Master Thesis Degree Project

A Study on Feasibility of the Distributed Battery Energy Storage Systems in Spanish Retail Electricity Market

European Institute of Technology

"KIC InnoEnergy" Master of Science
in
Smart Electrical Networks and Systems

Author	MAKSIMS ŠIŠOVS

Supervisor	Assoc. Prof. F. JAVIER HEREDIA CERVERA
Collaborating entity mentors	ENRIC FARGUELL MATESANZ ALBERTO BARROSO DEL TORO

In collaboration with
Minsait by Indra

Escola Tècnica Superior d'Enginyeria Industrial de Barcelona
UNIVERSITAT POLITÈCNICA DE CATALUNYA
Av. Diagonal, 647, 08028 Barcelona, Spain

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Abstract

The main focus of this master thesis project is to evaluate the economic, technical and regulatory feasibility of distributed battery energy storage systems (BESS) and the potential opportunity of electricity companies to increase their profits through advanced operation in energy services, such as electric energy time-shift, ancillary or electric vehicle incentives in Spanish electricity market.

To assess the feasibility, an optimization tool has been developed. This tool simulates energy trading between different market participants with particular features extracted from data analysis and literature.

Load consumption profiles had been developed from smart meter real data by applying several data mining techniques. This part had been guided by external collaborating entity *Minsait*.

Electricity market analysis includes the overview of its functionality principles and regulatory side regarding storage adaptation and specific service applicability. Market historical prices were used for further electricity trading simulation.

A brief technical insight explains current storage situation and tells about high-potential technologies in emerging markets. Benchmark analysis covers several products of battery manufacturers with relevant technical and price information.

Spanish electricity market showed low adaptability to distributed BESS solutions: energy arbitrage incomes have resulted being insufficient. Ancillary services, despite promising economic figures, are to a large extent prohibited to be provided by distributed storage. Electric vehicle incentives, though, resulted being of a high interest due to absence of direct investment.

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List of Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
ACF	Accumulated cash flow
AGC	Automatic generation control
ARMA	Autoregressive-moving-average
BESS	Battery energy storage systems
BMS	Battery management system
CAES	Compressed-air energy storage
CAPEX	Capital Expenditure
CECOEL	Electricity Control Center
CECORE	Back-up Electricity Control Center
CES	Community energy storage
CO_2	Carbon-dioxide
CSV	Comma-separated values
CUPS	Universal code of supply point
DAM	Day-ahead market
DES	Distributed energy resources
DoD	Depth-of-discharge
DSO	Distribution system operator
DSRE	Decremental secondary reserve energy
EMS	Energy managements systems
ENTSO-E	European Network of Transmission System Operators in Europe
EOL	End of life
ESS	Energy storage systems
EU	European Union
EV	Electric vehicle
IDM	Intra-day market
IPP	Investment payback period

IRENA	The International Reneable Energy Agency
ISRE	Incremental secondary reserve energy
Li-ion	Lithium-ion
LV	Low-voltage
MILP	Mixed-integer linear programming
NPV	Net-present value
OMIE	Spanish electricity market operator
PHES	Pumped-hydro energy storage
PCS	Power conversion system
PV	Photo-voltaic
R&D	Research and development
RCP	Shared Peninsular Regulation
REE	Red Eléctrica de España
ROI	Return of investment
RTE	Round-trip efficiency
SAIDI	System Average Interruption Duration Index
SMC	System marginal cost
SOC	State-of-charge
SQL	Structured query language
SRM	Secondary regulation market
SU	Storage unit
T&D	Transmission and distribution
TPP	Trading period profit
TSO	Transmission system operator
V2G	Vehicle-to-grid
WCSS	Within-cluster sum of squares

1 Introduction

The concept of Smart Grids involves wide range of developments, innovations and incentives in order to transform current energy systems towards intelligent, efficient and ecological utilization.

A part of this transformation is referred to power systems’ decentralization, which is gaining sufficient importance [9] with tremendous growth of renewable energy [10]. Such decentralization, or distribution of energy resources adds to sustainability, specifically: reducing congestion of transmission network, providing distributed resources for grid management, electrifying remote areas and reducing CO_2 emissions in centralised units [9].

On the other hand, distributed energy resources (DES) are introducing new challenges for existing system topologies. Operation and control are required to be similarly distributed, therefore, larger number of interconnected energy management systems (EMS) has to be established. Luckily, technological advances in communication systems are boosting, thus being able to cope with the majority of challenges [11].

Energy storage is crucial technology in the scope of Smart Grids, offering extended list of services for all elements of power system: from generation to consumption [12]. Limited electricity storage opportunities oblige maintaining constant balance between production and consumption.

However, developing storage mechanisms is a key tool on the way towards flexible generation. In such way, the electricity demand may be solely covered by stored energy from zero-“generation-cost” resources, such as wind and sun.

Energy storage systems (ESS) is an important driver and contributor to the evolution of DES for three main reasons. Firstly, renewable generation units, that require storage support, are normally placed in decentralized areas. Secondly, long-distance high-power transmission is subject to large losses, whereas storage allows reducing line congestion, exceeding capacities of installed systems. Thirdly, distributed energy storage will play a crucial role in grid support.

Taking into account mentioned above, the goal of this master thesis is to perform a study on feasibility of the distributed battery energy storage system (BESS) under defined technical, economic, geographical and regulatory conditions.

1.1 Description of the Problem

In order to achieve the above-mentioned goal and perform a study, it has been decided to optimize the operation of batteries in distributed network by creating mathematical optimization model with defined operational conditions. Model has to input the result of analysing load data, which were provided by *Minsait*. For understanding the topic, extensive problems from different areas must be addressed, when talking about storage implementation.

Energy policies in Spain are opposing small/medium storage unit installations on the distribution and consumption levels [13], but key energy companies are curious about the potential of this emerging technology, which in perspective may positively affect their revenues.

Besides, this topic gets of a high interest since many studies are contributing to the effectiveness of BESS and forecasting substantial decrease in the costs of batteries, for example [14].

Modern BESS provide a broad spectrum of energy services and may be distributed along whole power system, i.e. from generation to consumption. In generation section, main applications are renewable energy capacity firming, smoothing and peak-shaving. Transmission systems are provided by ancillary services and frequency control for congestion relief and grid stability issues. BESS may support the distribution system performing load management, peak-shaving and voltage control. Finally, for local energy management, time-shifting and local photovoltaic (PV) generation support, batteries are installed at the consumption level [5].

In Spain, electricity transmission and distribution companies are in charge of the transportation of power to designated customers, and are responsible for technical conditions and safety of the grid. Retail energy companies, on the other hand, are solely responsible for billing the customers, or better said, re-selling the energy bought from electricity markets [15], providing that in accordance with bilateral contracts.

Electricity spot market defines the price per unit of energy for every hour, taking into account several factors, for example, system load, renewable generation, etc. [15] An example of electricity market daily price distribution is shown in Figure 1.

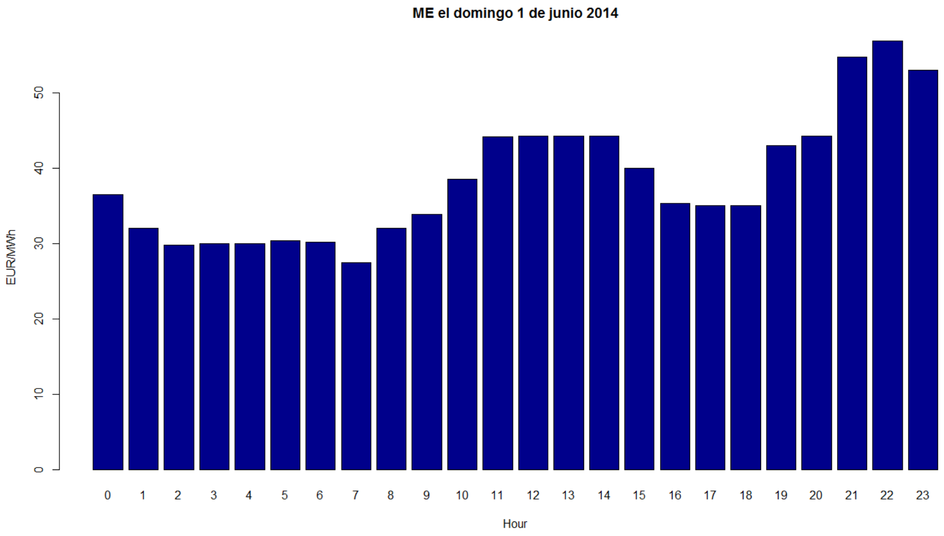

Figure 1: Electricity market prices on June 1, 2014 [1]

Local consumers with installed smart meters are capable of providing real-time data of their hourly consumption. This information may play an important role in storage management if interpreted and analysed correctly (both in terms of accuracy and time-efficiency).

As being said, in spot markets prices of energy vary extensively throughout the day (Figure 1), thus giving an opportunity for BESS-owning companies to store cheap power and to sell it when the price is on its peak.

Additionally, such institutions may participate in grid stability services, that may be provided by BESS, such as, reserve capacity or voltage regulation, gaining extra profits [5].

1.2 Background and Recent Research

As stated before, there are many studies developed by researchers from different energy industries and business sectors regarding technical and economic performance of energy storage [16, 17, 18, 19].

However, every study or project related to the battery storage is subject to local regulations, configuration of given electrical grid and storage technology. Besides, contributors to mentioned studies inevitably have to deal with estimations regarding operation conditions and economic figures. Hence, it is not a surprise that performed investigations lead to diverse conclusions for particular examples.

When addressing data analysis, existing papers and publications regarding big data from smart meters are of a major importance for working with historical information of electrical load and electricity market prices.

1.2.1 Battery Energy Storage

For energy storage being a part of the evolving and rapidly-developing technologies, it is important to follow the most up-to-date publications and researches. That being said, in fast-growing technology and with plummeting prices, the information dated more than 5-6 years ago may become misleading or of little validity.

Nevertheless, the unique value and tremendous potential of battery storage systems is a general message of the majority of researchers.

For instance, The International Renewable Energy Agency (IRENA) had published a report on battery storage in 2015 [5], which claims "storage may be essential to integrate reliably power generated by renewables", as well as provide frequency support for the grid and "make variable renewables more dispatchable". Besides, the report emphasises the potential flexibility of battery storage, which is to a large extent important in reliability of the system.

The scope of papers [17, 18, 20, 21] discusses the state of development of particular technologies, pointing out the applicability of each for specific energy service. Advantages and drawbacks are fairly evaluated, giving sufficient knowledge for defining specific requirements for a research project.

Although only exceptional research papers and articles provide technical information and prices for specific models; in most cases this information is confidential and is subject to particular project conditions, restrictions and regulations. However, some manufacturers [22, 23] have limited technical data of their batteries available publicly.

Talking generally, in almost 100% of cases, the battery design is dependent on the application, and the storage manufacturer is unlikely to produce a certain capacity battery for general purposes. This barrier leads to large variations in cost per kWh among cost-analysis publications. Apart from that, the prediction of cost reduction with the technology development is also hard to estimate.

One particular publication - "Electricity Storage Handbook" [21] - gives a detailed cost-estimation depending on application areas, storage size and manufacturer (the latter are remained anonymous).

More recent report by "Lazard" [14], published in 2015, provides a comparison of capital costs for various use cases and technology combinations, including projected/expected capital cost declines. The data, presented in the paper, is based on the information, collected from a survey of industry participants.

1.2.2 Optimal Operation

Despite the positive tendencies in battery storage, the study [17] had concluded that "profits from energy arbitrage are insufficient to achieve capital cost recovery" without providing other services.

The community energy storage (CES) performance report [18] estimated a levelized cost of battery that could justify the investment, however the actual cost of battery was almost three times higher.

Another study conducted regarding CES [16] had been able to develop the gradient-based heuristic optimization algorithm for calculating the optimal charging and discharging schedule. Author points out the importance of marginal electricity price, which significantly affected CES profits caused by small derivations, whilst the impact of feeder losses on profitability was considered "rather small".

The work in [19] presents a mathematical optimization model for BESS, providing services of energy arbitrage and ancillary within an operating wind power plant, resulting in a 10-year investment payback period, whereas over a half of total profit was coming from trading in secondary reserve market, i.e. services other than energy time-shifting.

1.2.3 Data Analysis

Consumption data importance is essential for electricity providers, because revealed and analysed information may affect positively their business processes.

A research paper [24] underlines the central importance of data mining technologies for the development of future Smart Grids; and along with other publication [25] proposes a clustering method for grouping consumers with similar load profiles. Pre-clustering stage involves creating clustering scenarios, that distinguish the consumption in winter or summer, during working week or holidays.

Another research paper [26] claims segmentation of load profiles of electricity consumption "should be characterized through the socio-demographic factors, like household size, income and employment status and the respective equipment with electric appliances and new technologies". However, in most cases, such information is unavailable due to high privacy standards.

A common method of consumer profile clustering - "k-means" - is applied in a conference publication [27], where the number of clusters is decided based on the "elbow" of the graph which relates within-cluster sum of squares with the number of clusters. The usefulness of this technique is elevated when working with the cases of unequal number of daily readings or when there are no data for particular dates (data gaps). Despite this approach showed similar shapes within a cluster, actual load readings were fairly wide spread.

1.3 Objectives of Study and Main Contributions

The focus of this thesis project is to develop and analyse a study case of an installation of BESS in a particular city located in Community of Madrid, Spain.

Therefore, a general objective is to optimize the operation of storage systems under certain conditions, which would take into account the aspects of desired interpretation and provide fair and discussable result allowing to conclude on the perspective of a business case.

1.3.1 Mathematical Model Inputs

Smart meter electricity consumption data provided by *Minsait* have been used as a basis for the study. In order to transfer this information into a mathematical model input, data analysis tools have been used, such as, segmentation, interpretation and clustering of different load profiles.

Another task that needs to be completed for providing an input for the mathematical model is a battery systems' benchmark. The way of storage implementation has to deal with the most recent and up-to-date information, despite the limited availability of such data. To tackle this issue, fair assumptions with minimized impact on uncertainty have to be made.

The third input is the Iberian electricity market prices that should serve as a reference for the prices that electricity companies pay for the power they distribute. The variability of these prices is playing a key role in time-shifting services of BESS.

As most studies claim that time-shifting services are insufficient for cost recovery [16, 17, 18], additional inputs for a range of optional services may be required. These services, mainly, are: reserve outage capacity, T&D (transmission & distribution) investment deferral, grid stability.

1.3.2 Mathematical Model Development

Mathematical model must represent electrical and economic relations between the elements in the system. Such are described in terms of a set of linear equations, parameters, decision variables and their limits. System design may vary depending on the optimization scenario and desired output. For example: one may consider operating batteries in community (small) or distribution grid (larger) scale; or participating only in desired range of services.

Once defined, the optimization problem is created by stating objective function and constraints which the optimization is subject to. The goal is to maximize the profit or to minimize the costs and to output the optimal charge/discharge schedule, which would comply with mentioned conditions.

Ultimately, for the purpose of addressing particular problem from different angles, several optimization problems should be formulated, describing different system and operation conditions, maintaining same goal of maximizing profits or minimizing costs - the most important measures of feasibility.

1.3.3 Post-optimization Analysis

Once obtained the results of the optimization, it is necessary to identify and evaluate the main sources of expenses and incomes, thus discussing the opportunities of modifications. The modifications may involve variations in the battery units, their operation conditions, i.e. increasing/decreasing and combining a certain number of available energy services.

Post-optimization analysis implies brief economic overview of resolved problems, leading to conclusion of project feasibility. With the guidance of *Minsait* as a business consulting institution, economic analysis is supplied by extended comments on a potential of business case.

1.4 Motivation

Smart electrical systems (or Smart Grids) is a global challenge for electrical engineering industry, that aims to reshape the existing structure towards a sustainable, flexible and environmental-friendly way. Finite energy resources and massive impact of CO_2 push towards renewable sources, thus sufficiently decentralising generation.

A study of BESS is of a special interest since being related to several adjacent electrical engineering fields. Briefly described as follows, these areas make a unique combination of knowledge, additionally allowing giving a broader outlook on Smart Grid challenges. In that way, a student can understand the technical and economic state of development of Smart Grid and learn to approach given problems from different angles.

Analysing smart meter data allows understanding of behaviour of different type of consumers, the impact of social-economic, ageing or ambient conditions. The billing technologies of electricity retail companies help one to get an overview of their cash flows and evaluate the profitability of any alterations, such as installation of BESS.

Power system analysis includes technical characteristics of the network, its capabilities and limitations. Implementing BESS in low-voltage or medium-voltage networks allows providing different services and has to be evaluated and regulated corresponding to respective grid stability norms.

On the other hand, the development of optimal dispatch for power plant or charge/discharge schedule for BESS is resolved by energy planning and optimization. Whilst real-time models are stochastic, involving high degree of complexity, a deterministic programming is preferable when working with historical data. The trade-off between accuracy and computational time is an important issue of optimization.

Finally, an insight to the current market status of BESS is good measure to stay up-to-date with the emerging sector of energy storage (in parallel with many other sectors).

In conclusion, developed project is of an exceptional interest. That being proved by the range of topics covered: electricity markets, smart meter data analysis, optimization, BESS technology; and by the orientation to business side of developing sustainable solutions for Smart Grids.

2 Smart Meter Data Analysis

2.1 Overview and Understanding

A common approach of storing big data is to do so in CSV-files (Comma-Separated Values). For project development of the potential business case, *Minsait* provided 3,37 GB of different CSVs and SQL (Structured Query Language) relation tables. R-Studio software [28] has been used throughout all the stages of data analysis and creation of required inputs for mathematical model.

Initial categorisation of available information is as follows: smart meter readings of hourly consumption, ambient temperature data, local calendar of national and public holidays. Subsequently, smart meter readings are separated into numeric power measurements and applied information, for instance: contracted power, location, zone codes, etc. Consumers' geographical distribution remains in the range of a city within Community of Madrid, Spain.

The data consist of electrical load units that are supplied with electricity by two Spanish retail companies. For confidentiality sake, those companies from now on shall be referred as "RC1" and "RC2", corresponding to "Retail Company 1" and "Retail Company 2", respectively.

Each load unit is adjacent to a smart meter, that has a unique identification number - CUPS (Código Universal de Punto de Suministro[1]) - which corresponds to one installation.

The initial overview of the available data is presented in Tab. 1.

Data analysis has been applied in order to identify and produce necessary outputs, according to the objectives of the study. In this case, the goal is to obtain a range of electricity consumption profiles, distributed geographically.

2.2 Initial Steps

It may occur that data provided by clients of consultancy companies tend to be incomplete, unstructured or having irrelevant to the problem information. As a data scientist, one requires to address this challenge, when creating the outputs of his work by proposing missing value replacement or some assumptions.

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[1] Universal Code of Point of Supply.

Table 1: Initial data overview

	"RC1"	"RC2"
Measurements		
File size	2,28 GB	0,98 GB
Num. of observations	20 249 948	19 312 749
Num. of meters	6379	12110
Date range	2013/12/11 to 2014/06/29	2013/12/23 to 2014/07/01
Days observed	201	160
Applied Information		
File size	869 KB	2074 KB
Contracted power	1,1 - 9,9 kW	0,345 - 14,5 kW
Num. of meters	6465	9073
Num. of geographical zones	106	1 110

This step involves an overview of the data available and explains the initial solutions working with data.

The key output for building load profiles is electricity consumption, hence, the major attention is paid to smart meter readings.

First of all, after studying the data, it had been discovered that energy consumption measurements of retail company 2 ("RC2") did not stated their matching CUPS, but rather the code of meter itself. This confusion does not allow performing extended analysis in relation to the consumer information, because no pattern to match consumption with CUPS had been found. Thus, "RC2" data become irrelevant to the study, and are disregarded.

The distribution of smart meter measurements is not monotonous, as specified in Tab. 1, which means it is represented by different amount of measurements per day. The availability of this data also is limited. Such data incompleteness is displayed in Figure 2.

It is important to observe that the number of measurements is high in the period from May to July, but rest of the time scale is deeply affected by gaps in measurements. Up to this point, it is unknown whether these gaps follow a pattern or not, but this definitely restricts from using direct measurements in optimization for a particular customer during available period of time (Figure 2).

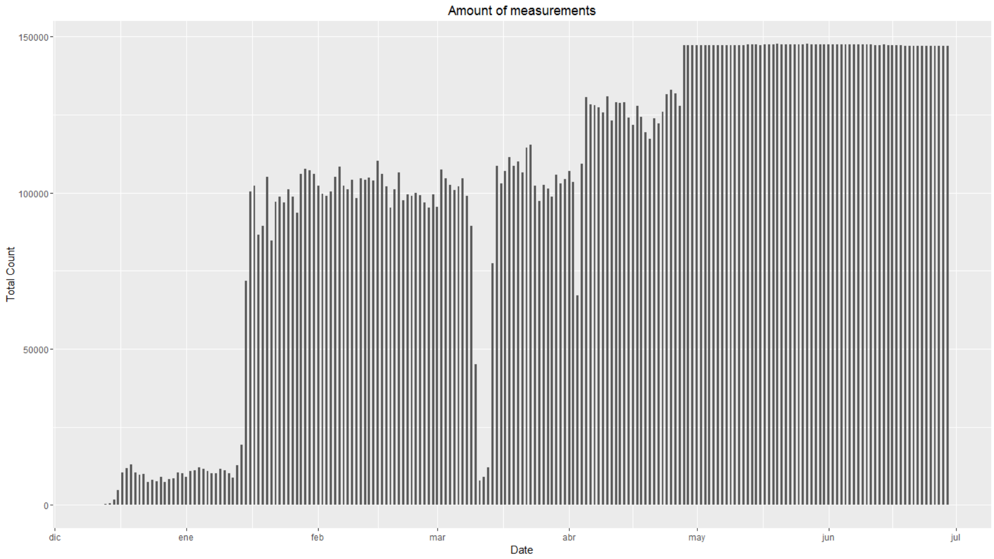

Figure 2: Number of daily measurements from "RC1" available throughout the period

When plotting the daily consumption of one random customer, the gaps are observable from Figure 3. Here, a sufficient lack of measurements is related to the time interval between April and May.

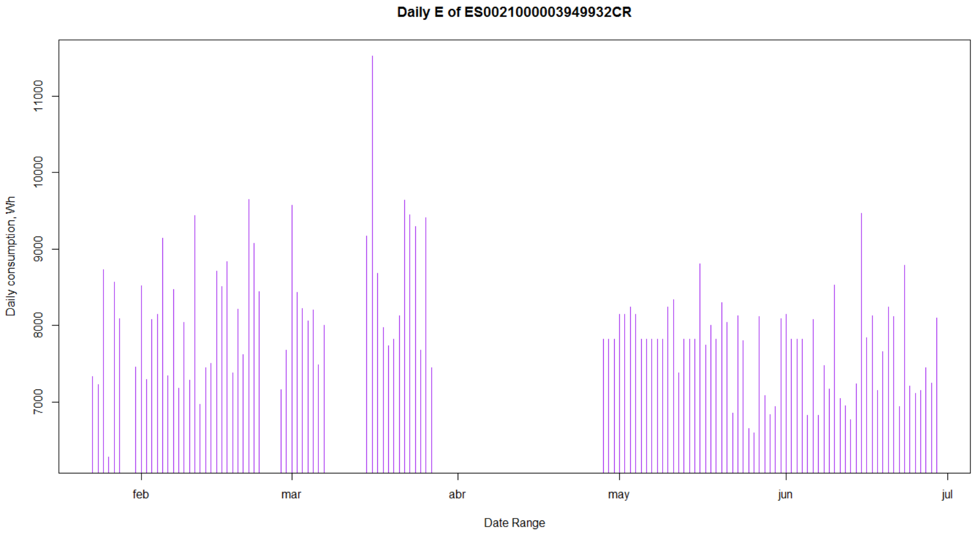

Figure 3: Daily measurements of random consumer

This issue calls for a solution in terms of data recuperation or approximation, since in given conditions it would be problematic to use actual consumption data. Techniques of gap-filling are severely complex and, thus, are considered out of the scope of this work. Hence, a solution of approximation or generalisation is needed.

Further data processing involves several steps of linking, categorizing and classification of the information.

When reading the data, some measurements with unnaturally high consumption were spotted. Eventually, in order to reduce the variance and standard deviation, those readings were removed, so were the uncharacteristic measurements with zero power consumption. After having made these corrections, average customer load curve with its standard deviation has been constructed in Figure 4. This consumption pattern is build by plotting 24 average hourly readings of all available data from “RC1”.

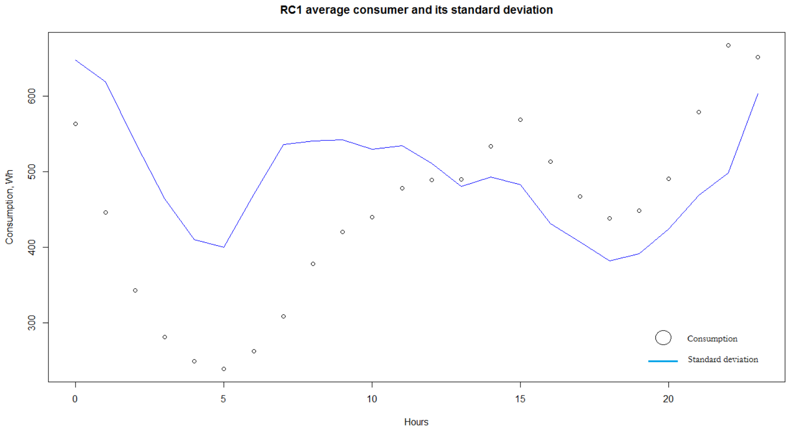

Figure 4: Average profile and its standard deviation of all “RC1” data

Analytically, electrical load pattern for average customer has low consumption during the night hours and reaches its peaks in the morning and in the evening. The plot, demonstrated in Figure 4, is scattered for the general average of the scope of available “RC1” data into 24-hour profile. Standard deviation is quite high which may conclude on high dispersion of the data. Such issue calls for heuristic aggrupation solutions.

Indeed, the load is generally low in the night, whereas two local peaks are reached at hour 15 and hour 22. To validate these peaks, the figure of average

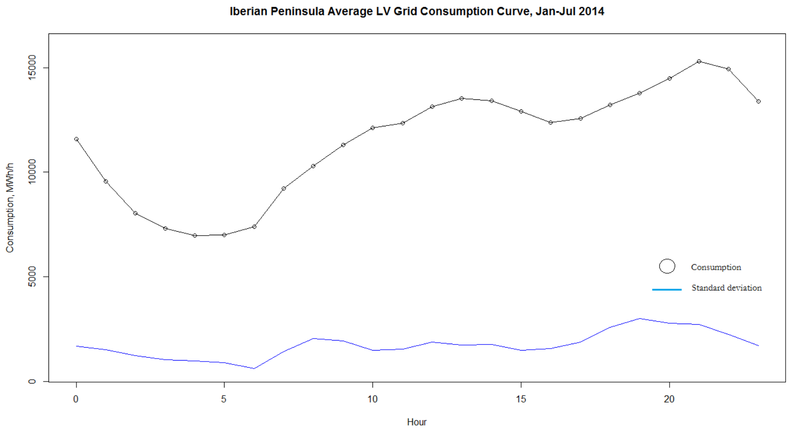

Figure 5: Iberian pen. average LV consumption and its standard deviation [2]

consumption during first six months of 2014 is presented in Figure 5. This figure has been extracted from REE (Red Eléctrica de España) on-line informational system.

As may be observed, the LV (low-voltage) grid average consumption in selected period of January to July of 2014 demonstrates the strong correlation with consumer data from Figure 4. Two daily peaks are representative with first one occurring at hour 13 (Figure 5), whereas the second one takes place during hour 21. The fact that both graphs are identified with two consumption peaks: afternoon and late evening; and that they repeat their corresponding incremental and decremental phases allows validation and confirms the initial steps of analysis had been performed correctly.

2.3 Segmentation & Clustering

It has been claimed, that sufficient gaps in data are problematic for creation of usable load profile outputs. This leads to the need of creating several load profiles and relating each consumer to one of existing patterns. This step may be divided in three stages:

- Year season segmentation: winter or summer;

- Weekday segmentation: working day, Saturday or Sunday[2];
- Load profile generation: number of different profiles, each consisting of 24-hour vectors.

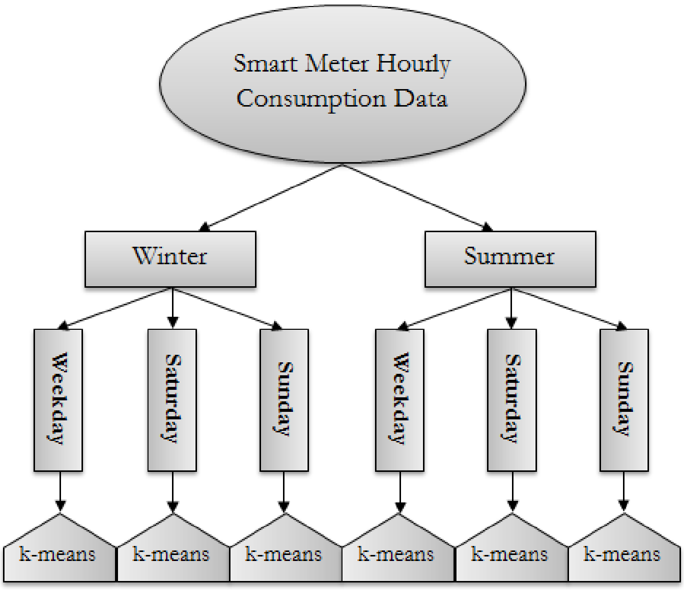

Figure 6: Data segmentation and clustering

Explanatory scheme of data segmentation and clustering is visualised in Figure 6.

As mentioned in [26], distinguishing between summer and winter consumption profiles is of a great importance. In winter season, the load is noticeably higher due to colder weather conditions, whereas during summer it is considerably lower, except the peak of the season when, taking into account Spanish climate, air conditioning is used extensively.

Another important point is to divide the general profile in perspective of weekdays. Generally, consumption varies largely between working days (when people usually go to work) and holidays (Saturdays, Sundays and public ones) [2]. For sake of higher accuracy, one may introduce further assumptions. In the scope of this thesis, three weekday load profiles are assumed: working day (from Monday

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[2] Public holidays are considered to be related to Sunday profile

to Friday), Saturday and Sunday. This choice has been made based on computing the Euclidean distance between means of each day. Since the largest distances were obtained between mentioned types of day, these profiles were selected. The Euclidean distance formula between two n-dimensional vectors p and q is:

$$d(q,p) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2} \tag{1}$$

Having the data segmented for seasonal and weekday sub-units, one is required to apply clustering technique, which in this case is "k-means" method. It should be applied to each one of the six blocks in Figure 6.

"k-means" is a common approach for vector grouping and data partitioning. This method of quantization aims to partition n vectors into k clusters, in which each observation belongs to the cluster with the nearest mean.

In a given set of observations, each vector is a d-dimensional vector. For the study case, d=24, because one vector corresponds to 24 coordinates of daily load measurement of one smart meter (early referred as CUPS). The partitioning into k sets is done in such way so it would minimize the total within-cluster sum of squares (WCSS). In mathematical terms, that is described as in Eq. 2.

$$\min_{S} \sum_{i=1}^{k} \sum_{x \in S_i} ||x - \mu_i||^2 \tag{2}$$

where:
$(x_1, x_2, \ldots, x_n)$ - a set of observations;
k - number of clusters;
$\mathcal{S} = \{S_1, S_2, \ldots, S_k\}$ - sets;
μ_i - the mean of points in S_i.

The "k-means" clustering method relies on a random starting situation and requires the number of clusters as an input. Thus, the decision has to be made regarding the number of clusters k preferred. For that, the relation of WCSS (Eq. 2) to the number of clusters is created for range of k and plotted. The final decision is then taken based on the graph "elbow", i.e. such number of clusters k, that introducing additional one: $k+1$, would give a WCSS reduction with lowest ratio towards the one of adding the k-th. Built-in function provides a good reasonable heuristic solution by building the minimum spanning tree for a number of nodes, however is limited by decided number of iterations and hence, with some degree of certainty, converge in local minimum WCSS rather than in global.

R-Studio [28] provides developed function for performing "k-means" clustering on a data matrix. The inputs for this function are:

- Data matrix
- Number of clusters k
- Maximum number of iterations
- Used algorithm

Correspondingly, six data matrices with segmented data, along with k=8, a maximum of 200 iterations and a default algorithm chosen by R-Studio have been selected as function inputs. The algorithm of Hartigan and Wong [29] is used by default.

2.3.1 Results

As a result of clustering, for every segmentation block, 6379 points of supply (consumers) are grouped to 8 clusters with each cluster having its average representative vector of 24 coordinates. Each clustered vector maintains its CUPS identification name for further relation to its corresponding geographical zone. This relation is relevant for further stage of the project.

A brief summarizing table is given in Tab. 2. WCSS represents objective function of Eq. (2), i.e. sum of distance functions (Eq. (1)) of each vector in the cluster to its center. Additionally, the size of largest and smallest clusters are given.

Eq. (3) calculates relative average root-mean square derivation per one measurements of n observations within their clusters, expressing the percentage by which average point in a d-dimensional vector is different from its cluster center. That index verifies WCSS numbers in Tab. 2 and results in deviations of 32,18

Table 2: Clustering results

	ε, %	WCSS	Largest	Smallest
Winter				
Weekday	6,01	$1{,}74 \times 10^{10}$	3538	41
Saturday	6,4	$1{,}96 \times 10^{10}$	2409	12
Sunday	7,6	$1{,}96 \times 10^{10}$	2279	115
Summer				
Weekday	5,92	$3{,}71 \times 10^{9}$	1622	33
Saturday	6,64	$4{,}70 \times 10^{9}$	2170	29
Sunday	6,94	$5{,}08 \times 10^{9}$	2018	36

- 74,61 Wh/h for within-cluster measurements. These numbers are quite large. Despite increasing the number of cluster k might reduce the error, additional experiments showed higher values of k have rather small impact on reducing WCSS.

$$\varepsilon = \sqrt{\frac{WCSS}{n}} * \frac{1}{d * L^{mean}} * 100\% \tag{3}$$

where:
n - number of observations;
d - clustered vector dimension ($d = 24$);
L^{mean} - average load measurement among certain group (winter, summer, working day, etc.) of consumers of "RC1".

WCSS is effectively larger when clustering winter consumption profiles due to higher dispersion in load: during winter electrical heating is used actively, lighting necessity hours are extended and generally, the consumption of other devices is higher, since consumers spend more time at home because of cold weather conditions.

Also, during the weekdays load is more monotonous since a general labour schedule is followed by the population, whilst weekend consumption is wider dispersed.

Figs. 7 - 12 display the clustering results, showing the centric vectors and cluster size of each. The curves that are represented by larger number of consumer profiles are selected to be bolder. Moreover, these curves are fairly correlated to the all-average consumer in Figure 4 and to LV-grid demand pattern in Figure 5.

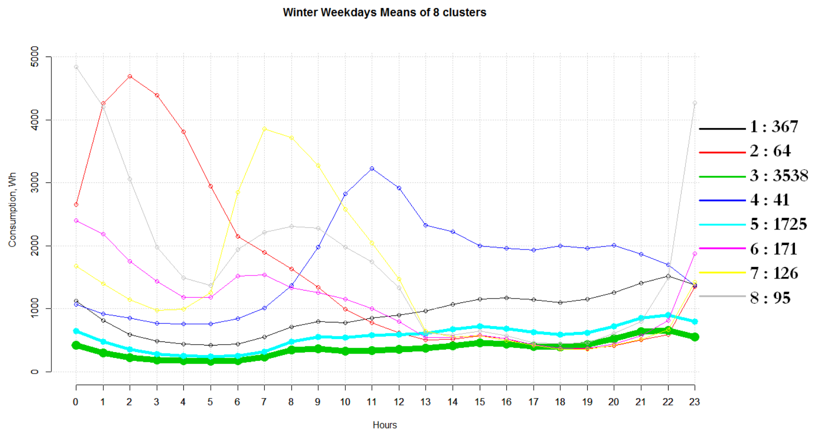


Figure 7: Eight clusters of winter weekday profile

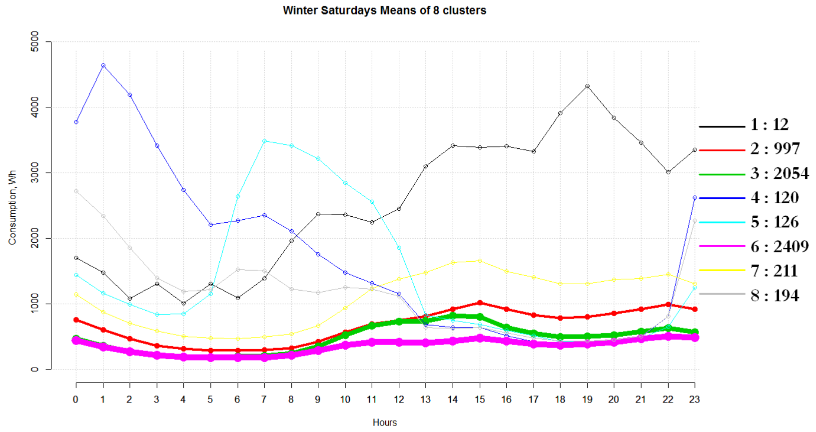


Figure 8: Eight clusters of winter Saturday profile

In the range of mentioned figures, the most representative clusters (largest ones) are repeating the shape of each other, i.e. are more or less uniform, however are differentiated by the absolute value of hourly load. To be more clearer, in Figure 7, cluster 3 (green), cluster 5 (magenta) and cluster 1 (black) follow similar pattern, but are distinguished by nominal Wh/h values. This case may resemble household consumption units with different amount of inhabitants, for instance: one, two and three. Typically, with larger occupation, electricity consumption per household rises, but such per person decreases [26].

Few consumers belong to the clusters with exceptional consumption curves.

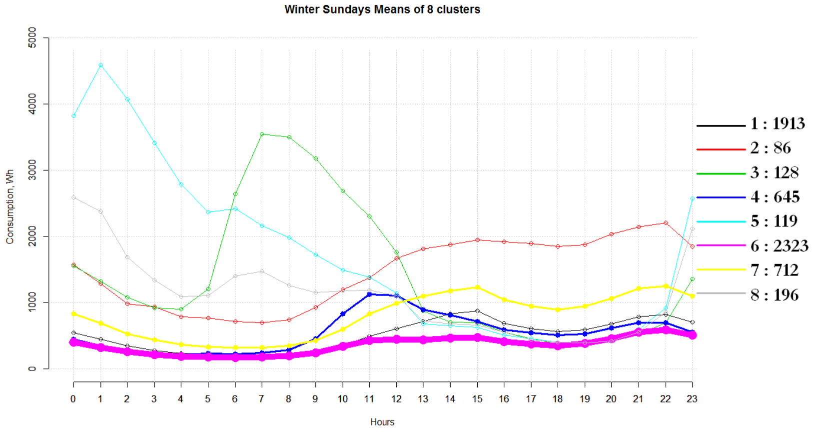


Figure 9: Eight clusters of winter Sunday profile

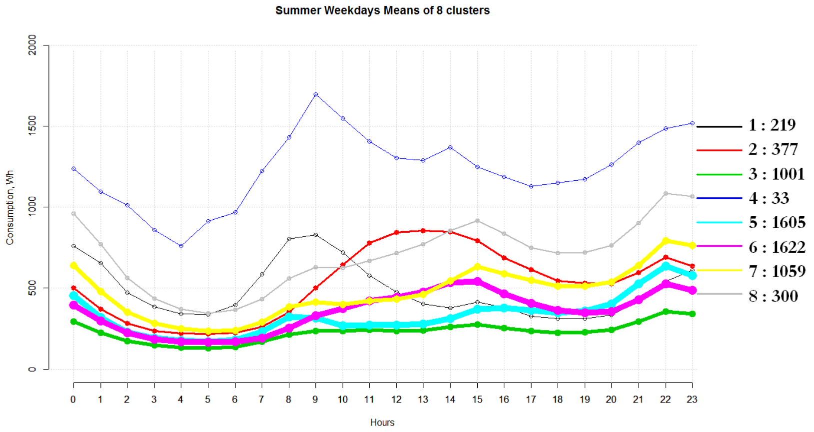


Figure 10: Eight clusters of summer weekday profile

Those could be clusters 2 (red) and 8 (grey) in Figure 7, or cluster 1 (black), 4 (blue) and 5 (magenta) in Figure 8, etc. The nature of such variability is complicated to explain. However, it must be stated that the data information files claim that not only residential loads are included in datasets, hence, we accept alternative load patterns, which are determined by the necessities of corresponding unities. The analysis of these necessities, though, is disregarded due to relatively small amount of consumers actually following those patterns.

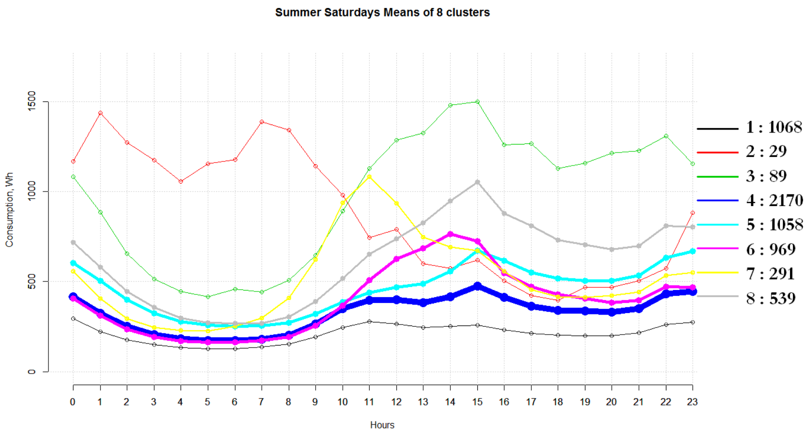


Figure 11: Eight clusters of summer Saturday profile

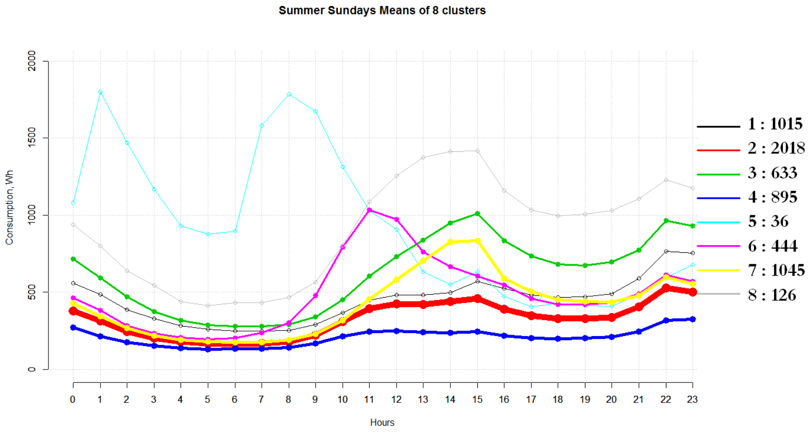


Figure 12: Eight clusters of summer Sunday profile

2.4 Applied Information Analysis

As a matter of fact, the study targets to perform an optimization on a limited geographic region. Identification of geographic distribution of consumers is done according to applied information of “RC1”, specifically, locational info (Tab. 1).

Smart meter data were complemented by additional CSVs, which consist of information on contracted power, geographical location, ambient temperature, etc.

Contracted power information, given in Tab. 1, is useful for identifying residential or industrial consumer, as far as their type of contract with electricity retailer. According to mentioned value, customer will pay a capacity tariff as a part of their bill. Such tariff may be briefly described as a payment for opportunity to consume. Therefore, in Spain, consumers with contracted power less than 10 kW are connected to LV grid (230/400 V). All "RC1" customers' contracted power is below 10 kW.

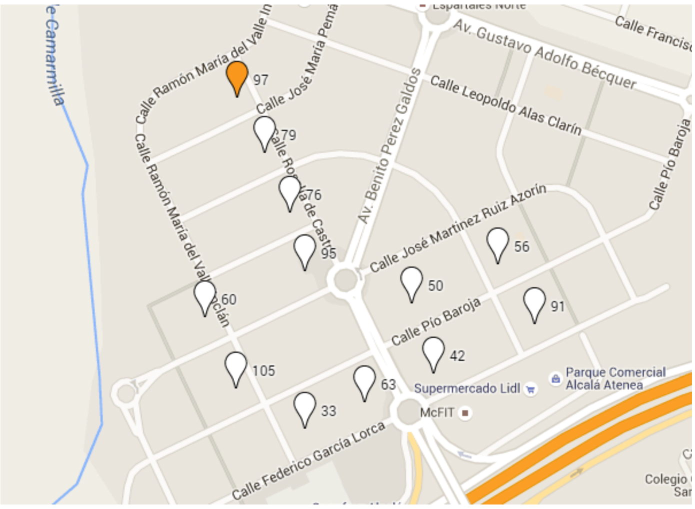


Figure 13: Example of concentrator location with number of units

The desired load profiles require the consumers to be distributed along a certain geographical area. The study case and the data are related to a city in Spain. Besides that, each CUPS is represented by one out of 106 (Tab. 1) names of data concentrators. Such unit serves as a common metering collection point or a layer for processing adjacent smart meters. Their exact geographical location is unknown, but can be estimated since concentrator point is named after an actual street where such is placed.

In a similar manner to Figure 13, 106 locations were estimated and a number of smart meters, attached to each location, has been displayed. Each point on the map, further on, will be called a "neighbourhood" or a location and will serve as an input for mathematical model.

2.5 Output Creation

Typically, applied information may serve as a basis for a variety of smart meter analytic algorithms and applications that are widely proposed in literature

[24, 25, 26]. These techniques may provide a high range of important results. Their relevance for electricity services companies is hard to be over-estimated, because the key for a precise load planning and grid maintenance prediction lies in understanding the consumer.

Some utilities are taking the initiatives to provide personalized feedback to consumers on how to adjust their habits for reducing electricity bills [30] or introducing hourly energy tariffs. Additionally, utility data analytic markets are growing constantly with advances of digital technologies [31].

This study, though, has been limited with techniques used for data analysis. Possible improvements may have included load temperature factor removal. This could have been done applying somewhat linear regression models. Gap avoidance could have been solved with stochastic estimations, for instance, with ARMA model.

In conclusion, several statistical data analysis techniques have been applied with open-source analytic software R-Studio [28]. This resulted in majority of 6379 supply points from initial data of “RC1” have been identified as low-voltage consumers. Further throughout investigation, by means of “k-means” clustering their summer, winter, working day, Saturday and Sunday consumption profiles were assigned to one of eight clusters. Clusters have been selected according to Euclidean distance equation in Eq. (1).

Geographically, using applied information, a set of concentrator nodes has been identified. Each one of them is described with a unique name, directed at the name of the street and with a vector of consumers (CUPS numbers). It then has been assumed that each specific consumer (CUPS) is following one of eight load patterns for given season and day of the week, thus leading to a half-year hourly consumption curve.

Once obtained half-year profile for every CUPS by knowing the cluster it belongs to, a complete neighbourhood profile can be calculated. This is done by summing the load of profiles, belonging to the same location l, resulting in 106×4344 array: $L^N_{l,t}$.

3 Electricity Market Analysis

Electricity market is a tool for trading electrical energy between the producers and consumers. Obviously, the institute of electricity markets has evolved significantly over the period of its existence. For that reason, the working principle of that is quite complex.

The uniqueness of such trading is that electricity may not be stored on a large scale, thus, it has to be consumed at the moment it is generated. Any unbalance between two terms of generation and consumption causes instability in power system and increases risks of a range of negative side-effects.

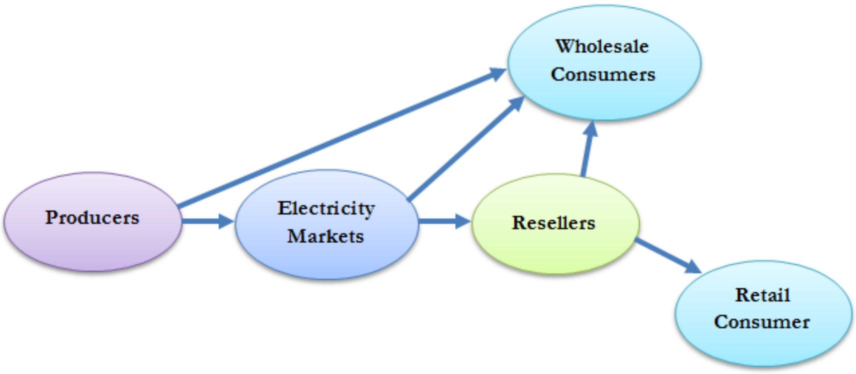


Figure 14: Overview of market operations

Simplified electricity market trading is demonstrated in Figure 14. Fair to notice, that its functionality varies throughout European countries. The majority of them have surpassed market liberalization, broadening the possibilities for privately-owned businesses to increase the competition, in such way, increasing the quality and efficiency of whole system.

3.1 Electricity Market in Spain

In Spain, market liberalization took place in 1997. Since then, many individual participants are competing in the areas of electricity production, distribution and retail. However, this market is hugely unbalanced due to only five of these participants (companies) are in control of 90% of retail consumer market and 60% of wholesale consumer market [32].

Unless traded between producers and wholesale consumers directly (Figure 14), producers and resellers are participating in electricity market. This market is marginal with marginal price determined by most expensive submitted bid that consumer is willing to accept. Bids are consisting of amount of power (MWh) players want to sell/buy and a price per unit (€/MWh) they intend to sell/buy it for. In other words, the final price per unit is set on the intersection of demand and supply curves. An example of such market equilibrium with SMC (system marginal cost) defined is shown in Figure 15.

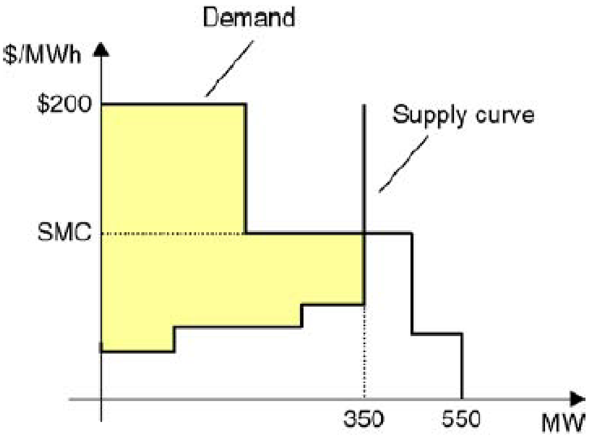


Figure 15: Illustration of optimal dispatch in a simple electricity market [3]

Electricity markets are complex and, as a rule of thumb, are composed of a range of trading operations, which consist of economic ones, operated by Operador del Mercado Ibérico Española (OMIE) [1]; and technical ones, regulated by Spanish transmission system operator (TSO) - Red Eléctrica de España. Complete scheduling and functionality may be observed in Figure 16, which clarifies trading procedures occurring at certain hours.

Retailers (reseller in Figure 14) neither provide any technical services, nor are responsible for grid stability; they are in charge of trading, providing a range of tariffs and, to a final extent, billing their customers.

One of the challenges of electricity retailers is to predict the load of contracted

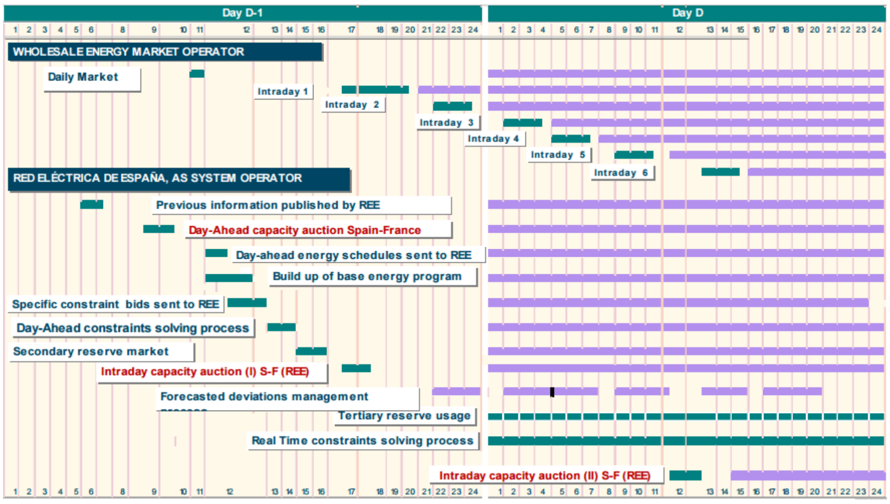


Figure 16: Electricity market scheduling [2]

consumers, since they have to bid fair amount of energy on day-ahead market (DAM). Such 24 hourly bids have to be submitted one day before the actual trading (Figure 16). Uncertainty in planning is compensated in intra-day markets (IDM), where the prices are noticeably higher, but traded amount of electricity way lower [1].

BESS is a solution that may tackle mentioned challenge by discharging stored energy in the hours with high load deviation. In addition to that, storage technology allows to buy energy at hours with low price and sell to the end-customers when the price is high - an example of daily DAM prices is shown in Figure 1.

Apart from day-ahead and intra-day trading (Figure 14), there are other electricity sub-markets for distinct services. Frequency regulation is grid stability service, which goal is to maintain frequency at regulated level of 50 Hz in Europe, allowing very small deviations. Frequency regulation service consists of three main components: primary regulation reacts in milliseconds to seconds; secondary frequency control operates within several minutes; and tertiary extends to hours.

3.2 Related Regulations and Policies

BESS still remains an innovation technology, that has not yet evolved to a large scale due to its high costs and grid adaptation issues. Governments play significant role in technological transfer, for instance: research excellence, innovation engagement and subsidies for renewable energy are contributing to positive business opportunities in electrical storage projects; but limited market competition and taxation, alternatively, create barriers for sustainable development.

The main European internal electricity market rules are described in Electricity Directive (directive 2009/72/EC [33]), however storage is not mentioned as a complete market participator. The directive does regulate TSOs and DSOs unbundling simultaneously with functions of generation and supply.

When it comes to storage, its contribution to system stability is not defined precisely. Hence, electrical storage systems are often regarded as generation [34].

On the other hand, one of the initiatives, mentioned in [33], regards creation of ACER (Agency for the Cooperation of Energy Regulators), which developed a framework for electricity balancing [35], directed by TSOs. Mentioned document does not restrict any specific technology from balancing operation, thus allowing utilising storage for such purposes.

Another powerful institution, namely, the European Network of Transmission System Operators for Electricity (ENTSO-E) in 2014 has finished their development of a draft network code for balancing, allowing ESS to provide generation and consumption balance services. Complementary, standard product for mentioned services shall "facilitate the participation of energy storage facilities" [36].

Nevertheless, proprietorial issue of storage system, i.e. whether those should belong to regulated operators or private market ones is undefined, being subject to local state electricity market politics [34].

Indisputably, European Union policies maintain little power in comparison to regulations of particular states. In majority of periods of time, member states are self-sustainable with relatively small amount of power being traded on international level. Despite that, few internal regulations support integration of storage technologies [34].

For instance, in Italy both TSOs and DSOs may build and operate BESS under certain conditions. These rules are defined in [37], according to the plan of advances integration of energy storage in national network.

Irish TSO, is about to lauch a program in 2017 that would allow energy storage owners to participate in regulatory markets by submitting respective bids [38].

3.2.1 Energy Storage Policies in Spain

Current Spanish electricity storage regulation is of a major interest since that allows concluding on applicability and feasibility of solutions proposed in this master thesis.

Spanish electrical system has suffered a major increase in renewable energies during last decades thanks to positive incentives from government adapting wind and solar energy and to EU 2020 targets [13]. At the same time, large state-owned coal and natural gas producers are fighting to protect their market, providing cheap power from their power plants. This collision results in Spanish electricity market being redundant, which leads to negative conditions for storage technologies.

[39] collects and discusses major keynotes from regulations about adaptability of storage systems in various parts of grid both from technical and economic points of view.

Specifically, it claims electricity and renewable energy regulatory framework does not mention any storage technologies, apart from pumped-hydro energy storage (PHES) and thermal storage in thermo-electric solar power plants. It describes them as special regime units, which may be considered as generation or consumption units, depending on operation state [39].

Articles 23-24 of royal decree 6/2010 [40] mention including system load manager participants, which would provide services of electrical charging for accelerating integration of electric vehicles. Those could be consumers, capable of supplying EV charging and storage services for better management of electric system.

Royal decree, identified as 1699/2011 [41], that regulates connection to the grid of low-power units of generation claims neither other generation nor storage units may be installed in electric circuit at any point before measurement equipment, than authorised one. That being said, legislation opposes low-power storage (commercial or distributed one) [39].

Additionally, article in [42] discusses the angle of affection of governmental policies on residential storage installations. Specifically, "battery owners are not allowed to reduce their contracted power" P^{contr}, which with a high degree of certainty will keep the electricity bills at current level, since largest share of that is a capacity payment.

On top of that, battery users will be a subject to several charges and in order to sell stored energy to the market, such units must be registered as respective businesses.

Further on, specific notification regarding different services will de explained:

- *Energy Arbitrage:* Energy storage is not specifically represented in regulation of electricity markets, however, as mentioned before, the participation requires to be registered as an energy trader. Also, such trader at each hour must maintain a positive trading balance, if being a seller, or negative in the case of buyer [39]. This adds to complexity of using other storage than PHES or "thermo", for which special operating conditions are allowed. The differences between day-ahead market (DAM) prices and volatility of storage are crucial for its feasibility.

- *Regulatory Services:* Whilst primary regulation is mandatory for all generation units, secondary regulation participants must comply with a range of technical requirements, specifically, communication to AGC and real-time response capability. Additionally, for each special regime production unit, the sum of all bid blocks must be at least 5 MW [43]. Secondary reserves are organized into control zones consisting of groups of AGC enabled generating units and their dispatch is controlled by the Shared Peninsular Regulation (RCP), the Control Center (CECOEL), and the Backup Control Center (CECORE) when necessary [1].

- *T&D Cost Deferral:* Even though being limited, compensations for high efficiency figures are available for electricity distributors. Moreover, the law does not restrict distribution system operators from using battery storage for postponing grid maintenance investments - obviously - under conditions of being acceptable by the main grid and system.

- *Minimization of outages:* In case of TSO has to limit sufficiently the production of power plants, they may justify an installation of storage equipment until the network is upgraded to necessary operating conditions [39].

Other services, for instance: voltage control, black-start, demand response; do not mention storage technologies as a potential service provider in regulations and rules of system operation.

3.3 Electricity Market Historical Data

3.3.1 Day-Ahead Market

This subsection deals with study relevant electricity market data overview and analysis.

It has been noted before from Figure 5 that average electrical load curve in Spain peaks at hours 13-14 in the afternoon and at hours 21-22 in the late evening.

Since electricity trading is a real-time process (except for relatively low volumes of storage), the day-ahead market prices may be expected to peak at same instants due to market rules. Annual price statistics are illustrated in Figure 17.

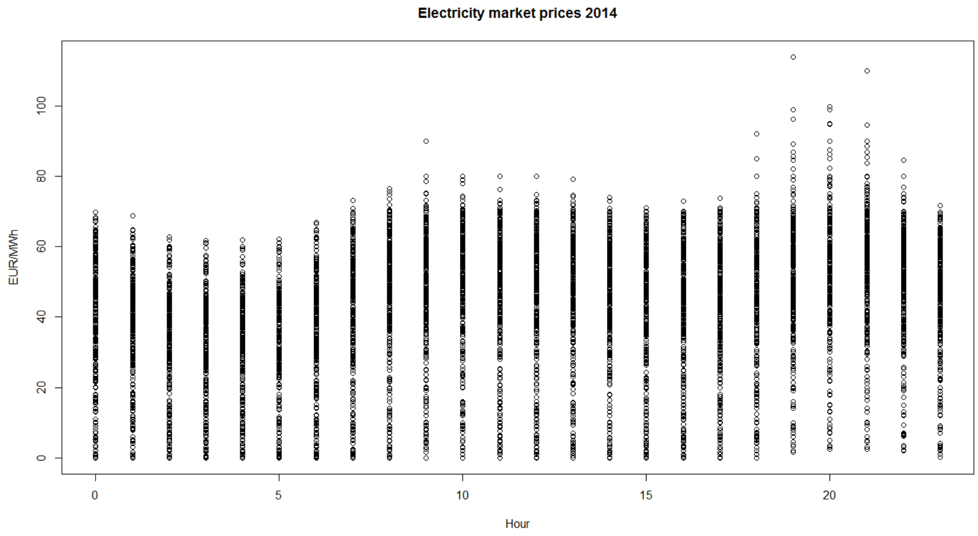


Figure 17: All hourly DAM prices, year 2014 [1]

The curve pattern is slightly altered from Figure 5 since load data referred only to low-voltage consumers. Highlighted peaks may be observable at hours 10, 12 and 21. For the sake of having more readable perspective on average prices, such daily curve is demonstrated in Figure 18.

Nevertheless, strong correlation between load and price curve remains, thus, both data are considered valid and appropriate for study case purposes.

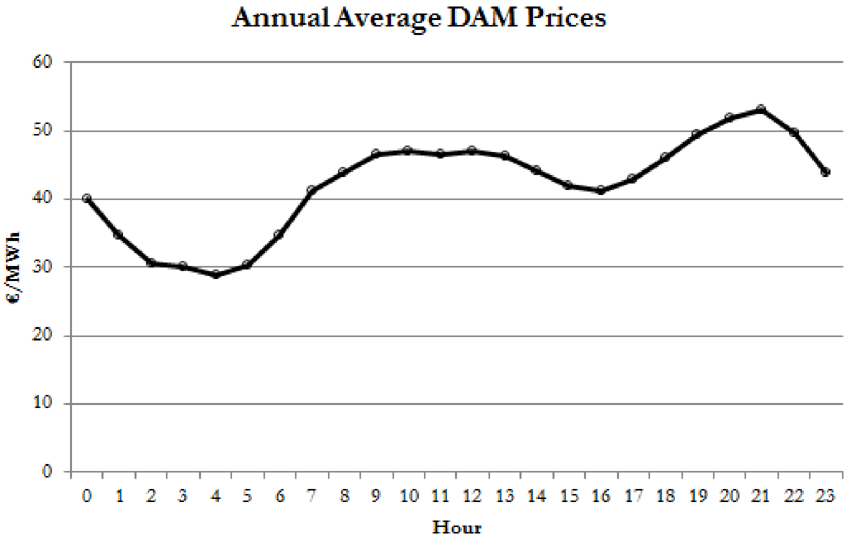


Figure 18: Average daily DAM prices, year 2014 [1]

When addressing energy arbitrage feasibility as a service, range of literature sources [16, 17, 44] emphasize the importance of minimum and maximum price difference in selected window of time. This gap is crucial due to the buying/selling strategy of energy arbitrage. Special perspective on DAM prices is required, taking a closer look at mentioned issue. Figure 19 visualises two daily extremes of prices in targeted time period of first six months of year 2014 (according to Tab. 1).

It is observable that the variation (in this case: the difference between maximum and minimum) in DAM prices is noticeably larger during first 90 days. This period corresponds to winter months of January, February and March. High prices arise when system demand reaches excessive values - for example, cold weather provokes increased usage of electric heating.

Low DAM prices are usually explained by exceed of generation. On the contrary to conventional power plants, which always maintain a certain generation cost due to burning fuel; renewable energy, like wind and sun, obtain their resources for free. At some hours with low demand, these generation units become price-setters, offering price of 0 €/MWh. Figure 20 visualises possible dependence of low-price occurrence (20a) on high wind power penetration (20b). Winter period, indeed, seems to complete proposed statement, although deeper research on that question

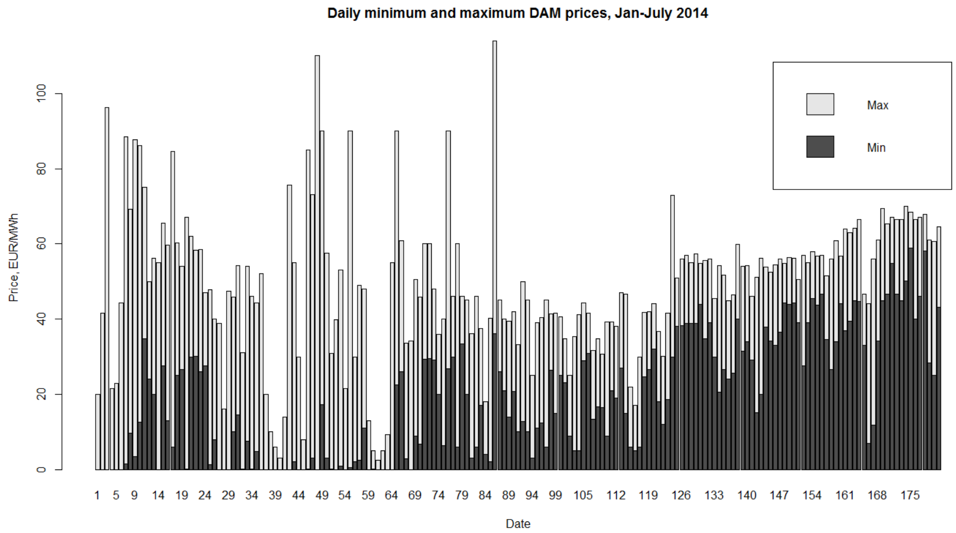
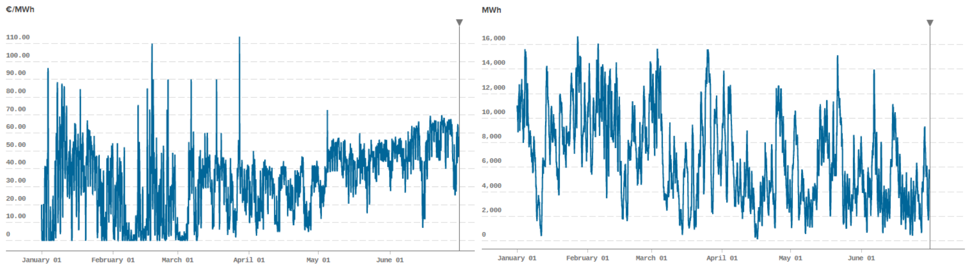


Figure 19: Daily minimum and maximum DAM prices [1]

is required for more certain conclusions.

Maximum and minimum price difference characterises monetary trading benefit per unit of energy at a single day - if such unit of energy was bought at instant of daily lowest DAM price and sold, respectively, at highest.

Daily price variation is better explained in Figure 21 - y-axis units are €/kWh. In that occasion, a battery with discharge capacity of 50 kW on January 1, if charged and discharged completely at respective hours, would save 50 kWh x 0.02 €/kWh = 1 €. If battery affords longer discharge time, earnings of following hours



(a) DAM prices: January-June 2014

(b) Wind power generation: January-June 2014

Figure 20: Influence of wind energy production on DAM prices [2]

should be added, but those per hour will be decreased.

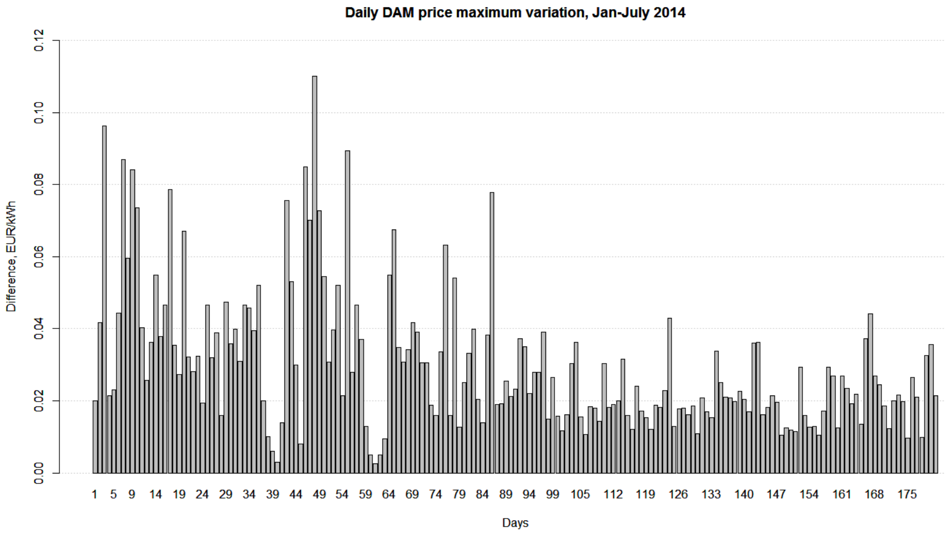


Figure 21: Daily maximum DAM price variation values [1]

Due to the fact, that every battery storage unit is described with somewhat value of cycle cost (Eq. (4)), it should be lower than potential earnings from full cycle trading for profitable operation. Referring to mentioned example of 50 kW battery and assuming its discharge time is 1 hour (i.e. energy capacity equals 50 kWh), the cycle cost must be less than 1€ to gain profits on January 1. For different batteries, this calculation becomes slightly more complex, since multi-hour discharge and round-trip efficiency must be taken into account. Nevertheless, used approach is a good measure to estimate battery's applicability for arbitrage. Further sections will mention this approach to compare several storage products.

3.3.2 Secondary Regulation Market

Another point of interest from the study's perspective is secondary regulation market operation, hence, that obliges to perform an overview of related market data.

Secondary regulation is used for frequency control and for balancing system generation and load. Since these operations are directly related to power system stability and control, they are gestured by TSO.

Secondary regulation service payment contains two components, referred to market: availability (secondary reserve) and use (energy) [39].

What can be interpreted as availability is essentially the capacity to either increase or decrease production in a generating unit according to Automatic Generation Control (AGC) signals, hence, battery electrical storage may provide such service due to possessing both somewhat reserve and not-used discharge capacity at every instant of time.

Secondary reserve of a single generation unit[3] is the maximum value of variation of power, within which it is capable of modifying its generation, according to the response signal, indicated by the technical requirements of TSO [43].

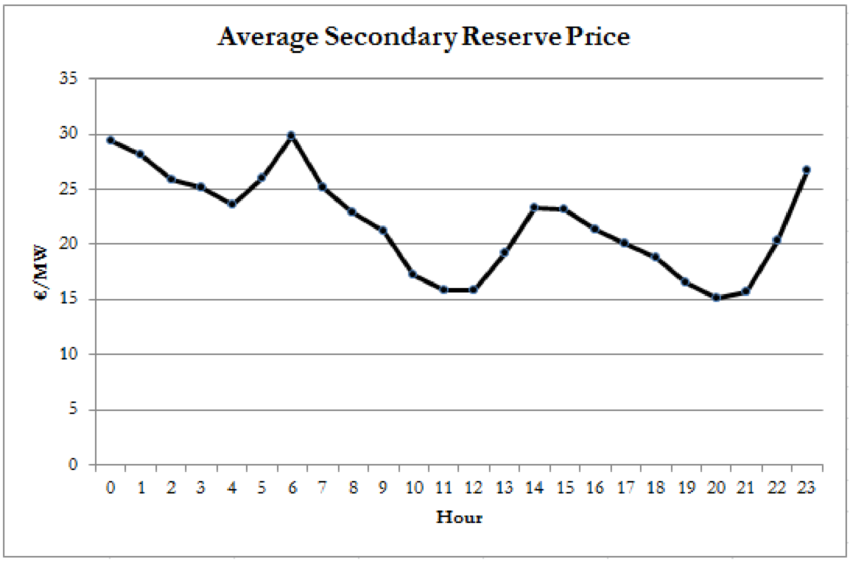


Figure 22: Average secondary reserve market price [2]

Figure 22 demonstrates average SRM prices for each hour of day. These statistics have been estimated from the data of desired trading period: January 1 - June 30, 2014. There barely is a characteristic pattern for the shape of the curve, since both reserve and its price depends on specific operation conditions, for instance, error in demand forecasting, unexpected outages and energy transferred through interconnections with other systems.

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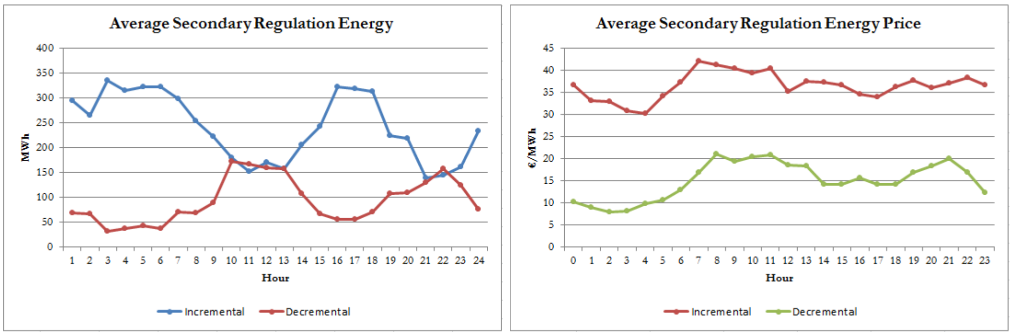
[3] It says generation unit, because the regulations reflect implementation of SR only in generation units (discussed in Section 3.2.1)



(a) Average energy traded (b) Average energy price

Figure 23: Secondary regulation energy characteristics in the system [2]

It is worth to mention that the upward reserve is always greater than downward one. This is maintained in order to take into account the possibility of generation unit failure. The ratio of upward/downward reserves is declared by TSO and is kept constant [43].

Secondary regulation energy defines amount of energy actually requested by TSO and traded. Undoubtedly, actual usage is much lower than offered availability (reserve). Moreover, regulation energy is separated into up-regulation and down-regulation with individual equilibrium prices. That describes whether energy has to be injected of withdrawn from the system.

Figure 23 illustrates average traded secondary regulation energy and its average market price for two terms: incremental (upward) and decremental (downward).

When generation unit provides incremental energy to the system, it gets compensated by market with price λ_t^{isre} times volume of energy supplied. Alternately, decremental service implies reducing production and may be interpreted as buying energy from market by generation unit for to a large extent reduced downward regulation price λ_t^{dsre}.

3.4 Output Creation

Relevant outputs that certainly would be required in mathematical optimization of storage system operation have been discussed in this chapter.

Day-ahead market trading is essential for energy arbitrage, thus, historical prices of related period has been transformed to a problem parameter, namely,

λ_t^{dam}.

Participation of storage technologies in secondary reserve market is questionable, but may play significant role in investment justification. Since this service involves two components of availability and energy, separated into upward and downward ones, respective prices must be imported. Nomenclature of those is assigned as λ_t^{srm} for secondary reserve market price, λ_t^{isre} for incremental energy price and λ_t^{dsre} for decremental energy price.

Apart from those parameters, electricity market legislation and functionality principles should be reflected in constraints and equations. The manner of the implementation is discussed in consecutive chapters.

4 Battery Energy Storage Systems

Clearly, it is a challenge to perform up-to-date technological and economic outlook of BESS with high accuracy. Firstly, global energy storage market is surviving significant changes occurring every year. Secondly, available sources of information may provide controversial values of battery costs in their surveys, because product manufacturers maintain confidential pricing politics due to competition.

This chapter aims to give such overview of storage technologies, that would carry the highest relevance to the study and would somewhat affect conclusions.

4.1 Technological Perspective

This subsection addresses technological aspect of energy storage, emphasizing batteries; briefly evaluating current market; its tendencies and exampling available products.

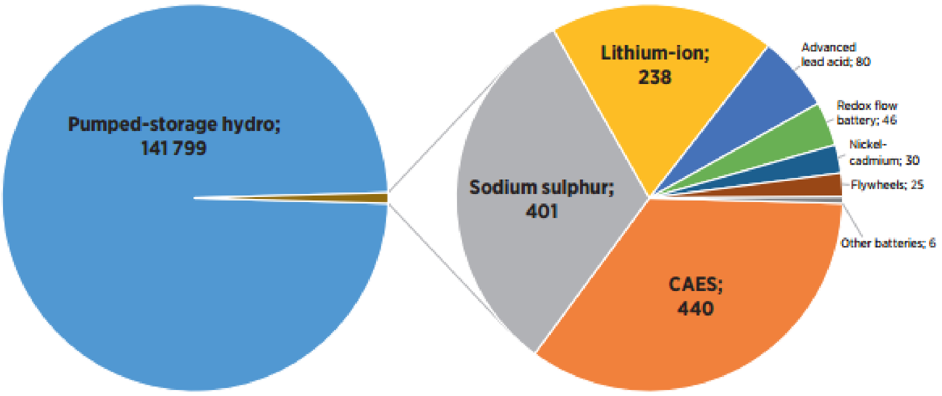


Figure 24: Global installed grid-connected electricity storage capacity (MW) [4]

Nowadays, vast majority of grid-connected storage capacity belongs to PHES, as observed in Figure 24. Despite huge dominance of one technology, the deployment of battery storage has suffered a significant increase in recent years [5].

Worldwide energy storage R&D (Research and Development) institutions maintain their focus on realising technology cost reduction and improving the performance of existing and emerging technologies.

Moreover, government subsidies, research and wide-scale demonstrations are constantly overcoming chains of technical challenges. These factors, along with cost reduction are expected to drive battery storage to a completely new level in nearest future. This is expressed in a battery storage development forecast in Figure 25 (states values for utility-scale storage, excluding residential and PV-coupled units). Additionally, expected global annual revenue increase for utility-scale applications is demonstrated.

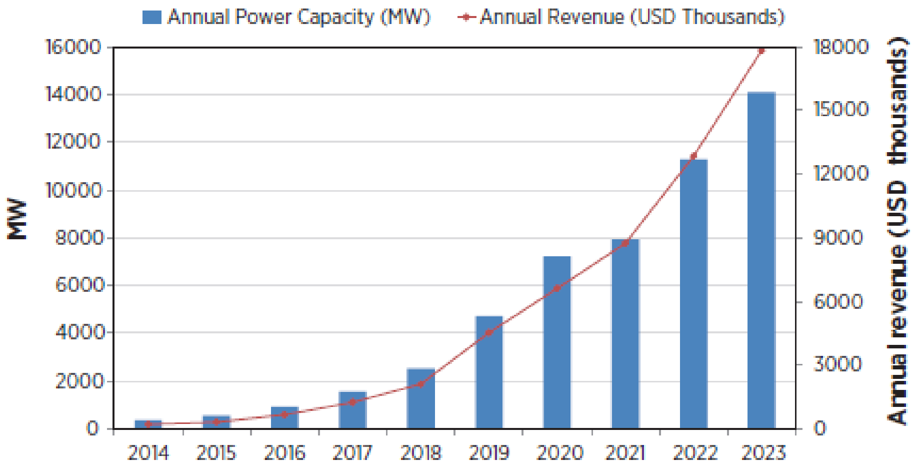


Figure 25: Worldwide battery storage forecast [5]

Electrical energy storage systems distinguish several physical forms of accumulating power, namely, mechanical, electrochemical, chemical, electrical and thermal. PHES, CAES and flywheel are main representatives of mechanical storage. Hydrogen fuel cells, possessing high values of efficiencies and low environmental impact are referred to chemical sub-group. Electrical storage market is supplied by capacitors and superconducting magnetic coils. Sensible heat storage belongs to thermal category [45].

Batteries are electrochemical storage units, where chemical reactions create current and voltage, together transforming into power and supplying the load. This technology is not new, but, as mentioned previously, in future years it is expected to occupy the market drastically.

Two primary characteristics of batteries are energy capacity E^{max} and discharge capacity d^{max}. All storage technologies may achieve almost any amount of these by parallel or series connection of units.

Batteries are appropriate for many applications. Their construction time is roughly around 1 year, which is relatively low in comparison to other technologies. Apart from that, it is quite flexible in locational issues. However, the disposal or recycling must be taken into consideration due to existence of toxic materials. Additionally, many batteries cannot be discharged completely due to high dependence of lifetime on the depth-of-discharge (DoD) [45].

This thesis is oriented specifically on batteries, hence, exceptional perspective is given on its classification, whilst detailed insight to other technologies is considered to be out of the scope of this thesis.

4.1.1 Battery Types

There are numerous different batteries currently available in the market, and each technology or manufacturer provide unique performance. Energy capacity of these batteries range between 1 kWh up to tens of MWh.

Variations in design have led to existence of exceptional amount of products. Therefore, there is no specific battery design for particular application, rather a range of factors that affect design specifications.

Battery storage in electricity sector is moving away from sodium-sulphur batteries. The shifting is directed towards lithium-ion and lead-acid technologies, which may be observed in Figure 26. Li-ion batteries have gained valuable advantages in terms of their characteristics [5].

Sodium-sulphur batteries are required to perform under high temperatures due to using molten salt as electrolyte. This chemistry has reached its maturity, since being available in the market since 2003. Those are long-discharge batteries, taking 6 or more hours for complete charge or discharge. Cycle life of sodium-sulphur does not exceed 3000 cycles. The average estimated cost in 2014 has been, roughly, 530 €/kWh [14, 45, 46].

Lithium-ion batteries, thanks to their high energy density, occupy little space. They are also suitable for fast-response applications, reacting in milliseconds. Li-ion batteries maintain high RTE comparing to alternatives, reaching 97 %. More-

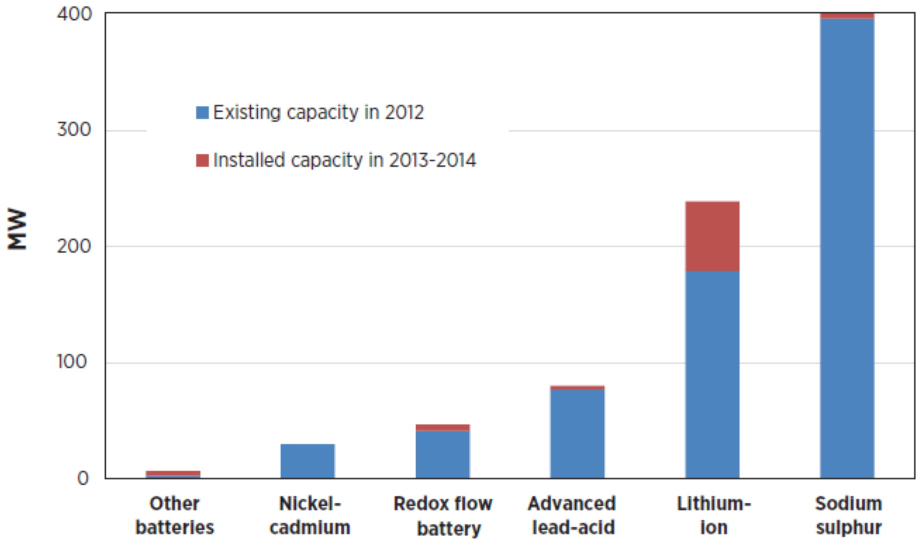


Figure 26: Estimated installed battery capacity by type in 2014 [5]

over, technical performance is continuing to improve due to large deployment in small electronic devices. Among disadvantages it is worth to mention safety, since cells may easily get overheated and catch fire. Additionally, cycle life is directly subject to ambient conditions. Bottom average price limit is estimated to be equal to 485 €/kWh [14, 45, 46].

Advanced lead-acid had been widely usable technology because of relatively low cost and sufficient maturity since 1980s. Technology still has high demand in developing countries and emerging markets. Despite that, technical performance is rather low with short cycle life, slow charging and maintenance issues. Nevertheless, researches are working on a solution to poor performance. Advanced lead-acid cost ranges from 530 €/kWh [14, 45, 46].

Flow batteries, according to their unique chemistry, are less affected by charge and discharge, hence, they can be used without severe degradation. On the other hand, such design remains expensive. Flow batteries optimal storage time ranges between 2 and 10 hours. Even though they possess small market share nowadays, they remain a promising long-term solution thanks to large energy capacity. Lower limit price in 2014 has been approximated to 600 €/kWh [14, 45, 46].

4.2 Proposed Product Solutions

This study focuses on distributed small-scale storage, due to character of consumer load data, grid architecture unavailability and general limitations of the project, like time-frame. Hence, it is important to propose suitable product solutions, which may be implemented into mathematical model and reflect current pricing situation. Final solution has been defined to be the community energy storage (CES), where BESS operate within a number of households. A demonstrative figure of CES with storage units installed on the secondary side of transformer, may be observed in Figure 27.

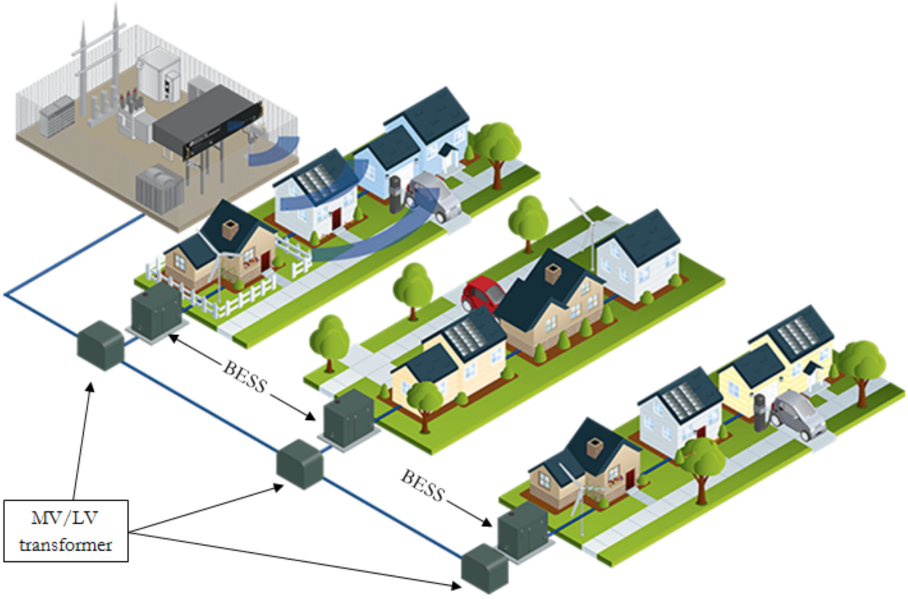


Figure 27: Example of CES

Battery storage systems are usually composed of several elements. Previously, it has been discussed that there is a range of chemistries for design of the battery. From practical point of view, battery is just a single part of what is named BESS. Safe operation requires installation of communication and control, power conversion and temperature control systems. Explained architecture is visualised in Figure 28.

Monitor and control systems are often referred to as battery management sys-

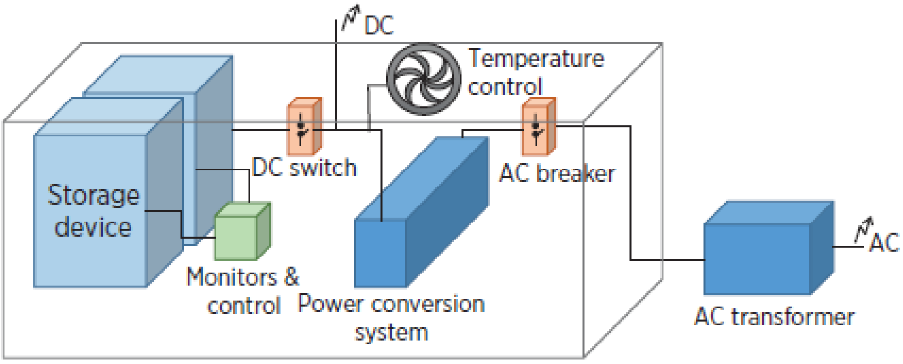


Figure 28: Simplified visualisation of BESS [5]

tem (BMS) and its role is to ensure desired performance and safety. Power electronics (PCS) are required to adjust voltage from grid to battery level and to communicate with utility. Temperature control is essential for heat-sensitive units, like Li-ion [5, 20]. Mentioned extensions add-up to BESS capital investment and thus have to be considered.

Overall, the market has shifted towards lithium-ion solutions, since its deep discharge rate, long life-cycle and plummeting cost have proved being preferable to other technologies [5, 14, 47].

Relying on that, and dealing with complications of product technical and price information availability, a number of BESS products has been collected into Tab. 3. Figures reflect deployed project costs or available prices, if so. Energy and discharge capacity rates are selected according to defined focus in CES.

In Tab. 3 corresponding battery product names are labelled with numbers, which identify: 1 - Saft SMUD CES©, 2 - SAFT LVGB© (Low Voltage Grid Batteries), 3 - PureWave CES©, 4 - BYD MSD©, 5 - Powerpack©. Lack of data reflects confidentiality politics of storage manufacturers. Also, complete technical and economic components are highly dependent on desired project, and often are negotiated directly between customer and manufacturer. In Tab. 3, in some cases of such data being available, the cost is divided between storage unit (SU) itself and the power conversion system (PCS).

Table 3: Comparison of different BESS products

Producer	SAFT		S&C	BYD	Tesla	Green-smith	Green Charge
Battery	1	2	3	4	5		
Type	Li-ion						
E, kWh	34	82,5	50	60	100	82	160
d^{max}, kW	30	33	25	50	50	50	100
RTE	0,9	-	0,88	0,9	0,8736	0,85	-
Cycle life	6000	-	7300	6000	5000	-	-
t_{min}, °C	-	-	-20	-	-25	-	-
t_{max}, °C	-	-	45	-	50	-	-
Information							
Year	2012	2014	2010	2010	2016	2011	2013
Source	[48]	[49]	[18, 50]	[51, 52]	[23]	[53]	[54]
Cost, €							
SU	-	-	44 694	89 394	41 768	-	-
PCS	-	-	37 906	92 789	59 623	-	-
Total	243 724	132 139	82 600	182 183	101 391	100 273	219 896
€/kW	8 124	4 004	3 304	3 644	2 028	2 005	2 199
€/kWh	7 168	1 602	1 652	3 036	1 014	1 223	1 374

4.3 Economics of Energy Storage

Implementation of energy storage highly depends on existing types of niches in electrical grid and market operation. Storage may be operated in a range of applications that under certain conditions become feasible or not.

Current market situation along with cost reduction, subsidies and increased knowledge of battery functionality allows these technologies to become highly competitive on global level [5].

Development of electrical storage projects must surpass several stages of verification and estimation of potential revenues for each application. Based on the conclusions of such studies, a design of battery is suggested. Such design intends maximizing profits under defined configurations of the grid.

However, this becomes questionable, because any cost-benefit assessment must reflect local conditions as well as up-to-date storage system characteristics. Even in that case, complete analysis additionally requires detailed models of power system and stochastic market price prediction models. This tends to lead to a wide dispersion of results and conclusions, hence, adding to the complexity of developed study.

An overview of storage services is presented, separately mentioning potential applicability in electricity markets.

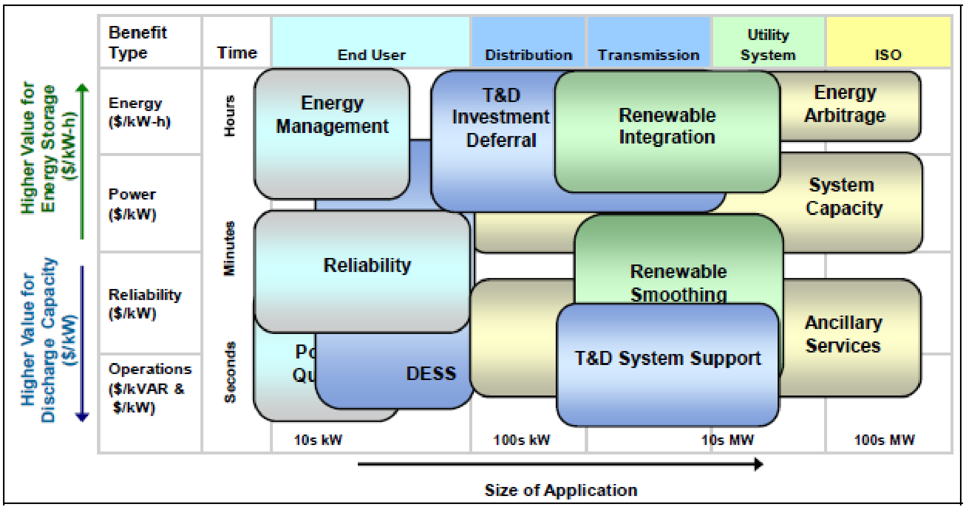


Figure 29: Overview of storage applications and their potential [6]

4.3.1 Energy Arbitrage

Almost all energy markets follow similar pricing pattern: overnight prices are significantly lower than afternoon/evening figures [55], though the value of this difference to a large extend depends on the available generation and system load in local conditions (weather, industry, etc.) [56].

The economics of energy arbitrage are quite straightforward, however the key factors that play determining role in economic feasibility are often difficult to identify and, frequently, depend on the case. Nevertheless, it is important to give an overview of the impact of the operational features of batteries.

The process of charging and discharging a battery always accounts with somewhat losses. A term which describes that, is called round-trip efficiency (RTE). From technological point of view, multi-hour storage remains quite difficult with high values of round-trip efficiency, whereas studies in [44, 57] claim adjusting RTE may sufficiently affect revenues of arbitrage, pointing out that relative increase is higher for longer-discharge time units.

Batteries, by their chemical nature, have limited lifetime, usually measured in number of cycles, when one cycle corresponds to one complete charge and discharge. Hence, the moment its end of life (EOL) is reached, the battery has to be replaced. The operation period continues for several years, lasting until 20 years for some technologies [21].

Nevertheless, the replacement cost must be considered as an up-front capital investment, meaning that each operation cycle of given battery wears a cost, which by the EOL would allow purchasing new battery. According to that, cycle cost of battery may be expressed as in Eq. (4).

$$C^{cycle} = \delta^{rep} * \frac{C^{capex}}{cyc^{max}} \tag{4}$$

where:
C^{capex} - CAPEX of the battery, €;
cyc^{max} - battery's cycle life, cycles;
δ^{rep} - replacement cost fraction of CAPEX;

Peak-off-peak electricity market price ratio and storage cycle cost, in most occasions, determine the feasibility of storage. Hence, number obtained in Eq. (4) must be compared to potential arbitrage benefit of 1 cycle of given storage product. Generally, this income is quite complex when many features and full range of battery's characteristics are considered. Nevertheless, simplified computation may look as follows:

$$Inc^{cycle} = \sum_{i=1}^{E^{max}/d^{max}} \left[A^i * \gamma^{rte} - B^i\right] \tag{5}$$

where:
A^i - i-th maximum value of λ_t^{dam} among $t \in \mathcal{T}$;
B^i - i-th minimum value of λ_t^{dam} among $t \in \mathcal{T}$.

Here, t belongs to desired set of time intervals $\mathcal{T}$ - for this expression those are 24 hourly periods per day. Ratio E^{max}/d^{max} is a discharge duration in hours. It is worth noting that Eq. (5) is only valid for integer values of discharge duration. In such manner, Eq. (5) defines one cycle income as the summation of differences between 1..i-th maximum and 1..i-th minimum DAM prices, considering the round-trip efficiency. Discharge duration in hours i is defined by the relation E^{max}/d^{max}.

Technological specification of batteries utilised for energy storage should to a large extend be compatible with service requirements. In other words, since arbitrage requires multi-hour storage, the energy capacity and discharge rating should be selected accordingly.

However, limitations of available storage product data obliges to use a number of market products with given technical parameters for arbitrage feasibility evaluation.

Several studies report different results on arbitrage profit sensitivity to key battery characteristics. For example, a literature review in [20] claims conducted studies lead to major controversies in their conclusion, thus, keeping the sensitivity question open.

Generally, energy systems providers claim retail energy time-shift do not produce sufficient value streams for business, hence, do not push the development of projects in most regions, except those with large variance in peak and off-peak prices (for instance, Hawaii) [58]. At the same time, [17] concluded that profits from energy arbitrage were insufficient to reimburse the investment, proposing simultaneous utilisation of storage for services, such as, load following, T&D cost deferral, grid stability, etc. The study, conducted in [19], had assessed the generation-coupled storage at a wind power plant, resulting in promising ROI thanks to its reserve capacity in secondary market.

Figure 30 demonstrates the values of potential daily earnings of one particular battery. Necessary expressions have been computed, according to Eqs. (4) and (5).

Since the red line expresses cycle cost (computed with $\delta^{rep} = 0.33$, and making one full cycle per day), it is straightforward, that only during three days out of 181, energy arbitrage would remain profitable.

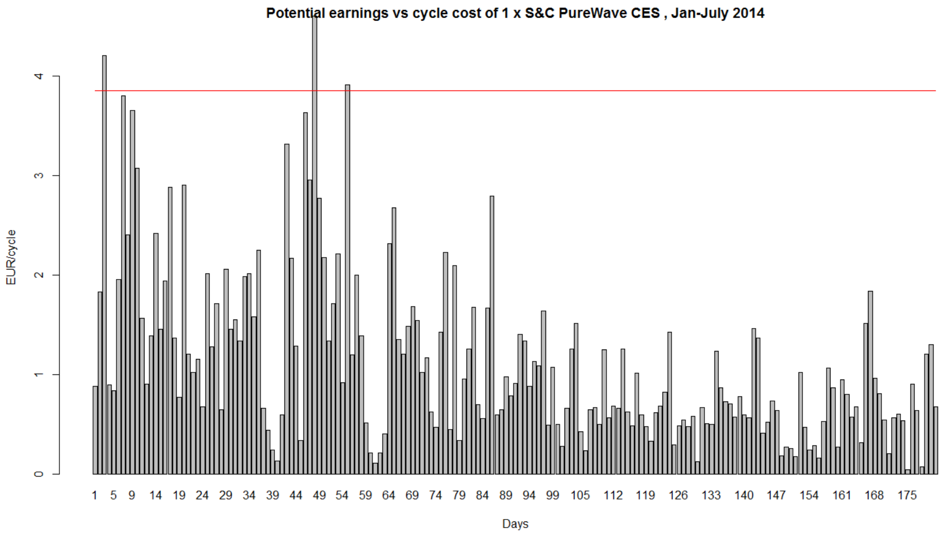


Figure 30: Potential earnings and cycle cost of S&C "PureWave" battery

4.3.2 Support of Renewables

Support of renewable generation is one of the promising applications of storage systems with a tremendous growth of penetration of wind and solar [10]. Highly-intermittent production is less accurate in forecasting, requires additional grid stability measures from operators and is hardly controllable or manageable.

Fast-response battery storage may provide frequency control at higher level than wind or solar power plant solely. Moreover, oscillating production profiles may be smoothed with assistance of BESS. Energy, stored in curtailment hours, may be served at peak hours, reducing market prices, system congestion and avoiding the need to run expensive CO_2-emitting power plants [58].

While currently the grid itself supports renewable generation, with the development of DES and distributed storage, the latter might out-take that role, becoming a significant player in grid support [58].

Study, conducted in [19] has optimized operation of a wind power plant with 6 MWh BESS and resulted in 10 year investment payback period.

Talking about small-scale, in Germany, the profitability of investment in residential storage with solar photovoltaic (PV) plant is higher than that of PVs on their own. Even though such result is dependent on regulatory environment, decreasing costs for solar panel and battery manufacturing are pushing the limits. Several studies showed Li-ion batteries with PVs maintain positive net-present value in Germany nowadays [47].

4.3.3 Frequency Regulation

As already mentioned, frequency regulation is a grid stability service provided by generation units installed in the system. Energy storage possesses a great technical and economic potential in providing this service and benefiting the power system in many ways.

Along with mentioned intermittency of wind and solar, conventional power plants that use fossil fuels are limited in adjusting their generation when required by the system. This arises from established ramp rates, i.e. the maximum available deviation from current production at time instant; large response time to the signals, which is much longer than current storage technologies. Batteries often respond to the control signal in the range between tens of milliseconds to one second [20].

A paper in [44] investigated simultaneous utilisation of energy storage for arbitrage and secondary regulation in New York, which resulted largest share of profits arise from frequency control service.

Similar conclusion has been achieved in [19], showing high annual revenues in secondary reserve market.

Literature review, conducted by [20], made a survey of energy storage revenues for frequency regulation. A range of participants described annual benefit ranging from 253 €/kW for 70 % RTE batteries up to 1775 €/kW for high-power and fast discharge (15 mins) units.

Report in [6] emphasises the importance of combining multiple benefits with frequency regulation, claiming it is a key for proposing high-value in business case of energy storage.

However, since adequate application in frequency regulation requires large MWh-scale fast-discharging storage units, completing large amount of cycles annually, the service combination remain questionable for distribution level and subject to additional computations.

4.3.4 Capacity Upgrade Deferral

Growing electricity demand repeatedly requires manufacturing transmission and distribution networks for operating with increased capacities and maintaining system stability. Network reinforcement procedures are conducted by corresponding unities - by TSO in case of transmission network and by DSO for distribution grids. The range of mentioned applications of storage provides certain benefits for grid thus allowing postponing next maintenance investment, prolonging the life of existing elements, like transmission lines or power transformers.

When the equipment is upgraded, its capacity accounts for several years and in the beginning is not utilised. These large up-front costs by system operators may be deferred, as mentioned, by storage. Clearly, such depends on cost of T&D upgrade, which usually is expressed in €/kW.

Complete cost-benefit analysis of distribution deferral, though, requires extended knowledge of particular grid topology and configuration. In this study, however, such information in unavailable, thus, the approach is heavily facilitated.

Report in [18] evaluated several scenarios of implementing community energy storage and obtained results, saying 53 % of storage project investment was returned from distribution upgrade deferral.

4.3.5 Other Services

Table 4: Current and expected utility-scale battery storage application market share [7]

Application	2014	2023
Renewable Support	29 %	40 %
Peak-shaving	20 %	15 %
Arbitrage	18 %	37 %
Ancillary	17 %	3 %
Other	16 %	5 %
Capacity	360 MW	14 GW

Undoubtedly, there is a wider range of battery storage applications in electrical grid, each having certain economic potential based on particular market, electrical system and regulatory conditions. Those applications include extended list of power quality services, system ancillary, T&D support, etc. (Figure 29)

However, these services are considered out of the scope of this thesis project, since they barely interfere with the definition of distributed battery systems. That being said, some services are impractical in selected project scale or had been decided not to implement due to their complexity.

In conclusion, Tab. 4 shows 2023 forecast for utility-scale battery storage applications, indicating that expected capacity would increase till 14 GW from 360 MW in 2014 [7].

5 Mathematical Model

Mathematical model is an equation-based definition of a problem. Within optimization problem it is required to describe parameters, variables, constraints and objective function (or functions, if several). This process itself has to be optimized by minimizing the number of total variables and constraints for least computational time. Large problems tend to run of out memory or be unable to reach optimality on most common-user machines, hence, each script had been defined/adjusted to avoid mentioned problems.

5.1 Overview

First of all, the mathematical model development, key ideas and related programming, to a large extent, has been adopted from paper in [19]. This publication served as a basis for implementation of the problems studied in this thesis. Initial design of the model had survived some changes, though, specifically:

- Load-pattern import from outer environment
- A shift from generation to distribution part of the power system
- Addition of locational distinction
- Implementation of EV problem

Secondly, the model interprets the problem as a set of locations (or neighbourhoods), that are to a large extent independent on each other. Despite location points are distributed along the same city and some of them may be adjacent, direct energy trading between neighbourhoods is neglected. However, some restrictions refer to an aggregation of locations. This shall be described thoroughly throughout this chapter.

Practically, in order to build a model of interconnected communities for electricity trading, corresponding electrical schemas of circuits are required, which involve bunch of parameters, such as, line length, resistance, inductance, nodal power flow conditions, etc. Apart from that, according to the assumptions made, BESS are installed on the secondary side of LV transformer, thus, such system

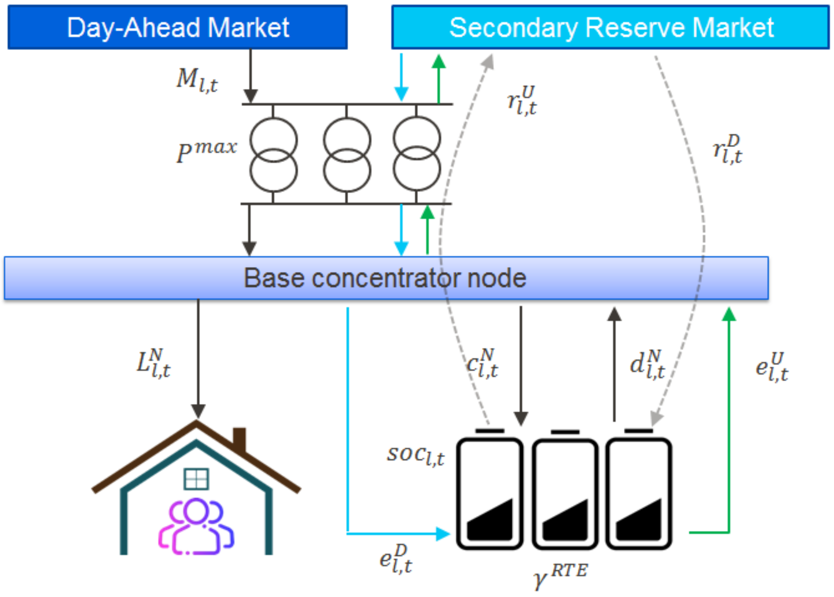


Figure 31: Model visualization of day-ahead and secondary reserve markets trading

would likely be not permitted to operate within distribution grid by technical operator (similarly, selling energy to DAM is forbidden).

Figure 31 demonstrates the trading of energy within DAM and SRM of one location with parameters and variables described in Subsection 5.2. Black arrows are related to the operations in DAM and basically, are used for energy arbitrage, whereas dashed lines visualise secondary reserve market bids. Blue and green lines stand for secondary energy trading. The desire is to store cheap power purchased in time periods with low price (at night) and to discharge it to the load when electricity prices reach their peaks.

5.2 Optimization Model

5.2.1 Sets

$\mathcal{T}$: Set of hourly time periods per half-year period $t \in \mathcal{T} = \{1, 2, ..., 4344\}$

$\mathcal{L}$: Set of geographic locations $l \in \mathcal{L} = \{L1, L2...L106\}$

$\mathcal{C}$: Set of clusters $cl \in \mathcal{C} = \{1, 2..., 8\}$

5.2.2 Parameters

Δt : Duration of the time period [h]
λ_t^{dam} : DAM market prices [€/kWh]
$L_{cl,t}$: Load of given customer profile [kWh/h]
$L_{l,t}^{N}$: Load of a neighbourhood [kWh/h]
P_l^{max} : Maximum transformer power in a neighbourhood [kW]
SOC^{min} : Minimum SOC
SOC^{max} : Maximum SOC
SOC^{ini} : Initial SOC
SOC^{0} : SOC level at the end of the day
N_l^{SU} : Number of storage units
γ^{rte} : Round-trip efficiency
E^{max} : Maximum storage capacity of storage unit [kWh]
d^{max} : Maximum discharge capacity of storage unit [kW]
cyc^{max} : Storage unit's cycle life [cycles]
C_l^{capex} : CAPEX - Capital cost of storage unit [€]
δ^{rep} : Ratio of replacement cost to CAPEX
λ_t^{srm} : SRM market prices [€/kWh]
λ_t^{isre} : ISRE market prices [€/kWh]
λ_t^{dsre} : DSRE market prices [€/kWh]
Δt^{sr} : Time response of secondary reserve [h]
α^{sr} : Ration between up and down reserve
β_t^{U} : Fraction of up-reserve energy allocated
β_t^{D} : Fraction of down-reserve energy allocated
γ_{EV}^{rte} : Round-trip efficiency of EV battery
E_{EV}^{max} : Maximum storage capacity of EV battery [kWh]

d_{EV}^{max} : Maximum discharge capacity of EV battery [kW]

cyc_{EV}^{max} : EV battery’s cycle life [cycles]

$C_l^{capex,ev}$: CAPEX - Capital cost of electric vehicle battery[4] [€]

N_l^{EV} : Number of EVs in a neighbourhood

t_{EV}^{on} : Hour of the day, when EV battery gets connected to the grid [h]

t_{EV}^{off} : Hour of the day, when EV battery gets disconnected from the grid [h]

id_t^{EV} : Binary parameter for EV battery grid commitment

SOC_{EV}^{on} : State-of-charge at the moment of connection to the grid

SOC_{EV}^{off} : State-of-charge at the moment of disconnection from the grid

P_l^{contr} : Total contracted power in a neighbourhood [kW]

ΔP : Annual load increase for T&D problem

$\lambda_{l,t}^{out}$: Per-hour of unexpected outage compensation price [€/h]

5.2.3 Variables

$c_{l,t}$: Charging rate in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kW]

$d_{l,t}$: Discharging rate in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kW]

$id_{l,t}$: Binary variable, establishing charge ($id_t = 1$) or discharge ($id_t = 0$) in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$

$soc_{l,t}$: SOC in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T} \bigcup \{0\}$

$M_{l,t}$: DAM energy bid in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kWh]

$r_{l,t}^U$: “Up” secondary reserve in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kW]

$r_{l,t}^D$: “Down” secondary reserve in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kW]

$e_{l,t}^U$: “Up” secondary reserve energy, allocated to location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kWh]

$e_{l,t}^D$: “Down” secondary reserve energy, allocated to location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kWh]

$O_{l,t}$: Energy not-supplied in location $l \in \mathcal{L}$ at time period $t \in \mathcal{T}$ [kWh]

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[4] Only used to estimate the price of battery replacement and therefore may not be considered as a fair cost of whole electric vehicle.

5.2.4 Constraints

At any instant of time, the balance between generation and production should be maintained. In given conditions, instead of producing energy, it is bought from the pool, thus, this balance may be referred to as market equilibrium:

$$\Delta t * (d_{l,t} - c_{l,t}) + M_{l,t} + O_{l,t} = L^{N}_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{6}$$

In Eq. (6) non-served energy $O_{l,t}$ is greater than zero only when outage subproblem is selected. Additionally, variable $O_{l,t}$ could serve as an interesting input for extended intra-day market (IDM) trading. Particular problems’ conditions are described in following chapters of this work.

Since the BESS are meant to be installed on the secondary side of LV transformer, its power capacity may not be exceeded. Therefore, both traded energy and SRM bids are limited by the value P^{max}_{l}:

$$M_{l,t} + e^{U}_{l,t} - e^{D}_{l,t} \leq P^{max}_{l} * \Delta t \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{7}$$

$$r^{U}_{l,t}, r^{D}_{l,t} \leq P^{max}_{l} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{8}$$

There were two separated variables defined for battery being charging $c_{l,t}$ and discharging $d_{l,t}$. An obvious relation must be introduced in order to restrict mentioned processes happening simultaneously. Binary variable $id_{l,t}$ assures that condition. Apart from that, locational value of charge and discharge is bounded by battery’s maximum discharge multiplied by number of storage units. Eqs. (9)-(10) combine mentioned restrictions.

$$0 \leq d_{l,t} \leq d^{max} * N^{SU}_{l} * id_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{9}$$

$$0 \leq c_{l,t} \leq d^{max} * N^{SU}_{l} * (1 - id_{l,t}) \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{10}$$

Some problems of developed model involve electric vehicle battery V2G operations. The specification of such operation is that it may be available only during certain hours, most often in the night hours (decided before running the optimization), while during the day they remain utilised by users (disconnected).

In the case of EV battery, when disconnected, it may not be charged nor discharged. Binary parameter id_t^{EV} defines mentioned characteristic, whereas binary variable $id_{l,t}$ restricts simultaneous charge and discharge:

$$0 \leq d_{l,t} \leq d_{EV}^{max} * N_l^{EV} * id_t^{EV} * id_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{11}$$

$$0 \leq c_{l,t} \leq d_{EV}^{max} * N_l^{EV} * id_t^{EV} * (1 - id_{l,t}) \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{12}$$

$$id_{l,t} \in \{0, 1\} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{13}$$

The evolution of state-of-charge (SOC) in every location throughout trading period is described with the following constraint:

$$soc_{l,t} = soc_{l,t-1} + \frac{\Delta t * (c_{l,t} - \frac{d_{l,t}}{\gamma^{rte}}) + (e_{l,t}^{D} - \frac{e_{l,t}^{U}}{\gamma^{rte}})}{E^{max} * N_l^{SU}} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{14}$$

Analogically to SOC of battery in Eq. (14), evolution of SOC in case of electric vehicle is tracked during the trading period, however, under the condition of grid connection, i.e. only night hours.

$$\begin{gathered} soc_{l,t} = soc_{l,t-1} + \frac{\Delta t * (c_{l,t} - \frac{d_{l,t}}{\gamma_{EV}^{rte}}) + (e_{l,t}^{D} - \frac{e_{l,t}^{U}}{\gamma_{EV}^{rte}})}{E_{EV}^{max} * N_l^{EV}} \\ l \in \mathcal{L}, t \in \bigcup_{k \in \mathbb{N}^0} \left\{ k * 24 + \left(\left[1; t^{off}\right] \bigcup \left[t^{on} + 1; 24\right] \right) \right\} \end{gathered} \tag{15}$$

However, there are technical requirements of minimal and maximal state-of-charge that are typically issued by the manufacturer for safer and longer battery operation. It is fair to note that in case of having multiple batteries, they are considered to operate similarly, whereas the model threats that interpretation as one battery with respective times capacity and discharge rate.

$$SOC^{min} \leq soc_{l,t} \leq SOC^{max} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{16}$$

For generating objective results, the anti-anticipation constraint, that maintains SOC at the same level once per every 24 hours, is introduced. Avoiding this restriction would result in far-fetched planning and, thereon, being too optimistic about market behaviour forecasting. Eq. (17) additionally splits the problem in terms of its time-frame $\mathcal{T}$ into a number of independent ones, each consisting of 24 hours.

$$soc_{l,t} = SOC^0 \qquad l \in \mathcal{L}, t = 24 * k, k \in \mathbb{N}^0 \tag{17}$$

EV battery must maintain a high SOC at morning hour of disconnection for daily utilisation and is connected to the grid in evening hours with low charge level.

$$soc_{l,t} = SOC_{EV}^{off} \qquad l \in \mathcal{L}, t = t_{EV}^{off} * k, k \in \mathbb{N}^0 \tag{18}$$

$$soc_{l,t} = SOC_{EV}^{on} \qquad l \in \mathcal{L}, t = t_{EV}^{on} * k, k \in \mathbb{N}^0 \tag{19}$$

If decided by the problem definition to participate in SRM, BESS will submit corresponding power bid, equal to available "up" and "down" reserve of each location, taking into account the transformer limitations in Eq. (8). In addition, power bids are defined by the difference between maximum and current locational discharge, explained in Eqs. (20) and (21) for BESS and in (22) and (23) for EV.

$$0 \leq r_{l,t}^U \leq d^{max} * N_l^{SU} - d_{l,t} + c_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{20}$$

$$0 \leq r_{l,t}^D \leq d^{max} * N_l^{SU} + d_{l,t} - c_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{21}$$

$$0 \leq r_{l,t}^U \leq d_{EV}^{max} * N_l^{EV} * id_t^{EV} - d_{l,t} + c_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{22}$$

$$0 \leq r_{l,t}^D \leq d_{EV}^{max} * N_l^{EV} * id_t^{EV} + d_{l,t} - c_{l,t} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{23}$$

The following limitations forbid submitting such power bid, that could potentially, together with current charge and discharge, make the storage SOC go beyond its limits. As it was observed from Figure 31, $r_{l,t}^U$ stands for the bid of opportunity of corresponding discharge, whereas $r_{l,t}^D$ - same, but of charge.

$$SOC^{min} \leq soc_{l,t-1} + \frac{\Delta t * (c_{l,t} - \frac{d_{l,t}}{\gamma^{rte}})}{E^{max} * N_l^{SU}} - \frac{\Delta t^{sr} * r_{l,t}^U}{\gamma^{rte} * E^{max} * N_l^{SU}} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{24}$$

$$SOC^{max} \geq soc_{l,t-1} + \frac{\Delta t * (c_{l,t} - \frac{d_{l,t}}{\gamma^{rte}}) + \Delta t^{sr} * r_{l,t}^D}{E^{max} * N_l^{SU}} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{25}$$

Supplemental constraints are required when SRM bids are submitted by EV battery. Its SOC should comply to similar limitations of correct price accepting bids.

$$\begin{gathered} SOC^{min} \leq soc_{l,t-1} + \frac{\Delta t * (c_{l,t} - \frac{d_{l,t}}{\gamma_{EV}^{rte}})}{E_{EV}^{max} * N_l^{EV}} - \frac{\Delta t^{sr} * r_{l,t}^{U}}{\gamma_{EV}^{rte} * E_{EV}^{max} * N_l^{EV}} \\ l \in \mathcal{L}, t \in \bigcup_{k \in \mathbb{N}^0} \left\{ k * 24 + \left(\left[1; t^{off}\right] \bigcup [t^{on} + 1; 24] \right) \right\} \end{gathered} \tag{26}$$

$$\begin{gathered} SOC^{max} \geq soc_{l,t-1} + \frac{\Delta t * (c_{l,t} - \frac{d_{l,t}}{\gamma_{EV}^{rte}}) + \Delta t^{sr} * r_{l,t}^{D}}{E_{EV}^{max} * N_l^{EV}} \\ l \in \mathcal{L}, t \in \bigcup_{k \in \mathbb{N}^0} \left\{ k * 24 + \left(\left[1; t^{off}\right] \bigcup [t^{on} + 1; 24] \right) \right\} \end{gathered} \tag{27}$$

According to the regulations of the secondary reserve in Spain, transmission system operator (TSO) declares the ratio of secondary reserve bids, which reflects whole regulation area, rather than independent units [59]:

$$\sum_{l \in \mathcal{L}} r_{l,t}^{U} = \alpha^{sr} * \sum_{l \in \mathcal{L}} r_{l,t}^{D} \qquad t \in \mathcal{T} \tag{28}$$

For given model, $\alpha^{sr} = 1.5$.

Parameters β_t^U and β_t^D regulate the amount of secondary regulation energy to be traded, depending on the bids $r_{l,t}^U$ and $r_{l,t}^D$. Fractions are determined by assuming only 70% of time periods secondary energy will actually be traded and, apart from that, “up” and “down” kWh values of $e_{l,t}^U$ and $e_{l,t}^D$ may not simultaneously be non-zero. In other words, charging and discharging within the same market at the same instant is not possible.

Additionally, the maximum time response of secondary reserve energy is up to 15 minutes [60], hence, Δt^{sr} in following equations is equal to 0.25:

$$e_{l,t}^{U} = \Delta t^{sr} * \beta_t^{U} * r_{l,t}^{U} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{29}$$

$$e_{l,t}^{D} = \Delta t^{sr} * \beta_t^{D} * r_{l,t}^{D} \qquad l \in \mathcal{L}, t \in \mathcal{T} \tag{30}$$

The value of secondary energy fraction remains in the range between 0 and 1, with certain probabilities, which are described in the table as follows:

$$p(\beta_t^U, \beta_t^D) = \begin{cases} 0.3 & \beta_t^U = 0, \beta_t^D = 0 \\ 0.35 & \beta_t^U = 0, \beta_t^D \in [0.7; 1] \\ 0.35 & \beta_t^U \in [0.7; 1], \beta_t^D = 0 \end{cases}$$

5.2.5 Objective Function

Objective function is expressed as a sum of components, which are positive numbers for incomes and negative numbers for costs. In Eq. (31) the revenues are secondary reserve market flows, whereas expenditures arise from day-ahead market purchasing and storage wear costs.

Optimization objective covers a certain time frame, or trading period, which in the case of this study is half of year (4344 hours).

In real conditions a market player submitting a bid to day-ahead or reserve market is not aware of the actual clearing price, since such is only determined once all bids are admitted and processed. Based on that, computation of the objective with actual price $\lambda_t^{srm} * (r_{l,t}^U + r_{l,t}^D) - \lambda_t^{dam} * M_{l,t}$ would assume anticipating perfect trading conditions by knowing that price before it has been decided. In order to avoid such overestimated prediction precision, it has been assumed that a decision maker submits a bid according to one-week-ago clearing price: λ_{t-168}^{srm} for SRM and λ_{t-168}^{dam} for DAM, as shown in Eq. (31).

$$\begin{aligned} \max \sum_{l \in \mathcal{L}} \sum_{t \in \mathcal{T}} \left[\lambda_{t-168}^{srm} (r_{l,t}^U + r_{l,t}^D) - \lambda_{t-168}^{dam} M_{l,t} \right] - \\ - \sum_{l \in \mathcal{L}} \left[\frac{C_l^{capex} \delta^{rep}}{cyc^{max}} * \frac{\sum_{t \in \mathcal{T}} (c_{l,t} \Delta t + e_{l,t}^D)}{N_l^{SU} E^{max}} \right] \end{aligned} \tag{31}$$

The term $\frac{C_l^{capex} \delta^{rep}}{cyc^{max}}$ is equal to C_l^{cycle} and is referred to the operation cycle cost for pro-visionary unit replacement, introduced inherently from Eq. (4), varying in different neighbourhoods due to variable number of storage units and non-linear CAPEX for some BESS units (for instance, Tesla) [23].

Relation $\frac{\sum_{t \in \mathcal{T}} (c_{l,t} \Delta t + e_{l,t}^D)}{N_l^{SU} E^{max}}$ (slightly altered for EV) performs as a cycle counter in single neighbourhood throughout the trading period. In such way, multiplication of this number by C_l^{cycle} results in total pro-visionary storage expenses in location l.

While in the case of energy arbitrage sub-problem, secondary reserve market remains disregarded (i.e. $r^U_{l,t} = r^D_{l,t} = 0$ and $e^U_{l,t} = e^D_{l,t} = 0$), the objective function may be reformulated to minimization of costs - as in Eq. (32).

$$\min \sum_{l\in\mathcal{L}} \sum_{t\in\mathcal{T}} \left[\lambda^{dam}_{t-168} * M_{l,t}\right] + \sum_{l\in\mathcal{L}} \frac{C_l^{cycle} \sum_{t\in\mathcal{T}} c_{l,t}\Delta t}{N_l^{SU} E^{max}} \tag{32}$$

When electric vehicle V2G operation is considered, objective function is slightly modified to the one shown in Eq. (33). No BESS are operated in this particular example.

$$\begin{aligned} \max \sum_{l\in\mathcal{L}} \sum_{t\in\mathcal{T}} \left[\lambda^{srm}_{t-168}(r^U_{l,t} + r^D_{l,t}) - \lambda^{dam}_{t-168} M_{l,t}\right] - \\ - \sum_{l\in\mathcal{L}} \left[\frac{C_l^{capex,ev} \delta^{rep}_{EV}}{cyc^{max}_{EV}} * \frac{\sum_{t\in\mathcal{T}}(c_{l,t}\Delta t + e^D_{l,t})}{N_l^{EV} E^{max}_{EV}}\right] \end{aligned} \tag{33}$$

5.2.6 Trading Period Profit Estimation

A solution to the optimization problem may be expressed in a vector of decision variables x. Such vector dimensions are limited, in accordance with $x \in \mathbb{R}^n \times \{0,1\}^k$, where n is the number of continuous variables and k - number of binary variables. Under the conditions of optimality, vector x possesses values that complete objective function from Eq. (31), (32) or (33), in other words, the solution is:

$$x_i^* \equiv \arg\max\{problem_i\} \tag{34}$$

Obtained solution allows computing trading period (half-year) profit (TPP) for the problem i, as in Eq. (35), decomposable to two main components, thus measuring the profit increase. For that, economic results of storage operation B_l^{load} is compared to conventional case without installed storage C_l^{load} in every location l.

$$TPP_l\left(x^*\right) = B_l^{load}\left(x^*\right) - C_l^{load} \tag{35}$$

Furthermore, storage profit B_l^{load} is decomposed to five main components, expressing different streams of expenses and incomes in Eq. (36).

$$\begin{aligned} B_l^{load}\left(x^*\right) = & \underbrace{\sum_{t\in\mathcal{T}} \lambda_t^{srm}(r_{l,t}^{U*} + r_{l,t}^{D*})}_{R_l^{srm}(r_{l,t}^{U*}, r_{l,t}^{D*})} - \underbrace{\sum_{t\in\mathcal{T}} \lambda_t^{dam} M_{l,t}^*}_{R_l^{dam}(M_{l,t}^*)} + \\ & + \underbrace{\sum_{t\in\mathcal{T}} \lambda_t^{isre} e_{l,t}^{U*}}_{R_l^{isre}(e_{l,t}^{U*})} - \underbrace{\sum_{t\in\mathcal{T}} \lambda_t^{dsre} e_{l,t}^{D*}}_{R_l^{dsre}(e_{l,t}^{D*})} - \underbrace{\frac{C_l^{capex}\delta^{rep}}{N_l^{SU} E^{max} cyc^{max}} * \sum_{t\in\mathcal{T}} (c_{l,t}^*\Delta t + e_{l,t}^{D*})}_{R_l^{wear}(c_{l,t}^*, e_{l,t}^{D*})} \end{aligned} \tag{36}$$

Storage unit wear costs may be used optionally when computing TPP, based on the structure and purposes of economic analysis. Eq. (36) includes that component, but in other cases TPP may solely consist of benefits from bidding to SRM, DAM expenses, incremental secondary energy incomes and costs of that decremental analogue.

Practically, every problem optimization and profit computation at its final step must be compared to the situation in which the electricity company would operate without any BESS installations. In that case, trading period would be only characterised with serving load costs. That is expressed in Eq. (37). Value C_l^{load} is computed for every location l.

$$C_l^{load} = \sum_{t\in\mathcal{T}} \lambda_t^{dam} * L_{l,t}^N \tag{37}$$

Investment payback period (IPP) is an important measure of project feasibility, thus, it has to be included in the analysis. It may be computed according to Eq. (38).

$$IPP_l = \frac{C_l^{capex}}{2 * TPP_l(x^*)} \tag{38}$$

Project investment verification accounts for a defined time-frame, or horizon. Potential investor may be interested in estimated return of investment (ROI) after j years of project deployment. Neglecting discount rate, locational ROI is computable as in Eq. (39), and usually expressed in percentage values.

$$ROI_{l,j} = \frac{2 * j * TPP_l(x^*)}{CAPEX_l} \times 100\% \tag{39}$$

5.3 Problem Definition

Analysing market trading performance with distributed BESS may be of a higher efficiency when defining several sub-problems for optimization. While literature review showed a wide range of different results and whilst potential benefits are easily affect-able by minor variations, conclusions in a broader scope of scenarios are preferable. Sub-problems reflect and imply certain specifications of mathematical model.

Initially, it had been desired to define problems, describing different operation conditions for a set of all 106 locations. Unfortunately, such implementation had led to the exceptional complexity, that was unable to be solved by given solvers. Initially defined problems' dimensions are expressed numerically in Tab. 5.

Table 5: Dimensions of 106 location problems

Problem	Continuous Variables (n)	Binary Variables (k)	Constraints
EAP	2 743 704	460 570	3 683 712
SRM	4 598 486	460 570	7 393 700
EV	4 521 561	460 570	6 703 004
OUT	3 203 872	460 570	4 144 176

Such outcome requires a stronger large-scale optimization algorithms in order to converge. However, application of optimization techniques on power system problems very often deals with extended complexity due to complicated structure of electric system and small decision making time-frames.

Somewhat heuristic decomposition is required for correct interpretation. Finding the exact algorithm for optimal locational clustering in given project conditions and with the data available results problematic. Geographic proximity would be a heuristic approach that could be proposed for finding the optimal aggrupation. Further work attention should be paid to mentioned issue. Nevertheless, lack of required data does not allow doing so in this study with a sufficient degree of certainty.

Hence, a decomposition strategy has been applied, dividing the set of locations $\mathcal{L}$ to a number of subsets m, 26 of them consisting of 4 locations and 1 - of 2 locations. In such way, every subset optimization solution is subject to the constraint in Eq. (28). Grouping in subsets has been performed in the sequence of neighbourhood names. For instance, first subset of locations consists of elements $l1$-$l4$ of $\mathcal{L}$.

5.3.1 Energy Arbitrage Problem

Under the conditions, given by this sub-problem, BESS operation is determined solely by energy arbitrage. In this case, BESS buys electricity from day-ahead market and when the power price is low and supplies the load during hours with high cost.

Described scenario is characterised by minimizing day-ahead market costs and storage wear costs by supplying electrical load of every consumer. Energy arbitrage related trading is visualised in Figure 31 with black arrows. Any other market operations, for instance, secondary reserve, are not permitted in this sub-problem. In the end, m problems of EAP are defined as follows:

$$EAP_{m\in\{1,2..,27\}} = \begin{cases} \min & (32) \\ s.t.: & (6),(7),(9),(10),(13),(14),(16),(17) \end{cases}$$

5.3.2 Secondary Reserve Market Problem

Further problem of secondary reserve market performs as an extension of the arbitrage problem, explained previously, because it inherits existing parameters, variables and constraints, introducing new ones on the top of that.

This sub-problem allows retailing units, equipped with BESS, to submit price-accepting bids to both day-ahead and secondary reserve markets. In such manner, the optimization objective is extended by maximizing profits from submitted bids to SRM.

$$SRM_{m\in\{1,2..,27\}} = \begin{cases} \max & (32)\\ s.t.: & (6)\text{-}(10),(13),(14),(16),(17),\\ & (20),(21),(24),(25),(28)\text{-}(30) \end{cases}$$

5.3.3 Electric Vehicle Problem

The intention of incorporating battery energy storage in a sense of electric vehicle has arisen due to the interest in potential revenues from vehicle-to-grid (V2G) operations. In studied case, electric vehicles are used for energy arbitrage and secondary regulation. These problems have been already defined in previous sections, although certain conditions must be adapted.

Given sub-problem implies a number of EV's in a neighbourhood, each characterised with a battery of energy capacity E_{EV}^{max} and maximum discharge capacity of d_{EV}^{max}. Additionally, the model assumes EV batteries operate repeatedly within the time gap between the hour of connection t_{EV}^{on} and the hour of disconnection t_{EV}^{off}. Those may be altered by the user.

At disconnection hour the battery must have high SOC, because EV users intent to use their vehicles throughout the period between disconnection and connection. Therefore, mentioned SOC value SOC_{EV}^{off} should be defined in advance. Similarly, when EVs are connected, the state-of-charge is usually low or close to zero. Such is determined by parameter SOC_{EV}^{on}.

$$EV_{m\in\{1,2..,27\}} = \begin{cases} \max & (33)\\ s.t.: & (6)\text{-}(8),(11)\text{-}(13),(15)\text{-}(19),(22),(23),(26)\text{-}(30) \end{cases}$$

5.3.4 Outage Problem

One of the grid reliability characteristics is the number of hours of expected and unexpected outages, i.e. when customers are disconnected from electric supply without their own will. Though European reliability indices remain relatively high [61], outages is an inevitable part of operation with the risk being always above zero.

Relative indexes represent described value, particularly, *System Average Interruption Duration Index* (SAIDI), which is demonstrated in Eq. (40). It explains the relation of average interruption duration per customer in a conjunction of supply points.

$$SAIDI = \frac{\sum_i (U_i * N_i)}{\sum_i N_i} \tag{40}$$

where:
U_i - annual failure rate [mins/year];
N_i - number of customers in the point of supply i.

Hence, this sub-problem tries to study the possibility of BESS to cover the outage completely or partially with stored energy, taking into account the sudden nature of such disconnections, i.e. one may not predict at which hour it may occur and, therefore, may not charge the batteries up-front.

Distribution system operator may benefit from increasing grid stability, as well as from avoiding outage compensation, defined in [62], and expressed in Eq. (41).

$$D = 5 * P^{contr} * (N^h_{int} - N^h_{fix}) * \lambda^{trf} \tag{41}$$

where:
D - customer outage compensation [€];
P^{contr} - customer contracted power [kW];
N^h_{int} - number of hours of interrupted supply [h/year];
N^h_{fix} - maximum permitted and fixed by law number of hours of interrupted supply [h/year];
λ^{trf} - contracted tariff energy price [€/kWh].

Due to limitations of the study we assume every neighbourhood suffers a complete outage for a number of hours, derived from SAIDI index; and is compensated in accordance with neighbourhoods contracted power P^{contr}_l, fixed number of outages $N^h_{fix} = 5$ from [62], and with 2.0A tariff price λ^{trf} from year 2014, which is available in the database of Spanish TSO [2] or market operator [1].

It is fair to note that implementation of this sub-problem should extend the problem of energy arbitrage or secondary reserve market, as desired by the user.

$$OUT_{m\in\{1,2..,27\}} = \begin{cases} \min & (32) \\ s.t.: & (6)\text{-}(7),(9),(10),(13),(14),(16),(17) \end{cases}$$

Practical idea behind this problem is randomly[5] deciding hours of outage and identifying the proportion of power that BESS may supply at this hour. Since the random decision regards whether the system suffers an outage or not, it shall be implemented with binary number (for example: 1 - stable, 0 - outage). Randomization of this binary number is dictated by certain probability, which is defined by the index of SAIDI. Average SAIDI in Spain within the period from 1999 to 2011 is estimated to be 133,9 minutes [63]. To avoid anticipation, batteries must operate in conditions of energy arbitrage ot secondary reserve market problems.

5.3.5 Transmission and Distribution Costs Deferral Problem

European electrical system demand is suffering annual increases over last decades [10], which requires system operators to deal with issues of extending the capacities of electrical networks, or transmission and distribution systems.

This problem investigates the financial benefit from BESS on postponing T&D (transmission and distribution) maintenance investment.

Spanish TSO Red Eléctrica de España has studied the evolution of national electrical demand in [8], that showed in years 2011-2014 the national demand has been decreasing, followed by a 1,9 % increase in 2015. Mentioned evolution may be observed in Tab. 6.

Table 6: The Spanish electrical system demand evolution [8]

Year	Demand, GWh	Increase, %
2011	255 597	-1,9
2012	252 014	-1,4
2013	246 368	-2,2
2014	243 544	-1,1
2015	248 181	1,9

---

[5] Actually, reproducible random number streams are used to repeat same results after running the code several times.

For a case study of a set of neighbourhoods, distribution transformer capacity extension may be required if maximum transmitted power will be exceeded. Thus, formulating this sub-problem implies supposing a value of annual electricity demand increase, applying that to the peak power consumption in a neighbourhood P_l^{peak} and, consequently, identifying those zones, where during the period of project accumulation the maintenance will be required.

However, no optimization is needed to solve given problem, but rather a simple calculation, estimating demand growth in every location and, consequently, deciding on necessity of maintenance that can be deferred thanks to existence of storage.

6 Case Study

This chapter covers the study case, which has been developed in previous sections. As determined, this process was composed of four main steps:

- Smart meter data mining and analysis for electrical consumption estimation, depending on seasonal, locational and consumer type characteristics;
- Overview of electricity market functionality principles, emphasizing particular mechanisms of that in Spain and evaluating its tolerance towards BESS;
- Technological overlook of battery energy storage market products, its limitation and benchmarking
- Creation of mathematical model, that would allow evaluating performance of BESS under certain conditions with fairly adjustable inputs.

Once having done mentioned steps, the aim of the projects is to obtain results of economic viability of BESS for defined sub-problems.

6.1 Parameter Value Assignation

A range of numerical values for parameters from the model (listed in Section 5.2.2) has to be assigned before launching the optimization. This section explains the nature of assumed values and limitations made throughout this process.

6.1.1 Data Obtained From Previous Chapters

Previous sections of this thesis had described a spectrum of procedures for obtaining customer load data, electricity market prices and battery storage technical and economic characteristics.

As it has been concluded in those chapters, corresponding parameter inputs are created from made assumptions and available resources. It has been decided to implement the design of Tesla Powerpack© battery, that showed lowest cost per unit of energy and most actual cost figures (Tab. 3). Defined parameters are visualised in Tab. 7. Actual electricity market prices of first six months had been implemented for parameters λ_t^{dam}, λ_t^{srm}, λ_t^{dsre} and λ_t^{dsre}. Those prices are available in [1, 2]. Apart from that, parameter β_t^U and β_t^D definitions are explained in Section 5.2.4. Annual demand for T&D problem has been assumed being 1,9 %, according to Tab. 6 most recent value.

Table 7: Parameter values obtained throughout the study

Parameter	Value	Parameter	Value
λ_t^{dam}	Array	SOC^{ini}	0.5
λ_t^{srm}	Array	SOC^0	0.5
λ_t^{isre}	Array	γ^{rte}	0.8763
λ_t^{dsre}	Array	E^{max}	100
$\lambda_{l,t}^{out}$	Array	d^{max}	50
$L_{l,t}^N$	Array	cyc^{max}	5000
P_l^{contr}	Array	C_l^{capex}	$59623+41768*N_l^{SU}$
Δt	1	SOC^{min}	0
Δt^{sr}	0.25	SOC^{max}	1
α^{sr}	1.5	ΔP	1,9 %

6.1.2 Case Study Assumed Values

Remaining parameter values have been assumed or defined for particular case study, thus, are requiring further comments to be made. Primarily, those parameters and their respective values are listed in Tab. 8.

Table 8: Parameter values assumed

Parameter	Value	Parameter	Value
P_l^{max}	Array	N_l^{SU}	$\in [1,2,3,4,5]$
δ^{rep}	0.216	N_l^{EV}	$0.1*N_l^{cust}$
t_{EV}^{on}	20	t_{EV}^{off}	8
SOC_{EV}^{on}	0.1	SOC_{EV}^{off}	0.9
E_{EV}^{max}	25	d_{EV}^{max}	15
γ_{EV}^{rte}	0.8763	cyc_{EV}^{max}	5000
$C_l^{capex,ev}$	$10675*N_l^{EV}$		

Power transformer maximum capacity P_l^{max} is a technical limitation of hourly transmitted energy, thus, when installed, it must be able to serve secondary-side load's peak power with finite gap for emergency situations.

Data analysis and locational distribution showed average neighbourhood has 59 customers, and average peak power of 52 kW. Hence, one transformer maximum capacity has been assumed to be 80 kW. Moreover, neighbourhoods which peak consumption exceeds 80 kW are determined to have two transformers, increasing power limitation to 160 kW. Similarly, the number of transformers within neighbourhoods with higher peak loads is selected. Resulting table in Tab. 9 displays frequencies of locations with different number of transformers.

Table 9: Locations with different P_l^{max}

Number of transformers	1	2	3	4	5
P_l^{max}, kW	80	160	240	320	400
Frequency	85	18	2	0	1

Previous chapters claimed battery prices are set to reduce heavily next years. However, precise estimation is hard to achieve and majority of studies apply sensitivity analysis to their forecasts. Taking into account [5, 14, 21], it has been estimated that the fraction of current cost of battery after j years will be:

$$\delta_j^{rep} = 0.88^j \tag{42}$$

Additionally supposing battery performs 400 full cycles annually, a lifetime of 5000 cycles, in case of Tesla Powerpack© product, would stretch to 12.5 years. This means replacement cost δ^{rep}, according to Eq. (42), would simulate the case of $j = 12$. The calculation, thus, has been resulted in $\delta^{rep} = 0.216$ (stated in Tab. 8).

The next question regards the number of storage units in every location. Since this decision affects optimal operation and, consequently, estimated profits; it is advisable to make N_l^{SU} an integer variable and find optimal solution. However, in such way the mixed-integer problem becomes non-linear and with existing scale requires exceeding amount of computational time.

That being said, it has been decided to run a set of optimizations with N_l^{SU} remaining as a parameter and adjusting its value from 1 to 5. Posteriorly, number of storage units which gives better economic prognosis, is decided to be optimal. Mentioned range has been preferred due to non-linear CAPEX of used storage units, when one power converter is capable of serving 250 kW of maximal discharge [23].

In that occasion, per kWh storage unit price will remain lowest when purchasing 5 units, since they provide exactly 250 kW of maximum charge/discharge capacity.

In order to perform an optimization on electric vehicle problem, one must define a number of electric vehicles in every location N_l^{EV}. Implementing actual EV-ownership percentage would result less demonstrative, since only 10 000 EVs are in operation currently in Spain [64]. For that reason, the study assumes at every location 10% of contracted consumers possess an EV.

Supplemental parameters are required for defining EV operational conditions. Those are the hours of the day when the devices are connected and disconnected from the grid, hence, stating a period of time of connection and disconnection. Additionally, state-of-charge at these instants of time must be fixed for obvious reasons of EV utilization routine.

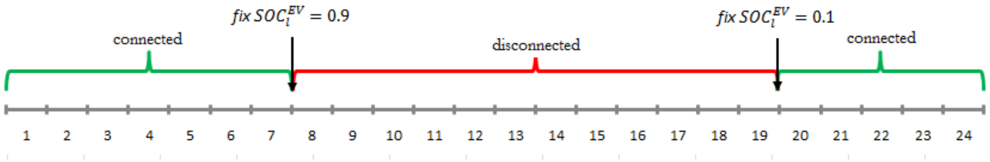

Figure 32: Visualization of EV operation implementation

Illustratively discussed parameters describing EV operation in case study are demonstrated in Figure 32 specifying assumptions made in Tab. 8.

Characteristics of electric vehicle for specific problem had been sourced from several references regarding existing EV batteries, combined in [65]. Based on that, and after several approximations, it has been decided that energy capacity of EV battery E_{EV}^{max} should be equal to 25 kWh, whereas discharge capacity d_{EV}^{max} yields 15 kW.

Apart from that, [66] claims battery costs for electric vehicles ranges between 350 up to 440 €/kWh. Therefore, final price of 427 €/kWh has been implemented. This, however, is only required for calculation cycle cost prior to battery replacement (as in Eq. (4)).

6.2 Problem Complexity

SAS/OR 9.3© software [67] was used for implementing optimization problems in algebraic modelling language **OPTMODEL**. Described implementation has been based on the code, developed in [19]. Mixed-integer linear programming (MILP) solver has been called on a transportable PC with brief characteristics being i7 CPU @ 2.40 GHz and 8 GB of RAM. Mathematical programming reference used throughout the development of model is available in [68].

Selected sub-problem with applied constraints and declared objective function defines a large-scale mixed-integer linear optimization problem with a number of variables and constraints, depending on the problem. Numerical figures, characterizing computational complexity, are observable from Tab. 10.

Table 10: Different optimization problem vastness

Problem	n	k	Cons.	Time, s
EAP_1	104 264	17 380	139 008	17,07
SRM_1	186 800	17 380	304 084	52,21
EV_1	186 800	17 376	232 408	16,12
OUT_1	121 640	17 380	156 384	31,87

Numbers in Tab. 10 represent the amount of continuous variables n, binary variables k and constraints when running the optimization for a subset of locations m. In this example, $m = 1$, which consists of four locations: $l1$-$l4$.

6.3 Optimization and Results

Since every problem reflects a set of locations, complete results have been moved to Appendices of this thesis project. Hence, this subsection will address more generalised and relevant numbers.

Optimization program had been run several times varying number of storage units N_l^{SU} in corresponding problems from 1 to 5 at every location. Further on, the number that resulted in lowest IPP per location, has been decided the optimal.

It is important to remind to the reader that presented figures represent the time period of six months, according to the load data available. Any longer period (year or years) estimation is subject to multiplication of obtained results to required amount of times.

Table 11: Energy arbitrage problem results (5 locations)

Location	$l23$	$l8$	$l94$	$l50$	$l66$
N_l^{SU}	5	4	5	4	5
N_l^{cyc}	250,45	214,42	161,52	209,01	161,88
C_l^{load}, €	**-19 987,39**	**-10 429,20**	**-11 480,93**	**-9 040,03**	**-10 402,82**
R_l^{dam}, €	-18 856,85	-9 605,80	-10 595,71	-8 240,75	-9 524,99
R_l^{wear}, €	-329,47	-238,18	-212,48	-232,17	-212,95
B_l^{load}, €	**-19 186,32**	**-9 843,98**	**-10 808,19**	**-8 472,92**	**-9 739,94**
TPP_l, €	**801,07**	**585,22**	**672,74**	**567,11**	**664,87**
IPP_l, yrs	16,76	19,37	19,95	19,99	20,19
EOL, yrs	9,98	11,66	15,48	11,96	15,44
$ROI_{l,10}$, %	59,68	51,63	50,11	50,03	49,53

Short table of energy arbitrage problem results is presented in Tab. 11. It displays figures of 5 locations that demonstrated lowest IPP. Initially, the problem had been initialised with actual CAPEX of batteries. However, such solution had extremely impractical values of IPP and low values of TPP. Due to high cycle cost (function of CAPEX in Eq. (4)), BESS were barely operated.

It was decided then to investigate whether an assumption of reduced CAPEX would affect the results. Such small sensitivity analysis had concluded that even applying a CAPEX coefficient of 0,1 did not justify the investment in majority of locations. Five most suitable locations, though, could reimburse the investment in 16,76 - 20,19 years. Average TPP of all 106 locations is 333,65 € and average IPP is 71,22 years.

Tbls. 11, 12 and 13 use a range of symbols for streams of expenses and incomes. For simplicity, expenses in mentioned tables are written in negative numbers. C_l^{load} expresses total expenditures of electricity company serving load without any storage installations. B_l^{load} explains profits of the battery operation. It is composed of: R^{dam} - day-ahead market expenses; R_l^{wear} - storage wear cost; R_l^{dsre} - decremental secondary reserve energy expenses; R_l^{isre} - incremental secondary reserve energy incomes; R_l^{srm} - secondary reserve market incomes.

Similar presentation of results of secondary reserve market problem is found in

Table 12: Secondary reserve market problem results (5 locations)

Location	$l8$	$l7$	$l23$	$l5$	$l50$
N_l^{SU}	5	3	5	3	5
N_l^{cyc}	131,36	113,10	331,11	197,41	119,18
C_l^{load}, €	**-10 429,20**	**-7 754,92**	**-19 987,39**	**-7 179,58**	**-9 040,03**
R_l^{dam}, €	-11 039,61	-7 957,50	-23 608,32	-7 663,50	-9 591,87
R_l^{wear}, €	-1 727,98	-1 024,88	-4 355,75	-1 788,85	-1 567,76
R_l^{dsre}, €	-402,47	-297,47	-95,67	-462,02	-313,50
R_l^{isre}, €	1 927,29	958,81	4 409,32	1 626,16	1 612,54
R_l^{srm}, €	42 334,88	27 045,69	41 691,76	26 841,61	38 101,71
B_l^{load}, €	**31 092,10**	**18 724,65**	**18 041,35**	**18 553,41**	**28 241,12**
TPP_l, €	**41 521,31**	**26 479,57**	**38 028,74**	**25 732,99**	**37 281,16**
IPP_l, yrs	3,23	3,49	3,53	3,59	3,60
EOL, yrs	19,03	22,10	7,55	12,66	20,98
$ROI_{l,10}$, %	309,32	286,86	283,3	278,3	277,74

Tab. 12. This time, actual CAPEX has been used from collected manufacturer data in Tab. 3. Five most promising locations require 3,23 - 3,60 years to recover battery cost. Regional average TPP yields 14 042,15 € with average IPP being equal to 5,75 years. In resulted operation conditions average BESS installation will operate 19,48 years.

Table 13: EV problem results (5 locations)

Location	$l69$	$l75$	$l10$	$l23$	$l101$
N_l^{EV}	10	10	9	23	5
N_l^{cyc}	182,86	276,67	210,70	296,60	159,03
C_l^{load}, €	**-6 741,69**	**-7 030,77**	**-7 326,13**	**-19 987,39**	**-2 800,96**
R_l^{dam}, €	-7 690,28	-8 301,01	-8 661,07	-24 078,20	-3 208,26
R_l^{wear}, €	-390,40	-590,69	-449,83	-633,25	-339,53
R_l^{dsre}, €	-97,53	-304,32	-14,38	-331,68	-37,62
R_l^{isre}, €	447,87	1 098,38	547,30	2 729,95	74,83
R_l^{srm}, €	14 466,62	14 323,91	13 088,65	32 525,55	7 264,49
B_l^{load}, €	**6 736,27**	**6 226,27**	**4 510,68**	**10 212,38**	**3 753,91**
TPP_l, €	**13 477,96**	**13 257,04**	**11 836,80**	**30 199,77**	**6 554,87**
$\frac{TPP_l}{N_l^{EV}}$, €	1 347,80	1 325,70	1 315,20	1 313,03	1 310,97

EV problem does not involve any investment, since it has been assumed that there is already a particular amount of electric vehicles per location, supplied by direct EV buyers. This number is proportional to the amount of actual consumers. Thus, TPP has been calculated per EV and then the Tab. 13 has been sorted descending on that. No stationary BESS are considered installed in this problem, only EVs. In perspective, simultaneous implementation of both solutions may lead to interesting results, that are worth to study. However, this thesis addresses these problems separately due to defined goals and limited time-frame.

It is worth mentioning, that despite neglecting CAPEX, battery wear cost still remains included, though, it is optional to consider that. This usually depends on the structure of desired economic analysis. The wear cost has been computed, basing on assumed cost of EVs in a neighbourhood $C_l^{capex,ev}$.

Total results account for average number of 6,3 EVs per location, 5 955,64 € average TPP, thus reaching a demonstrative profit figure of 928,86 €/EV.

Table 14: T&D and outage problem results (5 locations)

Location	$l1$	$l2$	$l3$	$l4$	$l5$
N_l^{cust}	76	1	69	113	123
N_l^{tr}	1	1	2	2	2
P_l^{contr}, kW	334,65	3,45	318,1	529,2	570,8
P_l^{peak}, kW	55,32	1,72	88,81	150,71	88,11
$P_l^{peak} - P^{tr} \times N_l^{tr}$, kW	-14,47	-77,96	-54,79	18,52	-55,62
N_{int}^h	3	6	3	1	3
D_l, €	0	6,23	0	0	0

Results of outage and T&D deferral problems had been grouped to same table due to most computations had been performed outside SAS/OR environment. Tab. 14 demonstrates number of customers N_l^{cust} in five locations, number of 80 kW power transformers N_l^{tr}, total contracted power of consumers in a neighbourhood P_l^{contr} and their peak consumption P_l^{peak}.

Term $P_l^{peak} - P^{tr} \times N_l^{tr}$ measures kWs, by which the peak consumption will be exceeded at year 10. This allows concluding on necessity of transformer capacity increase. In total, it resulted that during the period of 10 years, in 15 locations out of 106, transformer extension is required. With assumed price of one transformer, total cost shall be 25 682,10 €.

Regarding outage, whenever the number of interruptions hours exceeds 3 (maximum allowed number of hours of unpredicted shortage), consumer gets somewhat compensation. A part of that compensation that has been avoided thanks to BESS is expressed as D_l and is calculated from Eq. (41).

In total, avoided outage compensation cost resulted to be 8 641,58 €.

Tab. 15 compares the results of different problems, showing the calculations for whole spectrum of locations l in $\mathcal{L}$, avoiding average values, but rather summarizing total expenses and incomes. ROI values account for a 10-year period and HP - for horizon profit (similarly, 10 years).

Table 15: Comparison of results

Problem	$N^{SU/EV}$	CAPEX	TPP, €	IPP, yrs	HP, €	ROI, %
EAP	339/0	2 047 956	35 367	28,95	707 340	34,53
SRM	225/0	15 717 948	1 448 468	5,28	29 769 362	189,4
EV	0/667	-	631 298	-	12 625 955	-
T&D	-	-	-	-	25 682	-
OUT	-	-	-	-	8 642	-
OPT	132/377	9 031 198	1 259 721	3,58	25 194 415	278,97

It has been claimed previously that EV problem does not account for any CAPEX cost and remains profitable throughout the horizon of 10 years. Therefore, it is worth to compare each neighbourhood on the subject of the most profitable investment. That means, one may want to determine whether buying storage or providing solely V2G services result in maximum profits for system operators.

The computation has been done in a quite straightforward way - by comparing two terms for every location: horizon profit of batteries operating in secondary reserve market $HP_l^{SRM} - CAPEX_l$ and horizon profit of operating EV in the same market, but with limited hours of commitment HP_l^{EV}.

Mentioned comparison resulted in 47 locations reaching higher 10-year profits with 10% of population having EV, whereas 59 locations would achieve larger monetary benefit with installed storage units. Economic indicators are shown in the last row of Tab. 15 under the name of “OPT” problem.

6.4 Cost-Benefit Analysis

This chapter converts obtained results of optimization into a brief cost-benefit analysis for the purpose of project financial investigation under more realistic conditions and determine the best investment strategy.

In this cost-benefit analysis the goal is to compare several investment perspectives, evaluating those on a defined project horizon (10 years), calculating cash flows for different annual discount rates. Discount rate stands for the interest rate and measures the present value of future cash flows.

As a computational basis, 5 specific locations and their optimization results have been studied: ones with most promising figures, when solving secondary reserve market problem, as demonstrated in Tab. 12. Moreover, those solutions have been compared to the option of implementing EV V2G service solutions. In other words, it has been determined whether V2G operation with 10% of population driving EVs or investing in BESS would result in higher net-present value (NPV). This term is calculated according to the following formula:

$$NPV = \sum_{j=0}^{\mathcal{J}} \frac{Q_j}{(1+i)^j} \tag{43}$$

where:

$\mathcal{J}$ - is the horizon of the project in years,
Q_j - cash flow during period j in €,
i - discount rate.

This computation requires prepared cash flow for the horizon period. For brief analysis, 10-year time interval is assumed. Additionally, cash flow requires dividing fixed and variable costs. Even though the results of the optimization are quite straightforward, several alterations have been made when transmitting the number from Tab. 12 to cash flow tables.

Primarily, battery wear cost has been excluded. Instead, an investment at its EOL has been implemented, yielding $C_l^{capex} \times \delta_j^{rep}$, where j is the year of EOL and δ_j^{rep} expression is inherited from Eq. (42). That implementation refers to battery owner purchasing new storage unit, when the old has reached its EOL. The purchase price is reduced due to large-scale technology development and deployment [14].

Secondarily, a small operation and maintenance cost has been implemented. This cost is measured in €/kW/year and, as mentioned in [18, 50], may be estimated at around 14 €/kW/year.

Taking into account mentioned above, the annual cash flow Q_j for certain location may be computed, using the indices from previous chapters and the operation cost, which shall be marked with R_l^{op}. Eq. (44) demonstrates the computation.

$$\begin{aligned} Q_j = 2 * (R_l^{srm} + R_l^{isre} + C_l^{load} - R_l^{dam} - \\ -R_l^{dsre}) - d^{max} * N_l^{SU} * R_l^{op} - C_{l,j}^{capex} \end{aligned} \tag{44}$$

The term $C_{l,j}^{capex}$ is non-zero at year 0, when the first investment is made; and also at EOL, when the investment yields $C_l^{capex} \times \delta_j^{rep}$, as mentioned previously.

Other terms are withdrawn from optimization results and are assumed to repeat every further year of the project horizon. Deepened implementation of variable market prices and load might be valuable, but, unfortunately, will remain out of the scope of this project.

An example of cash flow computation is presented in Appendix B, where cash flow components are demonstrated for every year j. Mentioned example regards the investment of BESS implementation in neighbourhood $l23$ with secondary reserve market operations. Investment is made at year 0 and at year 7, because the battery reaches its EOL after 7,55 years (shown in Tab. 12).

Once the annual cash flow Q_j is obtained, it may be proceeded to the NPV computation from Eq. (43). A range of discount rates i is assumed, varying from 7% to 12%.

The cost-benefit analysis is extended to evaluate NPVs in all locations from Tab. 12. The results in terms of NPV justify the business case perspective of BESS installation. Those results are posteriorly compared to the NPVs of EV problems' solutions in same locations. Figure 33 visualises the results of that comparison.

From the graph, one may conclude that the business of adapting V2G operations in Location-23 ($l23$) provides the largest NPV, followed by BESS investment in Location-8 ($l8$). Moreover, it is noticeable that with higher values of the dis-

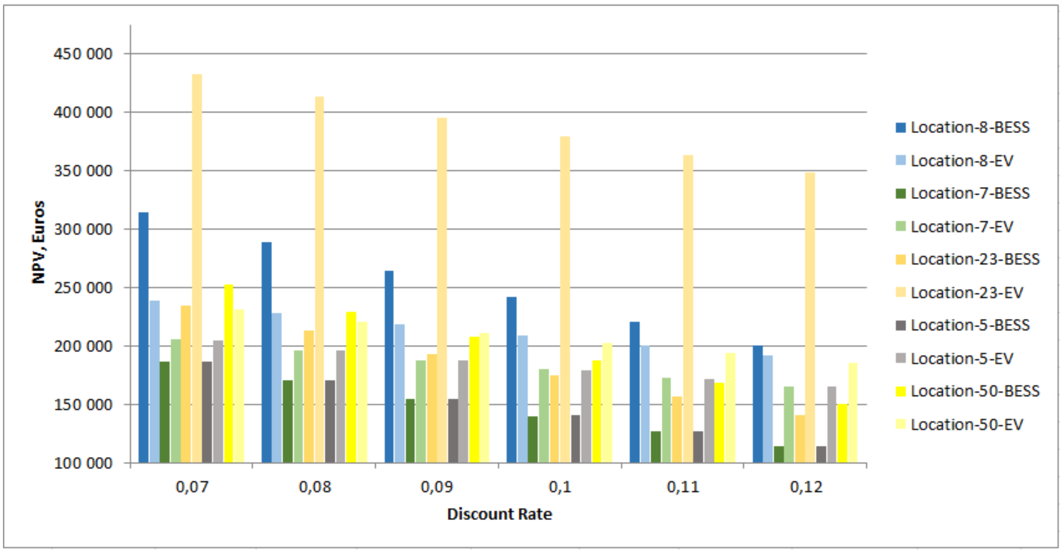

Figure 33: NPV for a range of projects with BESS or EV for 10-year horizon and different discount rates

count rate i, the NPV of BESS projects shows a higher decrease rate than those of EV projects. This is a consequence of higher cash-flow dispersion of BESS investment projects.

6.5 Discussion

Result discussion intents to give an explanation and comments on obtained results and concludes on whether they fulfil theoretical hypothesis from previous chapters.

Energy arbitrage problem results showed poor community BESS feasibility. Even with impractical CAPEX coefficient of 0,1 a minimum IPP of 16,76 years has been obtained among all locations.

Taking a closer look, one can see from Tab. 11 that the savings from DAM expenditures, as compared between "with" storage - R_l^{dam}, and "without" BESS - C_l^{load}; are relatively low despite having 400-500 kWh of energy storage and 200-250 kW of available discharge. That being said, the issues of low variability of DAM prices in current market and high cycle cost do not provide enough possibilities to justify the investment with given battery prices.

There has been a reference to mentioned problem in previous chapters, specifically, Figure 30 showed high cycle cost together with low price variance had made BESS operation for arbitrage purposes highly unreasonable.

Factors, like transformer limitations, anti-anticipation constraints or unavailability to sell energy to the pool barely affected result, when sensitivity optimization had been run. Thus, for increased profitability, severe battery cost decrease yet is required, along with suitable electricity market conditions, like price variability.

Such conclusion on energy arbitrage solution confirmed the hypothesis from references [16, 17, 18] that stated the benefits from arbitrage are insufficient to justify the investment.

BESS participation in **secondary reserve markets** showed feasible results and quite promising IPP figures, with average per location of 5,75 years. 10-year period ROI for a set of 106 locations has remained in the range between 109,27 % and 309,32 %.

Solutions demonstrated that the large share of profit is received from submitting price-accepting bids for secondary reserve - R_l^{srm}. This means the battery owner gets paid for opportunity to supply at any time a certain amount of power for ancillary services. With values of discharge reaching 250 kW for 5-unit BESS, daily profits are noticeably higher than those of energy arbitrage.

Despite having promising feasibility figures, distributed storage utilisation for secondary regulation is not permitted by several electrical system juridical articles. Firstly, this service initially is intended only for power generation units. Secondly, participants of this market must comply to a range of requirements regarding communication to AGC and minimum bid size (5 MW). It is extremely doubtable that a conjunction of neighbourhood may be identified as one generation unit.

This concludes on implementation of secondary reserve market operation being unacceptable due to local regulations, but quite promising in its financial perspective.

Some countries in Europe are more actively deploying renewable energy, non-carbon power systems and electric vehicles. For instance, in Germany, a wide range of participants may bid in regulation market, including wind and solar power plants. This enlarges the potential market of generation-coupled batteries and big-scale storage facilities. Thanks to fast response time, batteries are an exceptional provider of primary control, which is unavailable for renewables.

Domestic storage, on the other hand, is expected to play a significant role in reducing pressure on transmission systems with peak-shaving and time-shift operations, though currently not being found economically feasible [69].

EV problem is of a particular interest, since Spanish government is working towards promotion of electric vehicles by incentives and subsidies for EV buyers [70]. Additionally, it is said that 1 million EVs may be adopted by electric system without further grid investment [70].

Grid-connected vehicles may provide additional services, but their technical capabilities remain questionable. Apart from that, the impact to the load profiling of high amount of EVs is hard to estimate. Despite that, electricity companies would benefit from acquisition of EVs by their customers. Taking into account “zero” investment, an increase of profits from reserve market or solely arbitrage is indisputable. Higher EV penetration will transform EV into an important grid stability and renewable energy integration player. This promises the evolution of additional storage-related markets, where storage-owning companies and particulars might obtain a range of economic benefits.

High technical and economic potential of V2G regulatory strategies in Germany is mentioned in [71]. The paper demonstrates profitability in primary and, especially, negative[6] secondary control ancillary. During the night, the demand for such reserves is high due to low electricity consumption, which offers a high potential for “free charging”. From the system point of view, such utilization is preferable to generation unit production decrease. Clearly, with higher penetration of renewables, the requirements for mentioned services will increase.

A study, conducted in [72] had arrived to the same conclusions. Moreover, it had pointed out that German system operators require certain reserve availability time of EV-connected mode; and that detailed and accurate analysis requires the study of individual driving patterns.

T&D deferral and outage reduction, according to possible estimations, may save somewhat investment in project horizon, thanks to BESS, but a total of 34 323,68 € over 10 year period seem of a little significance. Clearly, transmission

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[6] Means providing the opportunity to withdraw the energy from the grid.

maintenance cost and additional reliability issues that may be solved by BESS are not considered in this study. Ultimately, these costs are highly case-dependent and require wider system perspective.

7 Conclusions

This thesis project assessed the problem of feasibility of distributed BESS. A theoretical discussion went along with development of optimization model, followed by combining obtained knowledge in creating an optimization tool. The tool is meant to schedule energy trading between market, consumer and BESS throughout given period of time under specified conditions.

Performed investigation consisted of three main points: working on smart meter data to define possible load profiles of electricity consumption; study the functionality principles of electricity markets and regulations regarding energy storage; and perform a brief benchmark of technological battery solutions.

The practical part combined obtained data into a equation-defined optimization model, with a range of parameters, variables, constraints and objective functions. The model has been implemented in SAS/OR© [67] software with specifications subject to different problems.

Results demonstrated low feasibility of energy arbitrage problem, but rather promising numbers of secondary reserve problem. Electric vehicle V2G operation alternative allows benefiting to electricity companies due to absence of direct CAPEX (except for costs of advanced metering and communication technologies). T&D deferral and outage reduction may act as additional values for BESS owners, postponing and saving unnecessary expenditures.

It has been discussed that practical implementation is highly subject to local policies and regulation, which remain quite restrictive in terms of battery storage in distribution grids in Spain. However, country’s governments is realising incentives towards EV acquisition, thus, boosting the development of charging systems and engaging big energy players to adapt innovative Smart Grid solutions.

Implementation of such solutions is of high importance on the way towards Smart Grids and non-carbon future. Batteries with their decreasing costs and growing market penetration are expected reach parity and be used on a wide-scale, reshaping current standards of power systems and electricity markets.

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A Appendix: Complete Optimization Results

A.1 Energy Arbitrage Problem

Table 16: Energy arbitrage problem results (sorted ascending by IPP)

Location	N_l^{cyc}	R_l^{dam}	R_l^{wear}	C_l^{load}	C_l^{capex}	EOL	TPP_l	IPP_l	N_l^{SU}
Location-23	250,45	18 856,85	329,47	19 987,39	26 846,55	9,98	801,07	16,76	5
Location-8	214,42	9 605,80	238,18	10 429,20	22 669,70	11,66	585,22	19,37	4
Location-94	161,52	10 595,71	212,48	11 480,93	26 846,55	15,48	672,74	19,95	5
Location-50	209,01	8 240,75	232,17	9 040,03	22 669,70	11,96	567,11	19,99	4
Location-66	161,88	9 524,99	212,95	10 402,82	26 846,55	15,44	664,87	20,19	5
Location-100	158,60	7 848,91	208,63	8 701,95	26 846,55	15,76	644,41	20,83	5
Location-48	157,98	7 694,04	207,82	8 542,49	26 846,55	15,83	640,63	20,95	5
Location-4	181,29	8 333,95	201,38	9 066,08	22 669,70	13,79	530,76	21,36	4
Location-7	174,03	7 031,39	193,32	7 754,92	22 669,70	14,37	530,22	21,38	4
Location-5	170,94	6 460,44	189,88	7 179,58	22 669,70	14,62	529,25	21,42	4
Location-61	176,17	7 682,36	195,69	8 406,47	22 669,70	14,19	528,42	21,45	4
Location-11	154,50	6 802,12	203,24	7 626,35	26 846,55	16,18	620,99	21,62	5
Location-60	181,07	7 828,47	201,14	8 552,65	22 669,70	13,81	523,05	21,67	4
Location-68	172,93	6 937,33	192,09	7 650,13	22 669,70	14,46	520,71	21,77	4
Location-67	168,34	6 208,79	187,00	6 912,42	22 669,70	14,85	516,63	21,94	4
Location-10	175,52	6 620,45	194,97	7 326,13	22 669,70	14,24	510,71	22,19	4
Location-75	148,61	6 231,10	195,50	7 030,77	26 846,55	16,82	604,17	22,22	5
Location-69	169,67	6 043,18	188,47	6 741,69	22 669,70	14,73	510,04	22,22	4
Location-104	164,85	5 166,99	183,12	5 833,14	22 669,70	15,17	483,03	23,47	4
Location-63	172,52	5 914,17	191,63	6 586,37	22 669,70	14,49	480,56	23,59	4
Location-43	118,29	5 543,51	131,40	6 153,59	22 669,70	21,13	478,69	23,68	4
Location-44	118,47	5 631,64	131,60	6 239,47	22 669,70	21,10	476,24	23,80	4
Location-76	118,37	5 602,28	131,48	6 209,86	22 669,70	21,12	476,10	23,81	4
Location-49	117,39	5 968,44	130,39	6 573,80	22 669,70	21,30	474,97	23,86	4
Location-64	119,45	5 056,94	132,68	5 660,59	22 669,70	20,93	470,96	24,07	4
Location-18	118,82	5 646,22	131,98	6 248,16	22 669,70	21,04	469,96	24,12	4
Location-35	119,64	4 951,55	132,90	5 553,31	22 669,70	20,90	468,86	24,18	4
Location-55	119,14	4 931,62	132,34	5 531,77	22 669,70	20,98	467,80	24,23	4
Location-62	119,35	4 829,41	132,57	5 429,73	22 669,70	20,95	467,74	24,23	4
Location-24	119,07	5 370,64	132,26	5 970,60	22 669,70	21,00	467,71	24,23	4
Location-82	118,61	4 473,62	131,76	5 064,40	22 669,70	21,08	459,02	24,69	4
Location-103	117,99	4 269,78	131,06	4 859,43	22 669,70	21,19	458,58	24,72	4
Location-81	113,85	5 266,30	126,46	5 846,46	22 669,70	21,96	453,69	24,98	4
Location-1	118,33	4 257,66	131,44	4 841,27	22 669,70	21,13	452,17	25,07	4
Location-39	120,33	4 889,13	133,66	5 474,88	22 669,70	20,78	452,09	25,07	4
Location-3	160,46	4 647,26	178,24	5 274,60	22 669,70	15,58	449,09	25,24	4
Location-54	117,97	4 134,85	131,05	4 713,39	22 669,70	21,19	447,49	25,33	4
Location-21	117,27	4 072,76	130,27	4 649,69	22 669,70	21,32	446,66	25,38	4
Location-41	117,39	3 981,16	130,40	4 556,19	22 669,70	21,30	444,63	25,49	4
Location-102	117,82	4 127,41	130,88	4 702,69	22 669,70	21,22	444,40	25,51	4
Location-16	116,77	3 893,03	129,71	4 465,69	22 669,70	21,41	442,94	25,59	4
Location-6	117,59	4 054,74	130,62	4 627,87	22 669,70	21,26	442,51	25,62	4

Location	N_l^{cyc}	R_l^{dam}	R_l^{wear}	C_l^{load}	C_l^{capex}	EOL	TPP_l	IPP_l	N_l^{SU}
Location-40	117,45	3 976,21	130,47	4 548,68	22 669,70	21,28	442,00	25,64	4
Location-17	115,83	3 757,89	128,66	4 326,71	22 669,70	21,58	440,16	25,75	4
Location-65	114,72	5 214,99	127,43	5 781,40	22 669,70	21,79	438,98	25,82	4
Location-105	117,15	3 907,42	130,13	4 473,93	22 669,70	21,34	436,39	25,97	4
Location-47	115,14	3 573,63	127,90	4 137,52	22 669,70	21,71	436,00	26,00	4
Location-84	116,39	3 777,31	129,29	4 342,05	22 669,70	21,48	435,46	26,03	4
Location-79	116,04	4 801,80	128,90	5 361,56	22 669,70	21,54	430,86	26,31	4
Location-96	142,23	5 310,36	128,89	5 789,73	18 492,85	17,58	350,49	26,38	3
Location-42	112,74	3 295,29	125,24	3 837,50	22 669,70	22,17	416,97	27,18	4
Location-37	113,06	3 272,24	125,59	3 811,73	22 669,70	22,11	413,91	27,39	4
Location-56	111,27	3 074,24	123,60	3 611,23	22 669,70	22,47	413,39	27,42	4
Location-46	109,53	2 845,59	121,67	3 367,14	22 669,70	22,82	399,88	28,35	4
Location-59	107,37	2 721,01	119,26	3 235,45	22 669,70	23,28	395,17	28,68	4
Location-15	132,93	3 195,14	120,46	3 636,21	18 492,85	18,81	320,61	28,84	3
Location-45	104,54	2 495,15	116,12	2 994,70	22 669,70	23,91	383,42	29,56	4
Location-73	104,47	2 469,53	116,05	2 968,83	22 669,70	23,93	383,24	29,58	4
Location-86	102,54	2 337,62	113,90	2 827,95	22 669,70	24,38	376,43	30,11	4
Location-101	117,94	2 387,98	106,87	2 800,96	18 492,85	21,20	306,10	30,21	3
Location-83	117,84	2 379,06	106,78	2 789,57	18 492,85	21,22	303,74	30,44	3
Location-38	113,00	2 113,42	102,40	2 511,49	18 492,85	22,12	295,66	31,27	3
Location-93	114,50	2 250,01	103,75	2 646,50	18 492,85	21,83	292,73	31,59	3
Location-98	123,60	2 480,58	112,00	2 883,72	18 492,85	20,23	291,15	31,76	3
Location-74	112,43	2 104,13	101,88	2 494,82	18 492,85	22,24	288,80	32,02	3
Location-97	110,48	2 027,70	100,11	2 416,59	18 492,85	22,63	288,78	32,02	3
Location-51	109,42	1 852,08	99,15	2 235,08	18 492,85	22,85	283,85	32,57	3
Location-99	109,27	1 951,52	99,01	2 331,96	18 492,85	22,88	281,43	32,86	3
Location-53	103,16	1 643,24	93,48	2 000,63	18 492,85	24,23	263,91	35,04	3
Location-77	102,10	1 607,60	92,52	1 963,45	18 492,85	24,49	263,33	35,11	3
Location-36	100,27	1 507,61	90,86	1 856,14	18 492,85	24,93	257,66	35,89	3
Location-91	97,32	1 401,34	88,19	1 744,87	18 492,85	25,69	255,34	36,21	3
Location-85	80,52	1 222,54	89,44	1 605,35	22 669,70	31,05	293,37	38,64	4
Location-80	82,05	1 285,42	91,15	1 666,95	22 669,70	30,47	290,38	39,03	4
Location-89	88,77	1 173,80	80,44	1 484,55	18 492,85	28,16	230,31	40,15	3
Location-12	87,47	1 111,49	79,26	1 414,81	18 492,85	28,58	224,07	41,27	3
Location-57	85,08	1 081,02	77,09	1 377,25	18 492,85	29,38	219,14	42,19	3
Location-13	81,77	955,35	74,09	1 241,81	18 492,85	30,58	212,37	43,54	3
Location-78	82,09	967,91	74,38	1 253,45	18 492,85	30,46	211,16	43,79	3
Location-90	81,58	946,01	73,92	1 227,00	18 492,85	30,65	207,08	44,65	3
Location-52	73,25	748,42	66,37	1 005,60	18 492,85	34,13	190,81	48,46	3
Location-27	80,96	627,60	56,79	818,95	14 316,00	30,88	134,55	53,20	2
Location-9	80,65	634,71	56,57	823,80	14 316,00	31,00	132,51	54,02	2
Location-88	77,83	584,02	54,60	762,69	14 316,00	32,12	124,07	57,69	2
Location-87	50,77	271,86	35,61	406,43	14 316,00	49,24	98,96	72,33	2
Location-32	74,99	329,36	37,26	423,28	10 139,15	33,34	56,67	89,46	1
Location-22	50,21	321,39	35,22	433,98	14 316,00	49,79	77,37	92,52	2
Location-29	69,39	281,20	34,47	366,50	10 139,15	36,03	50,83	99,74	1
Location-26	64,58	246,64	32,09	327,04	10 139,15	38,71	48,31	104,93	1
Location-58	61,16	229,21	30,39	301,39	10 139,15	40,87	41,79	121,30	1
Location-30	57,06	213,61	28,35	283,04	10 139,15	43,81	41,07	123,43	1

Location	N_l^{cyc}	R_l^{dam}	R_l^{wear}	C_l^{load}	C_l^{capex}	EOL	TPP_l	IPP_l	N_l^{SU}
Location-31	55,39	205,72	27,52	274,13	10 139,15	45,13	40,88	124,00	1
Location-14	43,95	159,52	21,83	215,05	10 139,15	56,88	33,70	150,45	1
Location-33	47,31	161,54	23,51	218,57	10 139,15	52,84	33,53	151,20	1
Location-20	37,10	130,70	18,43	178,37	10 139,15	67,39	29,24	173,40	1
Location-70	29,68	86,48	14,75	130,30	10 139,15	84,23	29,08	174,35	1
Location-106	28,79	100,59	14,30	136,76	10 139,15	86,84	21,87	231,78	1
Location-34	27,78	96,36	13,80	131,76	10 139,15	90,01	21,60	234,68	1
Location-2	22,81	79,11	11,33	107,90	10 139,15	109,61	17,46	290,40	1
Location-95	18,99	61,66	9,43	88,38	10 139,15	131,66	17,28	293,38	1
Location-72	15,86	45,03	7,88	68,50	10 139,15	157,67	15,60	324,99	1
Location-25	20,87	75,64	10,37	101,20	10 139,15	119,77	15,19	333,74	1
Location-28	19,29	69,07	9,58	93,30	10 139,15	129,59	14,65	346,12	1
Location-92	14,44	52,82	7,17	71,06	10 139,15	173,13	11,07	457,94	1
Location-19	14,44	52,92	7,17	71,06	10 139,15	173,13	10,97	462,02	1
Location-71	9,00	30,69	4,47	42,51	10 139,15	277,71	7,34	690,80	1

A.2 Secondary Reserve Market Problem

Table 17: Secondary reserve market problem results (sorted ascending by IPP)

Location	N_l^{cyc}	R_l^{dam}	R_l^{wear}	R_l^{dsre}	R_l^{isre}	R_l^{srm}	C_l^{load}	TPP_l	IPP_l	N_l^{SU}
Location-8	131,36	11 039,61	1 727,98	402,47	1 927,29	42 334,88	10 429,20	41 521,31	3,23	5
Location-7	113,10	7 957,50	1 024,88	297,47	958,81	27 045,69	7 754,92	26 479,57	3,49	3
Location-23	331,11	23 608,32	4 355,75	95,67	4 409,32	41 691,76	19 987,39	38 028,74	3,53	5
Location-5	197,41	7 663,50	1 788,85	462,02	1 626,16	26 841,61	7 179,58	25 732,99	3,59	3
Location-50	119,18	9 591,87	1 567,76	313,50	1 612,54	38 101,71	9 040,03	37 281,16	3,60	5
Location-10	167,82	8 001,96	1 520,68	294,96	1 471,72	26 483,32	7 326,13	25 463,57	3,63	3
Location-60	162,98	9 428,95	1 476,84	197,29	1 479,34	26 486,51	8 552,65	25 415,41	3,64	3
Location-67	160,52	7 759,35	1 454,53	218,22	1 441,97	25 548,19	6 912,42	24 470,49	3,78	3
Location-48	173,91	9 500,96	1 575,84	210,68	1 533,30	25 463,84	8 542,49	24 252,15	3,81	3
Location-66	170,37	11 256,35	1 543,80	260,75	1 534,50	25 155,34	10 402,82	24 031,76	3,85	3
Location-61	164,20	9 251,26	1 487,87	155,47	1 421,09	24 885,05	8 406,47	23 818,01	3,88	3
Location-3	200,37	5 769,14	1 815,65	486,55	1 691,72	24 348,99	5 274,60	23 243,97	3,98	3
Location-104	174,38	6 983,95	1 580,12	90,87	1 577,06	24 445,84	5 833,14	23 201,08	3,99	3
Location-68	175,87	8 522,96	1 593,66	236,76	1 554,90	24 301,38	7 650,13	23 153,02	3,99	3
Location-11	172,18	8 350,25	1 560,21	241,11	1 476,13	24 052,14	7 626,35	23 003,04	4,02	3
Location-75	172,05	8 080,24	1 559,05	86,17	1 493,24	23 842,19	7 030,77	22 640,74	4,08	3
Location-69	172,32	7 612,48	1 561,44	191,02	1 485,35	23 704,16	6 741,69	22 566,27	4,10	3
Location-4	212,50	9 170,38	1 490,63	349,39	1 010,80	17 462,89	9 066,08	16 529,37	4,33	2
Location-94	181,15	12 515,63	1 641,45	98,94	1 532,62	20 536,28	11 480,93	19 293,82	4,79	3
Location-47	114,31	3 808,07	801,84	293,46	460,27	14 131,95	4 137,52	13 826,39	5,18	2
Location-52	97,37	844,49	683,06	250,78	470,61	14 066,88	1 005,60	13 764,75	5,20	2
Location-31	131,02	449,76	919,06	229,38	787,87	14 105,37	274,13	13 569,16	5,28	2
Location-35	142,31	5 572,14	998,29	271,77	780,22	14 042,42	5 553,31	13 533,75	5,29	2
Location-27	137,64	929,88	965,50	257,17	785,42	14 075,67	818,95	13 527,49	5,29	2
Location-15	138,40	3 732,55	970,87	251,69	802,52	14 032,46	3 636,21	13 516,08	5,30	2
Location-24	126,82	5 539,03	889,59	358,10	442,59	13 883,30	5 970,60	13 509,78	5,30	2
Location-46	112,05	3 041,93	786,04	306,95	413,85	13 849,76	3 367,14	13 495,82	5,30	2
Location-55	139,90	5 655,38	981,36	237,98	820,47	14 016,80	5 531,77	13 494,32	5,30	2
Location-39	140,71	5 605,99	987,03	238,21	829,48	13 991,05	5 474,88	13 464,19	5,32	2
Location-43	137,73	6 282,72	966,17	237,07	803,37	13 960,45	6 153,59	13 431,45	5,33	2
Location-63	243,32	7 534,21	1 706,87	95,82	1 303,26	14 848,84	6 586,37	13 401,58	5,34	2
Location-9	135,87	568,65	953,09	373,35	620,32	13 828,56	823,80	13 377,59	5,35	2
Location-19	140,61	335,56	986,36	205,77	888,20	13 921,14	71,06	13 352,72	5,36	2
Location-12	147,10	972,04	1 031,86	401,62	503,41	13 741,70	1 414,81	13 254,40	5,40	2
Location-22	88,45	375,59	620,49	237,06	497,85	13 520,62	433,98	13 219,30	5,41	2
Location-59	103,59	2 935,03	726,67	271,94	373,84	13 536,82	3 235,45	13 212,48	5,42	2
Location-51	114,16	1 869,93	800,79	299,22	403,06	13 495,80	2 235,08	13 164,00	5,44	2

Location	N_l^{cyc}	R_l^{dam}	R_l^{wear}	R_l^{dsre}	R_l^{isre}	R_l^{srm}	C_l^{load}	TPP_l	IPP_l	N_l^{SU}
Location-6	209,01	3 792,95	1 466,20	587,01	497,52	13 538,20	4 627,87	12 817,42	5,58	2
Location-21	127,20	4 212,13	892,28	348,59	428,48	13 175,02	4 649,69	12 800,19	5,59	2
Location-62	111,95	5 082,67	785,29	272,52	372,99	13 112,57	5 429,73	12 774,80	5,60	2
Location-28	133,22	334,40	934,55	247,06	820,23	13 331,68	93,30	12 729,20	5,62	2
Location-16	138,10	4 565,12	968,73	263,43	762,65	13 293,74	4 465,69	12 724,80	5,63	2
Location-32	136,71	631,00	959,00	246,40	817,02	13 318,08	423,28	12 721,98	5,63	2
Location-36	142,00	2 019,31	996,13	243,66	814,80	13 242,23	1 856,14	12 654,08	5,66	2
Location-44	141,47	6 377,96	992,37	267,94	836,75	13 212,88	6 239,47	12 650,84	5,66	2
Location-45	115,17	2 677,95	807,87	331,28	445,70	13 022,84	2 994,70	12 646,14	5,66	2
Location-58	82,20	291,93	576,62	200,33	488,37	12 871,79	301,39	12 592,66	5,68	2
Location-56	141,96	3 795,10	995,79	250,50	841,51	13 163,31	3 611,23	12 574,65	5,69	2
Location-40	142,92	4 712,40	1 002,54	262,12	826,81	13 176,05	4 548,68	12 574,48	5,69	2
Location-20	139,69	466,05	979,89	221,52	863,28	13 195,96	178,37	12 570,15	5,69	2
Location-73	91,02	2 914,03	638,50	198,42	421,75	12 911,53	2 968,83	12 551,15	5,70	2
Location-57	91,79	1 230,20	643,87	237,45	435,05	12 840,23	1 377,25	12 541,01	5,71	2
Location-49	132,97	6 127,28	932,78	394,77	479,79	12 902,36	6 573,80	12 501,11	5,73	2
Location-74	95,61	2 456,28	670,70	195,92	466,28	12 837,40	2 494,82	12 475,60	5,74	2
Location-72	82,01	179,58	575,30	131,46	500,92	12 658,79	68,50	12 341,87	5,80	2
Location-76	94,24	6 104,69	661,09	198,74	435,67	12 620,76	6 209,86	12 301,78	5,82	2
Location-65	147,89	5 375,29	1 037,42	339,70	446,63	12 794,36	5 781,40	12 269,98	5,83	2
Location-80	132,43	2 017,00	929,00	146,02	799,65	12 870,49	1 666,95	12 245,08	5,85	2
Location-18	140,94	6 311,54	988,65	263,87	757,09	12 801,08	6 248,16	12 242,26	5,85	2
Location-26	137,50	536,02	964,51	232,22	829,01	12 760,77	327,04	12 184,08	5,87	2
Location-30	140,42	494,49	985,05	245,60	852,91	12 759,69	283,04	12 170,50	5,88	2
Location-54	146,11	4 864,59	1 024,91	252,71	796,85	12 763,88	4 713,39	12 131,90	5,90	2
Location-81	129,49	6 097,51	908,38	161,33	765,08	12 686,89	5 846,46	12 131,20	5,90	2
Location-38	146,11	2 713,75	1 024,90	230,33	828,69	12 732,98	2 511,49	12 104,17	5,91	2
Location-34	140,76	396,76	987,37	230,85	849,23	12 730,93	131,76	12 096,95	5,92	2
Location-64	143,76	5 251,44	1 008,48	337,09	423,13	12 595,03	5 660,59	12 081,74	5,92	2
Location-103	71,89	4 722,95	504,32	138,83	267,94	12 311,56	4 859,43	12 072,82	5,93	2
Location-42	148,02	4 053,52	1 038,37	227,61	820,89	12 732,62	3 837,50	12 071,52	5,93	2
Location-105	73,35	4 341,55	514,52	142,33	271,66	12 317,62	4 473,93	12 064,81	5,93	2
Location-14	145,24	496,59	1 018,81	234,64	878,96	12 720,75	215,05	12 064,72	5,93	2
Location-98	84,51	2 974,48	592,85	104,13	444,16	12 329,51	2 883,72	11 985,93	5,97	2
Location-97	92,51	2 522,74	648,97	116,07	480,75	12 358,88	2 416,59	11 968,46	5,98	2
Location-100	193,55	9 876,37	1 753,85	117,47	1 699,36	16 615,92	8 701,95	15 269,55	6,06	3
Location-2	139,73	333,65	980,15	247,35	854,96	12 410,47	107,90	11 812,17	6,06	2
Location-102	77,27	4 562,58	542,05	159,35	326,47	11 909,56	4 702,69	11 674,75	6,13	2
Location-88	131,74	1 182,36	924,15	87,60	810,74	12 290,66	762,69	11 669,99	6,13	2
Location-87	128,66	826,29	902,54	118,83	797,96	12 271,51	406,43	11 628,24	6,16	2
Location-99	91,29	2 451,44	640,36	138,53	488,19	11 973,06	2 331,96	11 562,88	6,19	2
Location-1	75,69	4 708,12	530,95	165,05	285,28	11 806,64	4 841,27	11 529,07	6,21	2
Location-83	126,95	3 106,67	890,55	144,26	751,20	11 994,80	2 789,57	11 394,10	6,28	2
Location-106	62,05	208,23	435,24	117,94	381,09	11 625,57	136,76	11 382,02	6,29	2
Location-82	124,09	5 354,98	870,46	150,71	716,07	11 913,03	5 064,40	11 317,35	6,32	2
Location-101	77,00	2 699,25	540,18	145,12	327,32	11 564,69	2 800,96	11 308,42	6,33	2
Location-92	96,33	290,96	675,75	123,05	611,63	11 532,64	71,06	11 125,57	6,43	2
Location-89	129,14	1 874,73	905,88	107,29	783,06	11 715,19	1 484,55	11 094,90	6,45	2
Location-71	90,41	202,28	634,18	155,36	539,39	11 429,51	42,51	11 019,59	6,50	2
Location-79	134,11	5 635,11	940,77	161,31	815,30	11 517,31	5 361,56	10 956,98	6,53	2
Location-91	127,81	2 128,89	896,56	125,20	766,27	11 450,41	1 744,87	10 810,89	6,62	2
Location-90	126,43	1 632,62	886,91	97,25	770,12	11 290,16	1 227,00	10 670,50	6,71	2
Location-96	90,45	5 840,80	634,51	150,04	474,42	10 971,20	5 789,73	10 610,01	6,75	2
Location-95	96,89	341,53	679,65	108,93	596,56	10 541,95	88,38	10 096,77	7,09	2
Location-29	173,54	541,93	862,18	129,32	503,92	7 772,43	366,50	7 109,42	7,13	1
Location-33	190,51	496,75	946,49	113,53	595,90	7 831,25	218,57	7 088,96	7,15	1
Location-13	188,75	1 466,09	937,75	115,40	561,91	7 785,27	1 241,81	7 069,77	7,17	1
Location-25	177,94	320,17	884,05	121,80	537,56	7 739,09	101,20	7 051,83	7,19	1
Location-37	192,34	4 016,99	955,56	121,20	544,37	7 754,42	3 811,73	7 016,77	7,22	1
Location-17	217,33	4 505,61	1 079,72	134,18	549,10	7 799,58	4 326,71	6 955,87	7,29	1
Location-53	201,13	2 214,05	999,23	115,51	556,74	7 720,90	2 000,63	6 949,48	7,29	1
Location-41	212,31	4 800,26	1 054,80	113,76	588,00	7 744,74	4 556,19	6 920,11	7,33	1
Location-86	136,83	3 191,16	959,84	100,16	794,37	9 620,99	2 827,95	8 992,15	7,96	2
Location-70	96,02	273,25	673,59	170,82	619,06	9 343,60	130,30	8 975,29	7,98	2
Location-93	113,51	2 787,99	796,28	154,60	616,85	9 194,03	2 646,50	8 718,51	8,21	2
Location-78	184,69	1 669,62	917,59	46,67	559,02	6 726,33	1 253,45	5 904,93	8,59	1
Location-77	179,75	2 310,99	893,04	34,75	493,53	6 665,06	1 963,45	5 883,26	8,62	1

Location	N_l^{cyc}	R_l^{dam}	R_l^{wear}	R_l^{dsre}	R_l^{isre}	R_l^{srm}	C_l^{load}	TPP_l	IPP_l	N_l^{SU}
Location-85	177,73	1 939,86	883,01	28,00	471,44	6 460,87	1 605,35	5 686,79	8,91	1
Location-84	181,05	4 673,35	899,49	36,06	469,80	6 336,55	4 342,05	5 539,50	9,15	1

A.3 Electric Vehicle Problem

Table 18: Electric vehicle problem results (sorted descending by TPP per EV)

Location	N_l^{cyc}	R_l^{dam}	$R_l^{wear,ev}$	R_l^{dsre}	R_l^{isre}	R_l^{srm}	C_l^{load}	TPP_l	N_l^{EV}	$\frac{TPP_l}{N_l^{EV}}$
Location-69	182,86	7690,28	390,40	97,53	447,87	14466,62	6741,69	13 477,96	10	1 347,80
Location-75	276,67	8301,01	590,69	304,32	1098,38	14323,91	7030,77	13 257,04	10	1 325,70
Location-10	210,70	8661,07	449,83	14,38	547,30	13088,65	7326,13	11 836,80	9	1 315,20
Location-23	296,60	24078,20	633,25	331,68	2729,95	32525,55	19987,39	30 199,77	23	1 313,03
Location-101	159,03	3208,26	339,53	37,62	74,83	7264,49	2800,96	6 554,87	5	1 310,97
Location-50	345,84	11784,97	738,37	95,02	1839,15	17449,89	9040,03	15 710,71	12	1 309,23
Location-63	216,27	7876,48	461,74	21,47	640,52	14037,42	6586,37	12 904,63	10	1 290,46
Location-73	159,30	3334,41	340,11	65,23	90,81	7110,63	2968,83	6 430,52	5	1 286,10
Location-45	164,42	3501,23	351,04	0,11	105,63	7173,50	2994,70	6 421,45	5	1 284,29
Location-38	169,53	3018,56	361,94	13,86	105,52	7178,84	2511,49	6 401,47	5	1 280,29
Location-15	169,95	4165,83	362,85	1,80	122,40	7145,08	3636,21	6 373,21	5	1 274,64
Location-83	165,89	3305,85	354,18	0,64	80,23	7100,04	2789,57	6 309,17	5	1 261,83
Location-8	320,81	13243,96	684,92	104,20	1737,60	18212,57	10429,20	16 346,29	13	1 257,41
Location-86	350,02	3382,06	747,30	291,91	796,85	7040,11	2827,95	6 243,64	5	1 248,73
Location-104	356,57	7833,43	761,28	12,42	1278,06	11223,31	5833,14	9 727,38	8	1 215,92
Location-60	319,81	10147,05	682,80	320,82	1538,04	14319,20	8552,65	13 259,22	11	1 205,38
Location-36	308,18	2719,37	657,96	0,00	533,47	5803,66	1856,14	4 815,94	4	1 203,98
Location-53	259,31	2685,42	553,63	0,00	352,07	5631,46	2000,63	4 745,11	4	1 186,28
Location-89	263,79	1977,81	563,20	11,08	294,43	4325,02	1484,55	3 551,92	3	1 183,97
Location-51	259,00	2915,19	552,97	0,00	347,11	5596,93	2235,08	4 710,95	4	1 177,74
Location-85	269,61	2109,32	575,62	7,27	275,90	4340,78	1605,35	3 529,82	3	1 176,61
Location-88	151,25	972,44	322,91	6,16	25,45	2831,27	762,69	2 317,90	2	1 158,95
Location-59	162,96	3585,13	347,93	64,12	109,58	7485,64	3235,45	6 833,50	6	1 138,92
Location-4	178,14	9846,34	380,32	146,94	306,19	14663,40	9066,08	13 662,07	12	1 138,51
Location-11	226,84	8207,74	484,30	453,22	741,02	15550,56	7626,35	14 772,68	13	1 136,36
Location-74	291,15	3303,91	621,59	0,00	480,22	5489,10	2494,82	4 538,63	4	1 134,66
Location-56	162,20	3959,59	346,29	73,92	58,58	7499,84	3611,23	6 789,85	6	1 131,64
Location-99	287,16	3120,35	613,08	0,00	434,43	5460,31	2331,96	4 493,27	4	1 123,32
Location-97	286,41	3202,64	611,48	0,00	452,23	5434,58	2416,59	4 489,27	4	1 122,32
Location-93	292,20	3450,55	623,85	0,00	483,06	5433,58	2646,50	4 488,74	4	1 122,18
Location-52	168,91	1215,80	360,63	0,00	29,75	2779,61	1005,60	2 238,53	2	1 119,26
Location-98	285,48	3669,56	609,50	0,00	447,74	5419,87	2883,72	4 472,28	4	1 118,07
Location-42	163,91	4331,30	349,96	12,46	91,33	7471,74	3837,50	6 706,84	6	1 117,81
Location-90	151,08	1431,02	322,55	6,11	21,87	2732,93	1227,00	2 222,13	2	1 111,06
Location-3	441,49	7483,72	942,57	0,44	1521,37	9299,81	5274,60	7 669,04	7	1 095,58
Location-7	231,76	8391,72	494,81	427,60	658,41	15044,15	7754,92	14 143,36	13	1 087,95
Location-68	375,73	9486,78	802,18	461,77	2004,56	14124,63	7650,13	13 028,59	12	1 085,72
Location-5	296,53	8524,10	633,09	412,61	1430,98	14908,50	7179,58	13 949,26	13	1 073,02
Location-46	160,78	3874,08	343,27	2,14	75,87	6982,81	3367,14	6 206,33	6	1 034,39
Location-25	148,26	170,23	316,53	16,19	11,12	1421,16	101,20	1 030,53	1	1 030,53
Location-26	148,39	392,60	316,81	17,20	13,53	1413,83	327,04	1 027,79	1	1 027,79
Location-67	185,72	7858,44	396,50	94,96	375,56	12301,60	6912,42	11 239,68	11	1 021,79
Location-28	147,80	153,25	315,54	17,19	8,20	1398,63	93,30	1 014,14	1	1 014,14
Location-31	154,92	365,93	330,75	0,00	16,98	1383,81	274,13	978,24	1	978,24
Location-30	149,38	364,42	318,94	6,86	9,40	1363,56	283,04	965,78	1	965,78
Location-29	148,62	447,11	317,30	9,93	8,80	1363,80	366,50	964,76	1	964,76
Location-87	145,10	517,38	309,79	8,96	3,14	1376,55	406,43	949,99	1	949,99
Location-77	408,14	2776,29	871,38	0,00	559,77	3922,76	1963,45	2 798,32	3	932,77
Location-32	154,37	517,27	329,58	0,00	19,39	1321,45	423,28	917,27	1	917,27
Location-91	414,70	2554,47	885,39	0,00	579,95	3859,22	1744,87	2 744,18	3	914,73
Location-17	177,36	4932,36	378,67	31,94	199,36	7199,27	4326,71	6 382,37	7	911,77
Location-78	261,82	1559,13	558,98	0,00	138,50	2545,19	1253,45	1 819,02	2	909,51
Location-54	183,03	4932,72	390,77	234,30	205,98	7887,30	4713,39	7 248,88	8	906,11
Location-33	154,46	314,82	329,77	0,00	11,05	1310,17	218,57	895,21	1	895,21
Location-105	199,71	4819,11	426,38	202,49	273,86	7850,95	4473,93	7 150,76	8	893,84

Location	N_l^{cyc}	R_l^{dam}	$R_l^{wear,ev}$	R_l^{dsre}	R_l^{isre}	R_l^{srm}	C_l^{load}	TPP_l	N_l^{EV}	$\frac{TPP_l}{N_l^{EV}}$
Location-102	174,35	5088,32	372,24	158,37	182,28	7872,67	4702,69	7 138,71	8	892,34
Location-48	344,26	10799,24	735,00	390,62	2126,72	14619,08	8542,49	13 363,44	15	890,90
Location-76	209,23	6497,01	446,70	237,86	264,59	7738,91	6209,86	7 031,79	8	878,97
Location-66	343,57	12371,98	733,53	587,73	2194,45	15076,37	10402,82	13 980,40	16	873,78
Location-6	172,55	5044,13	368,39	127,10	97,85	7778,99	4627,87	6 965,09	8	870,64
Location-21	181,62	4908,72	387,75	183,17	162,59	6760,30	4649,69	6 092,94	7	870,42
Location-94	237,09	12750,35	506,19	349,02	918,12	15093,00	11480,93	13 886,48	16	867,91
Location-100	287,18	10019,06	613,13	472,78	1353,36	13961,93	8701,95	12 912,28	15	860,82
Location-82	177,34	5731,52	378,61	40,70	255,77	7654,03	5064,40	6 823,38	8	852,92
Location-34	159,34	227,24	340,19	0,00	13,78	1272,76	131,76	850,87	1	850,87
Location-47	175,27	4794,54	374,20	41,15	223,22	7644,13	4137,52	6 794,98	8	849,37
Location-103	197,59	5222,17	421,85	191,99	232,74	7485,23	4859,43	6 741,40	8	842,68
Location-84	179,56	5049,80	383,37	27,40	225,78	7626,43	4342,05	6 733,69	8	841,71
Location-40	221,23	5395,10	472,33	42,56	475,76	7598,63	4548,68	6 713,08	8	839,13
Location-41	222,30	5367,43	474,60	76,05	446,02	7627,03	4556,19	6 711,17	8	838,90
Location-12	395,96	2189,40	845,38	0,00	532,49	3599,79	1414,81	2 512,32	3	837,44
Location-27	486,48	1324,82	1038,64	77,75	518,94	2777,12	818,95	1 673,80	2	836,90
Location-57	433,68	2255,84	925,90	0,00	619,51	3643,16	1377,25	2 458,18	3	819,39
Location-9	301,42	1180,21	643,53	0,00	206,16	2394,58	823,80	1 600,79	2	800,39
Location-24	218,16	6280,04	465,76	229,93	323,03	7785,80	5970,60	7 103,69	9	789,30
Location-80	442,01	2555,71	943,69	0,00	635,21	3553,63	1666,95	2 356,39	3	785,46
Location-65	172,01	6321,79	367,25	108,46	135,77	7888,70	5781,40	7 008,37	9	778,71
Location-64	172,99	6268,74	369,32	71,81	150,98	7848,07	5660,59	6 949,77	9	772,20
Location-81	194,48	6530,14	415,22	104,19	302,75	7595,99	5846,46	6 695,65	9	743,96
Location-61	218,40	9753,96	466,27	29,50	725,19	9127,32	8406,47	8 009,25	11	728,11
Location-49	216,74	6758,95	462,74	363,16	287,82	7840,75	6573,80	7 117,52	10	711,75
Location-18	288,10	7117,01	615,10	364,12	1002,56	7851,94	6248,16	7 006,42	10	700,64
Location-70	184,98	240,88	394,93	0,00	23,99	1181,90	130,30	700,38	1	700,38
Location-71	184,84	153,25	394,63	0,00	24,00	1180,79	42,51	699,42	1	699,42
Location-96	175,31	6332,71	374,28	158,17	207,52	7841,71	5789,73	6 973,79	10	697,38
Location-72	184,93	179,00	394,83	0,00	23,99	1163,08	68,50	681,74	1	681,74
Location-19	183,56	179,56	391,89	0,00	27,37	1150,37	71,06	677,35	1	677,35
Location-35	240,65	6251,54	513,78	277,17	592,67	7622,27	5553,31	6 725,76	10	672,58
Location-13	355,08	1672,33	758,10	0,00	274,27	2256,69	1241,81	1 342,34	2	671,17
Location-92	167,61	172,38	357,84	0,00	15,11	1104,38	71,06	660,34	1	660,34
Location-20	184,72	287,32	394,37	0,00	27,28	1130,93	178,37	654,89	1	654,89
Location-55	194,76	6023,02	415,80	132,58	257,15	6002,01	5531,77	5 219,53	8	652,44
Location-22	184,57	543,14	394,07	0,00	26,06	1123,96	433,98	646,78	1	646,78
Location-16	211,04	5250,01	450,58	66,05	412,57	6014,34	4465,69	5 125,95	8	640,74
Location-58	188,12	411,82	401,64	0,00	26,78	1115,14	301,39	629,85	1	629,85
Location-95	171,84	192,39	366,88	0,00	18,21	1079,71	88,38	627,03	1	627,03
Location-1	173,68	5285,93	370,80	99,78	149,23	5768,13	4841,27	5 002,11	8	625,26
Location-2	186,59	217,25	398,38	0,00	27,80	1093,49	107,90	613,55	1	613,55
Location-106	181,18	243,54	386,82	0,00	21,12	1070,62	136,76	598,14	1	598,14
Location-62	173,17	6039,00	369,71	64,82	124,06	5987,69	5429,73	5 067,93	9	563,10
Location-14	192,02	326,24	409,97	0,00	28,82	1045,43	215,05	553,09	1	553,09
Location-37	179,78	4464,11	383,82	18,00	211,87	4626,16	3811,73	3 783,84	7	540,55
Location-39	346,75	6411,13	740,31	426,27	1296,95	5442,12	5474,88	4 636,23	9	515,14
Location-43	178,42	6828,85	380,92	113,03	234,48	5091,02	6153,59	4 156,29	10	415,63
Location-44	191,67	6971,78	409,23	140,39	323,88	5138,64	6239,47	4 180,60	11	380,05
Location-79	284,50	6252,50	607,41	395,92	1023,25	5022,97	5361,56	4 151,95	11	377,45

A.4 T&D Deferral and Outage Problem

Binary parameter id_l^{upg} is equal to 1 if an investment for transformer capacity increase is needed in location l during 10-year period. Otherwise, $id_l^{upg} = 0$.

Table 19: T&D deferral and outage problem results

Location	N^{cust}	P_l^{contr}	P_l^{peak}	N_l^{tr}	$P_l^{peak} - P^{tr} \times N_l^{tr}$	id_l^{upg}	N_{int}^h	D_l
Location-1	76	334650	55 316,93	1	-14 472,18	0	3	0,00
Location-2	1	3450	1 723,29	1	-77 958,61	0	6	6,23
Location-3	69	318100	88 811,55	2	-54 794,83	0	3	0,00
Location-4	113	529200	150 705,77	2	18 524,38	1	1	0,00
Location-5	123	570800	88 113,08	2	-55 622,22	0	3	0,00
Location-6	75	369650	58 436,05	1	-10 777,30	0	0	0,00
Location-7	125	603500	95 277,99	2	-47 134,75	0	2	0,00
Location-8	130	644800	191 844,68	3	-12 742,93	0	3	0,00
Location-9	14	64400	10 225,22	1	-67 887,32	0	2	0,00
Location-10	90	457746	119 809,64	2	-18 074,83	0	4	275,60
Location-11	122	596200	93 598,40	2	-49 124,37	0	3	0,00
Location-12	26	119400	18 336,17	1	-58 279,18	0	1	0,00
Location-13	18	62400	14 984,58	1	-62 249,44	0	1	0,00
Location-14	4	16100	2 621,40	1	-76 894,71	0	2	0,00
Location-15	44	196978	44 110,20	1	-27 747,54	0	3	0,00
Location-16	78	293300	56 056,73	1	-13 595,82	0	5	353,19
Location-17	69	306700	56 841,28	1	-12 666,45	0	1	0,00
Location-18	100	492396	74 923,16	1	8 753,14	1	1	0,00
Location-19	1	5750	609,95	1	-79 277,47	0	1	0,00
Location-20	3	11600	2 011,46	1	-77 617,25	0	2	0,00
Location-21	67	323500	58 065,40	1	-11 216,37	0	2	0,00
Location-22	7	42550	5 822,27	1	-73 103,00	0	2	0,00
Location-23	226	1167050	343 405,32	5	6 794,13	1	2	0,00
Location-24	89	439478	70 661,06	1	3 704,31	1	2	0,00
Location-25	2	9200	1 401,51	1	-78 339,78	0	3	0,00
Location-26	6	26450	4 204,54	1	-75 019,35	0	3	0,00
Location-27	15	72450	11 016,79	1	-66 949,64	0	0	0,00
Location-28	2	8050	1 219,89	1	-78 554,93	0	3	0,00
Location-29	7	31050	4 632,86	1	-74 511,96	0	3	0,00
Location-30	5	21850	3 711,10	1	-75 603,88	0	2	0,00
Location-31	4	18400	3 101,15	1	-76 326,41	0	2	0,00
Location-32	8	37950	5 540,93	1	-73 436,27	0	1	0,00
Location-33	3	13800	3 801,08	1	-75 497,28	0	3	0,00
Location-34	3	14950	2 011,46	1	-77 617,25	0	3	0,00
Location-35	97	439650	66 751,32	1	-927,13	0	4	264,71
Location-36	32	133500	24 459,70	1	-51 025,31	0	3	0,00
Location-37	63	272800	44 966,26	1	-26 733,46	0	0	0,00
Location-38	41	174000	32 357,51	1	-41 669,65	0	2	0,00
Location-39	90	406028	66 358,27	1	-1 392,73	0	2	0,00
Location-40	79	371440	57 971,17	1	-11 328,00	0	3	0,00
Location-41	76	357400	57 170,46	1	-12 276,50	0	1	0,00
Location-42	60	295700	48 161,43	1	-22 948,50	0	5	356,08
Location-43	94	393200	76 845,58	1	11 030,42	1	0	0,00
Location-44	105	453350	78 320,45	1	12 777,54	1	4	272,96
Location-45	50	236800	37 213,43	1	-35 917,38	0	3	0,00
Location-46	52	229950	43 198,94	1	-28 827,01	0	7	553,80
Location-47	71	329850	53 729,72	1	-16 352,37	0	1	0,00

Location	N^{cust}	P_l^{contr}	P_l^{peak}	N_l^{tr}	$P_l^{peak} - P^{tr} \times N_l^{tr}$	id_l^{upg}	N_{int}^h	D_l
Location-48	145	562800	102 320,67	2	-38 792,08	0	2	0,00
Location-49	99	497900	79 405,67	1	14 063,08	1	4	299,78
Location-50	120	590850	167 464,71	3	-41 623,17	0	2	0,00
Location-51	38	173650	27 688,16	1	-47 200,91	0	3	0,00
Location-52	15	80450	11 832,00	1	-65 983,94	0	5	96,88
Location-53	35	159050	25 213,54	1	-50 132,33	0	0	0,00
Location-54	79	378200	56 279,82	1	-13 331,55	0	4	227,71
Location-55	78	387700	67 426,40	1	-127,44	0	2	0,00
Location-56	59	279550	44 244,64	1	-27 588,29	0	2	0,00
Location-57	23	113700	16 582,54	1	-60 356,51	0	2	0,00
Location-58	5	20300	4 526,31	1	-74 638,18	0	3	0,00
Location-59	53	255900	40 193,95	1	-32 386,70	0	1	0,00
Location-60	103	489250	133 007,41	2	-2 440,90	0	7	1 178,29
Location-61	107	511450	142 926,22	2	9 308,82	1	2	0,00
Location-62	87	396550	66 320,11	1	-1 437,94	0	3	0,00
Location-63	92	393200	89 611,59	2	-53 847,11	0	5	473,48
Location-64	90	432150	67 758,93	1	266,47	1	2	0,00
Location-65	89	349550	71 337,30	1	4 505,37	1	3	0,00
Location-66	158	819650	130 147,82	2	-5 828,34	0	3	0,00
Location-67	110	509950	84 638,49	2	-59 738,18	0	1	0,00
Location-68	112	576350	97 263,43	2	-44 782,82	0	4	347,01
Location-69	99	401100	87 527,38	2	-56 316,04	0	2	0,00
Location-70	1	9900	828,34	1	-79 018,76	0	2	0,00
Location-71	1	6928	609,95	1	-79 277,47	0	0	0,00
Location-72	1	5500	609,95	1	-79 277,47	0	8	16,56
Location-73	46	203050	37 425,23	1	-35 666,49	0	4	122,25
Location-74	40	183250	31 570,11	1	-42 602,40	0	5	220,67
Location-75	100	515578	87 932,52	2	-55 836,11	0	3	0,00
Location-76	79	415240	74 651,27	1	8 431,06	1	1	0,00
Location-77	30	151850	23 603,05	1	-52 040,09	0	2	0,00
Location-78	20	96700	15 543,10	1	-61 587,82	0	3	0,00
Location-79	108	529700	74 462,08	1	8 206,96	1	2	0,00
Location-80	27	124900	20 152,35	1	-56 127,75	0	4	75,20
Location-81	89	467940	77 189,89	1	11 438,28	1	3	0,00
Location-82	79	364650	65 193,56	1	-2 772,43	0	2	0,00
Location-83	50	224600	34 362,72	1	-39 294,30	0	2	0,00
Location-84	71	298050	53 315,09	1	-16 843,54	0	3	0,00
Location-85	27	124950	19 398,09	1	-57 021,24	0	5	150,46
Location-86	47	198100	36 720,06	1	-36 501,83	0	4	119,27
Location-87	8	38000	6 678,93	1	-72 088,21	0	3	0,00
Location-88	14	73600	9 265,72	1	-69 023,93	0	3	0,00
Location-89	24	125350	16 753,04	1	-60 154,54	0	0	0,00
Location-90	20	97400	14 833,00	1	-62 429,00	0	4	58,64
Location-91	30	138050	22 694,94	1	-53 115,82	0	3	0,00
Location-92	1	5750	609,95	1	-79 277,47	0	8	17,31
Location-93	40	169750	31 570,11	1	-42 602,40	0	4	102,20
Location-94	153	645600	135 701,61	2	750,62	1	6	1 166,13
Location-95	1	6928	743,34	1	-79 119,45	0	2	0,00
Location-96	97	461474	71 629,99	1	4 852,10	1	4	277,85

Location	N^{cust}	P_l^{contr}	P_l^{peak}	N_l^{tr}	$P_l^{peak} - P^{tr} \times N_l^{tr}$	id_l^{upg}	N_{int}^h	D_l
Location-97	38	182942	28 664,24	1	-46 044,66	0	6	330,44
Location-98	36	160900	48 374,82	1	-22 695,72	0	1	0,00
Location-99	40	158800	27 303,77	1	-47 656,26	0	2	0,00
Location-100	141	572050	101 970,10	2	-39 207,35	0	1	0,00
Location-101	46	205850	35 202,01	1	-38 300,09	0	4	123,94
Location-102	74	357300	59 213,96	1	-9 855,80	0	1	0,00
Location-103	76	388600	56 978,96	1	-12 503,36	0	3	0,00
Location-104	76	348300	82 473,33	2	-62 303,01	0	5	419,42
Location-105	75	407200	55 940,65	1	-13 733,32	0	6	735,51
Location-106	3	14950	2 011,46	1	-77 617,25	0	2	0,00

B Appendix: Cash Flow Example for Cost-benefit Analysis

In Tab. 20, ACF stands for accumulated cash flow.

Table 20: Cash flow demonstration of "Location-23" investment problem

	Expenses					Incomes				Q_j	ACF
j	C^{capex}	R^{dam}	R^{op}	R^{dsre}	Total	R^{srm}	R^{isre}	C^{load}	Total		
0	268463	0	0	0	268463	0	0	0	0	-268463	-268463
1	0	47217	3500	191	50908	83384	8819	39975	132177	81269	-187194
2	0	47217	3500	191	50908	83384	8819	39975	132177	81267	-105925
3	0	47217	3500	191	50908	83384	8819	39975	132177	81269	-24656
4	0	47217	3500	191	50908	83384	8819	39975	132177	81269	56613
5	0	47217	3500	191	50908	83384	8819	39975	132177	81269	137882
6	0	47217	3500	191	50908	83384	8819	39975	132177	81269	219151
7	109714	47217	3500	191	160622	83384	8819	39975	132177	-28445	190706
8	0	47217	3500	191	50908	83384	8819	39975	132177	81269	271975
9	0	47217	3500	191	50908	83384	8819	39975	132177	81269	353244
10	0	47217	3500	191	50908	83384	8819	39975	132177	81269	434513