors focused on a single EWH and did not consider other services that the EWH could potentially offer.

The above studies show that there has been significant research into the potential of EWHs for peak load shaving as well as other services. An economic analysis of the potential of connected EWHs to act as a non-wires alternative to defer costly infrastructure upgrades was not considered.

1.3 Contributions

The main research question of this paper is how many connected EWHs are needed to provide a significant peak load reduction for a given transformer and is installing this number of connected EWHs optimal from an economic point of view instead of investing in upgrading into a new secondary substation. The paper has the following main contributions:

- An investigation into the peak shaving potential of a group of EWHs and quantification of this flexibility
- The analysis uses a data-driven approach using real-world load data
- An economic analysis of infrastructure deferral through the use of EWH as non-wires alternatives.

1.4 Paper structure

The rest of this paper is structured as follows: Section 2 contains the methodology employed in this study. The results derived from this methodology are presented and discussed in Section 3. Finally, Section 4 contains the conclusions drawn and suggestions for future work.

2. Methodology

2.1 Data collection and preparation

In order to calculate the potential of a group of connected EWHs to reduce the peak load experienced by the specific transformer, a data-driven approach was used. This involved collecting two sets of data. The first set of data obtained related the demand profile experienced by the specific transformer. Data for the month of December 2020 was selected with a granularity of 15 minutes. This specific transformer serves approximately 384 clients and has a rating of 630 kVA. The average load profile of the transformer is shown in Fig. 1. There exists a midday peak as well as an evening peak load.

To estimate the load reduction potential of the group of connected EWH, the load profiles of 10 connected EWHs were obtained. The load profile of the 10 installations is shown in Fig. 2 below. It can be seen that there is a significant morning peak load.

These connected EWHs were part of a pilot project run by Klugit Energy, E-REDES and Aveiro Municipality under the initiative - Aveiro Urban Challenges. This project saw smart plugs and hot water sensors (here referred as Klugit devices) installed in 10 EWHs in different locations in the city of Aveiro, Portugal, to gather data and convert EWHs into smart connected devices. The pilot project began in September 2020 and was largely concluded by December 2020. For this research, data for the month of December 2020 was selected. This was done because in December a number of the installations removed the smart plugs.

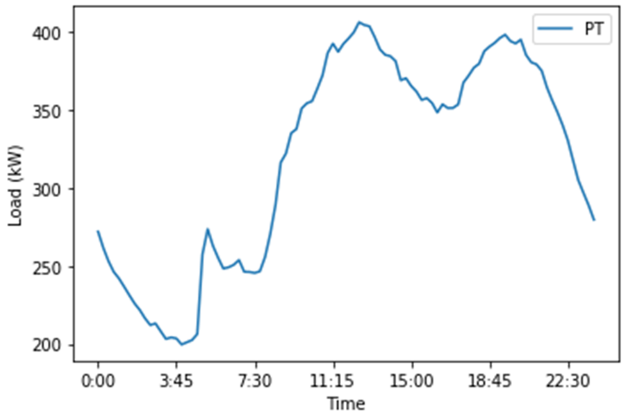

Fig. 1: Average active power load for December 2020

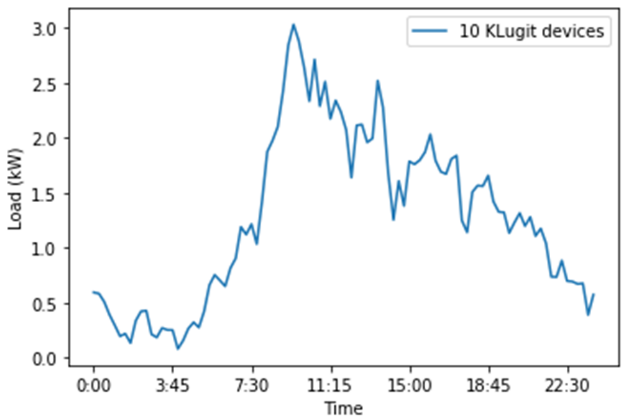

Fig. 2: Average load demand of 10 connected EWHs using Klugit devices

The main research question of this paper was to determine the number of Klugit devices that were needed to prevent a certain peak load from occurring or in other words, how many Klugit devices were required to ensure certain load reduction. To answer this, four different load reduction targets were chosen and they were 5%, 10%, 15% and 20% of the baseline peak load.

2.2 Economic analysis

Once the technical potential of the group of Klugit devices was calculated, the next step was to perform an economic analysis to investigate the feasibility of using a collection of Klugit devices to defer physical infrastructure upgrades to the specific MV/LV secondary substation.

This scenario assumes that is not possible to increase transformer power capacity and it's not predictable to verify a growth in installed power.

For this step, the costs of upgrading the MV/LV secondary substation were estimated and compared to the costs of installing and maintaining a certain number of Klugit devices. The costs for the referred upgrades were obtained from E-REDES. Both the costs associated with upgrading the secondary substation and the per unit costs of a Klugit device are shown below in Table *I* and Table *II*. For this analysis there are two costs associated with the Klugit device, purchase costs and then costs associated with operating and controlling the device throughout the year. For the transformer costs, there are also two cost items, namely the costs of a new transformer and the yearly maintenance costs. The analysis was carried out over a period of 25 years with a discount rate of 4%. The Klugit devices were assumed to have a eight year lifespan and need replacement after this time while the substation had a lifetime of 25 years.

Table I: Klugit costs

Klugit costs	Cost	Unit
Capital	40	€/unit
Operation	12	€/unit/year

Table II: Transformer costs

MV/LV Sec. Substation costs	Cost	Unit
Capital (new)	20 000	€/unit
Maintenance	250	€/year

2.3 Method

Once the data and relevant costs had been sourced and prepared the analysis used the following steps:

- Select the desired level of load reduction (5%,10%, 15%, 20%)
- Evaluate the number of periods where the transformer load exceeded this load threshold and record this number as the benchmark
- Use the load profile of an aggregated amount of Klugit devices to identify the time periods where intelligently curtailing the electric hot water heating load could prevent the transformer load from exceeding the threshold
- Repeat this process for various numbers of Klugit devices to determine the optimal number
- Perform an economic analysis based on the capital and maintenance costs of upgrading the transformer relative to the installation and maintenance cost of the optimal number of Klugit devices.

3 Results

3.1 Technical results

The load profile of the transformer was analysed and the distribution of loads across the entire month of December is shown in Fig. 3. The average load of the transformer was 318.8 kW with a maximum value of 503 kW and a minimum of 160 kW. The median was 318 kW and this shows that the loads follow a relatively uniform bimodal distribution. There are no significant tails in the distribution.

To investigate the required number of Klugit devices in the distribution system, the number of periods where the load demand of the transformer exceeded the given load reduction target was calculated. These calculations are shown in Table III. The 'baseline' column of Table III displays the number of periods where the peak load exceeds the given load in the current system, i.e. with no Klugit devices installed thus maintaining the system as is.

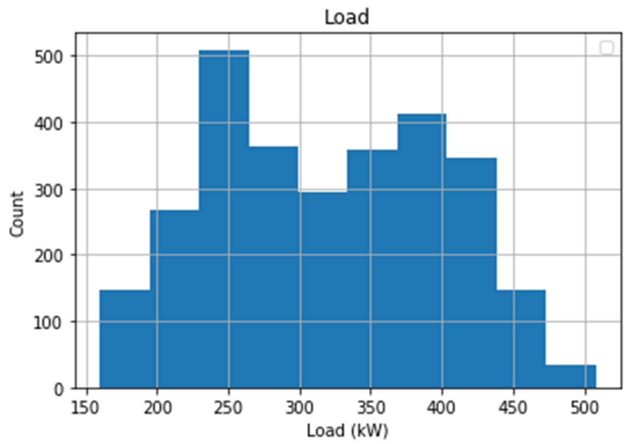

Fig. 3: Distribution of the transformer loads

The numbers in the baseline column of Table III can be compared to the numbers in the columns to the right to examine the effectiveness of installing a given number of Klugit devices. As an example, for a peak load of 482.6 kW, there are 15 periods where the load exceeds this number in the

Table III: Impact of a certain number of Klugit devices on the desired peak load reduction

			Periods where load exceeds threshold after installation of a given number of Klugit devices					
Load reduction	Load threshold (kW)	Periods where load exceeds threshold before Klugits	10 Klugits	50 Klugits	70 Klugits	150 Klugits	170 Klugits	190 Klugits
5%	457.2	15	14	7	5	2	1	0
10%	406.4	87	78	52	41	15	6	3
15%	355.6	222	210	170	157	97	61	46
20%	304.8	472	455	366	332	231	186	156

current system. By installing 110 Klugit devices it can be reduced to only 2 periods where the peak load exceeds 482.6 kW and by installing 190 Klugit devices, there will be no periods where the peak load exceeds 482.6 kW.
Table III shows that a 5% load reduction can be met on average through the installation of 190 Klugit devices. For a group of 190 Klugit devices, 96% of loads exceeding 406.4 kW can be prevented and 79.27% of loads exceeding 355.6 kW can be prevented. It should be noted that these are average values for a single month and more data is required before more accurate results can be calculated.

While a collection of 190 Klugit devices can guarantee a 5% load reduction, a group of 70 Klugit devices can reduce the periods exceeding 457.2 kW by 66%. Thus the Klugit devices can be used in conjunction with other smart grid devices to effectively manage the load profile experienced by the transformer. These smart grid devices such as intelligent appliances or battery storage systems are expected to become more prevalent shortly.

Fig. 4 shows the percentage reduction in periods exceeding a given load depending on the number of Klugit devices installed. For example, once the 100% line is reached, there are no periods where the load exceeds the threshold, on average. This level is only reached for the 5% load reduction. In other words, once the 100% figure is reached, the number of Klugit devices can ensure that there are no loads that exceed the specified threshold.

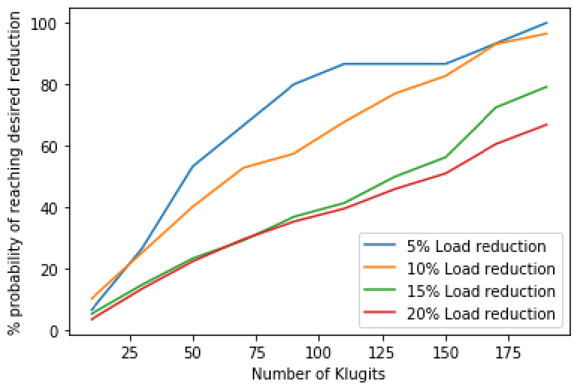

Fig. 4: Probability of reaching a given load reduction

3.2 Economic results

Using the data introduced in Section 2.3, an economic feasibility analysis was carried out considering both the installation of 70 Klugit devices as well as 190 devices as an alternative to the installation of a new substation to handle the expected peak load growth in the area. This assessment indicates whether it is financially feasible to defer investment in a new substation. The economic analysis showed that the net present value of installing a given number Klugit devices is positive when compared to investing in a new physical transformer. The economic benefit of installing a given number of Klugit devices is shown in Fig 5. and it can be seen even when 190 Klugit devices are installed there is a net economic benefit relative to the installation of a new secondary substation. This results in lower costs to the DSO which in turn can lead to lower electricity tariffs for the consumer. The economic benefit ranged from around €3300 when 70 Klugit devices are installed to around €1 900 showing when 190 Klugit devices are installed thus showing that this form of peak shaving is economically feasible.

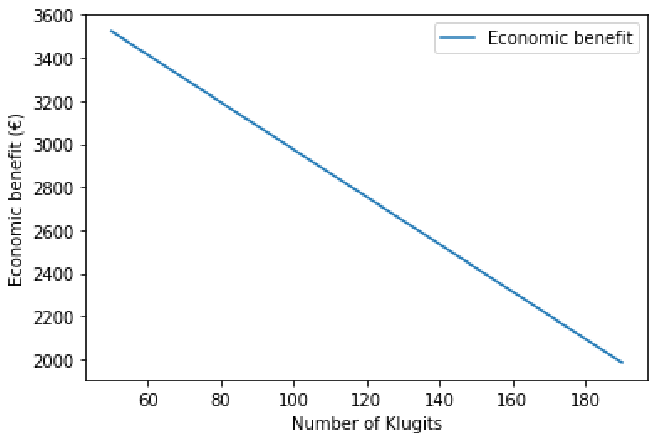

Fig. 5: Economic benefit to consumers

4 Conclusion

This document has investigated the ability of a group of Klugit devices, connecting EWHs and thus acting together to reduce the peak load of a distribution system by a certain percentage. Both a top-down and bottom-up approach was used. The methodology followed a data driven approach where the data from the transformer and the group of operating Klugit devices were directly compared to evaluate the peak load reduction potential. The approach estimates that 190 Klugits are required to reach a 5% load reduction, reducing the peak load from a peak of 508 kW to a peak of 457.2 kW. The bottom-up approach is thought to be more accurate.

The economic analysis showed that the economic benefit of installing a given number Klugit devices is positive when compared to investing in a new physical secondary substation. This results in lower costs to the DSO which in turn can lead to lower electricity tariffs for the consumer. The economic benefit ranged from around € 3 300 when 70 Klugit devices are installed to €1 900 showing when 190 Klugit devices are installed thus showing that this form of peak shaving is economically feasible.

The results showing that the load reduction target of 5% can be reached by 190 Klugit devices within the network of 384 low voltage consumers connected to this specific transformer. This corresponds to a required penetration of 49% of available consumers. This shows that individual EWHs offer the marginal potential for peak shaving but through the control of a large number, the potential for peak shaving can be realized. Installing connected EWH in 49% of households may be challenging in Portugal as only approximately 15% of Portuguese households have electric water heaters. However, this number is expected to increase in the future as deeper decarbonization of the economy occurs.

The results in this paper have shown that to effectively manage and control a rapidly decarbonizing electricity network, a host of solutions should be used. Both demand side and supply side resources can contribute to delivering a safe, secure and reliable distribution system. The Klugit device is shown to be one such tool which can offer peak load reduction in an effective and economically beneficial manner.

For future work, the duration of recorded data can be improved in order to estimate the any seasonality effects. In addition, the effects of the COVID-19 pandemic may reduce the loads experienced by the transformer as there may have been a reduction in the demand by commercial customers but there may have been an increase in the demand by residential consumers.

5 Acknowledgements

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6 References

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