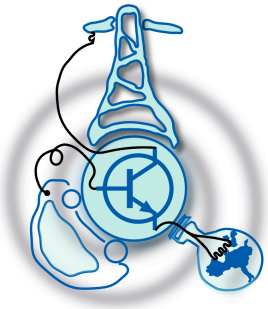
Energy Storage Integration for Industrial Processes

by

Irene Peláez Acedo



Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems
in partial fulfillment of the requirements for the degree of
Master Course in Electrical Energy Conversion and Power Systems
at the
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Abstract

In the last years, the price of storage technologies and power electronics have been considerably reduced. In fact, they are currently being under study for their application in industrial processes. This project seeks to analyze the feasibility of using a local energy storage system to shift loads to cheaper periods. Supercapacitors and batteries are the storage technologies considered in this work. The aim of this system is to reduce the overall energy cost by using demand side management techniques. As a result, the quality of the grid will improve as well.

As the main contribution, a software tool for sizing and optimizing energy storage systems to integrate them in industrial processes using the previous energy saving techniques is developed. The developed software also allows to calculate the optimal hybridization ratio between different technologies, based on the selected load.

Keywords: Demand Side Management, Energy Storage System, Sizing Algorithm, Industrial process.

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Glossary

ESS	Energy Storage System
SC	Supercapacitor
MPEI	Multiport Power Electronic Interface
PP	Peak Saving
LL	Load Leveling
AC	Alternating Current
DC	Direct Current
HMI	Human Machine Interface
DSM	Demand Side Management
PHS	Pumped Hydroelectric Storage
CAES	Compressed Air Energy Storage
Li-Ion	Lithium Ion battery
NaS	Sodiumsulfur battery
NiCd	Nickel-Cadmium battery
ZnBr	Zinc-Bromine flow battery
VRB	Vanadium Redox Flow Battery
PSB	Polysulfide Bromine flow battery
SMES	Superconducting Magnetic Energy Storage
BMS	Battery Management Side
$\boldsymbol{P_d}$	Power density
$\boldsymbol{E_d}$	Energy density
$\boldsymbol{P_{cc}}$	Power density
$\boldsymbol{E_{cc}}$	Energy density
H	hydrogen
$\boldsymbol{\eta_{dis}}$	discharge efficiency
DOD	Depth of Discharge
SOC	State of Charge
FFT	Fast Fourier Transform
$\boldsymbol{f_c}$	cut-off frequency
LPF	Low Past Filter
HPF	High Past Filter
LEMUR	Laboratory for enhanced microgrid unbalance Research.

Chapter 1

Introduction

Following the rapid price decline and technology improvements of energy storage [1], it becomes a promising technology to implement demand side management measures considering the electricity price fluctuations over the day.

This project seeks to analyze if it is feasible to store energy when the energy price is low and use it during high price periods. A trade-off between installation cost and savings is performed with the goal of maximizing the total savings over a period.

In addition to the savings, some other benefits can be obtained by installing an ESS. The power demand to the grid becomes smoother and helps the power quality to improve. Besides, the process is less susceptible to exceed the power hired and be penalized. On the other hand, the efficiency of the overall system can be enhanced. For instance, regenerative braking can be used in the motor without needing to inject power to the grid. As another example, residual heating can be leveraged by using thermogenerators.

One of the main advantages to consider this system in an industry application is because of the periodicity of the processes. Then, it is less likely to have great changes on the profile and its behavior can be predicted in advance. Moreover, it can help to improve the efficiency of industrial processes. By installing this system, pollution can be reduced and it can help to accomplish the last energy efficiency measures of the European Union.

1.1 Motivation

A price reduction trend for batteries has been observed as a result of economy of scale and technology development. This work seeks to analyze the feasibility of implementing an ESS comprising batteries and supercapacitors in an industrial process to reduce the electric bill. Thus, a toolbox is developed to get the optimum ESS based on the input load profile. Also, it is implemented the most suitable DSM measures for this profile in order to maximize revenue.

However, another application is currently on the market. HOMER Energy © company has a similar software for optimizing a renewable energy system based on the present cost of the system from a list of different configurations [2]. The present tool solves some of the limitations of HOMER software[2], focusing only in the load side without integrating any renewable energy. It does not require any experience in the field, giving only one solution where the savings are maximized. It is also less time consuming. Besides, the application can be computed with the current electricity price considering the Spanish law.

1.2 Objectives

The objective of this project is to develop a toolbox that gives you the optimum size of an ESS and DSM techniques to be implemented based on the profile selected. The study will focus on steel industry processes.

Supercapacitors and batteries are the technology proposed for storing the energy. The first technology has a high power density and low energy density, meanwhile batteries have a high energy density and low power density. Thus, combining both technologies they form a hybrid storage system able to provide the energy/power requirements of the load.

On the other hand, for interfacing the grid, ESS and the load, a MPEI converter is proposed. All components are connected to the same DC link. This topology brings some benefits over other technologies that will be seen in Chapter 3.

1.3 Thesis Structure

The research work done to support this thesis is to develop a tool that size an ESS based on the profile of the load. The methodology follow is summarized below.

1. Look for the most suitable energy storage technology for industrial application. Different technologies have been compared and the final components of the hybrid ESS have been chosen.

2. Process the profile data of the different processes. A frequency analysis of each case is made and that will help to think about how to implement DSM measures in the algorithm.

3. Economic analysis considering Spanish market and law. Look for the actual laws and develop a program to compute all the calculations. This part will be later implemented in the algorithm.

4. Development of an algorithm to optimize the ESS size in such a way the savings are maximized without compromising the physic restrictions of the system. It includes economic and technical considerations for examining the feasibility of the installation in case it is possible. Demand side management techniques are implemented as well.

5. An algorithm is developed to compare how the previous sizing works for the same process under different circumstances. It can be ensured the sizing selected works. Penalization as described in BOE-A-2001-20850 is also implemented.

6. Develop a user-friendly application to compute all the previous algorithms without needing to have experience on the field. This application can create an HTML report that summarizes all the results computed.

1.3.1 Project outline

This thesis is structured in ten chapters:

- **Chapter 1:** It describes the introduction, motivation and objectives.
- **Chapter 2:** This work takes part of a bigger project. This chapter summarizes its background and the prototype built up. The prototype can simulate the industrial process and check out the ESS performance.
- **Chapter 3** The state of the art includes the process where the study is applied, the DSM concept, MPEI, the energy storage technologies characteristics and some similar projects implemented.
- **Chapter 4:** This chapter presents all the information related with the tariffs and ESS required for the algorithm. The tariff is based on the Spanish law.
- **Chapter 5:** It is presented the previous signal processing and general model to size the ESS. A checking model is also implemented to make sure the previous ESS size can work for the same process under different circumstances.
- **Chapter 6:** This chapter describes the toolbox developed with the previous algorithms.
- **Chapter 7:** The analysis of the results are presented in this chapter. ESS sized, economic and physical results are presented for each process.
- **Chapter 8:** The conclusions and future developments of this work are collected in this chapter.
- **Chapter 9:** Quality report.

Chapter 2

Background

This study is an extension of a previous project where a prototype was built up. The previous study analyses the performance of an MPEI converter connected to the grid using supercapacitors and batteries for storing the energy. The aim of this study is to validate the performance of an hybrid ESS when using DSM measures. It can be applied to any application up to 50 kW. A model of a rolling mill motor was developed for testing. In the test, the energy was split into the ESS and the grid, and the theoretical results were validated.

2.1 Prototype

The prototype shown in Fig. 2-1 has been built up in order to check the performance of this kind of systems. It includes a MPEI connected to the grid, to an emulated load and to a hybrid ESS (formed by batteries and supercapacitors).

All the components are connected to a DC link, which is also connected to two converters (AC/DC and DC/DC) and two filters as shown in Fig. 2-2. The arrows indicate the power flow direction. Each port is connected as follows:

- **AC grid:** The system is connected to the AC grid by a AC/DC three-phase active rectifier. The AC side is connected through an isolation step-down transformer in order to keep the operating voltage on the adequate margins for the operation of the system.

Figure 2-1: Prototype formed by the ESS (left cabinet),controlbox, two converters and two filters (right cabinet up to down).

- **Battery:** The Li-ion battery is connected to the dc-link by a bidirectional DC/DC boost converter which allow for the charging/discharging operation of the energy storage system.
- **Supercapacitor module:** The supercapacitors are integrated by using the same power converter topology than the battery.
- **Load:** The load is a passive resistive load, interfaced by a unidirectional DC/DC buck converter, enabling the power-flow from the DC link to the load.

Fig. 2-3 shows the electrical connection of the power stages, filters and sources. Table 2.1 collects the parameters.

Energy storage system control is done by the Control Box placed on top of the cabinet. Inside the box, there is a DSC TMS320F28335 from Texas Instruments and a Raspberry Pi 3. Both share a communication interface for exchanging the

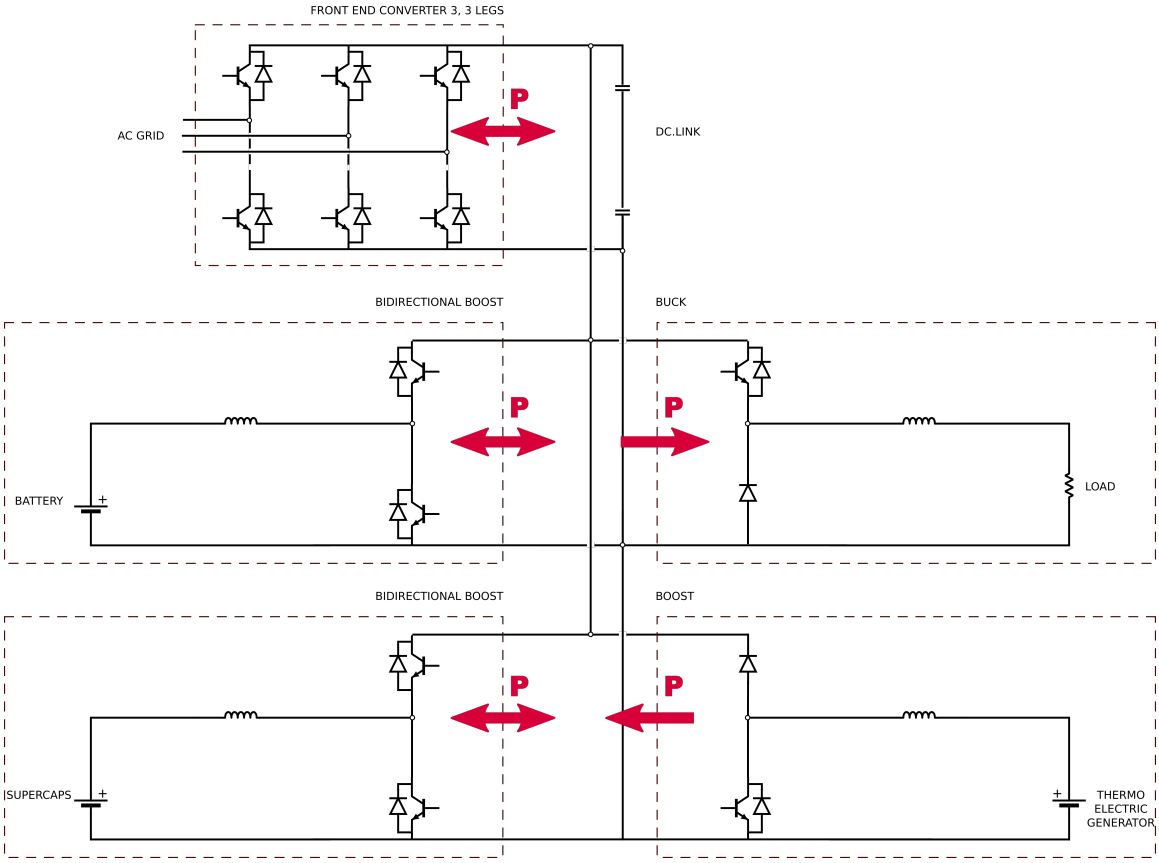

Figure 2-2: Scheme of the prototype.

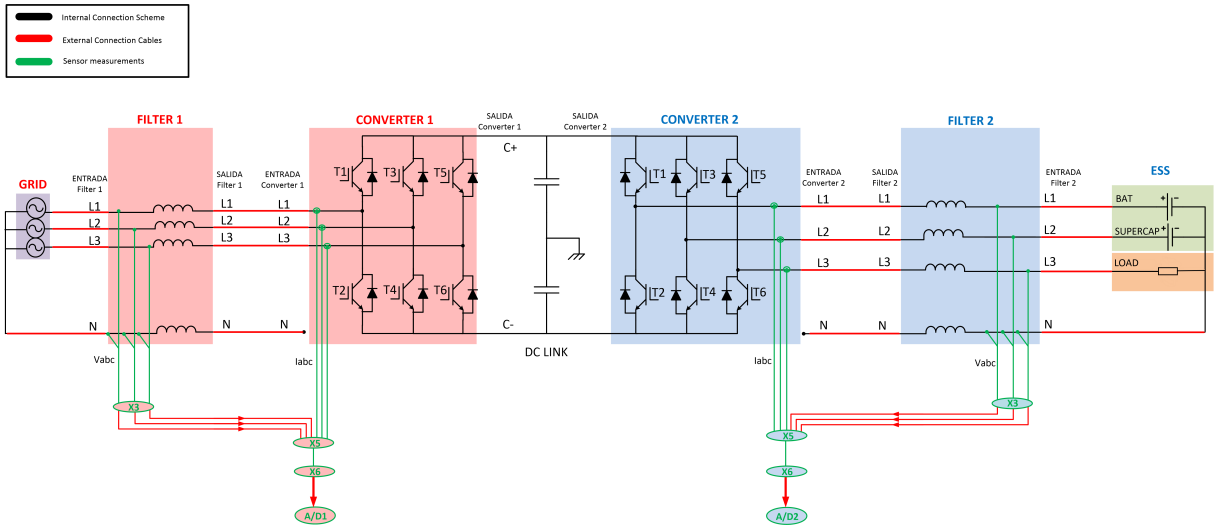

Figure 2-3: Electrical connection of the prototype

information. The system is operated through the included touch screen integrated at the power converter. Fig. 2-4 shows the initial screen.

Table 2.1: Parameters of the prototype

Parameters	Value
AC Voltage (V)	220
DC-link Voltage (V)	400
Switching frequency (kHz)	10
I max battery (A)	±20
I max supercapacitors (A)	±50
I max grid (A)	±30

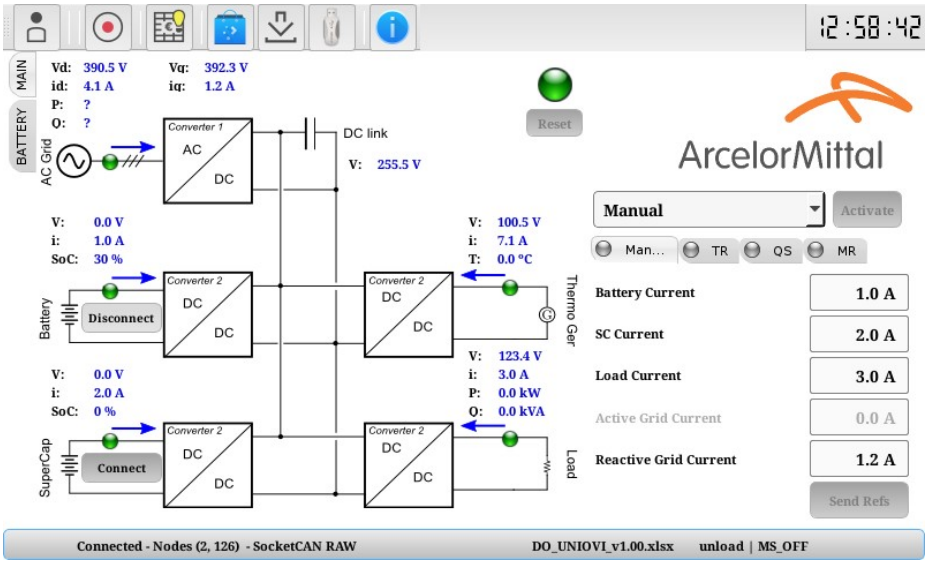

Figure 2-4: Screen of the Control Box.

From the control box, the energy distribution can be performed depending on the tariff selected. However, there is no DSM measures implemented. The prototype can work in two modes: *Manual* mode and *Tariff Reduction* mode.

- **Manual Mode:** The current references to the different converters are manually given by the user. All the references but the grid active current can be freely established.

- **Tariff Reduction Mode:** The system automatically calculates the references to the different energy storage systems. On this mode, it is possible to evaluate the economic impact of the tariff being used.

2.1.1 Prototype performance

In this section, it is showed how the prototype allocates the power. A first-order HPF filter is used for splitting the power between the ESS and the grid. This filter (2.1) has a bandwidth of 0.01 Hz and it provides the power to the ESS.

The ESS power is divided using two complementary first order filters with a bandwidth of 0.2 Hz. The LPF filter (2.2) signal goes to the battery, whereas the HPF (2.3) goes to the SC. The distribution is performed in that way because the battery has larger energy capacity than the supercapacitors, but lower power capability. Both signals pass through a saturation block to make sure the power accomplishes the physical constraints of the ESS. The remaining power is given by the grid. Fig. 2-5 represents the power flow.

$$HPFtotal = \frac{0.99686825 - 0.99686825z^{-1}}{1 - 0.99373649z^{-1}} \tag{2.1}$$

$$HPF = \frac{0.94088260 - 0.94088260z^{-1}}{1 - 0.881765205z^{-1}} \tag{2.2}$$

$$LPF = \frac{0.05911740 - 0.05911740z^{-1}}{1 - 0.88176520z^{-1}} \tag{2.3}$$

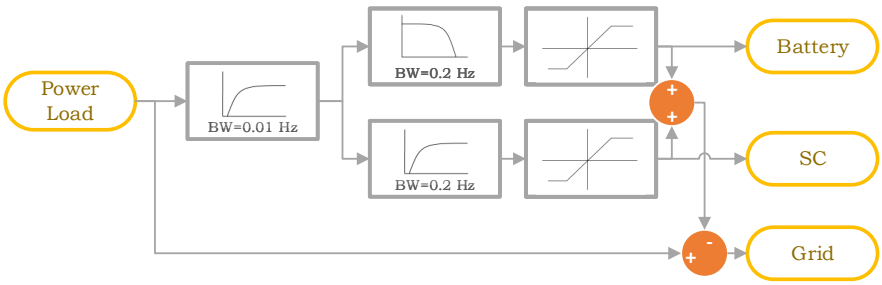

Figure 2-5: Power flow of the prototype.

Fig. 2-6 depicts the power contribution of each part. Without implementing any storage, all the power should be provided by the grid. A reduction of 2 kW can be achieved when implementing the storage.

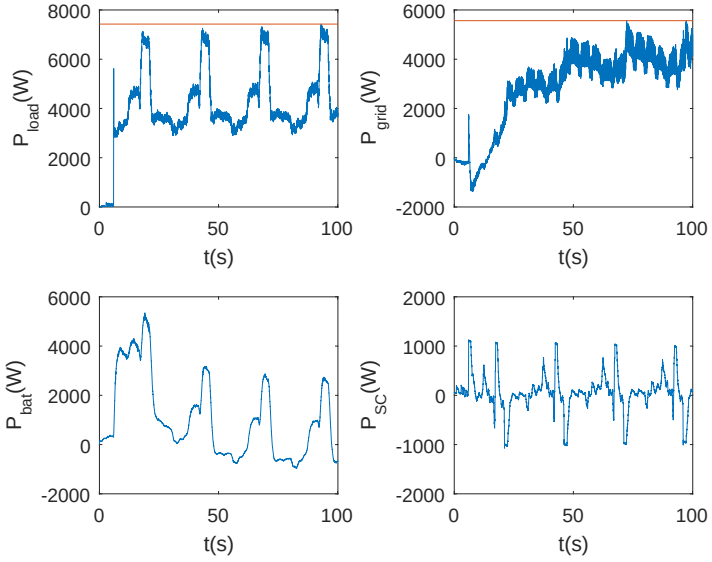

Figure 2-6: Power contribution.

Chapter 3

State of the Art

3.1 Introduction

There is a continuous effort to reduce energy costs in the industrial sector. Implementing DSM measures is currently under study. Some of the DSM techniques involve load shifting, peak saving and regenerative braking, which makes the system more efficient and the electric cost is significantly reduced.

The study focuses on the steel industry. In addition to economic savings, this implementation is of special interest in this industry for regenerative process. It will improve the overall grid quality if the regenerative braking is local and, as a result, less grid perturbations will occur. Moreover, most of the smaller motors dissipates their energy when braking, so regenerative braking can be also implemented, improving the efficiency of the process.

Section 3.2 introduces DSM concept. Section 3.3 summarizes the different processes to apply the study. On the other hand, for meeting the end-profile requirements, it is needed to install a ESS between the supplier and the load. The different ESS technologies considered are gathered in Section 3.4. In order to interface the grid, load and the ESS, a MPEI is implemented. Section 3.5 collects its benefits. Finally, a trade off between the cost of the ESS and savings must be performed. Section 3.6 summarizes some algorithms proposed up to now.

3.2 DSM

From the total world energy consumption, 50% corresponds to the industrial sector. From this percentage, motors contributes up to 70%. Generally, industrial processes are not as efficient as they could be. Thus, the implementation of DSM techniques to improve their energy efficiency can play a huge role [3]. Furthermore, DSM can help to reduce shortages in the future [4].

DSM is defined as *the implementation of measures that helps users to consume electricity with more efficciency, and also, develop strategies to control the power demand to save energy costs.* [3, 5]. The electricity price is inversely proportional to the load curve due to the conventional scheduling [6]. Thus, DSM can help to smooth the load curve, reducing the electric bill, improving the power quality and avoiding to maintain a lot of unused capacity needed to meet peak load situation. [4, 7].

Summing up, the benefits that can be obtained from DSM are [3, 4, 7]:

- Minimize load shedding.
- Revenue from the savings in the energy bill.
- Smooth load shape.
- Reduce environmental degradation and gas emissions.
- Improve efficiency of the process.
- Reduce shortages.
- More efficient use of the capacity.

On the other hand, there are some drawbacks when implementing DSM. The installation cost is quite high and it takes a few years to be amortized. Besides, it is limited for large power intallation due to the high cost of the switching. Another shortcoming of DSM in the provision of security is that it is harder to estimate accurately the size of the load reduction that will actually occur in the event of an emergency [8].

3.2.1 DSM in the steel industry

Up to 20% of the total costs in a steel producer manufacturing comes from electricity consumption [9]. There is a continuous effort to reduce those costs due to the competitive steel market. An effective way to lower the electric bill without compromising the production is by implementing DSM techniques [10].

The study case, presented in [11], implements some energy efficient techniques in a steel plant (including DSM measures) and it results in a electrical energy saving varying from 10-15%.

Another case of a steel plant, focusing on the motor efficiency of rolling mill processes, is presented in [12]. Apart from replacing some motors by other more efficient, transformers loads have been reschedule. Rescheduling of transformer loads helps in reducing the electric bill and losses and it saves the transformer insulation from undue stresses.

It is studied the implementation of DSM measures in a blast furnace of a steel plant in [10]. A load shift is proposed, decreasing the power by 1 MW at the peak period. However, the blast furnace consumption is so unpredictable and the risk involved in performing this solution is too high to justify the savings obtained. On the contrary, it concludes that it is feasible to reduce the morning peak period in a small portion.

In this work, it will be considered cyclic process with predictable behavior, so the risk diminishes.

3.3 Process Description

Descaling, *tinning*, *pickling* and *galvanizing* are the non-stop processes considered. They have the common property of being cyclic, which is very convenient for applying DSM measures to predict the load behavior in advance. Fig 3-1 locates those processes into the production chain.

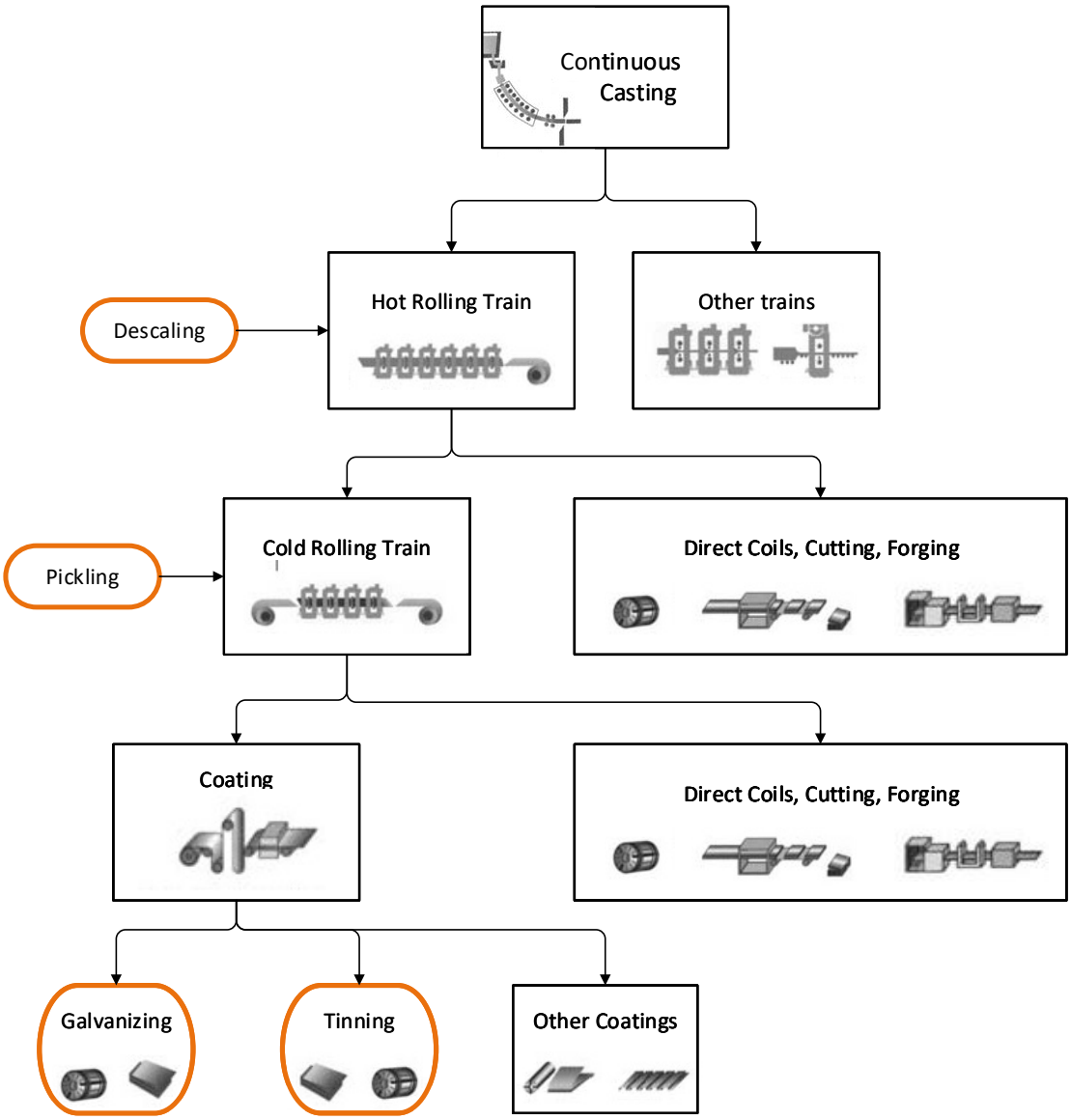

Figure 3-1: Location of the different processes.

3.3.1 Descaling

This processes is in the hot strip train. It is located in the devastating zone, between the furnace and the rolling mills that produce medium size slabs. Tins remove the scale formed inside the furnace. The descaling process is formed by two pairs of collectors that project water to the upper and lower surface removing the rolling scale [13].

3.3.2 Tinning

Tinning is a coating process. It produces the tin strip, defined as a steel sheet with low width (< 0.5 mm) and low carbon content covered by pure tin. It uses two electrodes connected by a liquid inside a tank with conducting liquid and metals bars. The metal particles coming from the metal bars through the liquid are added to the strip by adhesion [14, 13].

3.3.3 Pickling

It is the first stage in the cold rolling mill, where the steel is subjected to a cleaning process and gets ready for the rolling mill phase.

The coil obtained from the hot rolling mill process is covered with an oxide layer that can cause damages to the coil. In order to remove it, the coil goes through a rolling mill train before being cleaned in an acid bath. After the cleaning, the coil is washed with water, dried with fans and cover with a protecting oil [14, 13].

3.3.4 Galvanization

Once the hot coil is pickled and has the proper width to start the cold process, the galvanization process is performed. The steel strip is covered with cast zinc to obtain the galvanizing sheet. The zinc reacts with the steel, achieving a good junction [14].

3.4 Energy Storage Technologies

Energy storage plays a great role when implementing DSM measures. Energy storage as an effective way of enhancing energy utilization efficiency, it is also reported to be safe, flexible, unlimited and reliable [15, 16].

It is required to implement a ESS that can suit the energy and power demands by the profile, in such a way that the installation cost is minimized as the same time than the revenue is maximized. In this section, it is reviewed the storage technology main characteristics.

3.4.1 Load requirements

Different type of loads suitable for ESS are provided in [17]. The present application for the steel industry corresponds to a *Pulse load*. Rapid response and low cost per unit power are the most important characteristic when selecting the storage technology. Other factors to be considered are long life cycle and high efficiency of the storage [17]. Besides, low cost per unit energy will also be considered in the steel plant load, since this application requires a lot of energy for peak saving. Fig. 3-2 collects the main characteristics required for the ESS of this kind of load.

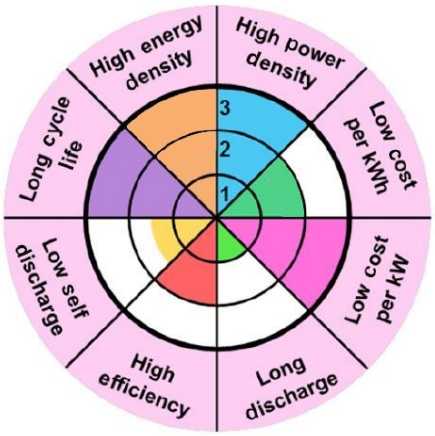

Figure 3-2: Importance of the energy storage characteristitcs [17]. 1-less important, 2-important, 3-very important.

3.4.2 ESS topologies

ESS can be classified into mechanical (pumped hydroelectric storage, compressed air energy storage and flywheels), electro-chemical(conventional rechargeable batteries and flow batteries), electrical(capacitors, supercapacitors and superconducting magnetic energy storage), thermo-chemical (solar fuels), chemical (hydrogen storage with fuel cells) and thermal (phase change storage)[18]. Table 3.1 provides the main important characteristics for a *Pulse load* application comparing all the ESS topologies.

All the technologies that have not a rapid answer (ms) are discarded, since it is the first requirement for the application. The technologies with larger number of cycles

Table 3.1: ESS topology comparison [17, 18]

Technology	Response time	Cycling (cycles)	η_{dis} [%]	Life time (years)	P_{cc} [$/kW]	E_{cc} [$/kWh]
PHS	min	10k-30k	87	+40	1200-4000	600-2500
small CAES	s-min	30k	-	23	1300-1550	200-250
Flywheel	ms-s	20k	90 - 95	15	250-350	1k-5k
Lead-acid	ms	0.5k-1k	85	5-15	300-600	200-400
Li-Ion	ms	up to 20k	85	5-15	1200-4000	600-2500
NaS	ms	2.5k	85	10-15	1000-3000	300-500
NiCd	ms	2.5k	85	10-20	500-1500	800-1500
VRB	ms	+12k	75-82	5-10	600-1500	150-1000
ZnBr	ms	+2k	60-70	5-10	700-2500	150-1000
PSB	20 ms	-	60-75	10-15	700-2500	150-1000
Capacitor	ms	+50k	75-90	5	200-400	500-1000
Supercap	ms	1000k	98	10-30	100-300	300-2000
SMES	ms	1000k	95	+20	200-300	1000-10000
H-Fuel cell	ms	1000k	59	20	1500-3000	15
TES	not rapid	-	-	10-20	100-400	20-50

are considered, which are supercapacitor, SMES and Fuel cells. They all have good efficiency and similar life time. However, supercapacitor achieves the best P_{cc}, so it will be considered for the ESS of the *Pulse load*. On the other hand, it is required another technology with lower E_{cc}. Fuel cells seem a good solution for supporting supercaps, however, it has two drawbacks that discards this solution: flammable (for security reasons is not viable in a steel process) and it is very expensive to produce [19].

Batteries are also proposed for supporting the ESS in terms of energy. The higher number of cycles, the better. Li-Ion batteries has the greater number of cycles, but VRB takes the second place in terms of cycles with a lower E_{cc}. Economy of scale and manufacturing capacity are helping to decrease battery cost rapidly (specially Li-Ion) and make them profitable in the next years for DSM implementation [20, 21]. On the other hand, VRB highly depends on vanadium price, which has wide price fluctuations in very short period times [22]. Besides, flow batteries have a very expensive maintenance cost due to all the mechanic devices involved in the flowing

(turbines) that makes this technology unaffordable [18].

Fig. 3-3 provides a comparison of power and energy density of the different technologies. Li-ion batteries and supercapacitors have really good power-energy/density properties. Both technologies are taken into account for the ESS proposed in this study, since they properly fit in *Pulse load* requirements [17].

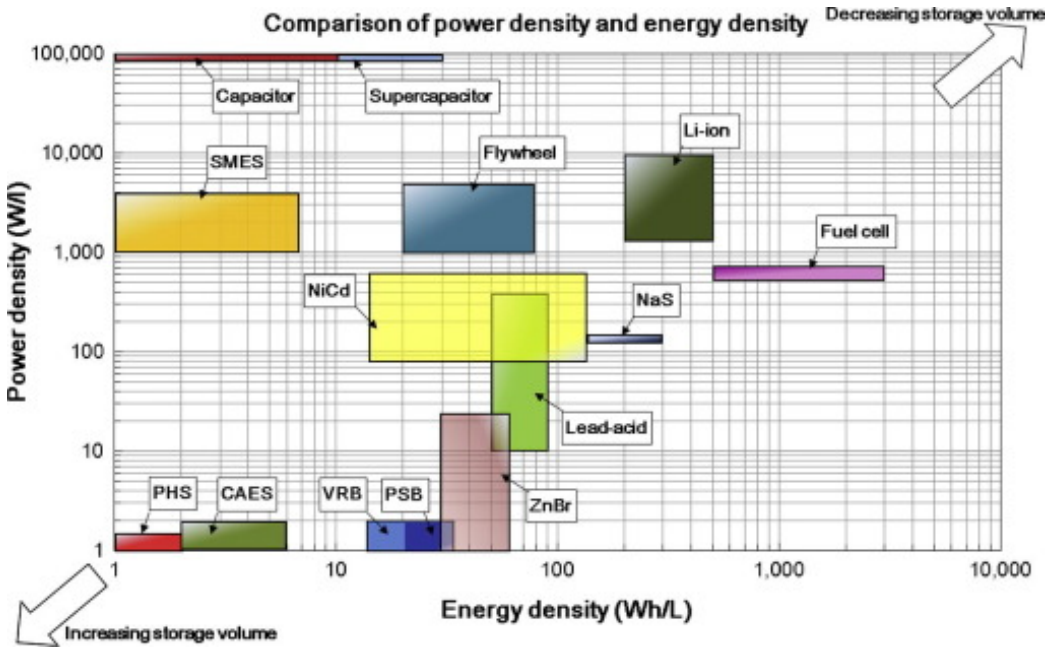

Figure 3-3: Energy and Power density comparison of different storage technologies [18].

Table 3.2 provides a comparison of Energy and power in terms of density and cost. It is shown that supercapacitors are so convenient for high power applications with low energy, when it is preferable to use batteries for higher energy application with lower power. Thus, these properties will play a key role when sizing the hybrid ESS.

Table 3.2: Energy-power comparison between supercap and Li-Ion battery [17]

Technology	E_d [Wh/kg]	P_d [W/kg]	$E_{capitalcost}$ [\$/kWh]	$P_{capitalcost}$ [\$/kW]
Supercapacitor	0.5-5	1000-10000	500-15000	100-400
Battery	70-200	150-500	600-2500	1200-4000

3.4.3 Lithium-Ion Battery

Lithium ion battery has the greatest oxidation potential of all known elements. These batteries have high energy and power capabilities [15]. During discharge, lithium ions move from the negative electrode to the positive electrode, and the other way around when charging. The cathode is made of a lithium metal oxide, such as $LiCoO_2$ and $LiMO_2$, and the anode is made of graphitic carbon. The electrolyte is usually a non-aqueous organic liquid which contains dissolved lithium salts, such as $LiClO4$[18]. Fig. 3-4 depicts its working principle.

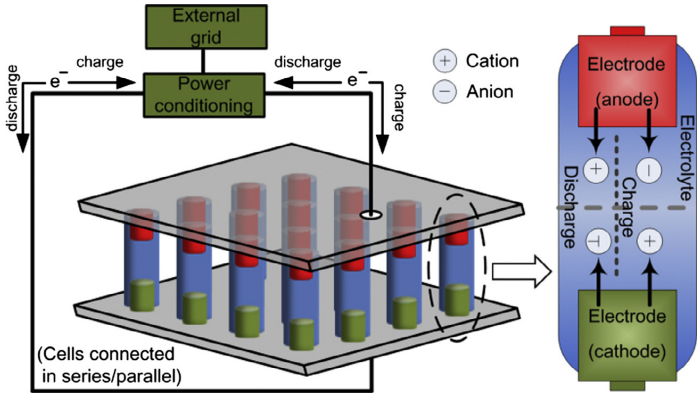

Figure 3-4: Battery working principle [18].

It has been widely used for high power applications [17] ([18] presents some installations). This battery suits properly for applications that needs a good response and long cyclic life. They also have high efficiency cyclings (up to 97%) and good scalability for versatil applications(from 1 kW to 100 kW). It is also the battery technology with highest energy density as shown in Fig. 3.2 [18, 17, 21].

On the other hand, the cycling affects its lifetime and battery requires a management system (BMS) for a proper operation which increases the overall cost [18]. Moreover, for a large-scale application, the main challenge is the cost which increases because of the special packaging, protection circuits and limited sources for lithium [17].

As mentioned before, there is a decreasing trend in battery price. Fig. 3-5 collects this tendency. It is expected a reduction of Li-Ion battery price becoming the cheapest technology.

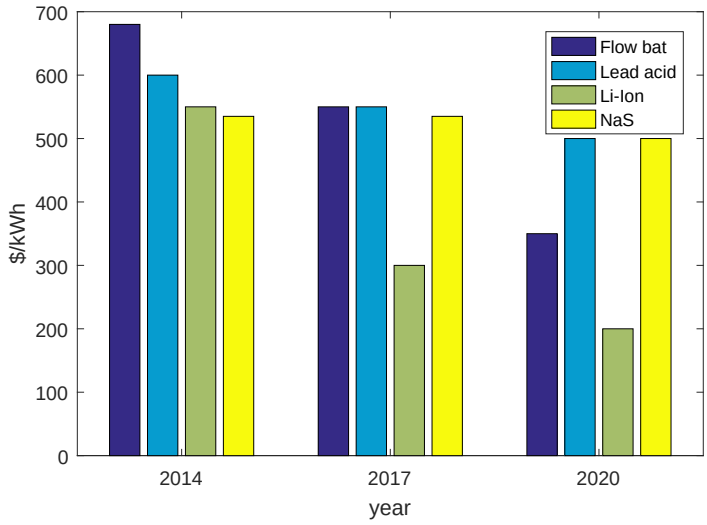

Figure 3-5: Battery price trend [20].

Cycling

On of the most interesting characteristics of the battery for this application is the cycling performance. It is known that the number of cycles has a logarithmic relation with DOD of the battery. Fig. 3-6 depicts the number of cycles depending on the DOD for the batteries used in this project.

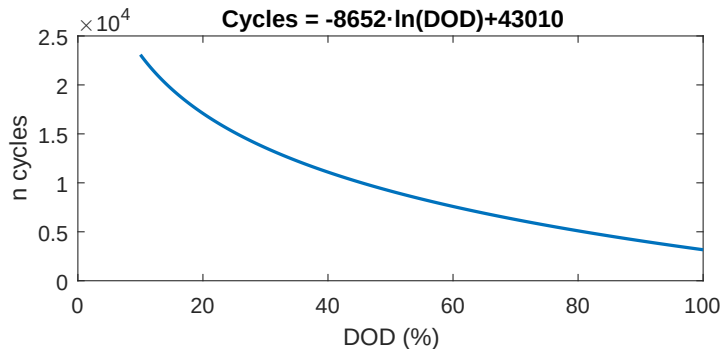

Figure 3-6: Cycling life.

The previous relation just takes place when the batteries run below 10 Hz, meanwhile for higher frequencies, the degradation is negligible (e.g. due to the converter) [23]. This is the main reason why batteries can not be used for filtering the signal: a cycling below 10 Hz will occur and the battery will be deteriorated quickly. Thus, supercapacitors will be in charge of filtering the signal.

3.4.4 Supercapacitors

Supercapacitors, also known as double-layer capacitor, contain two conductor electrodes, an electrolyte and a porous membrane separator (Fig.3-7). They store the energy on the surfaces between the electrolyte and the two electrodes in the form of static charge. The supercapacitors are based on nano materials to increase electrode surface area for enhancing the capacitance. The capacitance of this technology is thousand times larger than the conventional one [17, 18].

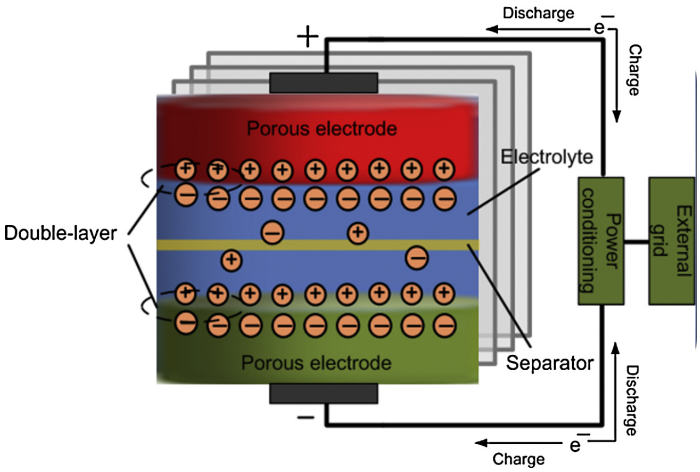

Figure 3-7: Supercapacitor working principle [18].

They are very efficient and fast when charging and discharging because they directly store electrical energy. However, the energy capacity is very low. An hybrid combination with a high energy density ESS for large-scale application offers a useful solution [17, 15], as in the present case.

Cycling

Supercapacitors play a key role in long-life applications with relatively deep DOD helping the system to extend their life [24].

Temperature is the mayor contributor to degradation, whereas DOD and charge voltage have minor effects on it. Degradation increases 1.3 times every 10°C added.

3.5 Multiport Power Electronic Interface

A MPEI has been proposed to interface all the components of the ESS with the grid and load. In this section, this technology is compared to the well-known multiple-input converter.

Multiple-inputport converter topologies have been studied in deep due to their advantages of low cost, high power density and ease of management. This topology is mainly classified into isolated (magnetically coupled) and non-isolated (electrically coupled). Both cases researched have not considered small disturbance injections, ac loads (ripple injections have to be attenuated) and bidirectional power flow. MPEI remedies those drawbacks [25].

MPEI is defined as *a self-sustainable multiple-input/output static power electronic converter, capable of interfacing with different sources, storages and loads. Its control system achieves a good static and dynamic performance which render optimal energy management* [25]. It has the advantages of high efficiency, low cost, high robustness and ease of management. This system fits better for integrating hybrid ESS to supply low/medium power loads such as microgrids, rural areas, military camps and critical industrial place [26].

Fig. 3-8 shows the scheme of the MPEI. As it is shown, all is connected through a DC link. The stability of the whole system highly depends on the stability of the voltage of this DC link, and the voltage control must be properly desinged [27].

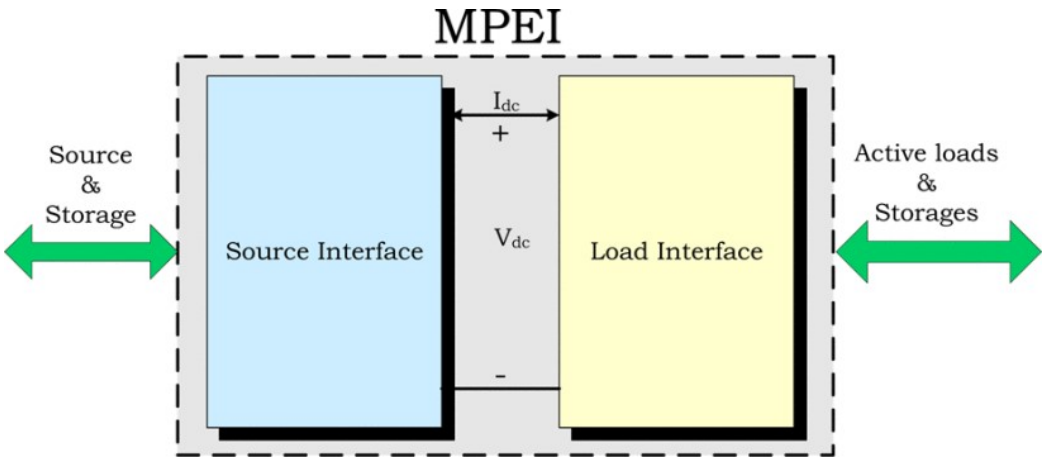

Figure 3-8: Scheme of the MPEI [25].

3.6 ESS Sizing Algorithms proposed

Pulse loads can cause several shortcomings as power disturbances and thermal issues. This hybrid ESS can improve the overall performance. Average pulse demands will be supplied by batteries, which is the long-time primary energy source. On the contrary, dynamic power requirements are provided by supercapacitors. The system will obtain some advantages as mitigation of thermal issues and voltage disturbances [17].

In [20], it is proposed a sizing optimization for smoothing the renewable generation in order to maintain system reliability and voltage concerns. Even this case is for the load side, since it is a big load it has the same effect.

A size of ESS for the electric power system is developed in [28]. Its aim is to maintain the power within the grid capabilities. For that propose, it generates an optimization algorithm that considers PS and LL, and the revenue in 10 years. It concludes that the power can be maintained withing its values, and also get a revenue of 400 USD.

A method to size an hybrid ESS composed of Li-Ion battery and supercapacitors for urban rail transit is proposed in [29]. It helped to reduced a 43% of losses and 32% of peak current. This hybridization enhanced voltage line and battery life (16%). The same hybrid ESS is proposed in [30] for an hybrid bus. It also concludes that by hybridizing the ESS with batteries and supercapacitors, battery life is extended, and the operation cost is reduced.

Chapter 4

Economic analysis for DSM in steel processes

Before performing the optimization, the initial parameters have to be chosen. Those parameters involves the tariff, the price schedule and ESS used. The access tariff depends on the line voltage of the process and the total power hired. The price schedule for the electricity varies along the day and also each month.

After selecting the tariff, it has to be selected one supercapacitor device from Maxwell technology and one battery device. Once this parameters are selected, the algorithm can be computed.

4.1 Electric bill

In this section, the tariffs and price scheduling are summarized. Besides, the equations for calculating the tariffs are given according to [31, 32].

4.1.1 Tariff

Spanish law [31] states the access tariff is divided into low, medium and high voltage. The profiles tested correspond to the last option. Table 4.1 summarized all tariff options for high voltage lines, which depends on line voltage and power consumed.

Table 4.1: Access Tariff [31]

Tariff	**3.1A**	**61.A**	**6.1B**	**6.2**	**6.3**	**6.4**	**6.5**
Voltage (kV)	(1,36)	(1,30)	(30,36)	(36,72.5)	(72.5,145)	$\geqslant 145$	International
Power (kW)	$\leqslant 450$	> 450[1]	> 450[1]	S/R[2]	S/R[2]	S/R[2]	S/R[2]
Number of periods	3	6	6	6	6	6	6

[1] in some periods
[2] No restrictions

The power of the loads for the cases proposed are always over 450 kW, so just six-period tariffs are taken into account. The time scheduling for those periods depends on each month as shown in Table 4.2 [33]. The price of each access tariff is collected in Table 4.3 [32].

Table 4.2: Price scheduling

h	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**[1]	**Jun**[2]	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dic**
0-8	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
8	P2	P2	P4	P5	P5	P4	P2	P2	P6	P4	P5	P4	P2
9	P2	P2	P4	P5	P5	P3	P2	P2	P6	P3	P5	P4	P2
10	P1	P1	P4	P5	P5	P3	P2	P2	P6	P3	P5	P4	P1
11	P1	P1	P4	P5	P5	P3	P1	P1	P6	P3	P5	P4	P1
12	P1	P1	P4	P5	P5	P3	P1	P1	P6	P3	P5	P4	P1
13	P2	P2	P4	P5	P5	P3	P1	P1	P6	P3	P5	P4	P2
14	P2	P2	P4	P5	P5	P3	P1	P1	P6	P3	P5	P4	P2
15	P2	P2	P4	P5	P5	P4	P1	P1	P6	P4	P5	P4	P2
16	P2	P2	P3	P5	P5	P4	P1	P1	P6	P4	P5	P3	P2
17	P2	P2	P3	P5	P5	P4	P1	P1	P6	P4	P5	P3	P2
18	P1	P1	P3	P5	P5	P4	P1	P1	P6	P4	P5	P3	P1
19	P1	P1	P3	P5	P5	P4	P2	P2	P6	P4	P5	P3	P1
20	P1	P1	P3	P5	P5	P4	P2	P2	P6	P4	P5	P3	P1
21	P2	P2	P3	P5	P5	P4	P2	P2	P6	P4	P5	P3	P2
22	P2	P2	P4	P5	P5	P4	P2	P2	P6	P4	P5	P3	P2
23	P2	P2	P4	P5	P5	P4	P2	P2	P6	P4	P5	P3	P2

[1]June 1-15th
[2]June 16-30th

Electricity cost

Once the tariff is established, the power hired and electricity are calculated according to [31]. The hired power (FP) has to be hired in such a way that it accomplishes (4.1). Once the power hired is settled for each period, the price of the power is calculated using (4.2).

Table 4.3: Access Tariff [31]

Tariff		P1	P2	P3	P4	P5	P6
6.1A	T_p €/kW	39.139427	19.586654	14.334178	14.334178	14.334178	6.540177
	T_e €/kWh	0.026674	0.019921	0.010615	0.005283	0.003411	0.002137
6.1B	T_p €/kW	31.020989	15.523919	11.360932	11.360932	11.360932	5.183592
	T_e €/kWh	0.021822	0.016297	0.008685	0.004322	0.002791	0.001746
6.2	T_p €/kW	22.158348	11.088763	8.115134	8.115134	8.115134	3.703649
.	T_e €/kWh	0.015587	0.011641	0.006204	0.003087	0.001993	0.001247
6.3	T_p €/kW	18.916198	9.466286	6.92775	6.92775	6.92775	3.160887
	T_e €/kWh	0.015048	0.011237	0.005987	0.002979	0.001924	0.001206
6.4	T_p €/kW	13.706285	6.859077	5.019707	5.019707	5.019707	2.290315
	T_e €/kWh	0.008465	0.007022	0.004025	0.002285	0.001475	0.001018
6.5	T_p €/kW	13.706285	6.859077	5.019707	5.019707	5.019707	2.290315
	T_e €/kWh	0.008465	0.007022	0.004025	0.002285	0.001475	0.001018

T_p - Power hired price (€/kW/year)
T_e - Electricity price (€/kW)

$$P_{n+1} \geq P_n \tag{4.1}$$

$$FP = \sum_{j=1}^{i=n} t_{pi} P_{fi} \tag{4.2}$$

where P_{fi} is the power hired in period i expressed in kW and t_{pi} is the anual price of the T_p in period i.

In case the real power exceeds the hired one, a penalization (F_{EP}) has to be computed according to 4.3.

$$F_{EP} = \sum_{j=1}^{i=6} k_i \cdot 1.4064 \cdot A_{ei} \tag{4.3}$$

where K_i is a the coefficient that varies with tariff period i (Table 4.4) and A_{ei} is calculated with the given equation (4.4). P_{dj} is the average demanded power in each quarter of hour that has exceed the hired one (P_{ci}).

$$A_{ei} = \sqrt{\sum_{j=1}^{i=n} (P_{dj} - P_{ci})^2} \tag{4.4}$$

Table 4.4: Coerfficent K_i

P	1	2	3	4	5	6
$\mathbf{K}_i$	1	0.5	0.37	0.37	0.37	0.17

The price of the energy consumed (FE) is calculated with (4.5)

$$FE = \sum_{i=1}^{i=n} E_i t_{ei} \tag{4.5}$$

where E_i is the energy consumed in the period i (expressed in kWh) and t_{ei} is the price of the energy in that period i.

Once FP, F_{EP} and FE, the regulated electricity bill E_{cost} is calculated (4.6). The current tax IVA is 21% and electricity tax (E_{tax}) is 5.11%.

$$E_{cost} = (FE + FP + F_{EP})(1 + E_{tax})(1 + IVA) \tag{4.6}$$

4.2 Analysis of ESS costs

The batteries and SC considered for this study are described in this section.

4.2.1 Supercapacitors

For this project, Maxwell SC modules have been used. Table 4.5 collects the modules available. Having the same life expectation for all the devices, it is computed the energy cost of each module, since it is the most restrictive parameter. The lowest the energy cost, the better optimization results. BMOD0165 P048 B01 model becomes the most suitable device for this application. Table 4.6 gathers their main characteristics.

Table 4.5: Supercapacitor models

Model	Energy Wh/module	Price €/module	E_{cost} €/Wh
BMOD0130 P056 B03	57	1608	28.2
BMOD0165 P048 B01	53	1093	20.6
BMOD0500 P016 B02	18	487	27
BMOD0083 P048 B01	27	1142	42
BMOD0006 E160 B02	21	1016	48.4

Table 4.6: BMOD0165 P048 B01

V_{nom} (V)	I_{nom} (A)	P_{nom} (kW)	E_{nom} (kWh)	C_{charge}	$C_{discharge}$	cycles
48	928	45	0.053	840	840	1M

4.2.2 Battery

Li-Ion batteries are proposed for the analysis. Table 4.7 contains the main characteristics of each battery proposed. Price includes the container and the BMS. Cycles mainly depends on the DOD, so the numbers provide here are for having an overall idea. The number of cycles will increase a lot with lower DOD as shown in the previous chapter. In the algorithm, the relation of DOD with life will be taken into account.

Table 4.7: Battery Models

Battery	P_{nom} (kW)	E_{nom} (kWh)	C_{charge}	$C_{discharge}$	cycles	Price (€/kWh)
NMC	208	69.4	2	3	3800	900
LFP	190	32.7	4	6	7300	1656
LTO	549	68.7	4	8	15100	2552

The most suitable technology will be chosen in the toolbox developed *inDSM*.

Chapter 5

Optimization method for DSM in steel industry

5.1 Global idea

This chapter explains the model developed for optimizing the ESS. As it has been explained, the ESS consists of SC and batteries. The sizing optimization can be split into two parts, one for sizing the SC and the other for calculating the number of batteries. The combination selected will be the one that obtains the greater savings in the total life of the system.

To get the proper number of SC, the total power is split by filtering with a low pass filter. Since SC have a long cycling life and has good power density properties, they will handle the high frequency filtered. Whereas the low frequency will be handle by the grid. The optimum cut-off frequency (f_c) of the filter will be one of the parameters determined by the algorithm. Frequency is related with the energy capacity of the SC, which as it has been seen in Chapter 2, it is the most restrictive parameter. The lower the cutoff frequency, the higher the capacity, the installation cost and the savings. Those savings comes from the power hired reduction in all the periods.

Batteries will perform a PS in the most expensive periods and then will be charged at night (LL). By performing PS, the hired power for the most expensive period can be reduced. Different power values for PS are tested, and finally, the one that obtains

the greater benefit is selected. In case there is some remaining energy in the battery, when the expensive period is about to end, the battery is discharge at 1C.

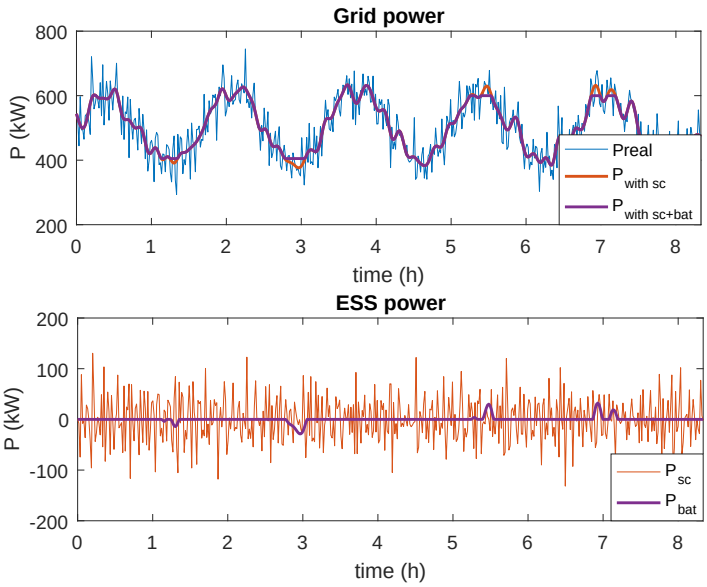

Figure 5-1: Power distribution idea. Negative values in the power of the ESS corresponds to charging process.

Fig. 5-1 represents the final power distribution in an example, assuming the expensive period occurs from hour 4 to 8.

Furthermore, physical restrictions (cycling, power/energy limits, power converter capabilities...), payback time, installation life are also taken into account and it will be later explained in this chapter.

5.2 Signal processing

Before starting with the optimization algorithm, some input data are processed. This part is specially important for sizing the storage of the SC. The energy handled by this devices is the most critical parameter and it will have a great impact on the installation cost. The trade-off between cost and energy of the SC will be one of the key issues of this project.

Fig. 5-2 collects the power profile of the four process to consider. Some of the process are no completely periodic, in these cases the most critical interval is analyzed

for performing the FFT. This is done to improve the quality of the results and avoid distortion. Fig. 5-2 points out those intervals.

The idea is to supply the higher harmonics of the profiles with SC. In the algorithm, an generic interval of cut-off frequencies is tested and this interval wants to be given by this section. This is very important for speeding up the program without missing the optimum solution.

As a first assumption, it is considered that the SC has to handle a total energy of 1kWh. All the processes are not pure period, which results in a distortion when performing the FFT. In order to get accurate results when calculating the Energy of those harmonics, an interval of frequencies is considered. Harmonics above 0.03 Hz are neglected. This is just an initial assumption that will be further validated in the optimization.

Fig 5-3 shows the scheme of the algorithm that obtains the proper cut-off frequency for having a ESS of 1kWh. The algorithm calculates the energy of each harmonic, from the upper frequency to the lower. The lower frequency corresponds to the cutoff frequency of the filter and the total energy would be 1kWh. The energy of the SC is calculated with equation 5.1, where A is the amplitude of the harmonic in kW, ω is the angular frequency in rad/s, T is the period and t is the time in *seconds*.

$$E(kWh) = \frac{\sum \int_0^{T/2} A sin(\omega t)}{3600} \tag{5.1}$$

FFT

The FFT of *Tinning* profile is depicted in Fig. 5-4. The f_c computed is 0.014 Hz.

On the other hand, *Pickling* time has larger high frequency harmonics as shown in Fig. 5-5. The resulting f_c is 0.024, a little bit higher.

In *galvanizing* process, there are two clear harmonics (Fig 5-6). The first harmonic corresponds to the resistors that heat up the the strip. The second one comes from the fans. The calculated f_c is 0.02 Hz.

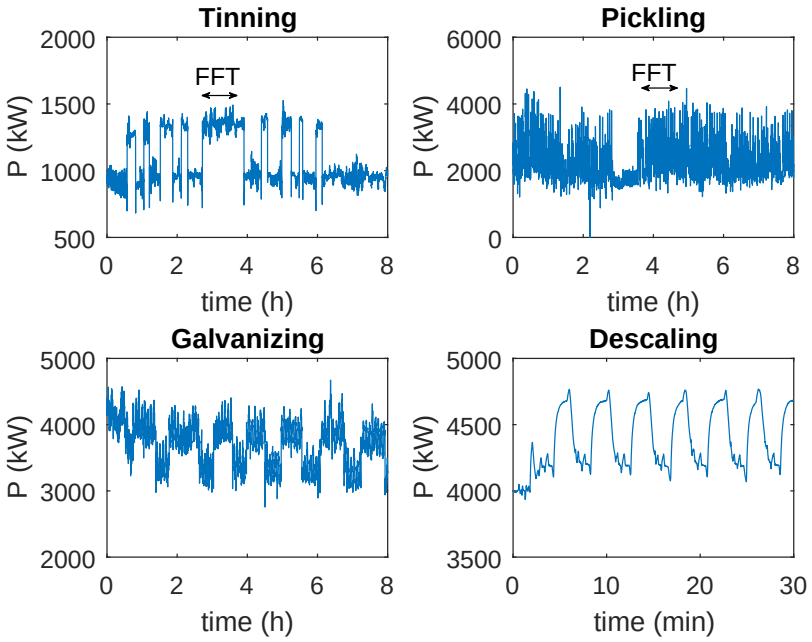

Figure 5-2: Steel Processes.

Finally, the *descaling* process has a FFT depicted in Fig. 5-7. It would have a filter with an f_c of 0.013 Hz.

Based on the previous data and giving some margins, the initial frequency interval goes from 0.01 Hz to 0.03 Hz.

Filter properties

As it has been shown, there is a large offset component (0 Hz) really close to the following harmonics. A fifth order filter is proposed to achieve a performance close to an ideal one. The filter will have five zeros as well, so the delay is highly reduced.

In addition, it is used command *filtfilt* that performs zero-phase digital filtering by processing the input data in both forward and reverse directions. Thus, the sum obtained from the LPF and HPF perfectly matches the total power. However, when moving to real implementation, it is required more memory and a delay when commanding the power for each device. In order to have a similar performance, the power can be processed with a lower sampling time, apply *filtfilt* every x samples, and split the power with a small delay.

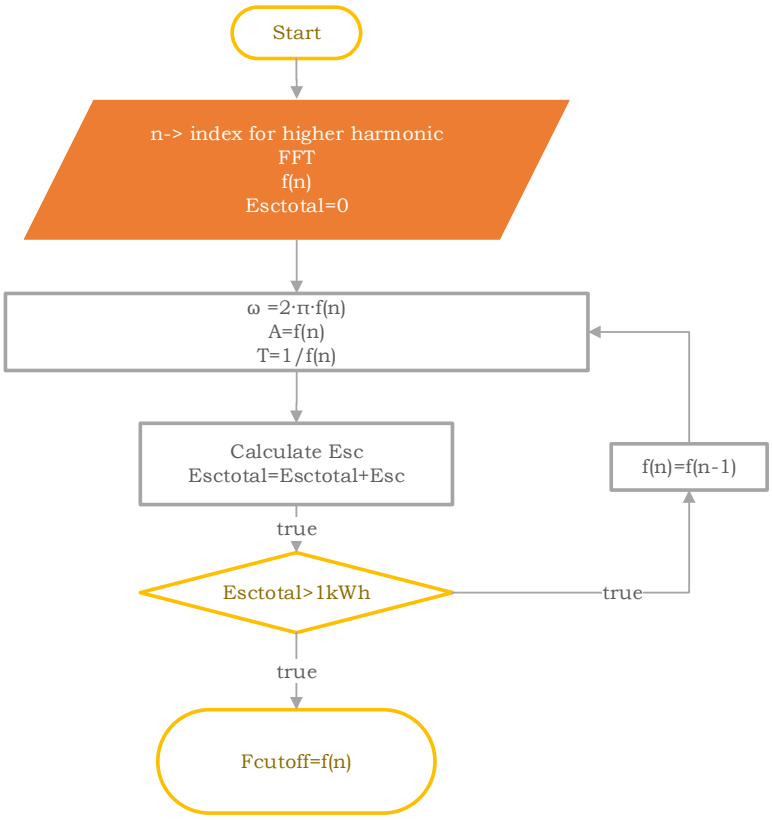

Figure 5-3: f_{cutoff} determination.

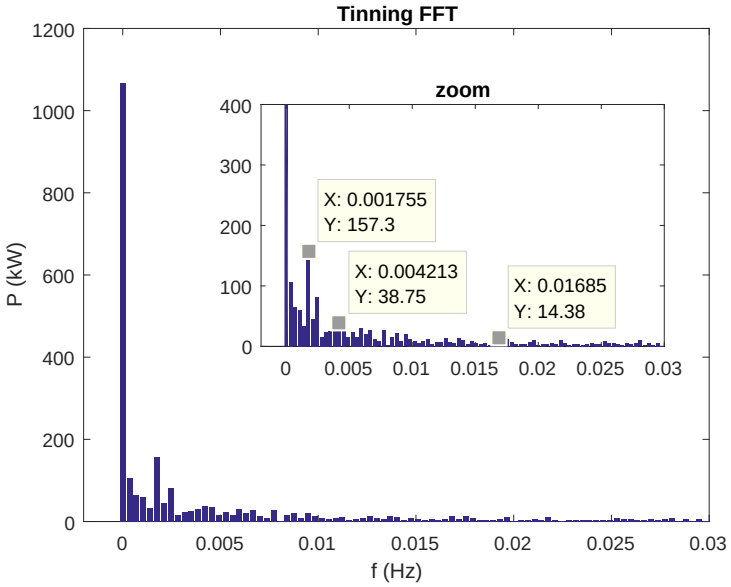

Figure 5-4: Tinning FFT.

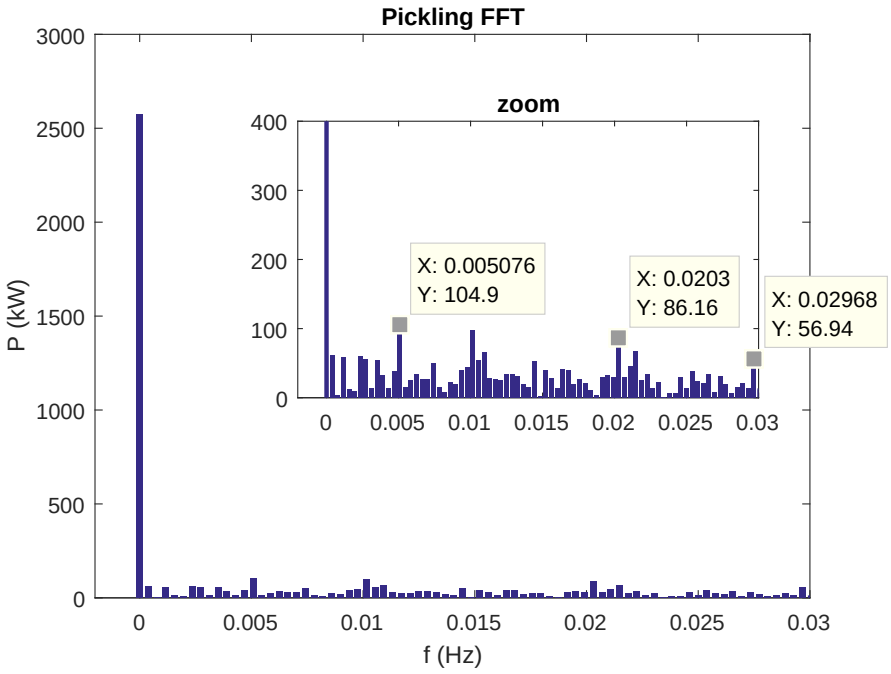

Figure 5-5: Pickling FFT.

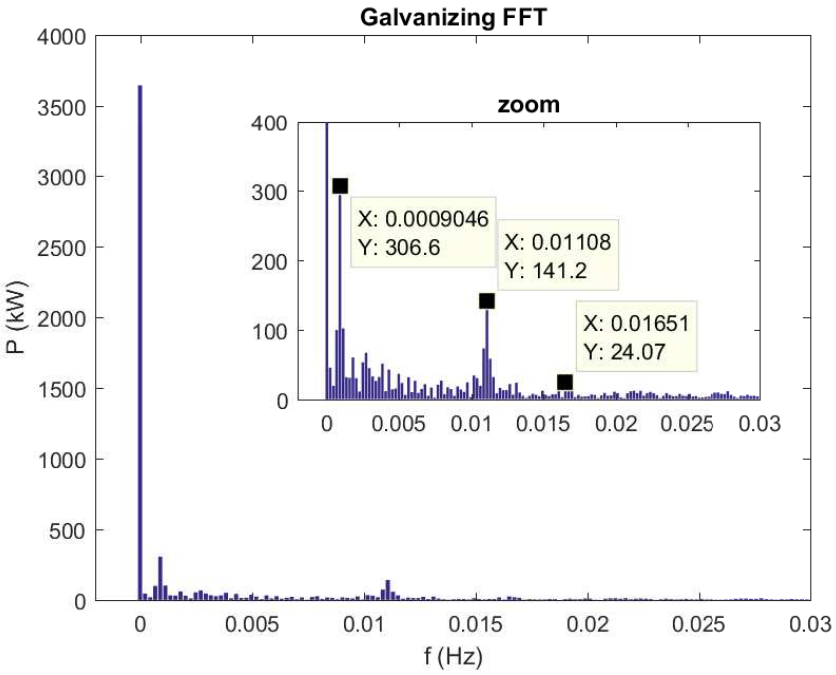

Figure 5-6: Galvanizing FFT.

As an example, Fig. 5-8 shows the energy distribution between the grid and the SC. Using an f_c of 0.01 Hz, the LPF and HPF used are (5.2) and (5.3) respectively.

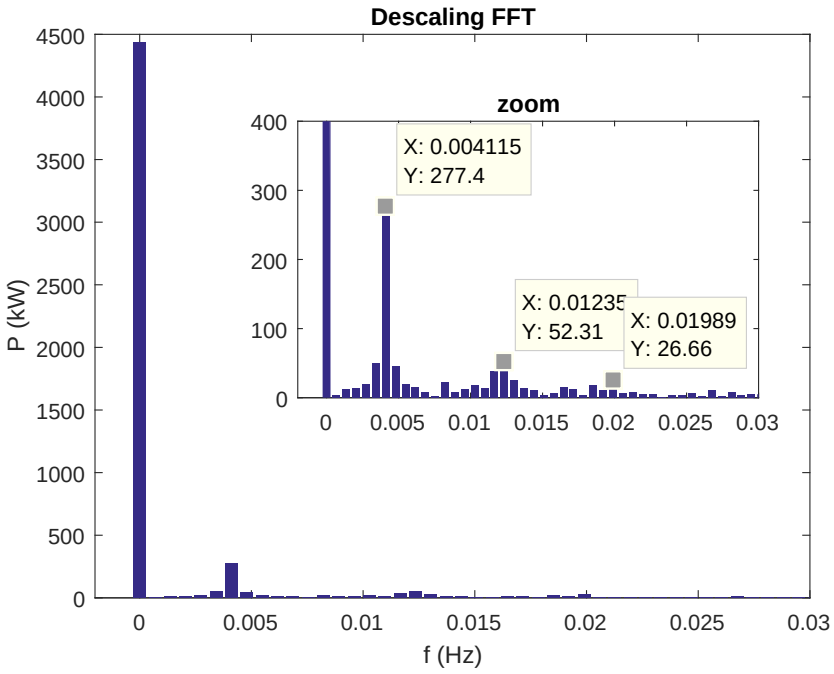

Figure 5-7: Descaling FFT.

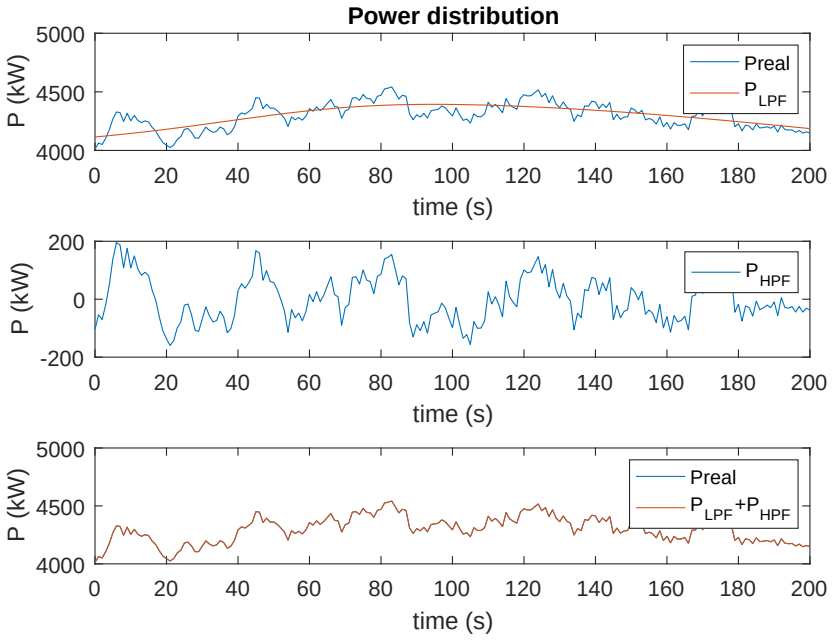

Figure 5-8: Filter comparison. The upper figure shows the load power and the LPF one. The middle figure shows the power obtained by the HPF. The last one shows the comparison between the sum of the power from the filters and the real power

$$LPF = \frac{10^{-6}(0.028 - 0.138z^{-1} + 0.277z^{-2} - 0.277z^{-3} + 0.138z^{-4} - 0.028z^{-5})}{1 - 4.797z^{-1} + 9.207z^{-2} - 8.84z^{-3} + 4.246z^{-4} - 0.816z^{-5}} \quad (5.2)$$

$$HPF = \frac{0.903 - 4.517z^{-1} + 9.033z^{-2} - 9.033z^{-3} + 4.517z^{-4} - 0.903z^{-5}}{1 - 4.797z^{-1} + 9.207z^{-2} - 8.84z^{-3} + 4.246z^{-4} - 0.816z^{-5}} \quad (5.3)$$

5.3 Physical constraints

The physical constraints considered in the algorithm are presented in this section. These are divided into Energy, Power and Life constrains. The constrains are computed right after allocating the power for each component.

5.3.1 Energy, DOD and SOC

Batteries have to handle the energy required for the PS performed. For that propose, equation (5.4) is used for calculating the energy.

$$E_{bat}[kWh] = \frac{\sum_{i=n} \int_{t_{start(i)}}^{t_{end(i)}} P(dt)}{3600} \quad (5.4)$$

where n is the number of times the battery carries out a discharge and t_{start}/t_{end} the starting/end time of each discharge. From this equation, it is determined how many batteries are required in terms of energy.

The battery should be capable to administrate this amount of energy considering its DOD and the SOC working operation. To make sure the battery does not get damage, the battery can only be chargued up 90%. Usually batteries use 60% of its capacity to work under save operation mode. Fig 5-9.a represents an example of battery SOC profile during a day, where most expensive periods are highlighted in purple. It is observed that the battery performs some discharges during high cost period and it completely discharges at 1C when the period P1 is about to end.

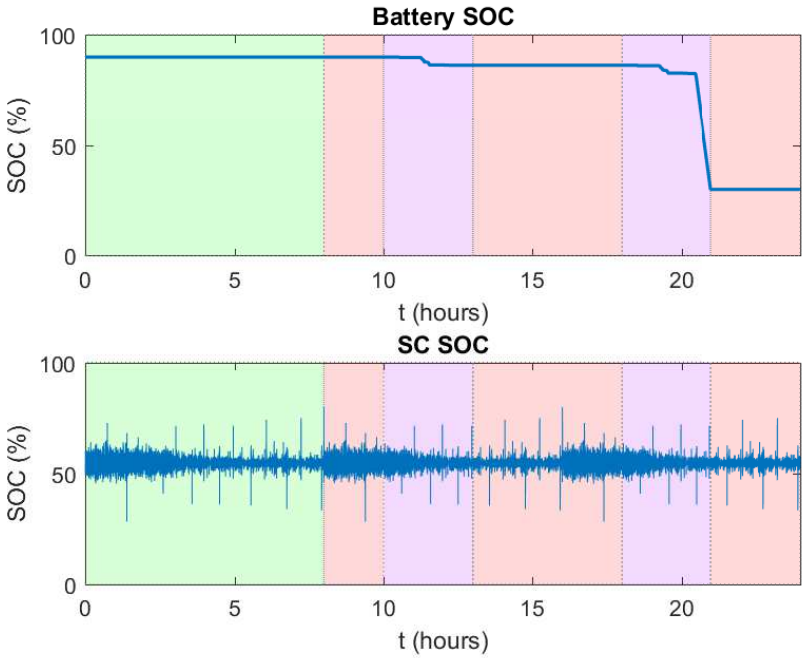

Figure 5-9: a)SOC of the battery. b)SOC of the SC.

On the other hand, the SC size is determined in a different way. It is calculated the energy required during all the performance using (5.5) and taking their maximum value to determine the number of SC. Then, the number of SC is increased until it fulfills the SOC requirements.

Fig. 5-9.b depicts the SOC of the SC during a day. It can be seen that the SC always work in safe operation mode without going beyond its limits.

$$E_{sc}[kWh] = \left(\left| \frac{\int_{t_0}^{t_{end}} P(dt)}{3600} \right| \right) \tag{5.5}$$

5.3.2 Power

The power should be accomplish also for both ESS and power converter. Batteries must handle the power of the PS, the number of batteries required needs a discharge C-rate able to supply the power required.

The power for the SC is calculated in the same way for the SC. The power capability of this technology is very good, so it is usually not a restriction.

The converter must be able to handle the maximum power of the ESS, so the maximum power handled by either the batteries or SC must be below the converter limits. This is the main limit of the converter assumed in this work, having a cost of 100 /kW.

5.3.3 Life

Cycling life is a very important restriction. Battery cycling is highly determined by its DOD. Eq 5.6 provides the relation between the number of cycles and DOD for the battery used. Once it is known the number of cycles, it can be obtained the life expectancy with the profile computed. It must be above the desired life expectancy of the overall system.

$$cycles = -8652 \cdot ln(DOD) + 43010; \tag{5.6}$$

On the other hand, the supercapacitors can reach up to one million cycles.

The life of the converter is not considered since it is less restrictive than the ESS life.

Summing up, the final size of the ESS has to be the minimum that accomplish the energy, power and life restrictions.

5.4 Optimization algorithm

5.4.1 Input Data

The input data required is obtained from a .csv file. Four .csv files are loaded:

- **Profile:** It is selected a 24 hours profile giving its sample rate in seconds.
- **Tariff:** The tariff is selected based on the voltage and power consumed.
- **Period:** It gives the different time schedule of the tariff cost depending each hour and month.
- **ESS:** This sheet contains both supercapacitors and batteries. The battery is

selected considering its C-rate, whereas the SC is selected based on its energy storage. Those parameters are the most relevant for this evaluation.

In addition to the previous data, it has to be set the payback year and the life expectancy of the system.

5.4.2 Optimization

The optimization algorithm will compute different combinations of SC and battery capacity. It mainly consists on two loops, the outer one determines the SC number and the inner one determines the battery size. Fig. 5-10 gives the flowchart of the algorithm.

The SC storage capacity required is given by the cut-off frequency of the filters that distribute the power between the grid and SC. Thus, a interval of different cut-off frequencies are tested. After performing the optimization, this interval has been readjust to 0.01 Hz to 0.0275 in steps of 0.0025 Hz.

For each previous frequency case, it is performed the inner loop where the power handled by the battery in the PS is computed. PS is only performed during the most expensive periods (P1), and the interval tested goes from 0 to 350 kW. Once it is determined the peak power, the energy required for supplying that power is calculated, and so the number of batteries. Usually there is a remaining energy not used for PS that is always used at the end of the period P1.

All the previous results are readjust to accomplish the physical constrains explained before. New costs, payback, life is computed before storing the value. The user sets a maximum payback and minimum life of the ESS. Only the cases that accomplish those restrictions are considered for getting the solution which corresponds to the one with greater savings during the ESS life.

For calculating the economic results, it is considered that this 24 h profile is the same each day of the year. Thus, the equations given in Chapter 4 are used for calculating the economic results, considering the tariff variation of each month. Leap years are not taken into account.

Once the algorithm is computed, if it accomplish both payback and life expectancy restrictions, it gives a solution. The main results given are the total installation cost, the payback in years, the electricity bill (with and without implementing the ESS) and the total savings. Furthermore, it is also displayed how the profile is optimized each month and also how the SOC of the ESS varies depending on the tariff condition.

The results obtained for each process will be discussed in the following chapter.

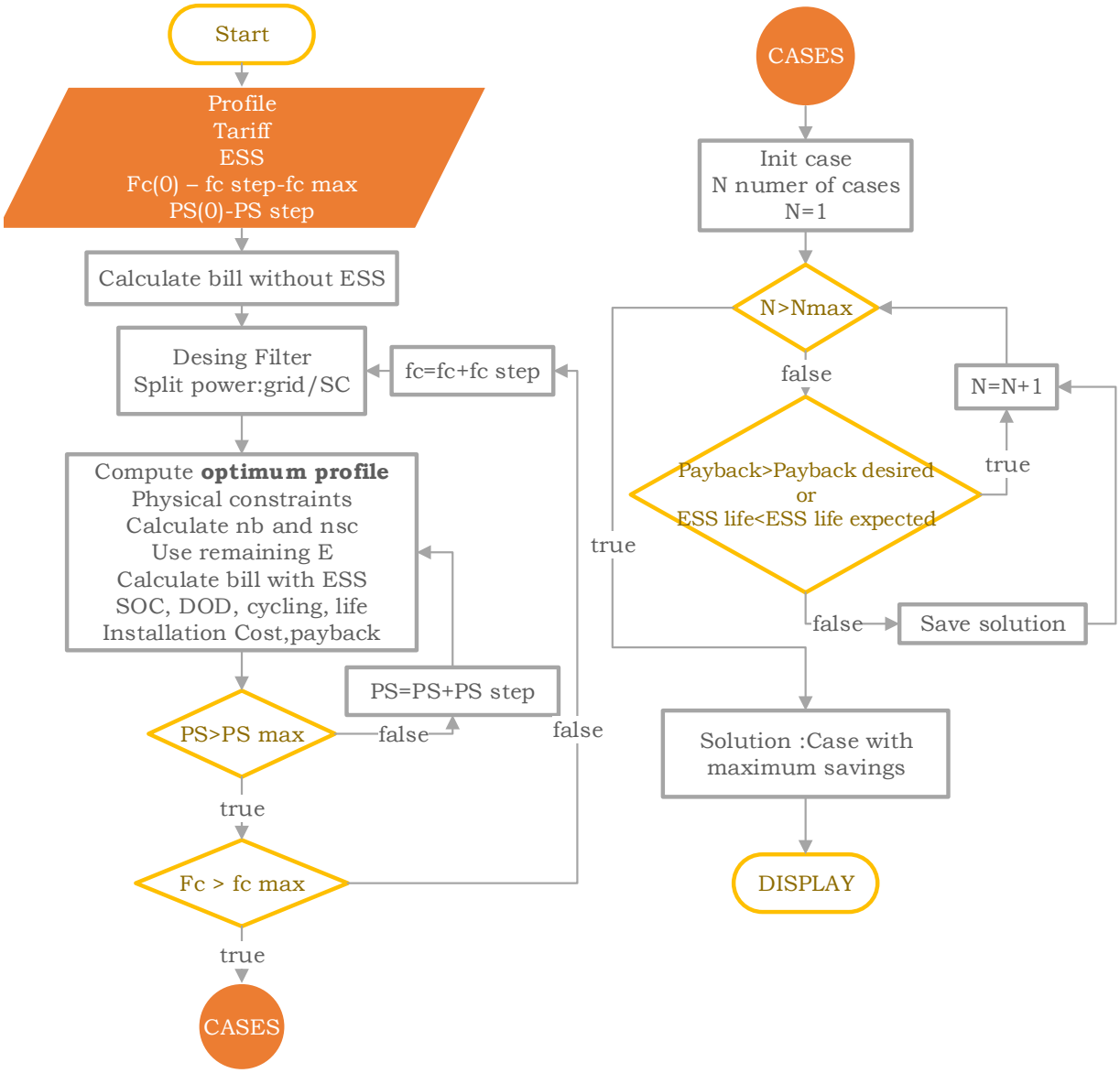

Figure 5-10: Optimization algorithm.

5.5 Validation algorithm

This algorithm aim is to validate the previous ESS size selected with a different load profile of the same process.

5.5.1 Input Data

The input data from this algorithm are:

- **Profile:** Another profile of the same process
- **Previous results:** ESS size, Tariff hired, previous filters, previous PS level, previous economic result

5.5.2 Optimization

Fig. 5-11 represents the algorithm. As shown, after calculating the electric bill without ESS, the power is split. The filter is already given by the previous optimization. However, the energy and power constraints might not be fulfilled, and the power allocation has to be readjusted to make it viable for the SC performance.

After that, the PS is performed in the algorithm getting the optimum profile. Also, it might be not feasible for the actual battery size. Energy and power constrains are applied to readjust the new profile given by the grid and the battery. When it accomplishes both SC and battery power constrains, it also accomplishes converter limitations and it does not need to be tested. After applying all the restriction, if there is remaining energy it is performed the 1C daily discharge at the end of the high cost period.

For the economic cost, penalization is taken into account. If the maximeter measures a power that exceeds the hired one, it is computed a penalization as described in Chapter 4.

Finally, all the new cost are calculated as in the previous algorithm. If it finally accomplishes the payback period and the ESS life expectancy, it displays the finally results compared to the previous ones.

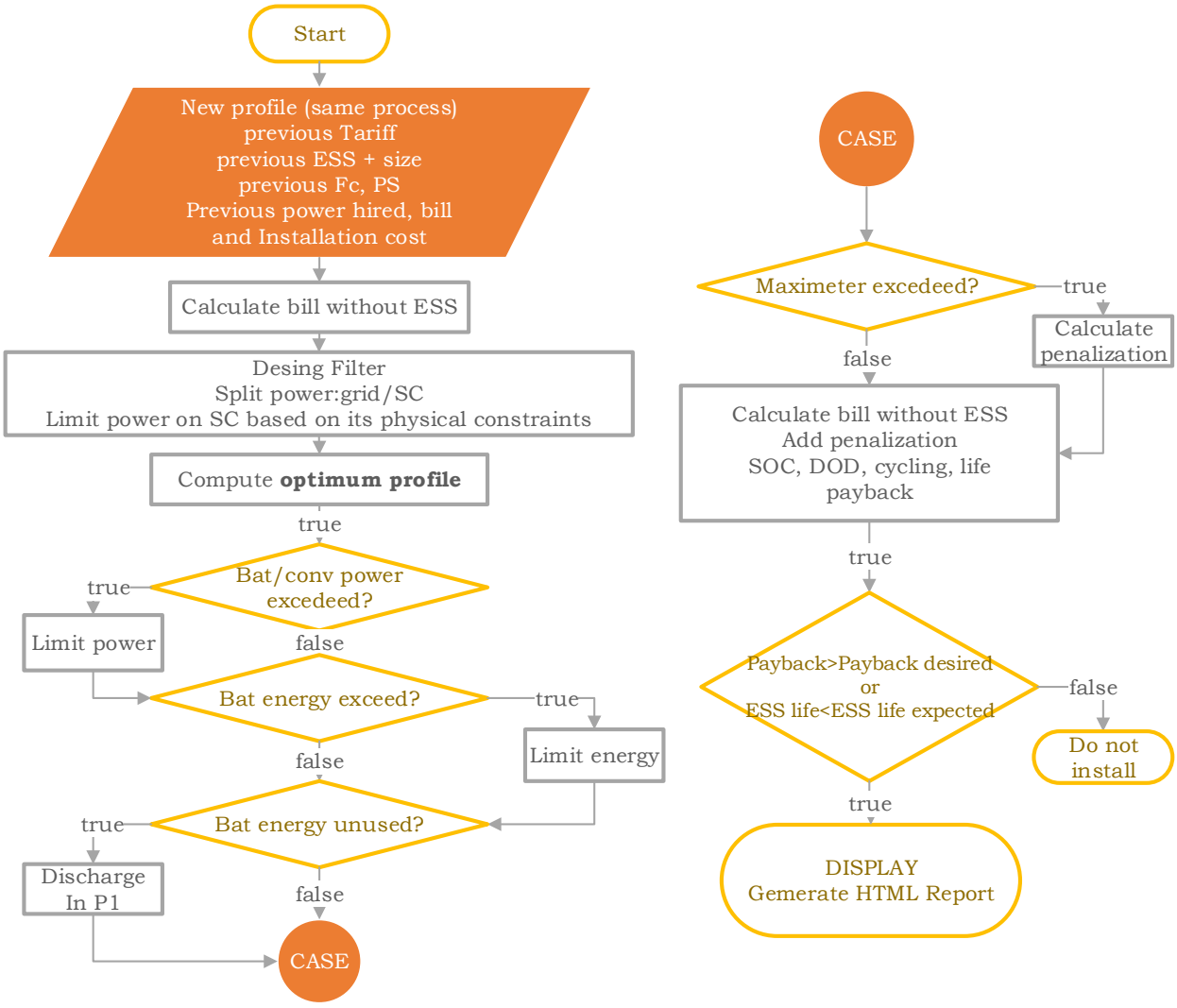

Figure 5-11: Validation algorithm.

Chapter 6

inDSM Toolbox

inDSM is the developed DSM toolbox valid for industrial processes to compute the algorithm in a friendly-user way. This chapter summarizes its features.

6.1 Optimization algorithm

First, the input data has to be chosen as explained in last chapter. Fig 6-1 depicts the initial screen. In the top of the window, there are four buttons for loading the data. First, the *profile* is selected, then, the *tariff* based on the line voltage and power demanded. From the *ESS* button, battery and SC type are selected by choosing its C-rate and energy capacity respectively. *Converter* button loads the converter. Fig. collects the prompts just mentioned. Not until all the data is selected the algorithm can be run.

All the prompts that appears when pressing the bottom are collected in Fig. 6-2. Furthermore, the input data are actualized in the bar that appears in the bottom of the screen. Once the input data are selected, the run button becomes visible and the program can be run. If there is a solution, the screen resulted is depicted as shown in Fig. 6-3 . Otherwise it prompts a 'Do not install' message.

SOC SC can be selected so the SOC of the SC is also plotted in the figure. If the arrows below the figure are pressed, it depicts the next/back month. The left arrow is disabled in the first month (January) and the right one is disabled in (December).

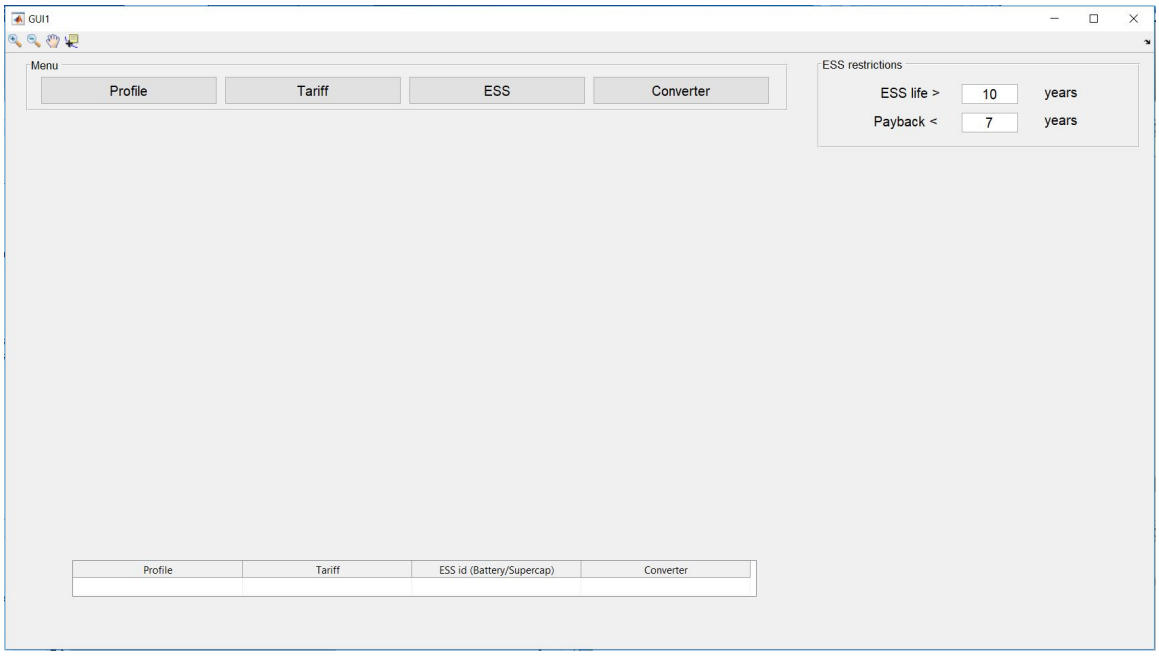

Figure 6-1: Inital screen.

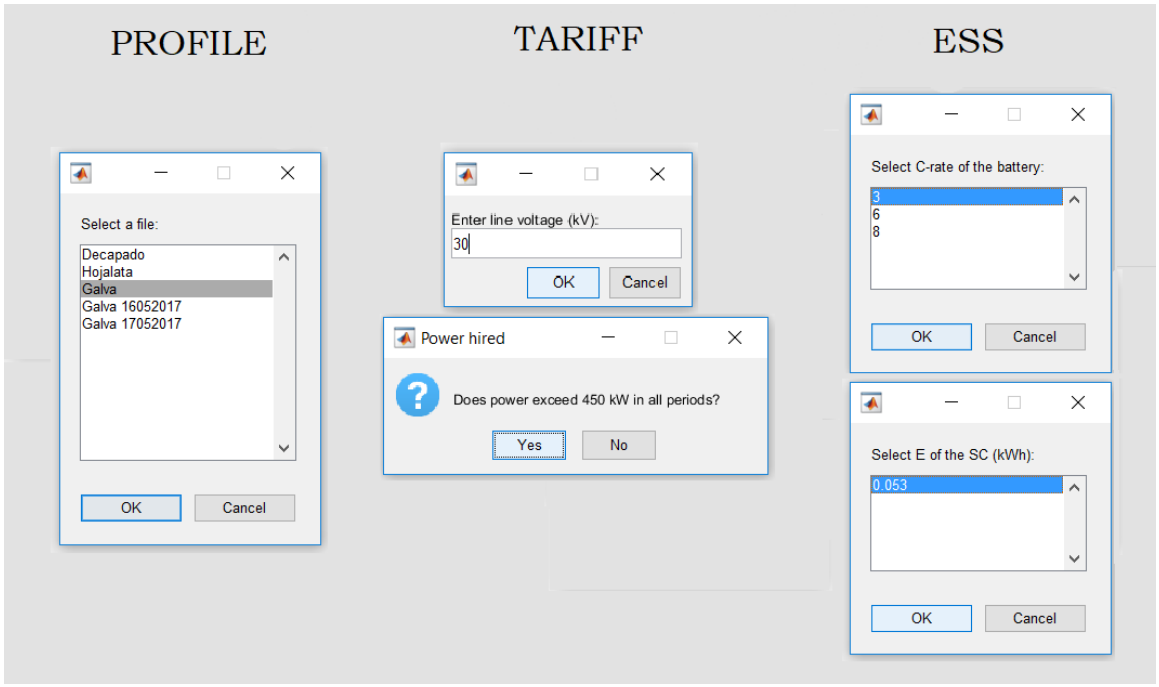

Figure 6-2: Prompts where the data is selected.

On the right table the results are collected. In the upper part the number of devices is printed, whereas the economic results are gathered in the table below.

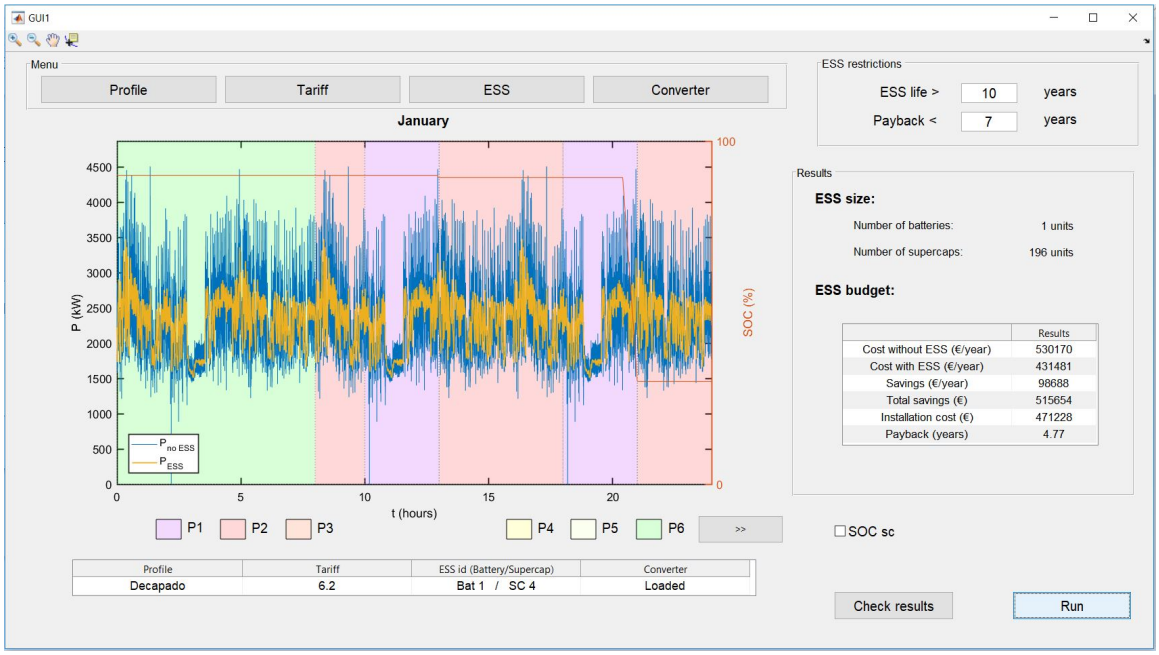

Figure 6-3: Solution screen.

6.2 Validation algorithm

By pressing 'Check results' button, the validation algorithm can be performed by choosing another profile.

Fig. 6-4 shows the screen after validating the previous results with another profile. In case a penalization occurs, it would be highlighted in red that period as shown in Fig. 6-5.

Finally, it can be generated a HTML report by clicking 'Generate report' Button. This report is attached in Appendix A.1.

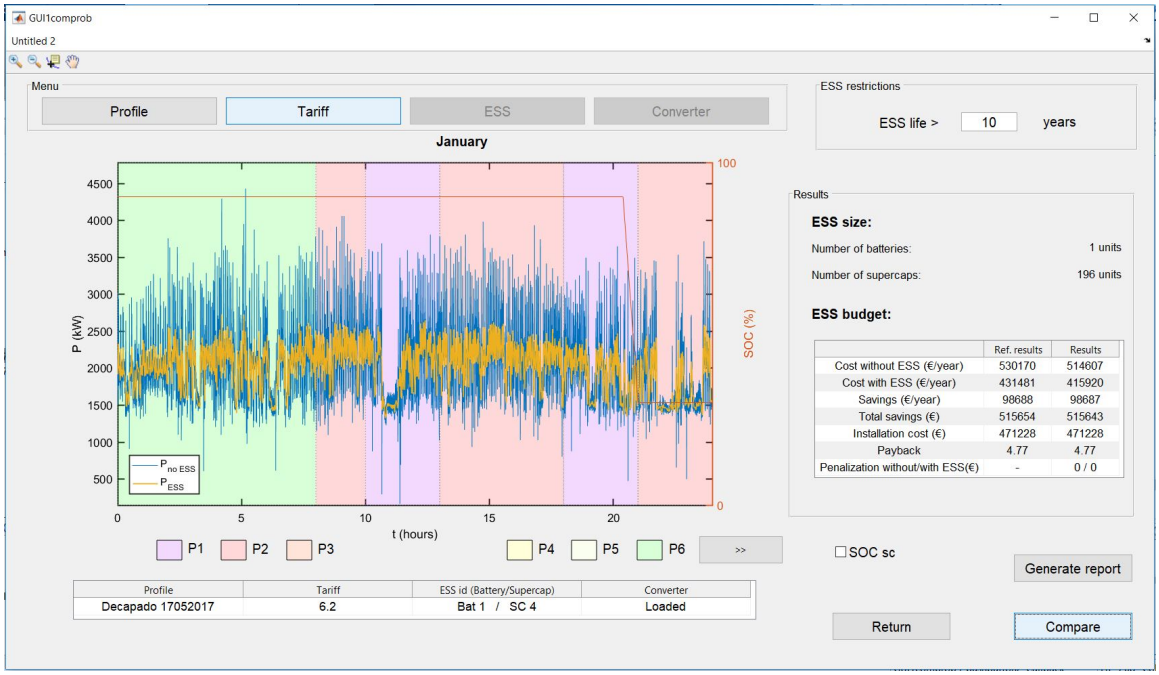

Figure 6-4: Validation screen.

Figure 6-5: Validation screen with penalization.

Chapter 7

Results

This chapter collects the results obtained. All the process have in common some initial considerations:

- Line voltage of 30 kV.
- Tariff 6.2 is used since all the process requires more than 450 kW in all periods (Table4.1).
- Life expectancy is 10 years.
- Payback below 6 years.

7.1 Galvanizing

Physical results

The characteristics of the storage technology of hybrid-ESS for this process are collected in Table 7.1. A total of 2 batteries and 47 SC are used for storing the energy. Fig. 7-1 depicts the grid profile with and without ESS.

Table 7.1: ESS selected

Type	V_{nom} (V)	P_{nom} (kW)	E_{nom} (kWh)	C_{charge}	$C_{discharge}$	DOD
SC	48	45	0.053	840	840	80
Battery	788	208	69.4	2	3	60

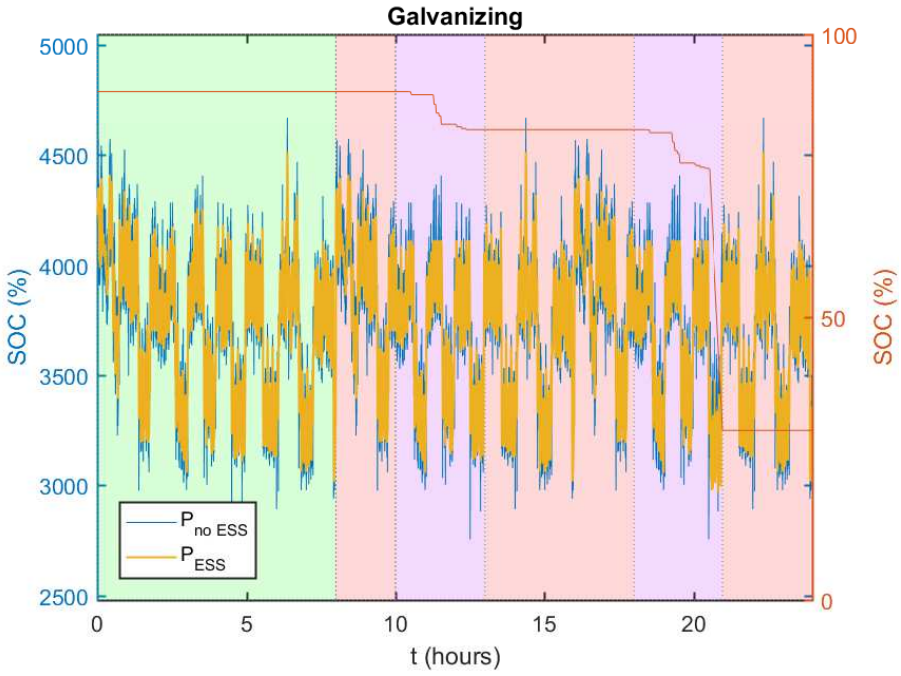

Figure 7-1: Galvanizing Profile.

ESS Power-energy requirements for each technology are collected in table 7.2. Those results come from the optimum f_c for the filtering, which is 0.02 Hz, and the reduction of power in period 1 by 400 kW.

Table 7.2: ESS requiremets for Galvanizing process

Type	number	P (kW)	E (kWh)
SC	47	563	0.74
Battery	2	400	83.3

Hence, before installing the ESS, the hired power is 6.2 MW. The new hired power is collected in Table 7.3 for each period.

On the other hand, the power has been redistributed as shown in Fig. 7-2.

Table 7.3: Hired power in Galvanizing process

Period	P_{hired} (MW)
P1	5.7
P2-P6	6.1

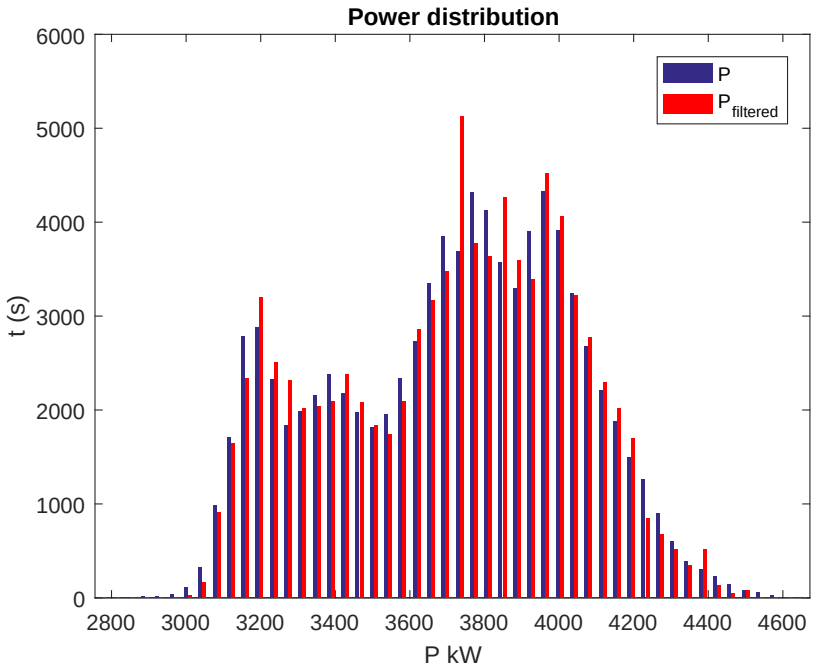

Figure 7-2: Power distribution in Galvanizing.

Economic results

It has been result that *galvanizing* process does not accomplish the payback requirements. It takes 6.8 years to start getting revenue from this installation. The savings obtained mainly comes from the hired power tariff reduction (99%). Table 7.4 gathers the economic results.

.

Table 7.4: Economic Results for Galvanizing.

Period	without ESS	with ESS
Energy term (€/year)	221385	221115
Power term (€/year)	489142	464353
Energy cost (€/year)	710526	685467
Savings(€/year)	-	25059
Total savings (€/10 years)	-	80443
Installation cost(€)	-	170148
Payback (years)	-	6.8

If the SC price is reduced a 40%, it will become feasible to have a payback period below 6 years and earn a total revenue of 101000 €.

7.2 Descaling

It was not possible to find a ESS suitable with descaling process. The issue is that for reducing the peak of this process, a lot of energy needs to be stored. Besides, it is perfectly periodic. Process with random peaks are more likely to reduce the electric bill without a big storage capability: the tariff can be reduced a lot when decreasing the hired power. The amortized period for the optimum case starts in 32 years.

Summing up, it is not feasible to implement an ESS here due to the high energy required for supplying those peaks.

7.3 Tinning

Tinning results are discussed in this section. It is needed to move to a 10 year amortization for getting results of this process. Fig 7-3 depicts the power with and without ESS.

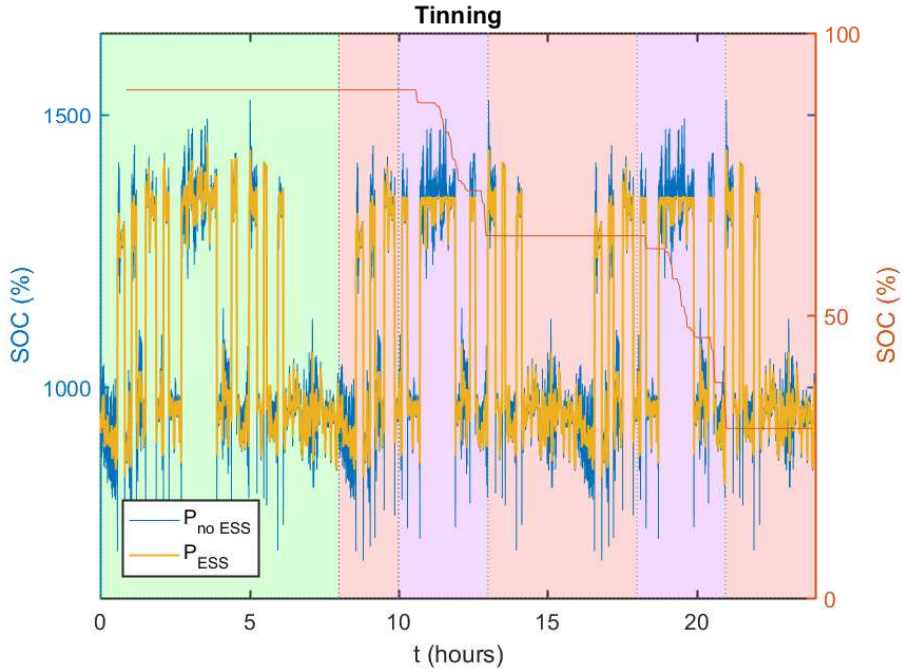

Figure 7-3: Tinning profile.

The resulting ESS consists of 1 battery and 19 SC (Table 7.1 collects the parame-

ters of these devices). The energy/power requirements for the system are collected in Table 7.5. Those parameters comes from having a f_c of 0.0225 Hz and a PS reduction of 100 kW.

Table 7.5: ESS requirements for Tinning process.

Type	number	P (kW)	E (kWh)
SC	19	380	0.3
Battery	1	100	41.6

Before installing the ESS, the hired power is 1.75 MW. The new hired power is collected in Table 7.6 for each period. The new distribution of the power is showed in Fig. 7-4.

Table 7.6: Hired power in Tinning process.

Period	P_{hired} (MW)
P1	1.57
P2-P6	1.66

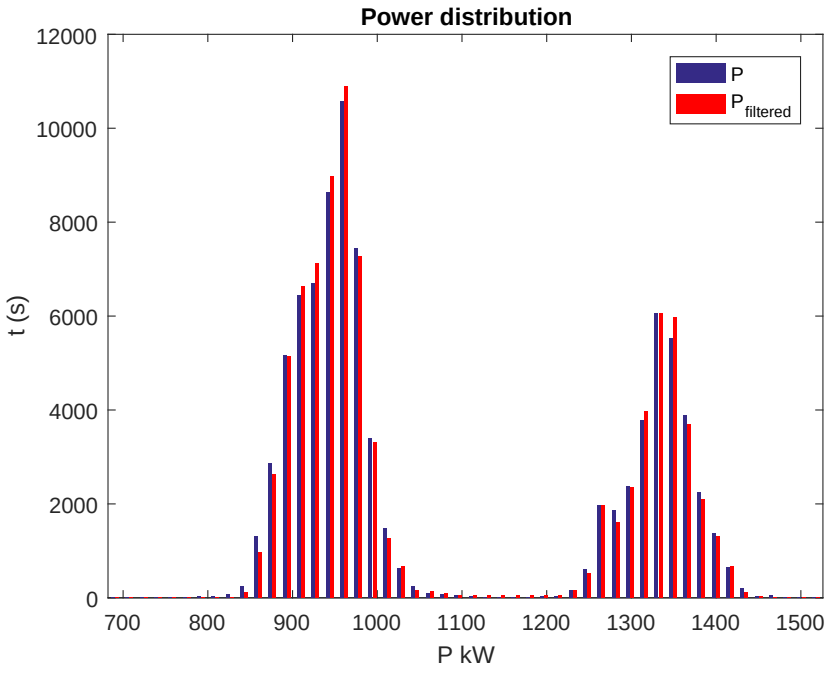

Figure 7-4: Power distribution in Tinning.

7.3.1 Economic results

The economic results are discussed below. As it has been mentioned, the payback period of the system has been extended up to ten years. The saving obtained do not compensate the installation cost.

Table 7.7: Economic Results for Tinning.

Period	without ESS	with ESS
Energy term (€/year)	59898	59763
Power term (€/year)	136813	126978
Energy cost (€/year)	196711	186741
Savings(€/year)	-	9970
Total savings (€/10 years)	-	9713
Installation cost(€)	-	121216
Payback (years)	-	9

7.4 Pickling

Physical results

Pickling process results a very convenient process for DSM. It contains a lot of power pulses that requires a big amount of power, but not energy, which make it very suitable for implementing SC.

By implementing an ESS in Pickling process a lot of benefits can be obtained. The optimum size computed consists of 2 batteries and 196 SC. Their main characteristics are collected in Table 7.1.

Table 7.8 collects the power-energy storage of each device. For getting these results, f_c of the filter is 0.01 Hz and the power at the high cost period is reduced 400 kW. Fig. 7-5 shows in an histogram how the power is distributed with and without ESS. The maximum power goes from 4.5 MW to 3.5 MW after filtering. Fig. 7-6 depicts the grid demand with and without ESS for January. Appendix A.2 collects all the profile shapes (with and without ESS) for each month and the SOC of the battery.

For hiring the power, it is given a 15% of margin over the maximum power. Hence,

Table 7.8: ESS requirements for Pickling process.

Type	number	P (kW)	E (kWh)
SC	196	1900	3.1
Battery	1	400	83.3

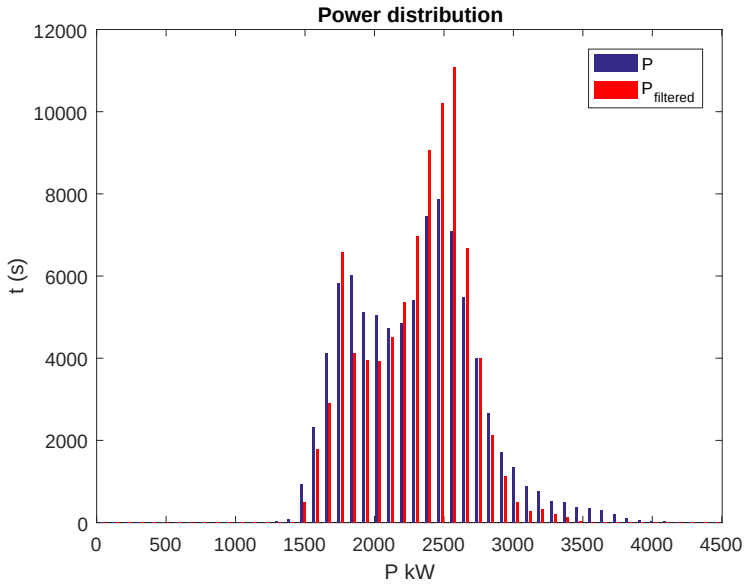

Figure 7-5: Power distribution with and without ESS.

before installing the ESS, the hired power is 5.2 MW. The new hired power is collected in Table 7.9 for each period.

Table 7.9: Hired power in Pickling

Period	P_{hired} (MW)
P1	3.6
P2-P6	4

7.4.1 Economic results

From the economic results, it has been resulted that the savings obtained comes mainly from the power hired reduction rather than from the energy shifted to lower cost periods (less than 1%). Table 7.10 collects the Economic results.

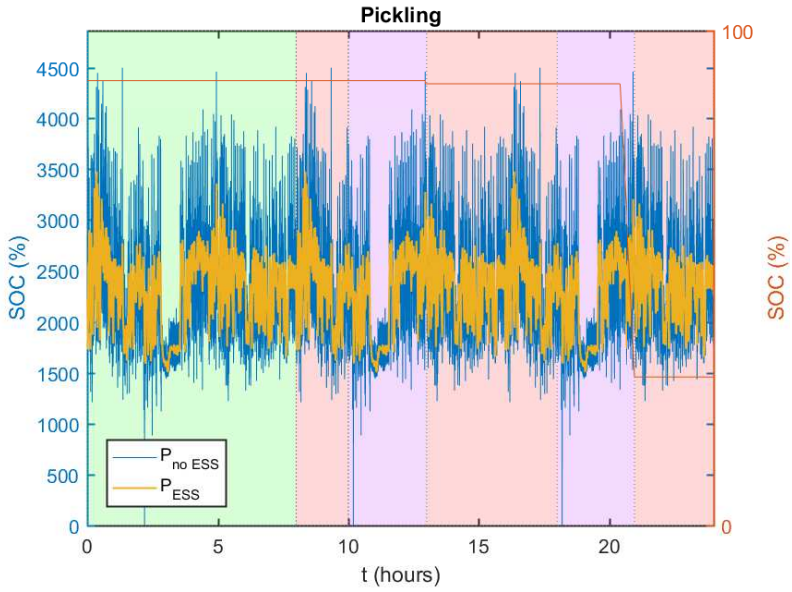

Figure 7-6: Pickling grid profile with and without ESS.

Table 7.10: Economic Results for Pickling process.

Period	without ESS	with ESS
Energy term (€/year)	126478	126208
Power term (€/year)	403692	298657
Energy cost (€/year)	530170	424865
Savings(€/year)	-	105305
Total savings (€/10 years)	-	581819
Installation cost(€)	-	471228
Payback (years)	-	4.7

7.4.2 Compared results

When validating the ESS with another profile it has been resulted that there is no penalization. Table 7.11 gathers the comparison performed.

Table 7.11: Economic Results Validated.

Period	referenced ESS	without ESS	validated ESS
Energy term (€/year)	126208	110915	110593
Power term (€/year)	298657	403692	298657
Energy cost (€/year)	424865	514607	409250
Savings(€/year)	105305	-	105358
Total savings (€/10 years)	581819	-	582349
Payback (years)	4.5	-	4.5
Penalization (€)	-	0	0

7.5 Final results

Finally, only one of the process is suitable for implementing DSM measures. Table 7.12 collects the most representative results for each process.

The installation cost and savings, increase with power reduction. It is also calculated the amortization each year, which comes from dividing total installation cost by the payback period. Fig. 7-7 represents the comparison of savings and amortization per year in terms of power hired reduction. They both have the same trend, being slightly higher the savings when the power reduction increases. Thus, more benefits can be obtained if it is feasible to reduce higher powers in the process.

Table 7.12: Final results.

	Galvanizing	Descaling	Tinning	Pickling
Feasibility	No	No	No	Yes
Payback	6.8	32	9	4.5
Power hired reduction (kW)	500	-	200	1600
Savings (€/year)	25059	-	9970	105305
Installation cost (€)	170150	-	89986	471228
Installation cost (€/year)	25022	-	9998	104720

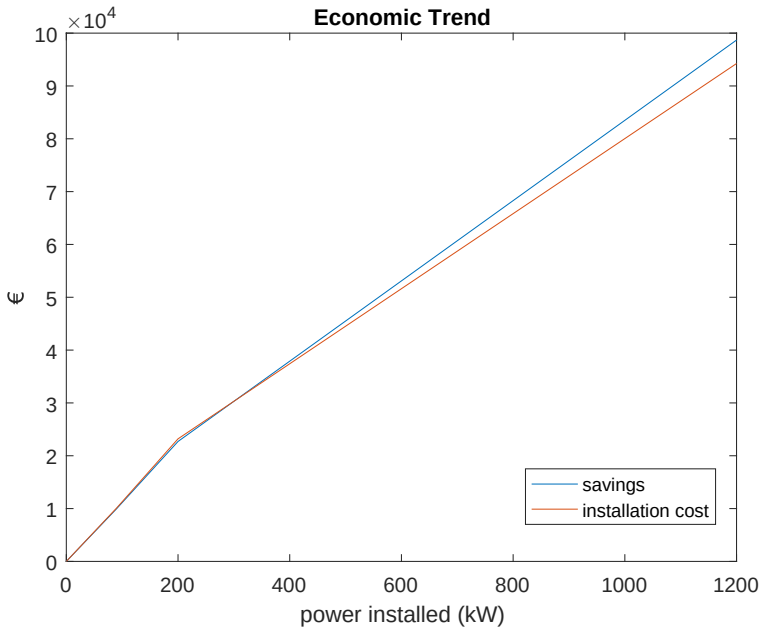

Figure 7-7: Economic trend.

Chapter 8

Conclusions

8.1 Conclusions

All the conclusions obtained from this analysis are summarized as follows.

- As a main conclusion, ESS applied to the steel industry is more suitable for those processes which contain a high power ripple with low energy consumption. Rather than for shifting energy, what it makes these systems profitable is by reducing the power hired of the tariff. Hence, a profile that requires a ESS with high power capabilities and low energy consumption will be the one suitable for applying DSM.
- Power installation and savings have a very similar trend. Savings are slightly higher when the reduction tariff achieved is greater. If the profile has the properties of having low energy contain in that power reduction, savings will be enhanced. This conclusion has to do with the previous one.
- In addition to the adequate profile mentioned, the storage technology with high power capabilities and low power cost is the most suitable for this process.
- Besides, this high ripple will interfere in the grid. In terms of power quality, it would be better to handled this high ripple locally rather than sending it to the grid.
- On the other hand, the tariff needed for this kind of profiles does not make high

differences between price in each period. DSM is more likely to be implemented in lower power profiles, where the difference between period prices is noticeable.

- The tariff reduction seems to be accurate in terms of penalization. With the margin given, penalization does not occur frequently when installing. Low risk is added by lowering the hired tariff when this system is implemented.
- On the other hand, it is also added a risk to the process in case the ESS fails, since failure trend has not been considered.

8.2 Future development

This work can be continued by implementing a lot of features summarized below.

- **Regenerative loads** : It will improve the overall efficiency of the system as the same time the electricity bill is further reduced.
- **Include degradation model** : For this study, degradation has been neglected. Usually ESS lost a 20% of its capacity in 10 years, the model will compute the degradation for each technology based on their profile making the results more accurate.
- **ESS** : Develop an optimization that also selects the optimum ESS technology based on the profile selected.
- **Algorithm** : Further improvements on the algorithm can be performed, finding other DSM measures that might be more suitable for each profile.
- **Failure estimation** : A statics analysis to calculate the risks when implementing an ESS should be made. So based on the ESS performance, it can be estimated which is the probability of failure. The study would become more reliable.
- **Power Converter** :Include different technologies for the power converter.

Chapter 9

Quality report

The project was developed in ArcelorMittal and LEMUR group office from March to July. From March to June, I spent three days a week in ArcerlorMittal. My supervisors always supported me and gave me all the instructions I needed. They were really helpful.

Related with the technical issues, at the very begging I was a bit lost. I think it always happens when you start a project from scratch. I did not know how this technology would response and how to develop the algorithm. After developing some algorithms, I could pick the most suitable for this proposal.

A lot of integral calculation is implemented in this algorithm to obtain the energy consumed by the ESS of all cases. One of the big issues when computing the algorithm was the long time consuming. Thus, what I did for reducing this time was to find faster commands, minimize integral calculus and also move from for loops to matrix calculation. For the same results, the time consuming was reduced by a factor of four.

9.1 Internship

In ArcelorMittal, I was working for the Energy Department. However, I develop my work in another office. I usually have an appointment with my adviser once every fortnight. He gave me all the data I asked him for. My adviser of the university was the one that gave me the steps to follow for developing this project.

Appendix A

A.1 HTML report

Local ESS for industrial processes

Optimization results for "Pickling"

Irene Peláez

31-Jul-2017 01:05:10

Abstract

It has been result that it is feasible to implement an Energy Estorage System (ESS) for the process "Pickling". For that propose, Demand Size Management (DSM) techniques are used in order to reduce the energy bill. This report includes the size obtained for the ESS and the economic results. Furthermore, the same process is compared using the previous ESS under different circustances and new results are also presented.

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4.1. Economic results

Chapter 1. ESS size

It has been result that the optimum size of the ESS for this process consists of 2 batt and 196 supercapacitors. The main characteristics of both technologies are presented below in Table 1.1.

Table 1.1. Energy Storage system components

	Battery	Supercapacitors
ID	1	4
V nominal (V)	788	48
I nominal (A)	88	928
P (kW)	208	45
E (kWh)	69.40	0.053
C-rate chargue	2	840
C-rate discharge	3	840
Price (€/kWh)	450	20619
DOD (%)	60	80

Chapter 2. Tariff

The tariff selected is based on the line voltage hired. This process has a line voltage of 30 kV that corresponds to Tariff 6.2. This tariff is split into 6 different periods. The details of this tariff are collected in Table 2.1.

Table 2.1. Tariff 6.2

	P1	P2	P3	P4	P5	P6
TE (€/kWh)	0.0156	0.0116	0.0062	0.0031	0.0020	0.0012
TP (€/kW)	22.1583	11.0888	8.1151	8.1151	8.1151	3.7036

The periods of all the tariffs are distributed as shown in Table 2.2.

Table 2.2. Six period time schedule

	0 - 8 h	8 h	9 h	10 h	11 h	12 h	13 h	14 h	15 h	16 h	17 h	18 h	19 h	20 h	21 h	22 h	23 h
Enero	P 6	P 2	P 2	P 1	P 1	P 1	P 2	P 2	P 2	P 2	P 2	P 1	P 1	P 1	P 2	P 2	P 2
Febrero	P 6	P 2	P 2	P 1	P 1	P 1	P 2	P 2	P 2	P 2	P 2	P 1	P 1	P 1	P 2	P 2	P 2
Marzo	P 6	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 3	P 3	P 3	P 3	P 3	P 3	P 4	P 4
Abril	P 6	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5
Mayo	P 6	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5
1-15 Junio	P 6	P 4	P 3	P 3	P 3	P 3	P 3	P 3	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 4
16-30 Junio	P 6	P 2	P 2	P 2	P 1	P 1	P 1	P 1	P 1	P 1	P 1	P 1	P 2	P 2	P 2	P 2	P 2
Julio	P 6	P 2	P 2	P 2	P 1	P 1	P 1	P 1	P 1	P 1	P 1	P 1	P 2	P 2	P 2	P 2	P 2
Agosto	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6	P 6
Septiembre	P 6	P 4	P 3	P 3	P 3	P 3	P 3	P 3	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 4
Octubre	P 6	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5	P 5
Noviembre	P 6	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 4	P 3	P 3	P 3	P 3	P 3	P 3	P 4	P 4
Diciembre	P 6	P 2	P 2	P 1	P 1	P 1	P 2	P 2	P 2	P 2	P 2	P 1	P 1	P 1	P 2	P 2	P 2

Chapter 3. Optimization results

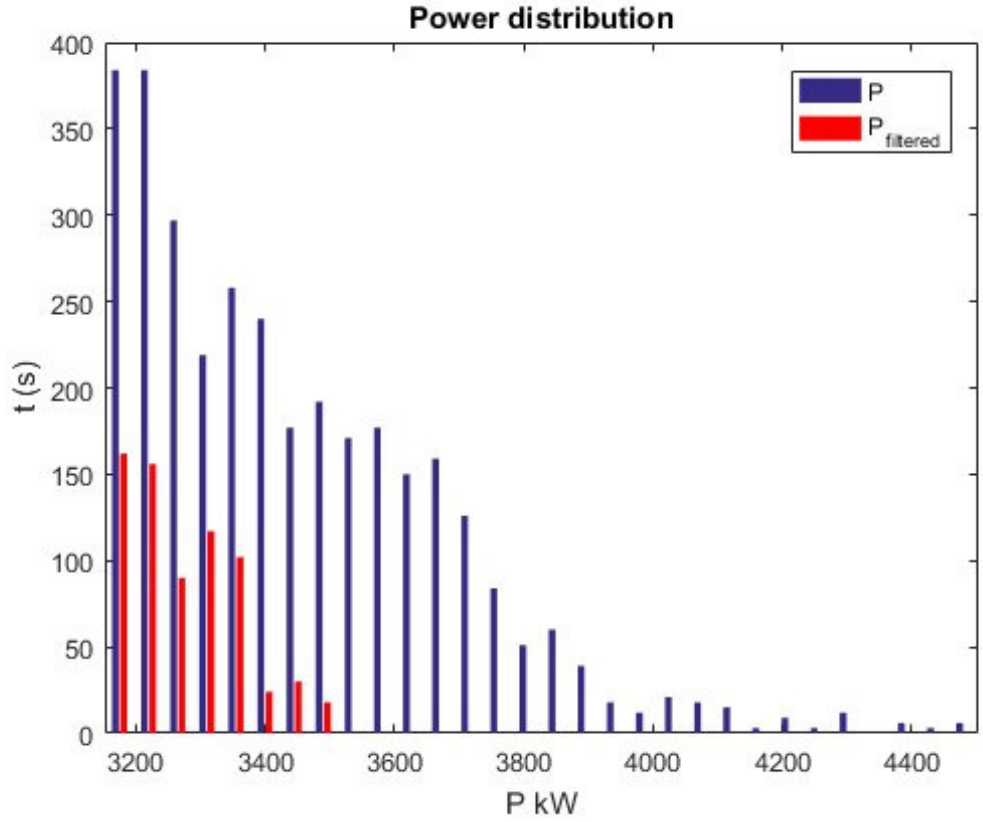
By using DSM techniques, the electric bill is reduced. Supercapacitors are used for peak saving, whereas batteries are used to ensure the power doesn't exceed the hired power at expensive periods. If the batteries are not used for last propose, a full discharged is performed at the end of the most expensive period. Table 3.1 shows the energy and power required for both storage technologies.

Table 3.1. Storage Technology Requirements

Storage Technology	number	P (kW)	E (kWh)
Battery	2	400	83.28
SC	196	1946	3.11

The following histogram (Figure 3.1) shows the highest 10% power distribution before and after implementing the ESS. By implementing supercapacitors, the power hired can be reduced from 4503 to 3476 kW. Moreover, during the most expensive period, the batteries makes feasible to reduced the maximum power up to 3076 kW.

Figure 3.1. Power distribution



It is given a 15% of margin for hiring the power. Thus, it is considered that for the original profile, the power hired is 5178 kW for all the periods. Table 3.2 collects the new power hired when installing the ESS for each period.

Table 3.2. Power hired

Period	Power (kW)
P 1	3537
P 2	3997
P 3	3997
P 4	3997
P 5	3997
P 6	3997

Table 3.3 gives the economic results for 10 years and the comparison for both cases: with and whithout the ESS. 0 % of the savings comes from the energy term, whereas the other 100 % is saved from the power term.

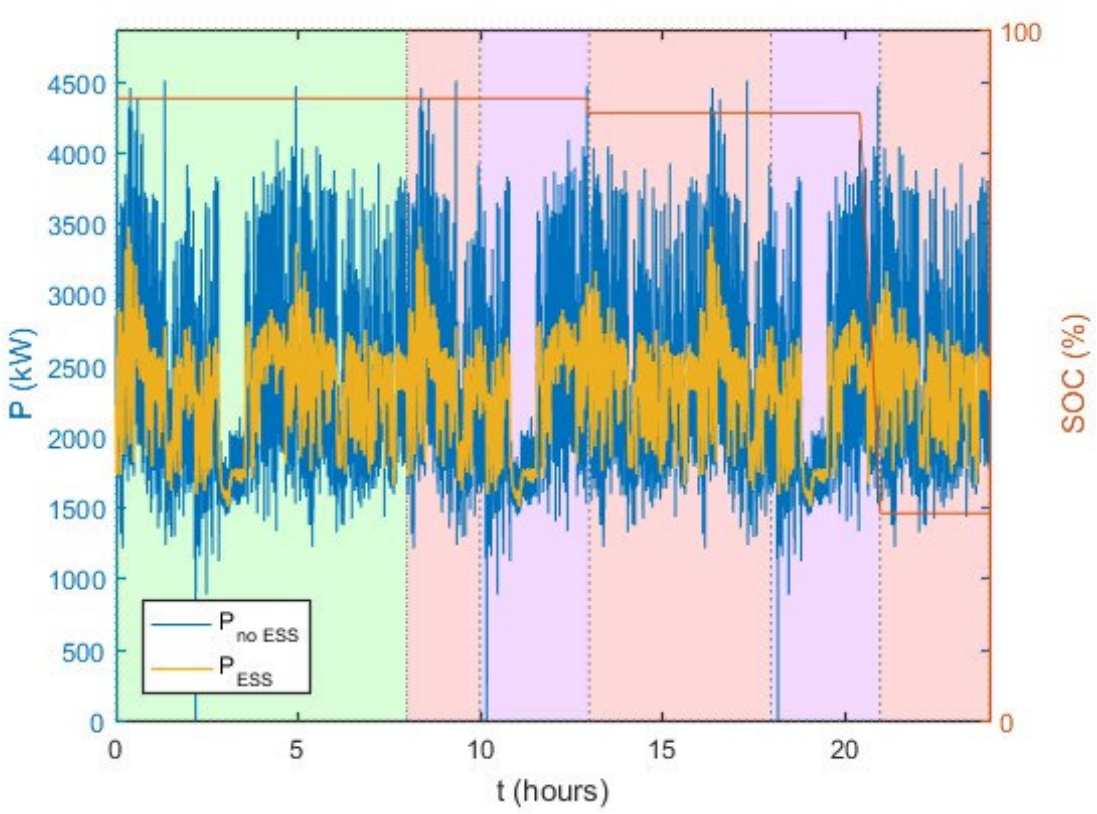
Table 3.3. Economic results

	no ESS	ESS
Energy term (€/year)	126478	126208
Power term (€/year)	403692	298657
Energy cost (€/year)	530170	424865
Savings (€/year)	-	105305
Total Savings (€)	-	581819

Installation Cost (€)	-	471228
Payback (years)	-	4

Figure 3.2 shows the old power profile and the new one, during one day. Besides, it is also depicted the State of Charge (SOC) of the battery.

Figure 3.2. Grid profile with and without ESS



Chapter 4. Comparing results

In this chapter, the economic results for the same process under different circunstances are obtained. For that propose, the same ESS obtained in the previous step is used and also, the same tariff is considered. When the power consumtion exceeds the hired power, the system is penalized according to the spanish law "Real Decreto 1164/2001". The batteries and the supercapacitors work the same way than in the previous case. In case they go outside their state of charge boundaries, the grid will support them. Table 4.1 collects the previous results of the optimization plus the new ones.

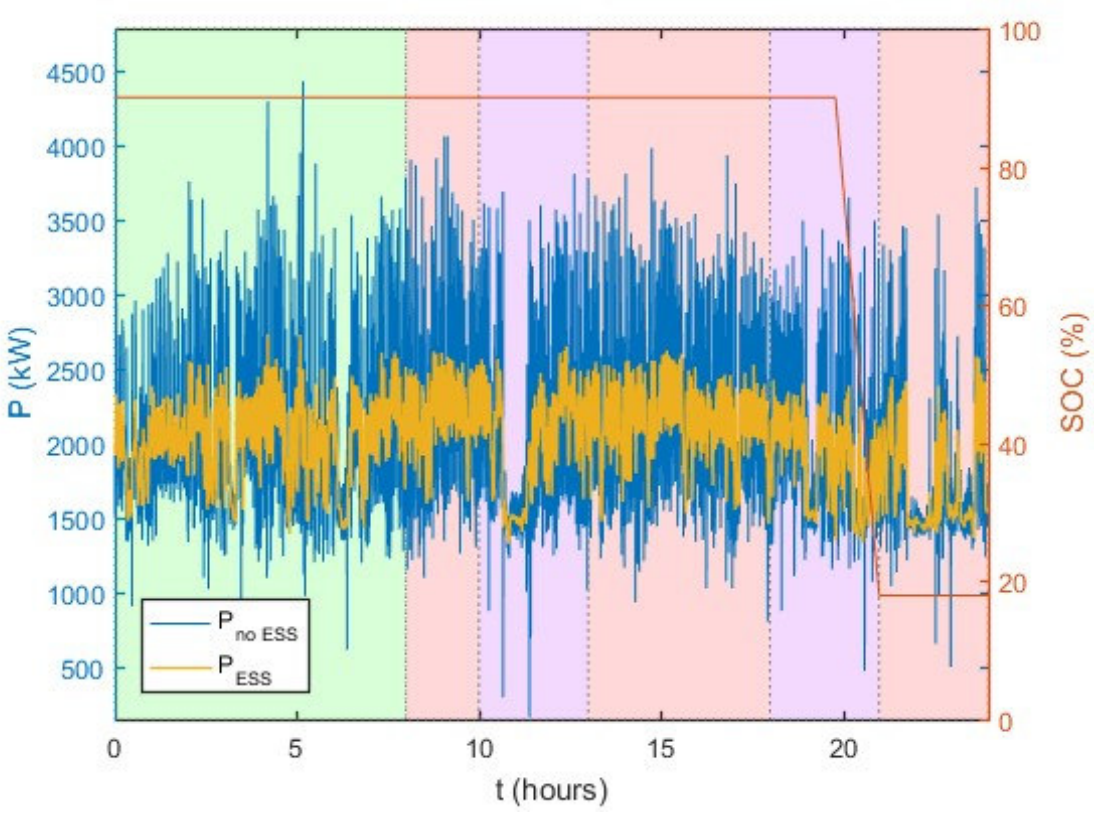
Table 4.1. Economic results

	reference ESS	no ESS	ESS
Energy term (€/year)	126208	110915	110593
Power term (€/year)	298657	403692	298657
Energy cost (€/year)	424865	514607	409250
Savings (€/year)	105305	-	105358
Total Savings (€)	581819	-	582349
Installation Cost (€)	471228	-	471228

Payback (years)	4.47	-	4.47
Penalization (€)	-	0	0

Figure 4.1 shows the new profile, with and without ESS. In case the profile is coloured in red, it means that it corresponds to a penalized period.

Figure 4.1. Grid profile comparison with and without ESS



A.2 Results example for each month

The real and optimized profile are depicted below in all possible tariffs. Besides, the battery SOC is included in each graphic.

January, February and December Fig A-1

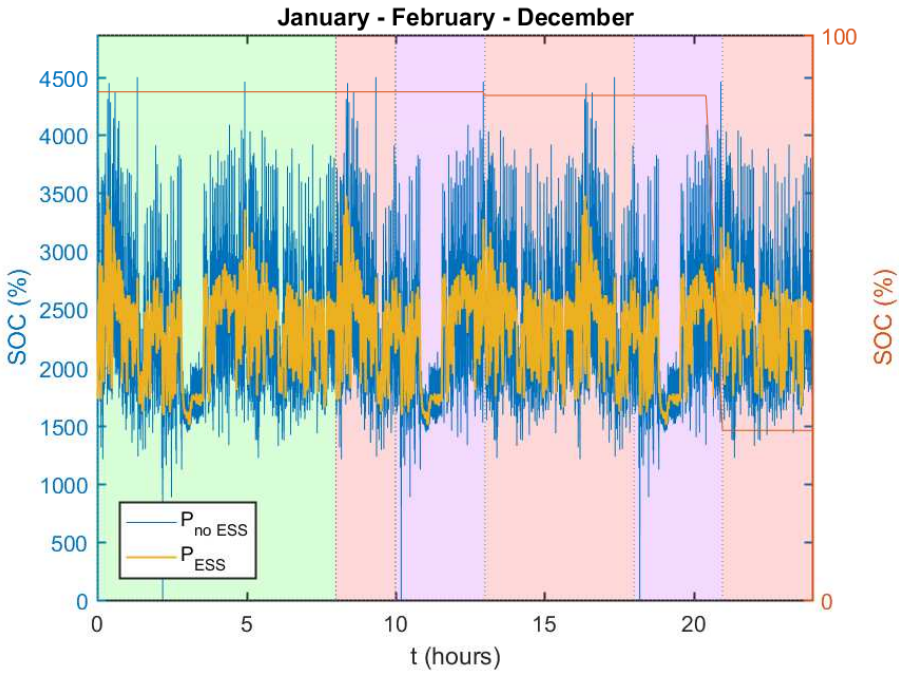


Figure A-1: Validation screen with penalization.

March and November Fig A-2 .

April, May and October Fig A-3 .

Jun 1st-15th and September Fig A-4 .

Jun 30-15th and July Fig A-5.

In august batteries does not work.

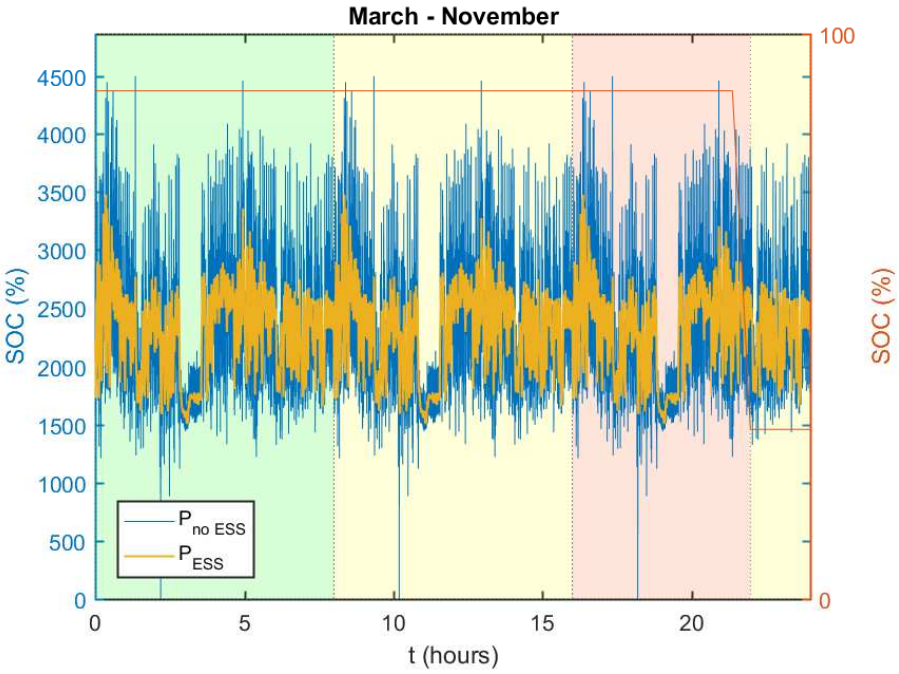


Figure A-2: March and November tariff.

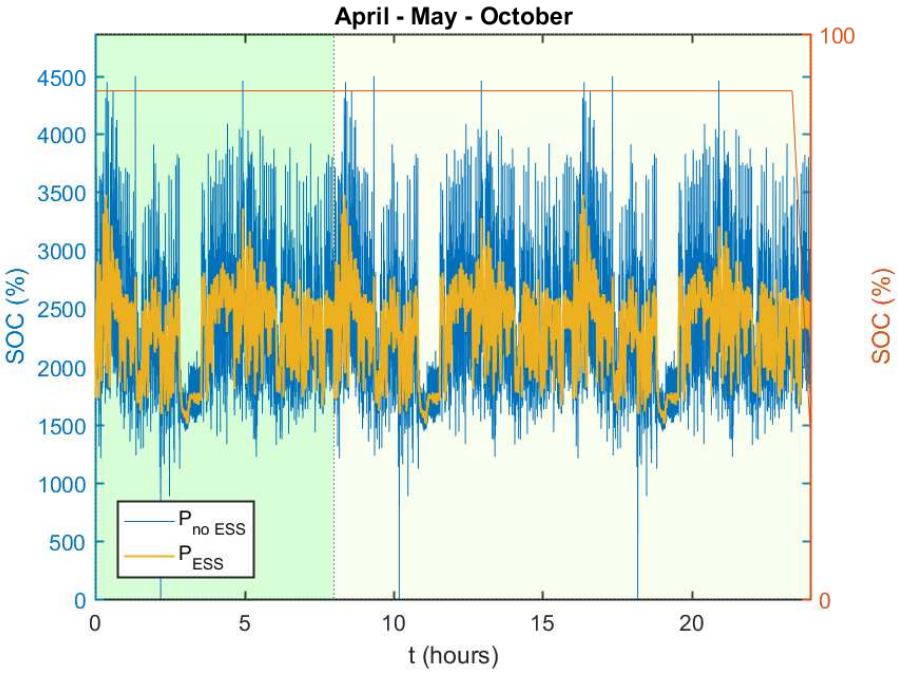


Figure A-3: April, May and October tariff.

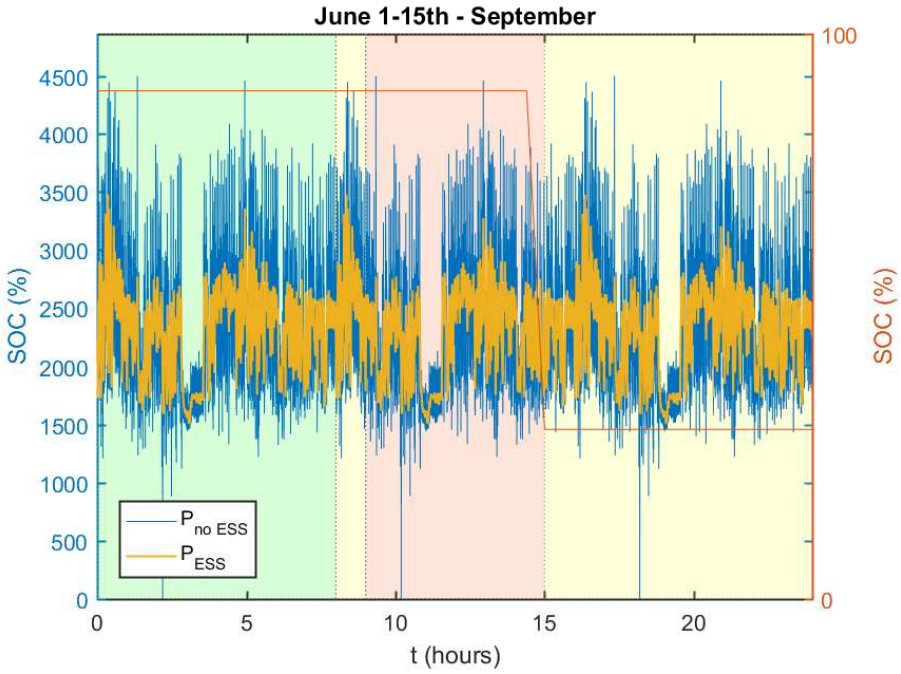


Figure A-4: Jun 1-15th - September tariff.

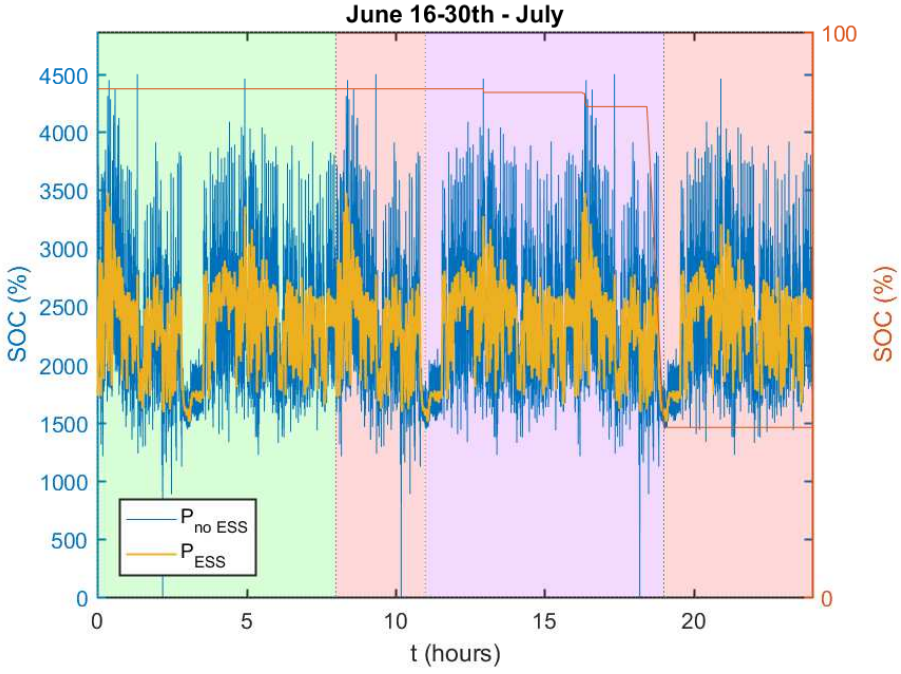


Figure A-5: Jun 30-15th - July tariff.

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