Architecture and operation of a Demand Side Management Evaluation Tool in the Residential Sector

Tommaso Mura

Tommaso.mura@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

November 2018

Abstract

The electricity demand management of the residential sector proved to have a high potential for boosting the transition towards a cleaner and more decentralized energy sector. This practice is still underdeveloped in Europe, thus creating an obstacle to the penetration of renewable energy sources and a threat to a capital-intensive electric network upgrade. In this context, this thesis considers the combination of LV grid status assessment and Non-Intrusive Load Monitoring (NILM) techniques at the secondary substation level to overcome those limitations.

The scope of this dissertation is the ideation of a commercial service that can combine LV grid assessment and NILM to facilitate the management of the LV network flexible loads for the DSOs. The techno-economic analysis of this service, the Demand Side Management Evaluation Tool, is performed to establish the accuracy of NILM when applied at the secondary substation and the economic viability of the service.

The market feasibility study shows the regulatory maturity of the UK for the first application and the DSOs interest for this kind of service. The cost-benefit analysis proves that the generated benefits surpass the costs assessing with a good degree of certainty the financial viability of large-scale application. On the other hand, the outcomes of the testing phase reveal that the performance yielded by the reference algorithms when applied to multiple aggregated houses is not yet adapted for commercial application. The weak points are identified to adjust the most promising algorithms and untap the high environmental and economic benefits of the Demand Side Management Evaluation Tool

Key words: Non-intrusive Load Monitoring; Demand Side Management; LV Network; EV identification; Distribution System Operator

1. Introduction

Global warming, energy security and local pollution are just an example of the innumerous factors pushing towards a cleaner and more decentralized energy supply that presents itself as the antithesis of the current one. The necessary growing electricity consumption and the higher penetration of intermittent renewable power sources are generating a great challenge for the electricity grid and its operators. The aging power grid is approaching its capacity constraints and the fluctuating energy supply is increasing significantly the difficulty of balancing the demand. The possibility of a blind increase of capacity and storage of the power system is not an option because of the incredibly high investment that would be needed. Demand-Response (DR) appears in this transition environment as a possibility to match the electricity consumption with the supply with an upside-down approach, where the end users participate actively consuming electricity when it is abundant and receiving an incentive to do so. The residential sector represents the 20% [1] of the total energy consumption worldwide and its potential as a low cost flexibility source is largely undeveloped in Europe. Load disaggregation, also known as nonintrusive load monitoring (NILM), is a technique to deduce what appliances are used in a household and their individual electricity consumption analyzing changing in current and voltage at smart meter level. The contribution of load disaggregation in demand response consists in the identification of flexible assets or inactivity periods in the end users' electricity consumption pattern. Utilities could know at any time the amount of flexible or deferrable loads in the electricity grid and, if a direct control infrastructure is in place, could suggest or activate load sheds to conserve energy during peak load times or perform other grid services.

2. Distribution network demand response services

Despite the potential of flexible loads and DER to deliver low cost ancillary services for the DSO and the opportunity to identify these resources in the grid with NILM techniques, this does not represent the real-world scenario and two main technical barriers are identified and analysed. The first is the lack of a geographical information in the demand response environment and the second is the violation of customer privacy when NILM techniques are applied at single house level. Nowadays, the DSO, that is in charge for solving the LV network problems, has nearly zero visibility on the flexible loads in the LV network and the regulation framework does not allow to involve the customers in the interested area only in the delivery of a load relief or other DSO ancillary services. This results in an almost complete inefficiency of DR programs to solve the DSO grid management problems. Nonetheless, the monitoring of end users' daily consumption gives information about their Typical Load Profile and the analysis of these data can yield to the disclosure of sensitive information about user behavior such as house occupancy and occupant activities causing severe privacy issues.

3. DSM Evaluation Tool

The main technical barriers for untapping the potential of demand side management to provide the distribution system flexibility services can be sum up as previously mentioned:

- The inability to dispatch flexibility at a precise geographical location reducing significantly its efficacy to solve DSOs' issues in the LV grid
- The violation of people privacy when NILM techniques are implemented at single house level

To overcome these barriers a new service is needed in the energy sector and this could be provided through the application of NILM techniques at distribution substation level, the DSM Evaluation Tool. Indeed, load disaggregation algorithms could extrapolate from the power readings the characteristic features of the flexible loads such as electric vehicles, heat pumps and distributed energy resources and identify where and when they are consuming or producing electricity in the low voltage network. When the data at the MV/LV transformer derivation are used to perform energy disaggregation multiple value propositions can be generated:

1. Deliver real-time notification and recommendations on the state of the LV network such as feeders' capacity, transformer thermal rate and grid voltage
2. Identify the demand response potential of the LV network due to flexible controllable loads in the area preserving the privacy of the end users
3. Boost the installation and limit the curtailment of the local distributed energy resources cross-checking the grid capacity and available flexibility

The described service would benefit both DSOs and energy aggregators. The former with a platform for the dispatch of localized distribution system services and the latter with a market to deploy its demand response solutions.

4. Methodology

At this stage, once a possible solution is elaborated, its techno-economic feasibility must be proved. This means that the research questions this dissertation is trying to find an answer to are, first, if a service such as the DSM Evaluation Tool can become a commercial service and second, if NILM techniques can be applied at secondary substation level yielding good results.

A 3-step process was selected to verify the research questions and it composed by:

1. Extensive literature review of NILM and LV grid monitoring to assess the software and hardware requirements to deploy such a service in the LV grid and understand which flexible assets are more valuable for the DSOs
2. Market feasibility analysis to evaluate the financial viability, the innovative connotation of the service and a first favorable application

3. Testing of NILM techniques at secondary substation level to prove the technical feasibility of the service

This thesis is realized within a commercial context in collaboration with Eneida.io, a company delivering LV grid assessment services for DSOs, hence the final goal of this dissertation is to assess if the DSM Evaluation Tool could represent a commercial product to add to their portfolio of services. The adopted approach is considered effective for reaching this scope because it takes into consideration both technical and economic aspects giving a 360° vision on the topic. The employed method in the NILM testing phase allows the complete reproducibility of the results, in fact data and algorithms are all available to the public and this is considered a strength point for benchmarking and improving the work. In addition, the extensive literature review allows not to start from the ground zero, but on top of what the research did creating a significant advantage. The limitation of the used method is the difficulty to dig into the details of each section and perform a specific and exhaustive analysis when a very wide approach to the problem is selected. Indeed, both the technical and the economic analysis will need a sperate, more detailed investigation to actually develop a commercial product. Nonetheless, the adopted line is chosen as a good tradeoff to estimate the potential and the restrictions of the DSM Evaluation Tool and understand if time and resources are worth to be invested on the topic.

5. System requirements

This chapter focuses its attention on the logic and algorithms that are behind the energy disaggregation and on the infrastructure needed at LV network. The scope is to understand the requirements of the whole system architecture and define the features that the DSM Evaluation Tool should include.

The decomposition of power consumption at house level into its components is possible because every electrical load presents a peculiar energy consumption pattern, often referred as appliance signature, that can be recognized by disaggregation algorithms. Diverse approaches have been adopted to recognize the appliances signatures, but they can be grouped in two main categories, event-based algorithms which try to identify the On/Off transitions in electricity consumption and non-event-based which identify if an appliance is On during the whole sampled record. The load disaggregation process is divided in three stages: the data acquisition, the features extraction which removes the signature to analyze and the learning and classification where the algorithms are thought how to recognize a specific waveform and assign it to the respective appliance [2] [3].

The concept of load disaggregation at secondary substation level aims to identify and track the electric loads in the LV network that represents a source of flexibility to perform demand response schemes and improve the network planning and operation. The ideal location to monitor the LV network is represented by the MV/LV substation and it is where the advanced metering infrastructure must be placed. This position represents multiple advantages for load disaggregation purposes because it is where the monitoring infrastructure is already placed for the management of the LV grid and because it limits the costs and preserve the customers privacy if compared to the single-house smart meters.

6. Market feasibility

A short Market feasibility analysis was performed to assess the viability of the idea to become a commercial product. The target market is the UK because it is the only market in Europe currently opening the access to the ancillary services to the DSO [4], hence the only one where a commercial product can be sold.

The market feasibility analysis is composed by 3 parts:

1. Study of the UK regulation framework and identification of a possible use case to assess the legal feasibility
2. Cost-Benefit Analysis of the DSM Evaluation Tool to evaluate its financial viability
3. Competition analysis to assess the innovative connotation of the DSM Evaluation Tool and identify possible threats

At the end of this process, it will be possible evaluate if the DSM Evaluation Tool can become a commercial product.

The UK was the first country to allow the participation of demand side resources to the electricity markets and demand response contribution is accepted in almost all the balancing services as well as demand aggregation. In addition, distribution network services like voltage control and congestion management are allowed for independent aggregators through a bilateral agreement with the retailer/BRP. A favorable first application for the service is found within the framework of UK Power Networks call for demand side flexibility where the elastic demand will be used for various scopes from outages avoidance to manage the uncertainty related to demand growth for investment decision making.

When taking on this new project, a prudent management needs to conduct a cost-benefit analysis (CBA). The CBA is a process that businesses use to analyze decisions; all the potential costs and revenues generated by the completion of a project must be accounted and compared to define if it is financially feasible. The CBA is generally divided in three phases [5]:

1. Compilation of a list of all the costs and benefits associated with the selected project.
2. Application of a common unit of monetary measurement to all the listed costs and benefits.
3. Quantitatively comparison of benefits and costs to check if the former overweight the latter. If yes, the project is financially viable, otherwise it should be review and adjusted to increase the benefits and/or reduce the costs. If in ultimate analysis this is not possible, the company should abandon the project.

Only the benefits for the DSOs are considered being the DSO the target client for this service. This procedure significantly facilitates the quantification of the benefits because now they can be all reconducted to the avoidance or postponement of investment in the grid infrastructure. UK Power Networks (UKPN) released a study where they developed a model to forecast the cost of grid upgrade because of the uptake of EVs in Great Britain. This is used as a reference to build an estimate of the benefits following a 3-steps process: the benefits related to the flexibility of the EVs fleet are calculated with UKPN model, the benefits are enlarged to the contribution of heat pumps flexibility and a sensitivity study and discussion are done over what percentage of the found value should be attributed to the service considered in the CBA. The estimation of the costs is obtained by the partner company that is already performing a monitoring service at secondary substation level. This means that the fixed costs related to the hardware will be kept the same. On the other hand, a multiplicator factor will be applied to the operation costs due to the additional data acquisition and transfer. In addition, the software development costs will be added on top of the currents ones. The monetary evaluation of costs and benefits is shown in Table 1.

Total calculated benefits (m€)	115,9
Total calculated costs (m€)	4,86
Cost/benefit ratio	4,2%

Table 1. Cost-benefit comparison

This low value of the cost-benefit ratio can be explained by two factors, the low-cost infrastructure deployed at Utility scale and the extremely high cost of grid infrastructure upgrade. In addition, the deployment of ancillary services is considered to completely avoid the need of grid upgrade. It is important to keep in mind that this is a preliminary CBA and its scope is not to assess the exact costs-benefits ratio, but only to establish if the benefits can actually surpass the costs with a good degree of certainty and this hypothesis is confirmed.

At this stage, the analysis of competitors in the Energy Disaggregation and LV Grid Assessment sectors is performed to see if the DSM Evaluation Tool represents an innovation and if some competitors could represent a threat. The market is considered a competitive environment, with few major players and some big companies among them such as Landys+Gyr and Silver Spring by Itron that could represent a big threat. Nonetheless, the analysis showed that the quick development of a service with innovative characteristics together with the right partnerships could potentially disrupt in the market.

7. Test of NILM at secondary substation level

The scope of this thesis includes the testing of the state of the art of load disaggregation techniques applied at secondary substation measurements to assess their potential and limitations for this application. The goal of the implementation of NILM techniques at the LV derivations of the distribution transformers is to identify where and when flexible loads such as EVs, heat pumps and PV systems are exchanging energy with the grid to be able to manage the flexibility services for the DSO.

A test bed is assembled to test the NILM techniques when applied at secondary substation level. the replication of a single-phase of the LV feeder is composed by three steps:

1. Choice of an energy dataset with enough data granularity and submetered measurement of the interesting flexible assets (EVs, heat pumps and PV)
2. Decision-making process over how many houses the single phase is feeding
3. Aggregation process of the chosen number of houses

The sum 3x6 single phases of the distributors will eventually represent the consumption at secondary substation. The dataset employed for the test is Dataport because of the availability of data regarding EVs, Heat Pumps and solar panels, and its compatibility with NILMTK, a data analysis tool for load disaggregation. An independent analysis performed on real substation data showed that 9 aggregated houses from Dataport dataset closely match the consumption of the secondary substation, then 10 houses is considered a plausible number of aggregation to reproduce the consumption of a single phase. The electricity consumption profiles to be aggregated are taken from a pool of 51 households that present both a residential EV charger and a heat pump that was available in Dataport database.

The choice of Dataport database as a test bed for load disaggregation techniques introduces two main limitations in the choice of the algorithms:

1. The steady-state analysis only can be performed on the data because of the low acquisition rate of the selected dataset
2. Active power change is the only feature that can be extracted from the data because no other electrical parameters are available

The detection of electric vehicles is identified as the simplest disaggregation problem, hence the chosen load disaggregation techniques will be first tested for this case and, if delivering satisfactory results, then extended to heat pumps and PV systems. For the problem of energy disaggregation, no new algorithms are realized but the state of the art, best-performing ones are employed to test their validity in a different condition, where several aggregated houses are considered instead of a single one. The benchmark algorithms chosen for the analysis adopt completely different approaches to the energy disaggregation problem and they were chosen for being among the best performers in term of accuracy. The significant difference between the chosen algorithms is considered as a strength point offering a broader analysis of the problem. Two benchmark algorithms are taken from literature and they are respectively:

1. Factorial Hidden Markov Model (FHMM), is a probabilistic tool using supervised learning to extrapolate the appliances signatures
2. EV Code by Zhilin Zhang, an unsupervised method based on sound physical knowledge of EV charging power draw.

The EV Code, when applied to a single house profile, is delivering very satisfactory results with an averaged estimation error of the monthly energy consumption of the EV of 7,5% only outperforming any alternative in the literature [6]. However, moving the same algorithm without applying any modifications to ten aggregated houses the situation radically changes. Figure 1 illustrates the disaggregation process with the EV Code in two randomly chosen days in the month of January.

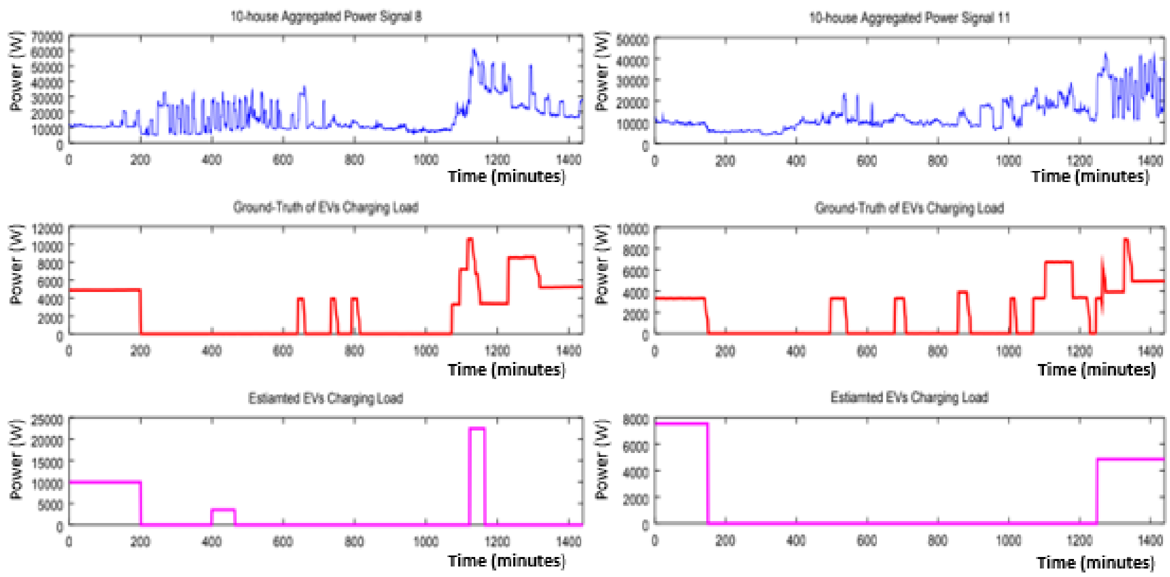

Figure 1. Two days EV disaggregation with EV_code

The results obtained with FHMM algorithms yield to even less accurate results and so they were discarded. Overall, the results were considered unsatisfactory in term of accuracy for developing a commercial service to identify the EVs charging load at the secondary substation. No quantitative analysis is performed to assess the accuracy of the algorithm and only qualitative considerations are done.

The failure of the algorithm in the disaggregation purpose can be easily recalled to its design. In fact, it was specifically built to be applied at a single house level and its parameters were not suited for an aggregated consumption. Nonetheless, because its better performance compared to FHMM and its structure easier to understand, it was decided to continue its testing in a simpler scenario, 5 aggregated houses, to improve its performance and see if it can be upgraded to a satisfactory level.

The aggregation of only 5 houses results in load profile much easier to understand and allows to see where and why the algorithm failed in its disaggregation purpose. In addition, 5 aggregated houses still represent a realistic scenario for real-world application. Therefore, the aggregation of 5 houses is considered an adapt playground for testing and improving the algorithm. Figure 2 illustrates one day randomly chosen in the month of January where the EV Code was having a satisfactory performance in estimating the EVs charging load.

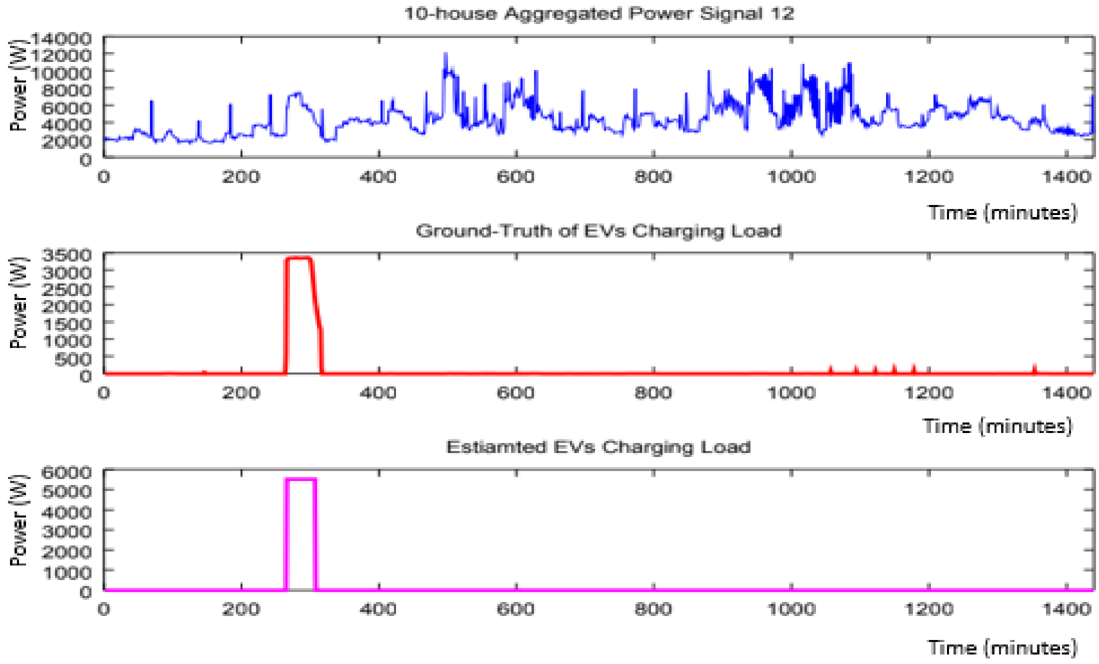

Figure 2. One day of EV consumption disaggregation

Figure 2 illustrates one day of total power consumption of 5 aggregated houses, the submetered consumption of the EV fleet of 5 vehicles and the estimated consumption by the EV Code. Along the day, a single electric vehicle is charged and the EV Code is able to identify it. As it possible to notice from Figure 2, the EV Code performed almost perfectly in its purpose to disaggregate the EV charging load. Indeed, the code was able to remove the short duration cycles of the heat pump and the Classification and Energy disaggregation were able to correctly assign the EV charging waveforms to their relative segments. The amplitude of the segments still represents an issue and it is probably due to a need for improvement of the noise removal section.

Unfortunately, despite the good performance registered in some days as the ones shown in Figure 2, the algorithm still has some issues in dealing with multiple aggregated houses consumption pattern and it is still often underperforming. In fact, it is affected by misidentification of EV waveforms where there are none and missed identification of others. The algorithm is still able to recognize the 3,5 kW charges correctly evaluating both the starting/ending points and the amplitude. However, when several appliances are overlapping or multiple EV are plugged in at the same time the algorithm misses the EV waveform or recognize other loads as EVs. These days make the monthly performance of the algorithm drop dramatically making inadequate any quantitative accuracy analysis.

The reason of the underperformance is that the Classification and the Energy Disaggregation Tools are mainly based on geometrical considerations, the gradient of the cumulative function and the effective width and height, that significantly change when multiple houses are aggregated.

The improvement of these tools requires some major modifications that are listed below:

- The redefinition of the Classification Tool in order to include all the new combinations of overlapping appliances with the EV charging including the same type appliances overlapping in different houses.
- The Effective Width and Height of the Energy Disaggregation Tool must be fine-tuned to the multiple-house condition either through a manual or supervised learning process.
- The Noise filter must be adjusted to get rid of the much higher background electricity consumption.

- Higher granularity of data should be used to avoid the excessive overlapping of different appliances that for 5 to 10 houses is consistent with 1-minute data.

The upgrade of the code would require an elevated amount of time for its realization and it goes beyond the scope of this thesis for time constraints. Furthermore, the difficulties encountered for disaggregating the EVs waveforms, which are the simplest to identify among the considered appliances, clearly state the impossibility to estimate the heat pumps and PV systems load profiles at this stage of advancement. Therefore, these tasks will be left as future work.

Overall, despite the relatively unsatisfactory results obtained, the EV Code presents a potential to disaggregate the consumption of multiple aggregated houses and this can be noticed in the days with a good performance in the process. In fact, it is designed with a specific focus on energy-intensive, 2-state loads and this represents an advantage on general-purpose methods such as FHMM when dealing with the complicated load compositions at secondary substation level. Moreover, the algorithm is designed to separate heat pumps and resistive loads waveforms from the EVs ones, then with few modifications they could be disaggregated as well from the total consumption. This procedure would upgrade the EV Code increasing the variety of flexible loads it can deal with, hence its value. For these reasons, the performed tests are considered a good starting point for a future work that could have important repercussions on the realization of a grid flexibility evaluation tool for the DSO.

8. Conclusion

The extensive work that has been carried out allows to have a broad view of what is the ideation, development, and verification of a commercial service for LV grid assessment and demand-side management. The literature review has shown the efforts done by the researchers in the energy disaggregation ecosystem and the creation of a big opensource movement that since 2011 released to the public several energy consumption datasets and analysis tools such as Dataport and NILMTK that are used for the purpose of this thesis. This phenomenon gave an incredible boost to the research in the field in the last years and allowed to use the state of the art of disaggregation algorithms for the technical verification of the DSM Evaluation Tool. In addition, the LV grid has been analyzed in an energy disaggregation perspective defining its challenges and highlighting the value of EVs and Heat Pumps as flexibility resources.

The market feasibility study has identified the UK as a mature market and a favorable first application within UK Power Networks (UKPN) flexibility services framework. In the cost-benefit analysis, the costs related to the installation and operation of the DSM Evaluation Tool infrastructure have been listed and quantified. Moreover, a reference study from UKPN on the impact of electrification of heating and transports sectors has been used to calculate the benefits of the service that result to be significantly higher than the costs for Utility-scale deployment. The overview of the competition has also defined the innovative character of the service and has recognized the possible threats and opportunities for partnerships.

Finally, the best performing benchmark algorithms for NILM have been tested. The secondary substation consumption has been recreated aggregating 5 and 10 single house data from Dataport dataset. Both FHMM and EV Code showed some limitations when trying to disaggregate the electric vehicle waveforms from the total consumption and they proved not to be ready for commercial deployment without major modifications. EV Code demonstrates to be able to correctly disaggregate the consumption of 5 houses for some of the trial days and it has the potential to radically improve its performance with some significant changes to the Classification and Energy Disaggregation Tools. The code also has the possibility to disaggregate heat pumps and resistive loads which are relevant for DR purposes with little additions.

The dissertation has shown the market feasibility and the highly beneficial impact of the DSM Evaluation Tool to decrease the costs of the LV grid upgrade and facilitate the transformation towards a cleaner and more decentralized energy system where the residential sector consumption is treated as a resource and not as an obstacle. Despite the unsatisfactory results of the tests, it is possible to see the light at the end of the tunnel and algorithms yielding satisfactory results will be seen in the near future. The wide scope of the thesis sometimes limited its accuracy of the single parts where deeper attention could be paid, and specific future studies are recommended. Even so, the selected approach is considered the best trade-off for the preliminary assessment phase where it is fundamental to understand if time and resources should be allocated for the development of a commercial product and the answer is yes.

References

[1] U. S. E. I. Administration, *July 2018 Monthly Energy Review*, vol. 0035, no. July. 2018.

[2] I. Abubakar, S. N. Khalid, M. W. Mustafa, H. Shareef, and M. Mustapha, “Recent Approaches and Applications of Non-Intrusive,” *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 7, pp. 4609–4618, 2016.

[3] A. Zoha, A. Gluhak, M. A. Imran, and S. Rajasegarar, “Non-intrusive Load Monitoring approaches for disaggregated energy sensing: A survey,” *Sensors (Switzerland)*, vol. 12, no. 12, pp. 16838–16866, 2012.

[4] SEDC, “Explicit Demand Response in Europe Mapping the Markets 2017,” pp. 1–223, 2017.

[5] “Cost-Benefit Analysis.” [Online]. Available: https://www.investopedia.com/terms/c/cost-benefitanalysis.asp. [Accessed: 24-Sep-2018].

[6] Z. Zhang *et al.*, “Training-Free Non-Intrusive Load Monitoring of Electric Vehicle Charging with Low Sampling Rate,” vol. 1, 2014.