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ESPECIALIDAD ELÉCTRICO

DEVELOPMENT OF A NETWORK PLANNING STRATEGY FOR THE FUTURE EUROPEAN TRANSMISSION SYSTEM

Autor: Virginia Hernández Vázquez
Director: Dominic Hewes

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Proyecto realizado por el alumno/a:

Virginia Hernández Vázquez

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ABSTRACT

The current infrastructure in the European Transmission System is insufficient to transport all the generation capacity available, resulting in the periodic overload of many lines and the operation of a more unstable system. The energy that is available but cannot be distributed is curtailed and causes economic losses. This effect is especially pronounced for renewable energy sources, as they are many times subsidized by governments and assured a minimum quantity of power feed into the grid. Therefore, to obtain the most economical system and make the most out of the resources available, the transmission capacity must be increased.

It is not always the most economic and environmentally friendly option to add new transmission lines. The new technologies allow an upgrade of the capacity of transmission lines making use of the infrastructure already present; more cost effective and less time and effort demanding comparatively to the latter.

This Project will focus in this second solution, and has as a main goal to develop a network planning strategy that optimizes the costs and transmitted power in the European Transmission System for the year 2030. Upgrade plans will be created after considering different preference selection criteria, the number of lines to be included in the plan and the power upgrade level. Finally, after the application and simulation of the different plans on the European Transmission System, their effectiveness will be tested and an economic study will be performed.

Key Words: line upgrade, European Transmission System Model, integration of renewable energy, Frequency Weighted Mean Energy.

SÍNTESIS

La infraestructura que conforma actualmente el Sistema Europeo de Transmisión es insuficiente para transportar toda la capacidad de generación disponible, causando la sobrecarga periódica de muchas líneas y la operación de un sistema eléctrico más inestable. La energía que está disponible pero no puede ser distribuida se traduce en pérdidas económicas. Este efecto es especialmente negativo cuando se trata de fuentes de energía renovable, muchas veces subvencionadas por los gobiernos y aseguradas una mínima transmisión a la red. Como resultado, para la obtención de un sistema más económico y la optimización en el uso de la energía renovable disponible, la capacidad de transmisión del sistema debe ser incrementada.

El añadir nuevas líneas de transmisión no es siempre la opción más económica ni más respetuosa con el medio ambiente. Existen nuevas tecnologías que permiten la renovación de las líneas haciendo uso de la infraestructura ya existente; una opción más económica y que requiere de menos tiempo y recursos.

Este proyecto tiene como principal objetivo el desarrollo de una estrategia que optimice los costes y la potencia transmitida para la actualización de la Red del Sistema Europeo para el año 2030 y para ello, hará uso de esta segunda solución. Se crearán y simularán distintos planes de actualización de la red, escogiendo el criterio a aplicar en la preferencia de selección, el número de líneas a incluir y el grado de potencia de renovación y se comprobará su eficacia realizando un estudio económico.

Palabras Clave: actualización de líneas de transmisión, modelo de Red Europea de Transmisión, integración de energías renovables, Frequency Weighted Mean Energy.

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MOTIVATION

1. Problems and Background

The balance between power generation, transport, storage and consumption has been a continuous problem since the great revolution of Electrical Engineering in the late 19th and early 20th century, starting with the Second Industrial Revolution. Electricity became an undeniable tool for activities of everyday life, developed by scientists such as Thomas Edison, Galileo Ferraris and Nikola Tesla. Since then, electrical systems have grown exponentially more and more complex than ever and promise to continue to do so. Globalization is currently a strong factor that contributes to the growing interconnection between power transmission systems, constituting electrical markets at national and even larger regional scales. One of the negative effects is the formation of operating conditions which are more difficult to control. However, a larger interconnection contributes to gain higher efficiencies and a better use of energy.

Firstly, it is necessary for the support between electrically connected zones, for instance at peak periods during the winter in the North of Europe or the summer in the South of Europe. As a result, a greater balance between generation and consumption becomes feasible and the total amount of generation is reduced; having also a reducing effect on the cost of building the necessary power plants. At the same time, a higher degree of interconnection helps to ensure the stability of the system. Without an interconnected grid, during load variations, faults or failures in the generators, electromechanical transients may take place and in the worst scenarios, lead to an uncontrollable balance between generation and consumption in the grid.

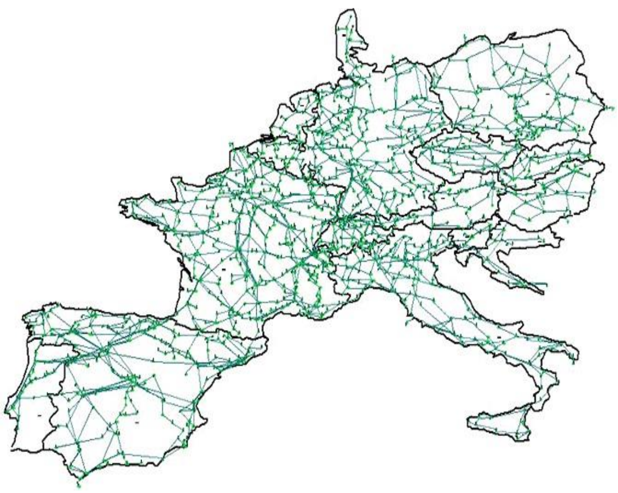

Figure 1: European Transmission System

Furthermore, new sources of energy are exploited as the technology necessary for it is continuing to be developed. As this happens, the cost for the exploitation of some of them reduces comparatively to other sources of energy until they become competitive enough to participate in the market. However, not only the economical part plays a role in the decision making of what sources of energy will supply the market.

The technical characteristics, such as flexibility to work at part load or the time periods at which some energy sources are available for example due to weather conditions, takes part in the logistics to meet the also fluctuating demand for electricity. Also, the capability of storing energy for its future consumption when it is required can help to avoid overload of transmission lines. Unfortunately, at the moment the findings in this area do not allow to store enough power capacity or for a sufficient period of time to solve this problem on its own.

Additionally, ideology and support from societies and economical backup from governments have a strong influence. The current concern about Global Warming, and consequently the desire to reduce the emission of green-house effect gases and use of fossil fuels, is causing in Europe the increase in the infeed of power into the system coming from renewable sources of energy, such as wind and solar energy.

According to energy**nautics** GmbH, in the report European Grid Study 2030/2050 [25] commissioned by Greenpeace International, the contribution of renewable energies to the total energy generation in Europe in 2030 will be of 68%. However, as reported after the performance of operation simulations, the current infrastructure is insufficient to transport such a capacity and many lines are periodically overloaded, making the system more unstable. As a result, due to the transport limitations, the energy that is available but cannot be distributed is curtailed and causes a loss of money. This effect can become even more pronounced when the sources being curtailed are renewable energy sources, as they are many times subsidized by governments and are assured a minimum quantity of power infeed into the grid. Therefore, to obtain the most economical system and make the most out of the resources available, the transmission capacity must be increased.

However, it is not always necessary or the most economic and environmentally friendly option to add new transmission lines, especially when long distances have to be covered, populations live near the area where they would need to be built or fauna and flora are disturbed. The new technologies allow an upgrade of the capacity of transmission lines making use of the infrastructure already present, comparatively to the latter more cost effective and less time and effort demanding. This Project will focus in this second solution and has as a main goal to develop a transmission line upgrade strategy to decide which lines are more adequate to be substituted.

2. Context in terms of content of research project

This Project has the goal of developing a transmission line upgrade strategy in the European Network of Transmission System for the year 2030. The system is made up of 41 electricity transmission system operators (TSOs) that form the so called European Network of Transmission Systems Operators (ENTSO-E), belonging to 34 different countries throughout Europe.

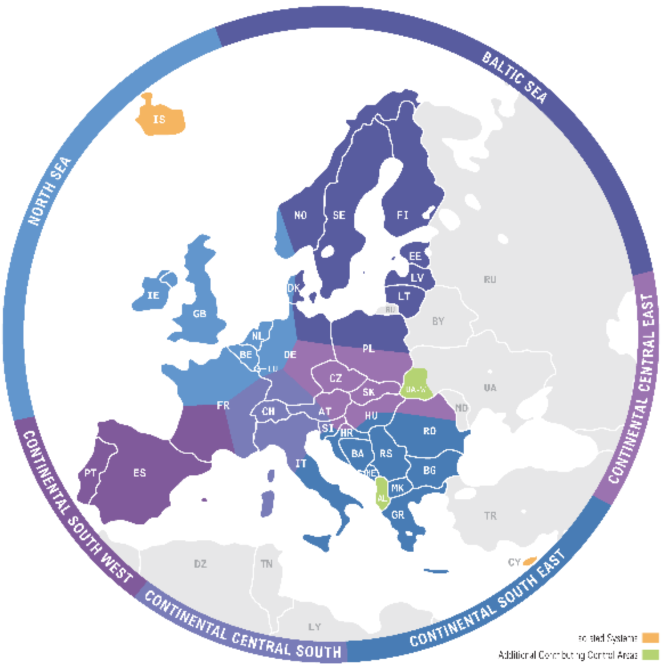

Figure 2: Transmission System Operators in Europe

Each of the TSOs operate independently in the electrical market and are in charge of the transmission of power in the main high voltage electric networks, provide access to generating companies, distributors, customers and other market players following previously rules that make the process fair and transparent for all. They must assure the supply, safety, maintenance and even in some countries, construct the necessary infrastructure for the grid to function correctly.

The final objectives of the ENTSO-E are the integration of renewable sources of energy (wind, solar, biomass, hydro, geothermal, wave and tidal generation) in the electrical power system and the completion of the Internal Energy Market (IEM) so that it meets the supply, sustainability and economic energy policies agreed in the European Union. By the year 2050, the goal is for renewable sources of energy to represent 97% of the electrical market, with the desired intermediate step of approximately 68% by the year 2030. At the same time, the expected curtailment of renewable sources of energy by the year 2030 (compared to the current 12%) goes from 6% in the worst case scenario (with inflexible generation) to 3% if we consider the contribution of energy storage; percentage which will remain approximately constant until the year 2050.

3. Aims

There are two basic problems that this project is trying to address. The first one is to provide a tool to integrate more power generated from renewable sources of energy. The actual transmission capacity of the lines that form the European Power Grid is not sufficient for the plan that the European Union has to increase the infeed of energy form renewable resources. Furthermore, the next important goal of this project is to contribute to the creation of a plan for the reduction of the total power and the frequency at which energy generated by plants of renewable sources is curtailed.

To achieve these goals, this project provides the resources to produce different upgrade plans determined by the number of lines to upgrade, the criteria used in the selection of the specific lines, and the level of upgrade that will be performed. The upgrade strategy that will be applied will optimize the number of lines to be upgraded based on the condition of the line upgrades being economically profitable. As mentioned in the European Grid Study 2030/2050, the main task is to find the situation in which the cost of upgrading is equal to the money saved from the reduction in curtailment after the project has been carried out.

The project will develop, using Matlab and Matpower, Optimal Upgrade Plans for the European Power Grid Plan for the year 2030, but may be applied to other systems. The input of the load model that wants to be studied and the weather data that wants to be used will be necessary.

4. Scope and Delimitations of My Study

The complete European Transmission System model has been used without applying any simplifications to obtain more precise results.

To develop the best strategy for the transmission line upgrade, only the cost of upgrading the lines and the cost of the curtailment of the renewable sources of energy were taken into consideration. Other policies or regulations were ignored in this project as well as the cost of the necessary upgrade of the transformers in the system.

The results and conclusions obtained from this study are also limited as the cost of building new power plants, for example to back up the increase in renewable energy sources, is not taken into account. There may be optimal combinations found where a higher reduction in curtailment is achieved, but that at the same time results in a higher investment in power plants. Or the complete opposite, where the maximum possible reduction in curtailment is not the most optimal option.

Furthermore, the power transmission capacity throughout the grid being studied is foreseen to increase and HVDC converters are expected to be widely present, and as a result no additional compensation will be necessary to assure the system voltage stability and other dynamic issues. Therefore, the core of the investment made to expand the grid will be based on the upgrading of the lines; another reason for only considering the upgrading costs.

In relation to the previous point, for reasons that will be explained later after a critical discussion and comparison between HVDC and HVAC lines in the section of Background Theory and Methods To The Study, the upgrade plans were only considered to be made with HVAC lines.

In opposition to the ENTSO-E study, the effect of storage has not been taken into account. According to recent studies, the influence of energy storage on the reduction of curtailed energy, taking into account the current technologies being developed and the expected quantities to be installed, is not very significant.

Also, unlike in the ENTSO-E study where wind, solar, biomass, hydro, geothermal, wave and tidal generation is considered, in this project the only renewable sources of energy that are taken into account are wind, photovoltaic and hydro energy. This was decided to be done to reduce the complexity of the model. Wind and photovoltaic generation are the two renewable sources form which the highest growth is expected and were therefore included. The data for hydro generation was additional included in the model, but no special observations were made in this sector, as no significant growth is expected.

Moreover, there are unpredictable problems that may arise that due to their nature cannot be considered in this project and for which a safety margin has not been applied. They could affect the quantity of integrated infeed of renewable sources of energy or even the investment on the grid upgrade itself. Such problems may be economical problems to finance the expected quantities of renewable energy sources, power plants or the upgrading of the lines itself due to the current economic crisis that Europe is going through. There is the possibility that some governments, due to the limited budget they currently have, restructure the areas where the largest investments will be made.

Also, there are social associations and communities that protest against the upgrading of lines in certain places. An example is a group of neighbors from the Bavarian District of Neumarkt in Germany. They protest under the phrase 'Trassen Wahn', or Delusional Routes in English. One of their claims is that the additional lines and the upgrading of others which are planned to be built will have a negative impact on nature and ruin the landscape in which they live. They also protest that the lines which are said to be necessary for the transport of energy from the north of Germany, where large quantities of wind energy are generated, to the highly industrialized South region have another purpose. They believe that one of the main reasons for its construction is the intention of transporting larger quantities of energy but that originate from the burning of fossil fuels, such as brown coal, as there are large lignite resources in the north coasts of Germany, and therefore, the conversion to a greener electrical market would be tricked. As a result, more transparency in the system and a larger divulgation of the project may be needed, otherwise it could have a limiting effect on the extension of the upgrade plan.

Another difficult aspect to predict is the change in weather that may occur from year to year, which largely conditions the infeed of Wind and Solar energy into the system. In this project, the weather data base of the year 2012 has been used.

Also, system operators must additionally consider ways to ensure the security of the system due to the increasing tendency in the penetration of renewable sources of energy. Some ways are ensuring the supply with additional reserves or expanding the grid with cross-border connections. However, other problems may arise, such as stability problems with the extension of the grid.

BACKGROUND THEORY AND METHODS TO THE STUDY

1. Techniques to upgrade transmission lines

There are different techniques to make the most out of the already existing electric grid and regulate power transmission across the lines and at the same time promote a faster growth in the implementation of renewable sources of energy. The technologies applied will have a big effect on the cost of upgrading and condition the extension plan, and are therefore important to analyze before the execution of this project. The approaches presented below try to achieve the optimization of the grid by making use of the already existing lines and trying to make the least possible modifications:

- Dynamic Line Rating (DLR):

This system makes a more realistic rating of the maximum transmission capacity of a line at a certain time based on the existing weather conditions, allowing a higher power transport. Very few times the extreme conditions (full sunny day and very low speed wind) that cause the maximum accepted sagging for which they have been designed, are reached. It has been estimated by some DLR promoters that an increase in 10ºC of the ambient temperature increases the line rating by 10% and an increase from no wind to 1mps at 90º by 40%. The result is using the same lines but in a more efficient way.

The negative aspects are that further apparatus has to be installed in order to exchange information between the line control system and the line itself. This process must be done offline, causing stability and supply problems in the system, especially when they are lines with a high transport capacity. Furthermore, the same cables are used, and as the current increases, the losses increase with the squared current, so it would be necessary to study in which cases it would be best to apply this method; for example in lines that are not overloaded during extended periods of time or to back up faults in other lines.

- High Temperature Low-Sag Conductors:

This system consists of upgrading the lines by substituting the conductor cores with high-temperature low-sag conductors. While having the same weight and diameter and using the already used transmission infrastructure as the traditional conductors, the line thermal rating is increased significantly, as although the temperature also increases with the current, the resulting sag of the line is much lower. The new HTLS conductors are made with composite materials that reduce the extra losses obtained at higher currents. Also, similarly to DLR, the application of this procedure enables other lines to also increase their energy transport or carry more power itself while other lines are disconnected for maintenance or during faults. HTLS conductors can additionally be very useful in areas where it is especially important to have a small sag, for example over a road or river.

The main disadvantage of this procedure is the cost of this type of conductors, 1.2 to 6 time the price of the traditional conductors, although again, the already existing infrastructure is used.

- Voltage Uprating:

The objective of voltage uprating is, as its name indicates, to raise the operating voltage of a line to the next larger voltage standard level and consequently, the power that it can transport but this time, without the need of raising the current, avoiding the increase of losses. This method can be especially attractive when a large increase in power is needed, otherwise the same ROWs could be maintained.

When the conductors can be reused and only for example transformers need to be substituted, this option becomes really feasible, however, many times there is an increase in the corona and Electromagnetic fields of the transmission lines that require further modifications. In such cases, larger diameters or bundle conductors may also be necessary, further requiring the modification or substitution of the transmission towers. At the same time, this could avoid the need for the expansion of the ROW and result in more compact infrastructures that reduce the negative environmental impact.

- Flexible AC Transmission Systems (FACTS):

These devices are a result of the great advances in the development of power electronics. They provide dynamic compensation and permit the operation of the system to have a closer fitting to the stability limits of the grid. As a result, an increase in the transmission capacity, or in other words, more closeness to the thermal limits can be achieved. There are three main types of FACTS:

1. Parallel-Connected FACTS Controllers: Provide continuous and controlled reactive power and maintain the system voltage constant, reacting quickly even to line faults. Although its main objective is to add stability to the grid, the capability of modifying the voltage magnitude and phase-angle independently form that of the system, the lines can operate closer to their thermal limits. It also has the ability of storing energy, although some require filters in order to reduce the current harmonics. Examples are Thyristor-Controlled Reactors (TCRs), Thyristor-Switched Capacitors (TSCs), Static Var Compensators (SVCs) or static compensators (STATCOMs).

2. Series-Connected FACTS Controllers: These controllers provide a variable capacitive compensation in a certain path even during operation and control power flow both in steady-state and dynamic conditions. They reduce the impedance of strategically selected lines connected parallel, shortening them electrically and reducing the line-angle. This not only contributes once more to the stability of the system, but also directs the power flow along the desired lines (as power flows in the path where it finds the lowest impedance). Examples are Thyristor-Controlled Series Capacitors (TCSCs) and Static Synchronous Series Compensators (SSSCs).

3. Combined FACTS Controllers: They are made of series and shunt FACTS devices combining the benefits from both controllers described previously. They can regulate the voltage, phase angle and vary the electrical impedance, influencing on the active and reactive power flow. A common example is Unified Power Flow Controllers (UPFCs), which is a fusion between STATCOM and SSSC controllers. It can additionally redirect power avoiding lines that need additional capacity in a parallel line. Another example are Dynamic Power-Flow Controllers (DFCs) that have a complex voltage divider to control the voltage across the series transformer.

<u>- Addition of HVDC (High Voltage Direct Current) systems:</u>

The main objective of this technology is to connect asynchronous systems and the transmission of electricity across long distances making use of power electronics and making use of converters and rectifiers. They offer important benefits: 1) The inductance or capacitance of the line doesn't need to be considered, as there is no flow or reactive power across the line, 2) The line will no longer have power transmission limitations depending on its length, but will be able to be uploaded to its thermal limit, 3) Stability problems that appear in AC lines when considering large distances will no longer need to be considered, 4) There is no skin effect and the whole cross-section of the cable is utilized, again increasing the conducting capacity of the lines, reducing the needed cross-section area and as a consequence the weight of the cable, 5) Only 2 phases instead of three are needed: one for the positive pole and one for the negative pole, 6) Two grid working at different frequencies may be connected. The main disadvantage, especially compared to HVAC is the cost of the line installation until the critical distance where the opposite happens (typically considered approximately 800km, but as a result of the development of new technology, estimated by some close to 600 km).

However, there are also technical limitations in the DC technology. For example, DC circuit breakers can only achieve a maximum allowance of one megawatt of power and cost approximately 100 times more than that of Alternating Current.

- Addition of HVAC (High Voltage Alternating Current) systems:

The main advantage of using HVAC lines, especially compared to HVDC lines is the cost of the line installation needed to be confronted. The money needed to be spent until reaching the critical distance, where the cost for both technologies intersect, is higher for HVDC technology than for HVAC. The critical distance is typically considered to be approximately 800km, but as a result of the development of new technology, estimated by some close to 600 km. Only a variable cost is considered for the installation of HVAC lines which is €400/MW/km, while the cost of building HVDC lines is broken up into €150,000/MW fixed costs and €1500/MW/km (These values were obtained from the European Grid Study 2030/2050 created by energy**nautics** GmbH).

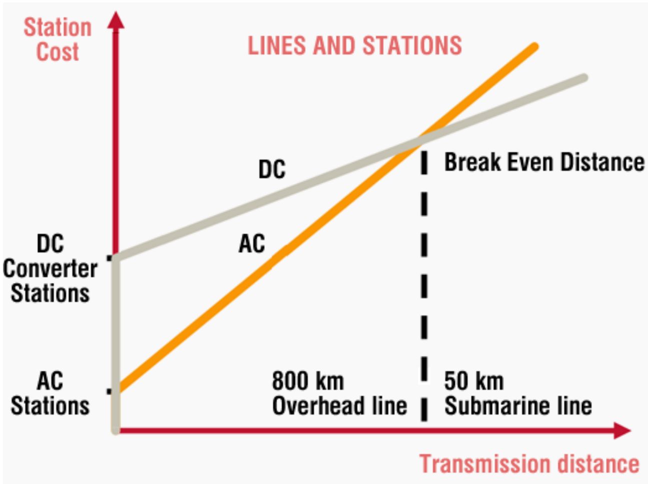

Figure 3: Comparison Price HVAC and HVDC Line Installation [2]

The disparity in price between both systems is principally due to the cost of the terminal equipment; HVDC requires converters, filtering smoothing reactors and other apparatus in the substations. However, at long distances, especially when lines are more than 600 km long, the opposite occurs. Every certain distance, it is necessary to install compensation stations to reduce the charging process that takes place and stabilize the voltage. Additionally, until now and also in the near future, the cost of the tap change transformers is lower for HVAC technology.

In this project, the maximum line length that is taken into consideration is 242.4 kilometers and therefore, the limitation of the critical length doesn't affect this case study. Also, in the European Transmission System, the frequency is 50 Hz in all sectors that form part of it, therefore the HVDC lines do not offer any benefits related to this aspect. For this project also, parameters like the sag of the cables is not considered as a determining characteristic and is not taken into account.

From a technical point of view, the benefits HVDC lines offer versus HVAC lines that were previously mentioned, do not offer a substantial profit from their use when considering their application in this project.

As a result of the analysis of all the factors described above, it was concluded that for this study, the lines to be implemented during the upgrade were to be HVAC lines, adopting the numerical value of the cost of upgrading a HVAC overhead line of €400/MW/km.

2. Simplification Methods for a Large Transmission System

The rise in size and interconnection of the transmission system network increases the approximation to operation under the steady-state stability system as the chances of experiencing voltage instability increase. In addition, the time and resources required to perform the necessary on-line and off-line analysis in such large systems make them infeasible to perform. As a consequence of these two issues that must be treated for a good operation of the grid networks, simplification methods into network equivalents with a reduced number of nodes have been designed.

Although at the same time some degree of precision will always have to be sacrificed, they are useful for several applications. Some are focused on planning, for which they need previous information about the network off-line, while others work directly on operation, identifying and estimating the different variables by using real-time data.

To get a view of how these simplifications have been designed, some examples were looked into. A common application that has been developed and widely used until now is the f genetic algorithm. A model based on this idea is the steady-state equivalent X-REI, useful for on-line calibration and for the planification of studies of the system. The simplification is made by maintaining the core study system without any variations and simplifying the rest of the system applying. However, there is a complex bus voltage in the part that is left untouched that is highly sensitive to the simulation of contingencies. Approaches to try to tackle this problem have been attempted, such as the addition of external buses, which improve the efficiency of the system.

Other simplification methods apply optimization methods such as Lagrange and the Z-Thevenin-Based Method that calculates the equivalent impedances of the lines between generators and the connected loads.

Hence the advantages of these equivalent models, it was concluded that to obtain more precise, realistic and applicable results to the real existing power transmission system, no simplifications were finally applied to the transmission system.

3. Strategies to create the best upgrade plan

In addition to deciding which upgrading procedures are the most adequate, the criteria to decide which upgrade plans are better to be applied and the way it is achieved are also a very important and complex issue that is still under development. Some strategies that are currently being considered are described below:

- Automated TLRbased selection process:

This method is able to calculate which single line will produce the highest marginal income considering the security of the system. After the calculation for these specific lines of the Aggregate MVA Contingency Overload (AMVACO) and the Weighted Transmission Loading Relief (WTLR), the bus values are calculated again to analyze and evaluate the variations in the security of the system and add any possible overloads that may have taken place.

One of the disadvantages of this method is that the WLTR bus value calculations vary considerably with small changes in the system and depending on which lines have been selected to be analyzed. However, the main disadvantage or limitation of this method is that it is not possible to study several connections at the same time. When considering different possible connections, even after using results from previous simulations, the application of this method may lead to worse situations. Its application then requires more time and effort to reach optimal solutions for the system; and many times, not reaching the best solution that requires the combination of many lines in the system.

In order to increase the efficiency and reduce the cost of the system, it is necessary to focus on the smallest number of substations possible, as for every simulation considering one line, it can only reach to calculate the cost of the next closest connections. This method is therefore not applicable to obtain good enough results in a reasonable amount of time in the grid considered in this project; the European Transmission system consisting of more than 6000 buses.

- Non-linear programming and evolutionary techniques:

This technique considers the DC model through a Non-Linear optimization problem using the genetic algorithm Chu-Beasly (CBGA). It is used to develop a transmission system extension, taking into account N-1 single contingencies and an accepted unpredictable variation in the future energy demand. Each suggested possible solution is obtained using the Higher order

Interior Point Method for Linear Programming or using a Predictor Corrector Method. The problem can be further solved applying exact methods or Combinatorial Algorithms. It has been proven to produce optimal solutions even including contingencies, and experimentally applied in three systems: the 46-bus South-Brazilian system, the IEEE 24-bus system and the 6-bus Garver system. The quantity, location and time needed for the installation of the transmission devices are considered.

- Heuristic Models:

This type of model is an interactive process by which the best circuit plans are provided to the computer program planner after all phases of the creation process and then, observing the results, the user can decide to accept the model or modify it and simulate the new plan. The advantages of this method are its simplicity in the model and logics applied, the ability of interacting with the program to perform changes, and the way the results are produced; this is, a group of different plans that are applicable and close to the most optimal solution to the upgrade plan are combined to reach a solution for the complete system.

There is also the option of combining this method with optimization techniques and base the problem in the search of the most direct connections between the generators and the loads without the production of overload, with the Garver 6-bus test system. The application of optimization techniques allows the determination of the level of uncertainty throughout the process.

- Single-Stage Optimization Problem:

The Single-Staged Optimization Method can apply linear programming, integer programming and the gradient search method. The first works by maximizing or minimizing and objective function, in this case the addition of the lengths of the lines that form the transmission system multiplied by the power magnitude they carry. The disadvantage of this procedure is that, despite the fact that it can output an optimized plan for the transmission system from one year to the next, it may not produce the optimum plan for the future.

L. L. Garver, through the combination of linear programming and Linear Flow Estimation, invented a way of producing an automated transmission system planning algorithm, that can indicate where overloads exist and the addition of new lines is needed. This system allows overload to exist to detect where the upgrades are necessary and then, by progressively adding new lines individually, the overloads are eliminated from higher to lower magnitudes until the complete elimination of overload is achieved. Finally, then the elaborated plan is tested using an AC Load-Flow program.

As it has been mentioned previously, integer programming can also be applied to Single-Stage Optimization Problems. E. K. Lee applies a DC current load-flow model to detect lines that suffer overload and at the same time analyze the sensitivity of the line flows to change the admittance along line paths. Then, a Branch-and-Bound procedure summates discrete transmission capacity quantities as indicated after an economic analysis that takes into account the cost of the additional lines. The procedure is repetitively applied until the conditions formulated are completed.

The advantage of this method compared to the use of linear programming is that as variables are given the condition of being integers, the problem represents better the reality, as lines will be added or not, but no portions of lines can be integrated into the system.

Finally, when combining the Gradient Search Method with the Single-Stage Optimization Problem, the starting stage is also the application of a DC Load-Flow Model on the current and predicted generation and load distribution and capacity. Then, with partial derivatives, the performance of the system and the admittances of the lines, the needed system updates are calculated. As in the previous method, this is an iterative process that is to be applied until the wanted conditions are met.

- Time-Phased Optimization Model:

In oppostioion to the previous methods, the Time-Phased Optimization model can extend and update the transmission extension plans by including and introducing continuous feedback of the inflation, interest rates and the cost of upgrading the lines to perform corrections in the calculations made. It had been applied together with ineger optimization methods at an annual basis. The feasible resulting plans that are produced are a result of the minimization of the time and the upgrading capacity to achieve the required performance of the transmission system. Also Dynamic Programming has been applied, but it must be combined with other procedures, as it can not produce new upgraded plans, only try to combine different states as optimally as possible.

In this project, the criterion used for the selection of the best upgrade plans was based on the methods previously described. The final objective was the generation of after its application by comparing the cost of upgrading and the money saved with the reduction in the renewable energy no longer curtailed. This makes the application of the project as economically feasible and effective as possible. Similarly to some procedures described above, it was performed at an hourly basis and after performing a DC Load-Flow Model, the results were analyzed and when they didn't produce the desired output (reduction in curtailment and revenue after the application of the upgrade plan), the parameters of the number of lines and the upgrade level were varied and simulations were repeated.

4. Predictions from Other Institutions

Predictions in the changes the European Transmission System will experience by the year 2030 and the necessary resources that will be required in order to perform them, have been developed and published by different institutions. They appear in reports and projects related with the grid extension and the addition of generation capacity, the integration of higher quantities of renewable sources of energy and the reduction of the bottlenecks produced in the grid.

These prognoses, among others, are related to the upgrade power, the economic investment, the total distance of lines to upgrade and the percentage of total power generated and proportion of power generated from renewable sources of energy being curtailed. Some values published by different organizations have been used in this project to compare the results obtained and are mentioned below:

- European Grid Study 2030/2050 [25]:

This report performed by energyNautics GmbH, commissioned by Greenpeace International, focuses on the feasibility of the integration of more renewables in the European Transmission system through the performance of an optimal planning for the adequatization of the grid infrastructure. For all the different parameters, the increase associated with the optimization of the system to reduce curtailment performing OPF simulations, has been added to the base scenario for 2030, as this is the main objective of this project. The values are given below:

- Upgrade Power

Firstly, the expected amount of power to be upgraded between the year 2010 and the year 2030 is 258GW, when adding the increase associated with the optimization of the system to reduce curtailment (54 GW) to the base scenario (204 GW), as it is the case of this project.

- Investment

Additionally, the total amount of money that has been estimated to be invested in this project by the European Union is € 98.32 billion, being the quantity related to the increase in optimization € 27.98 billion and that of the base scenario € 70.34 billion.

- Total distance of Upgraded Lines

When it comes to the calculated total distance of all the lines that will be upgraded, the resulting number has been set as 60794 km of HVAC lines. The length for the base scenario is of 44731 km and 16063 km for the increase associated with the optimization to reduce curtailment.

- Curtailed Power Generated by Renewable Sources of Energy

Similarly, the European Union has also established a numerical goal referring to the total power from all sources of energy being curtailed. The calculated curtailment produced during the year 2010 of renewable energy is 12%. The European Grid Study 2030/2050 predicts it is possible, with the resources invested in this project, for this percentage to drop to 4% by applying the global prioritization method. However, by optimizing the money invested in the infrastructure and the money saved from the reduction in renewable energy curtailment, this percentage sinks to 1%. This last objective is the one that will be considered in this project.

- Ten-Year Network Development Plan 2014, the 6 Regional Investment Plans and the Scenario Outlook and Adequacy Forecast 2014-2030 [10]:

The European Network of Transmission System Operators for Electricity (ENTSO-E) has developed these reports to describe the predicted investments that will be required for the grid upgrade until the year 2030. The focus on the assurance e of security of energy supply, the integration of renewable sources of energy, the socio-economic welfare and the flexibility and robustness as well as the environmental indicators. They offer different possible scenarios depending on the quantity of renewable energy integration, the prices of fuel and CO_2 emissions and the consistency of the generation mix.

- Total length of upgraded overhead HVAC lines:

In the breakdown the TYNDP-2014 makes for the length of the new lines and upgraded lines, the estimated total length of upgraded HVAC lines is of approximately 4000km. However, it has to be taken account during this project, that to achieve the numbers published, the building of new HVAC and HVDC lines was taken into account, while in this project, only the upgrade of HVAC lines is considered as a solution for the extension of the grid. Also, to obtain these values, the prevention of creating any interference with areas that are urbanized or environmentally protected, however, these variables have not been taken into account in this project.

- Investment on Upgrade of Lines:

The total investment predicted to be made by the year 2030 is of around €150 billion, representing the upgrade of the HVAC lines and existing AC assets 10% of this total expenditure.

<u>- A European Grid for ¾ Renewable Electricity by 2030 [27]:</u>

This report published in the year 2014 by Greenpeace, again with the partnership of energyNautics GmbH, attempts to develop a plan for the optimization of the grid taking into account different political scenarios and different quantities of renewable energy expected to be integrated in the system. Although it focusses on the creation of a grid formed by HVDC lines instead of HVAC lines which is what will be used in this project, it still offers important information necessary in the creation of this project:

- Cost of Upgrade of HVAC Line:

The published cost of an Overhead HVAC line is of €400/MW/km, which is the price that will be applied in this project to calculate the cost of each upgrade plan.

- Cost of electricity in the year 2030:

The price of the electricity predicted for the year 2030 for the conflictive case is of €60/MWh and is the one that has been considered in this project to calculate the money saved due to the reduction in the curtailment after the application of the upgrade plans.

- Total length of upgraded overhead HVAC lines:

It is estimated that 8300 km of HVAC lines will be upgraded, out of which 7620km are overhead lines.

- Renewable Energy 24/7 [28]:

This report, created by Greenpeace International, attempts to build a plan for the optimization of the European Transmission system through the development of a smart grid for a higher integration of renewable energies, considering a database of 30 years of weather data and the expected annual demand of the European Union at a 15 minute rate. The following data was published:

- Number of HVAC lines to upgrade:

The number of HVAC lines that has been suggested in this report to be upgraded is only of 34. However, it must be taken with caution, as the criteria behind the selection of these lines are unknown and the results for our project may largely defer when other criteria or upgrading levels or other limitations are set.

- Total length of upgraded overhead HVAC lines:

The total length of HVAC lines that has been suggested needs to be upgraded in the European Transmission System is of 5347km. For the same reasons that have been explained in the previous point, this number must be taken with prudence.

- The cost of Upgrade

As a result of the upgrade plan with the details described in the previous point, the estimated cost of the project is of €3 billion.

METHODOLOGY

1. Work plan

The following diagram shows the review of the work plan of this project that will be explained in more detail below in this section in order to attain the objectives set in the introduction. The part colored in blue is the material that has been provided and will be worked with, and the red the part is the section to develop in this project:

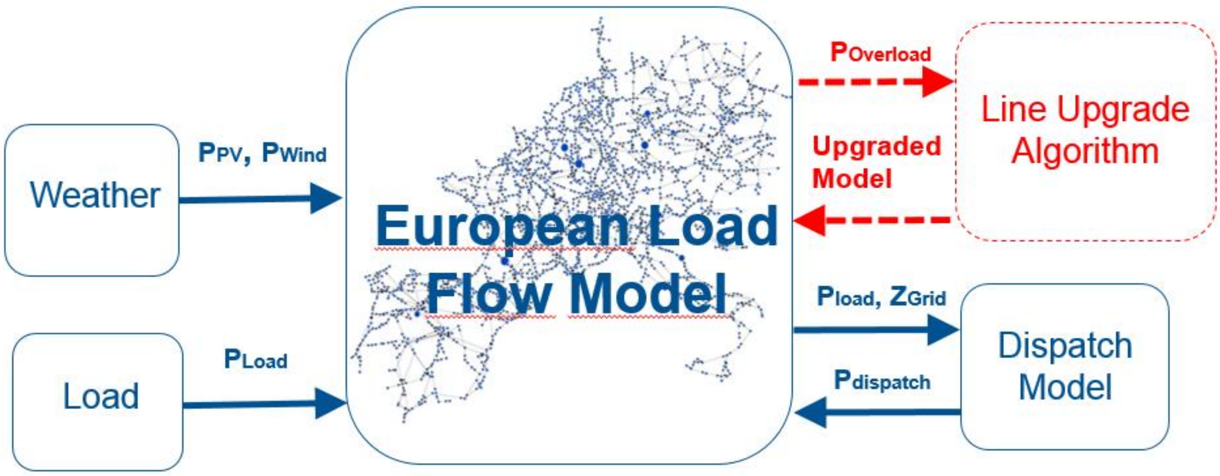

Figure 4: Scheme of Use of Working Tools and Project Development

The following Flow Diagram summarizes the steps taken to create the Line Upgrade Algorithm and develop a Network Planning Strategy for the Future European Transmission System:

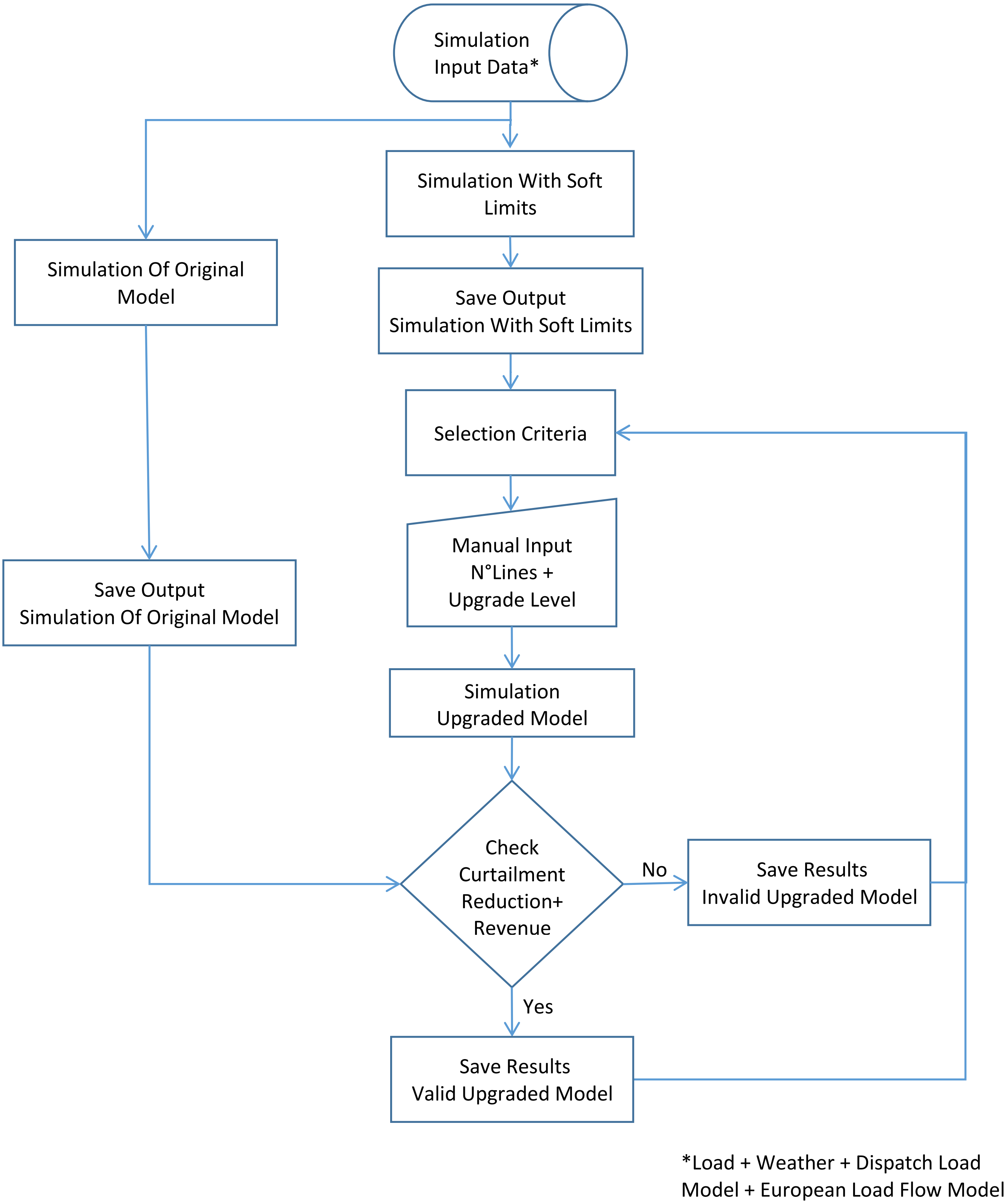

Figure 5: Flow Diagram of Work Plan

2. Working Tools

In order to handle all the information given and perform DC Optimal Power Flow simulations, the working environment that was used was Matlab. A DC OPF was preferred instead of an AC OPF because the latter is a nonlinear problem. In addition, Matpower was applied as a complement for Matlab to solve simulations with optimal power flow case studies. It is applied using a simple code language that can be easily manipulated and varied. Moreover, it includes different solvers, such as CLP, GLPK, MOSEK or Ipopt. In this project, the solver used was GLPK that, although it was relatively slow in giving results after each simulation (taking more than 72 hours per simulation), it is designed to solve linear programming at a large scale.

3. Starting Resources

As a starting point, a detailed model of the interconnected European Power Transmission System, made up of 5761 buses, was constructed by the Institute of Power Transmission Systems and incorporated into the study as the variable 'model2030.mat' in Matlab. The characteristics of the generators, buses and branches were included respectively in the variables mpcHernandez.gen, mpcHernandez.bus and mpcHernandez.branch inside the model.

This model includes the predicted load data for the year 2030. According to the European Grid Study 2030/2050 [25], performed by energy**Nautics** GmbH and the report EU Energy, Transport and GHG Emissions Trends to 2050 [29] published by the European Commission, the predicted demand for the year 2030 is expected to be between 6% and 7% greater than the demand in the system for the year 2012. This increase was applied to all load points in the grid on the load model of the year 2012 to obtain the model used for the year 2030.

Furthermore, the renewable infeed into the system was introduced by multiplying the maximum power output of the renewable energy generating buses, specified in the load model given, by a factor between 0 and 1 that depends on the weather data being used (in this case the correspondent to the year 2012), and the characteristics of the capacity of the turbines that are located in each generating plant.

In this project, the complete European Transmission System load model has been used without the application of any simplifications with the objective of obtaining more precise and realistic results, despite the time required for each simulation being longer.

During a simulation, the hourly load data is assigned to be produced by the different generating nodes that form the transmission system obtaining an Optimal Power Flow. In this process, the maximum power that can be offered by each generator and the maximum transport capacity by the lines are taken into account. For the latter, 80% was defined as the limit to be able to act in the case of N-1 contingencies.

4. Simulation European Power Transmission Model

The simulation of the European Power Transmission System model was performed at an hourly basis for 8784 hours (all the hours of the year 2030 which is a leap year) using the function qslfHernandez.m. The results obtained contain information about the amount of curtailed energy generated by wind and photovoltaic sources and the flow of energy along each line. These results serve as a reference to compare the effects of all different modifications and upgrade plans that will be tested along this project and observe the changes in the power curtailed and the cost effectiveness of each of them.

5. Single Time Instance Upgrade Plan

To create a strategy for the optimal upgrade of the transmission system and to decide if a line should be upgraded, the cost effectiveness of the upgrade of each line was obtained for a unique time instance.

Other variables, such as the degree of overload of each line or the time that it is overloaded are also important to consider, and will be considered later on in the project, but the economically viability of the line may be compromised. As a result, as a first analysis, the strategy developed was to formulate the comparison between the cost of the energy that is curtailed due to the limitations imposed by the maximum capacity of the lines, with the cost of upgrading those lines.

In order to do this, it was considered that the best way was using the callback function 'toggle_softlims', which is an extension of the functions of Matpower [24].

The way it works is by substituting the capacity branch flow limits set for each line in the DC optimal power flow model with flexible limits. This allows the maximum limit set previously in the transmission system model, to be surpassed. By additionally applying a 'punishment' cost, linearly related to the power overloaded and the length of the line, the function calculates the cost that would be necessary to be faced in order to upgrade the line with the capacity of the overload power. In this project, the cost used was €400/MW/km, obtained from the 201402-power-grid-report published by Greenpeace [27}.

The function then calculates the cost of the energy curtailed using the cost coefficients set in column 5 in the variable mpcHernandez.genscost included in the transmission system model and the input cost of the renewable energy inside the function qslfHernandez.m set as €60/MWh, also obtained from the 201402-power-grid-report published by Greenpeace.

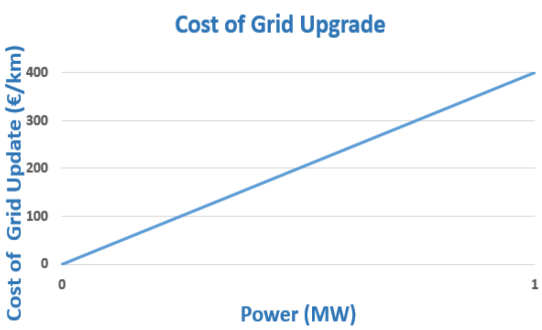

Figure 6: Graph of Cost of HVAC Line Upgrade (€/km)[27]

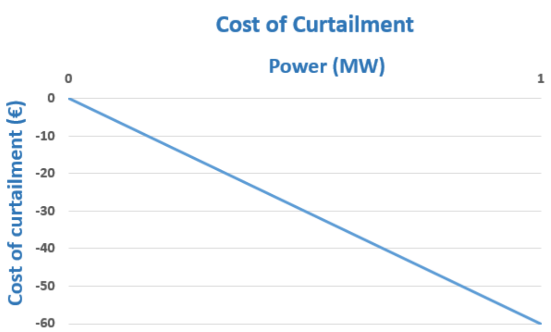

Figure 7: Graph of Cost of Curtailed Renewable Energy[27]

Finally, the function compares both of these values and outputs the list of the branches that have seen their maximum power flow capacity surpassed, the overload power of each of them, the branch flow penalty cost and the Kuhn-Tucker multipliers on the soft limit constraints.

The comparison between both costs couldn't be performed directly. On the one hand, the cost of upgrading a line as described before is the total cost, taking no consideration of the time that is taken to finalize it. On the other hand, the cost of the curtailed energy is calculated at an hour basis. Therefore, to compare the costs during the same period of time, both values were scaled to an hourly basis. To do this, the lifetime of a line was considered to be 40 years.

6. Implementation Line Upgrade Algorithm Over a Year

Furthermore, the Single Time Instance Upgrade Plan was extended to the whole year 2030. An algorithm was created and implemented to perform the line upgrade at an hourly basis, the same way it has been described in the previous section, in a recursive manner from hour 1 to hour 8784. The function responsible for simulating this algorithm on the European Transmission System Model is a varied version of the originally used qslfHernandez.mat, modified by adding:

- The instruction to activate the callback function of soft limits:

```
mpc = toggle_softlims(mpcHernandez,'on')
```

Figure 8: Activation of Soft Limits Function

- The input of the cost coefficient for the application of soft limits:

```
for i=1:length(lineLength(:,1))

     tempIndex=find((eq(mpcHernandez.branch(:,1),(lineLength(i,1)))&
eq(mpcHernandez.branch(:,2),(lineLength(i,2))))==1);

      for j=1:length(tempIndex(:,1))
mpc.softlims.cost(tempIndex(j,1),1)=(lineLength(i,3))*400/(24*365*40);
      end

 end
```

Figure 9: Input of Cost Coefficient for Soft Limits Application and Line Length Match

Note: The cost coefficient must be input in the function toggle_softlims with units €/MW. However, the cost considered for the line upgrade was in the units €/MW/km. Consequently, every line was assigned a different cost coefficient depending on its length. In the previous code instructions, taken from the function qslfHernandez.m, the multiplication of the cost by the length associated with each specific line can be appreciated.

- The integration of the cost of the energy generated from wind and photovoltaic sources:

```
mpcHernandez.gencost(860:end,5) = -60
```

Figure 10: Input of Cost of Curtailed Renewable Energy

As a result of the application of the modified function, the list of the branches that had their maximum power flow capacity surpassed, the overload power of each of them, the branch flow penalty cost and the Kuhn-Tucker multipliers on the soft limit constraints were obtained at an hourly basis for the whole year 2030.

7. Selection Criteria

Previously, the possible candidate lines to be included in the upgrade plan were identified by observing if they were economically viable to upgrade at an hourly basis to perform a first selection. However, to decide which of these lines will be finally incorporated into the plan, it is necessary to compare the cost of upgrading the lines and the cost of the energy being curtailed during the lifetime of the lines. Only then, it will be possible to decide which lines are economically viable to upgrade.

The next step consists in the application of decision criteria to perform the selection. To do this, the lines were studied under different orders of preference and different levels of upgrade.

7.1. Order of Preference

There are many different benchmarks behind the various ways to give some lines preference over the others to be upgraded, depending on the different objectives that want to be achieved. In this project, five criteria for order of preference were considered and evaluated: a) the overload frequency rate, b) the magnitude of energy overload, c) frequency weighted mean energy, d) total line length to upgrade and e) upgrade plan investment.

In all cases, the effect of ordering the lines in the ways described above were represented and compared to observe the relationships that exist among them and draw the necessary conclusions to decide that the upgrade plans will be studied using the criteria of Frequency Weighted Mean Energy.

a. *Overload Frequency Rate*

The reason for considering the approach of ordering the lines depending on their overload frequency rate is that they are responsible for the production of bottlenecks and those lines with a higher overload frequency rate have a higher probability of contributing to a larger energy curtailment. As a result, the lines were ordered from higher to lower overload frequency rate and in order of descending Frequency Weighted Mean Energy, in both cases as a percentage for more direct visual perception. The degree and rate of variation between the lines was observed.

The frequency at which lines are overloaded during the simulation of the model can be obtained by adding the number of hours each line appears to be overloaded among the 8784 hours being simulated. Two approaches are possible: (1) probability that, if overload takes place, it happens along a certain line, (2) probability of a certain line suffering overload along a year. The theoretical definition of the value of each tactic is different; however, the results will show the same pattern and the same relationship from line to line and will only be scaled. Therefore, only the effects of applying the second approach were studied.

b. *Magnitude of Energy Overload*

The magnitude of the overload power across each line is also an important factor to consider when deciding which lines are best to upgrade, as a higher amount of power curtailed makes the system more inefficient and raises the money paid for the renewables that cannot sell the minimum power generated. Respectively for the maximum and mean overload power experienced by every line during the simulated 8784 hours, the power was represented ordered from higher to lower values and in order of descending Frequency Weighted Mean. The degree and rate of variation between the lines was observed.

In order to be able to compare the results of the overload across each line from the simulation and compare it to other expectations set by other institutions, the overload was also represented in a cumulative manner in the Appendix section.

c. *Frequency Weighted Mean Energy (F.W.M.E.)*

As a result of the two previous criteria that have been considered and the output they have produced, it was considered to combine both to obtain a more powerful criterion. When selecting those lines with the highest curtailed power along a year, the consideration of the number of hours into which it is divided is not considered. As a result, if a large total overload power is result of a continuous curtailment extended uniformly in time or by contrast, it is caused by a high overload power peak during a short period of time cannot be distinguished. The same way, when basing the selection criteria on the frequency of overload, the quantity at which it occurs is ignored.

Consequently, the variable Frequency Weighted Mean Energy was created by multiplying the frequency rate of overload and the mean overload power across each line during the 8784 hours simulated. At first, by simply multiplying these two variables, the maximization of both parameters can't be assured, as a high result of the product may be a consequence of only one of the variables being large. However, both variables were represented in descending order of the Frequency Weighted Mean Energy and both describe a descending tendency. Also, the mean overload power was represented as a function of the frequency rate of overload, again in decreasing order of the Frequency Weighted Mean Energy, and the criterion proved to be feasible to apply.

The priority set for line upgrade using this variable is the maximization of both the overload frequency rate and the magnitude of energy overload, and therefore the maximization of the Frequency Weighted Mean Energy. Therefore, to observe the degree and rate of variation between the lines and to serve as a reference for the creation of the line upgrade plans that will be tested and analyzed; the lines were ordered from higher to lower Frequency Weighted Mean Energy.

d. Total Line Length to Upgrade

In this criterion, the number of kilometers of the candidate lines to be upgraded was set as the prioritizing reference. Similarly to the previous criteria, the lines were ordered in decreasing order of length and in decreasing order of the Frequency Weighted Mean Energy, and the grade and rate of variation between the lines was studied.

In this case, the order of preference to upgrade the power transmission lines can be from higher to lower total length or vice versus, depending on the objective that it is desired to be achieved. When upgrading from higher to lower line length lines, the idea behind this order can be the consideration that the upgrade of longer lines has a more difficult planification and require a larger investment to be made. As a result, they may be required to be included in large projects when searching for large coordination. In addition, longer lines have a higher probability of being in more than one country and consequently, need consensus for their upgrade between the governments. However, the European Union has already accorded to perform a line upgrade plan for the years 2030 and 2050, so this obstacle would be much easier to tackle. On the other hand, if shorter lines are given priority when selecting those that will be upgraded, as the cost of upgrade is dependent on the length as well as the power of overload, there is a larger probability that more lines will be able to upgraded whilst making the same investment.

The cumulative total length in decreasing order of the Frequency Weighted Mean Energy was represented also to allow a comparison between the results obtained and the estimated values of total line length upgrade given in reports written by the European Union and other organizations such as energyNautics GmbH.

e. Upgrade Plan Investment

The last preference order for the upgrade of the transmission lines to be considered was the economic cost of doing so. It must be remembered that the cost of upgrade that was considered was €400/MW/km, and therefore, it is linearly dependent on the length of the line to be upgraded and the power capacity of the new upgraded line. In this project, as it will be explained in the next section, three different upgrade levels were studied. The lines were once more ordered form higher to lower cost and in descending order of the Frequency Weighted Mean Energy, for the three upgrade levels to be analyzed.

Similarly to the previous idea behind the priority for upgrade, it can be preferred to include in the plan first those lines with a higher cost of upgrade or by contrary, those with a lower cost. In the first case, those lines that require a larger investment, have a larger probability of being longer lines and/or having a large overload power. As a result, they have a higher probability of decreasing the curtailment of renewable energy and therefore, are important to meet one of the goals set by the European Union by 2030 and 2050 related to the reduction of renewable energy curtailed to 1%. Also, as described before, longer lines may be wanted to be included in large upgrade projects such as the ones currently being planned and performed by the European Union. From another point of view, if lines with a lower upgrade cost are given priority, more lines will be upgraded, which can make sense in some cases. Many times, the shortest lines are located in urbanized areas, where it is complicated to build new infrastructure and new lines. In these situations, the option of upgrading the lines is more feasible and should be given priority when wanting to increase the transmission capacity.

To analyze this selection criterion also both the cumulative cost of the lines to upgrade and the cumulative cost of the lines that will not be upgraded are represented, as a function of the Frequency Weighted Mean Energy and for the three upgraded levels considered, were represented. The first one allows the observation and comparison of small changes in the limitations applied while the second gives a good vision of the cost of setting such limitations and how much money will still have to be spent due to curtailment.

7.2. Level of Upgrade

In addition to the criteria applied to prioritize which lines will be included in the upgrade plan, it is necessary to decide by how much each of them will be upgraded. In this project, three values have been considered, the mean power overload, the mean + the standard deviation of the power overload and the maximum overload of each line throughout the 8784 hours simulated. They were applied with the preference criteria Frequency Weighted Mean Energy as it was considered the most interesting of the preference selection criteria considered to achieve the aims set for this project. The analysis to get to this conclusion is explained later in the Analysis section.

The procedure that describes how the individual upgrade for each line was calculated and applied for each upgrade level is described below.

a. Mean Overload Power

The following formula shows how the mean overload power for each line along the simulated 8784 hours was obtained:

For every line: j = 1:7783

For every hour: i = 1.8784

Equation 1: Clculation of Mean Overload Power Per Line

$$Pow\_Upgrade\_Line\_j = \frac{\sum_{i=1}^{i=8784} P_{Overload}(i,j)}{8784}$$

b. (Mean + Standard Deviation) Overload Power

The next level of upgrade power attempts to perform a power upgrade that takes into account the amount of dispersion there is of the set of power values during the 8784 hours simulated with respect to the mean value of the latter for every line selected to be upgraded. This was done by adding the standard deviation of the power overload of the individual lines to the mean value. The formula applied for the power level of upgrade is the following:

For every line: j = 1:7783

For every hour: i = 1.8784

Equation 2: Calculation of Mean+Standard Deviation Overload Power Per Line

$$Pow\_Upgrade\_Line\_j = \frac{\sum_{i=1}^{i=8784} P_{Overload}(i,j)}{8784} + \sigma_j$$

c. Maximum Overload Power

To apply the upgrade of the transmission lines with the maximum overload power each of them experienced throughout the 8784 hours that were simulated, the following formula was applied:

For every line: j = 1:7783

For every hour: i = 1.8784

Equation 3: Calculation of Maximum Overload Power Per Line

$$Pow\_Upgrade\_Line\_j = Max.Pow._{Overload}(i,j) \quad ,\forall\, i = 1{:}8784$$

7.3. Effect of Application of Different Upgrade Plans at Different Upgrade Levels

Finally, the last step in the project is to create different upgrade plans with the selection of a different number of lines to update and at different upgrade levels, and calculate and compare the revenue each of them offers. Only after comparing the investment made in the installation and the money saved from the reduction in the curtailment of renewable energy through the upgrade, the real cost and benefit of the plan can be evaluated.

To do this, the European Power Transmission System model was simulated, as it was done at the beginning of the project, but incrementing the MVA power rating of those lines that are chosen to be upgraded in the struct mpcHernandez.branch. All the simulations were carried out without the application of soft limits, as the real output with the real new capacities after the upgrade plan is applied is desired. The variables obtained after the simulation will be the amount of curtailed energy generated by wind and photovoltaic sources and the flow of energy along each line of the system. These results are then compared to the original simulation of the model without the application of soft limits or any upgrade plan.

To calculate the revenue of each upgrade plan the following calculations were carried out using the results of the simulations previously performed. Firstly, the investment needed to be made for the upgrade of the selected lines was calculated using the upgrade cost and the length of each the respective lines. Then, the sum of the energy generated by wind and photovoltaic sources of energy in the individual nodes that form the system, separately for the situations before and after the upgrade plan, was calculated. The cost of the difference of the renewable energy curtailed in both cases was obtained by multiplying the total difference by the expected cost of the renewable energy in the year 2030 mentioned before, €60/MWh [27]. Finally, the revenue of each line upgrade plan was calculated by subtracting the cost of upgrade and the money saved with the energy that is no longer curtailed as a result of the application of the plan.

The upgrade plans were performed at 1/8 intervals of the cumulative Frequency Weighted Energy after ordering the lines in a descending order of the latter, resulting in 5, 12, 21, 34, 53, 88 and 155 lines upgrade plans. This process was repeated applying the upgrade level of mean and maximum power overload of each line of each throughout the 8784 hours being simulated. For better understanding, the following formulas were applied:

- Total Upgrade Cost:

  For every line: j = 1:7783

  For every hour: i = 1:8784

Equation 4: Calculation of Cost of upgrade Plan

$$Tot\_Upgrade\_Cost = \sum_{j=1}^{j=7783} \frac{€400}{MW * km} * Length(j) * Pow\_Upgrade\_Line\_j$$

- Total Cost of Difference in Renewable Energy Curtailed Before and After Upgrade Plan:

  For every line: j = 1:7783

  For every hour: i = 1:8784

Equation 5: Calculation of Money Saved with Reduction of Renewable Energy Curtailment

$$Tot\_Money\_Saved = \sum_{j=1}^{j=7783} \frac{€60}{MWh} * (Pow\_Curtailed\_Before - Pow\_Curtailed\_Before)$$

The changes in the renewable energy curtailed and the cost effectiveness of each of the plans were observed after being represented in graphs and tables and are analyzed in the Analysis section of this project.

RESULTS

1. No application of Soft Limits

The simulation of the European Transmission System model 'model2030.mat' was carried out firstly without any variations to obtain reference values related to renewable energy curtailment and the following output shown below was obtained. The power shown is the total power curtailed during one year, while the cost is the correspondent to the approximate lifetime of an HVAC line, considered in this project as 40 years [17] and based on the prediction of the price or renewable energy for the year 2030 to be €60/MWh [27]:

Table 1: Simulation of European Transmission Model with No Modifications

		Power (MW)	Cost (€ billion)
Curtailment	**PV**	277,534.9981372898	0.0166520999
	Wind	7,871,897.707827927	0.472313862
	Total	8,149,432.705965216	0.4889659619

2. Application of Soft Limits

The simulation of the European Transmission System model 'model2030.mat' was carried out with the application of the function toggle_softlims at an hourly basis and the output obtained was the cost and the overload of every line at an hourly basis for the simulated 8784 hours. Also, the overload cost that is generated by this function is the correspondent to the hypothetical cost of upgrading the line by the different overload powers every hour. However, the upgrade power of the line is a fixed number, so this variable will not be used for further calculations.

The resultant number of lines that experienced an overload and that were therefore candidates to be included in the upgrade plan were 1239.

Characteristic values of the results obtained are shown in the table below. In addition, sample graphs showing the results obtained for a line at a specific hour, and for a specific hour, all the lines, for both cost and overload, can be found in the Appendix.

Table 2: Simulation of European Transmission Model with Soft Limits

	Cost/MW/hour (€/MW/h)	Overload Energy/hour (MJ/h)	Overload Cost/hour (€/h)	Frequency/year
Mean/line	0.1724	148.6540	6.6815	318.88
Max./line	0.32	12133.00	553.07	8778.00

Cost of upgrading in (€/MW) of all the lines that form the European Transmission System Model studied:

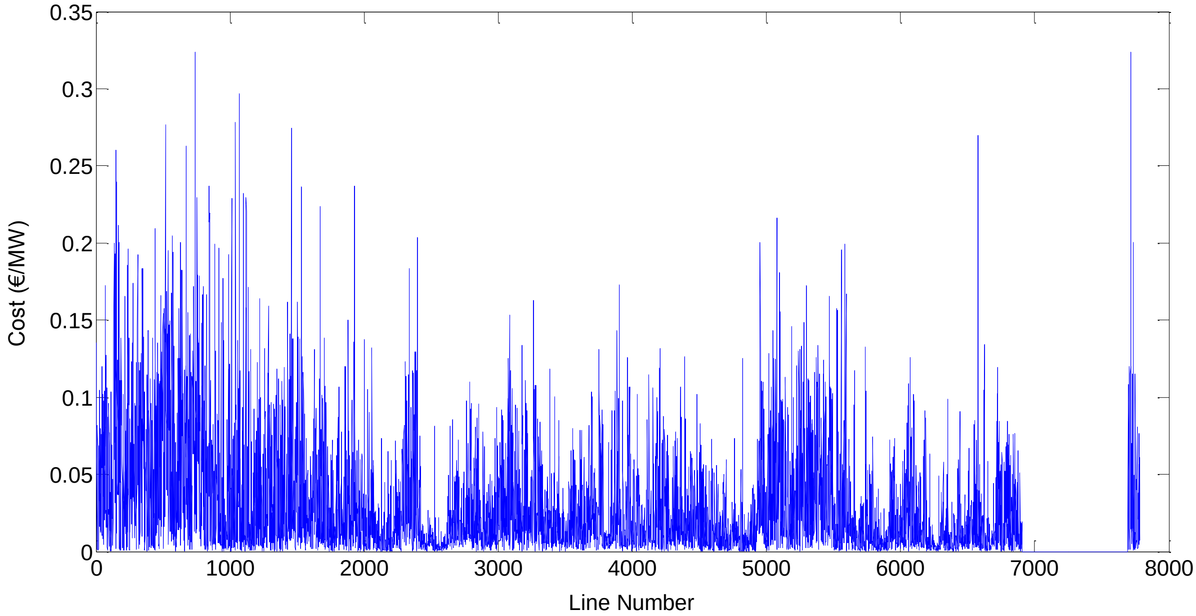

Figure 11: Output of Soft Limit Application: Upgrade Cost per Line (€/MW)

3. Relationship Preference Order Criteria

3.1. Overload Frequency Rate

The following diagram shows the probability of each of the lines of experiencing overload in a decreasing order as a percentage:

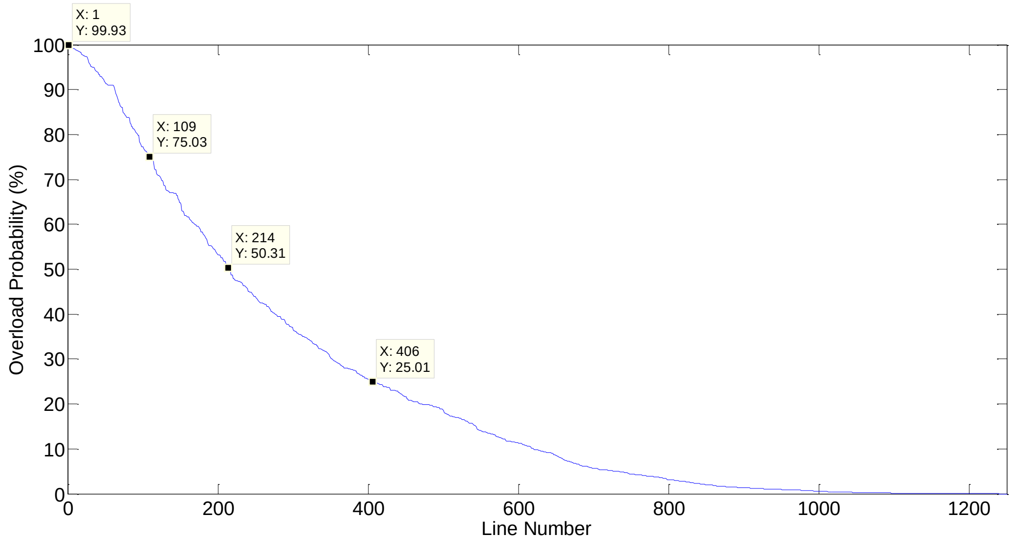

Figure 12: Probability of Line of Being Overloaded During the Year 2030 in a Decreasing Order

The next figure shows the overload frequency rate probability when the lines are ordered from higher to lower Frequency Weighted Mean Energy:

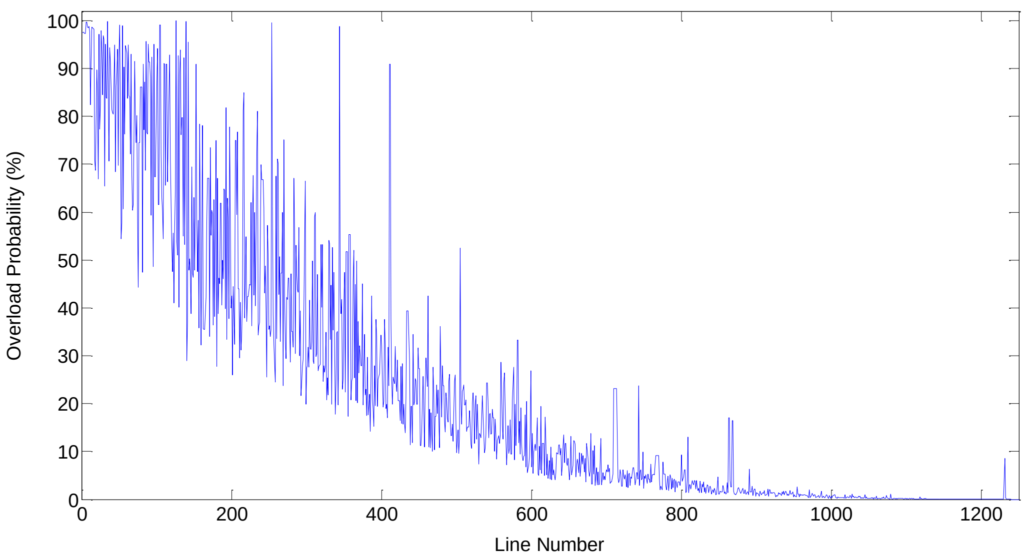

Figure 13: Probability of Overload Along Indiviual Lines, Decreasing Order of F.W.M.E.

3.2. Magnitude of Energy Overload

The following diagrams show, respectively for the maximum and mean overload power experienced by every line during the simulated 8784 in a decreasing order, the power ordered in a descending order and in order of descending Frequency Weighted Mean Energy and in a cumulative manner for both descending orders:

a. Maximum Power Overload

- Power in order of decreasing Frequency Weighted Mean Energy:

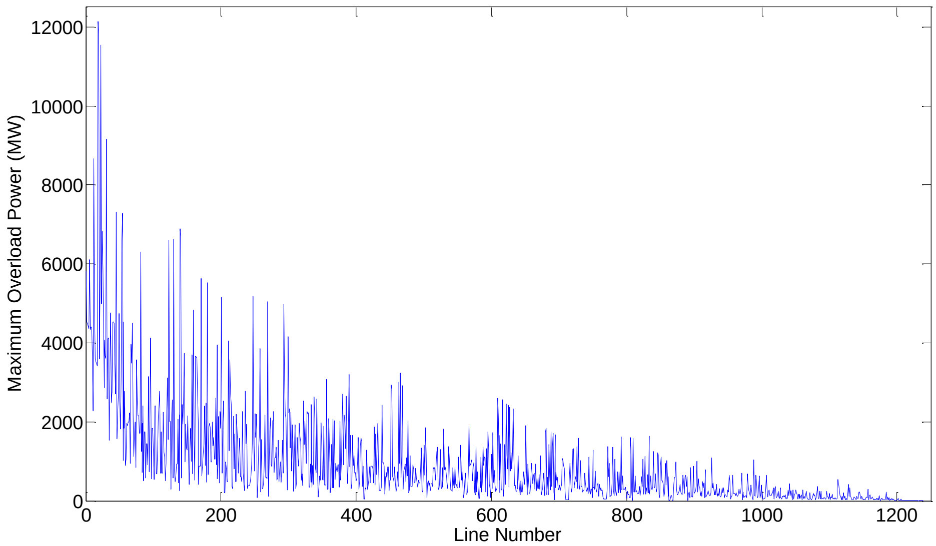

Figure 14: Maximum Power Overload, Descending Order of F.W.M.E.

- Cumulative power in order of decreasing Frequency Weighted Mean Energy:

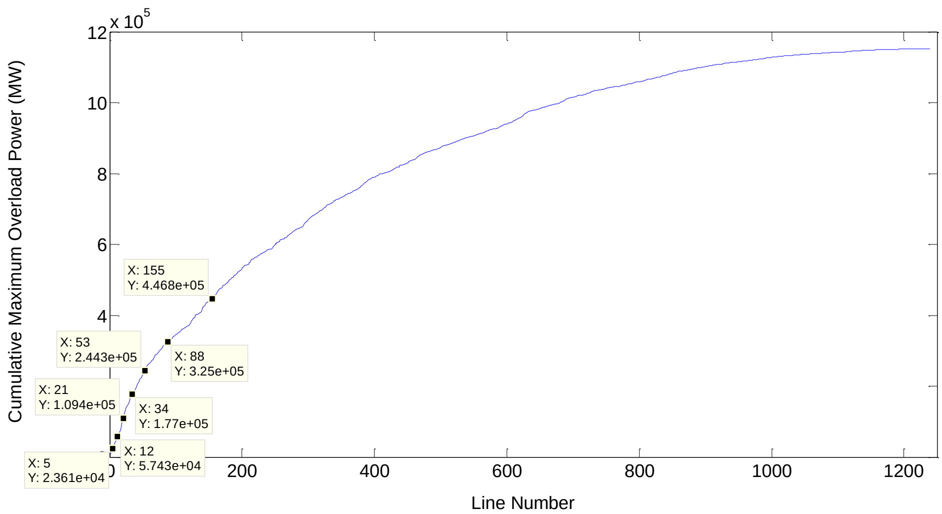

Figure 15: Cumulative Maximum Power Overload, Decreasing Order of F.W.M.E.

b. Mean Power Overload

- Power in descending order of decreasing Frequency Weighted Mean Energy:

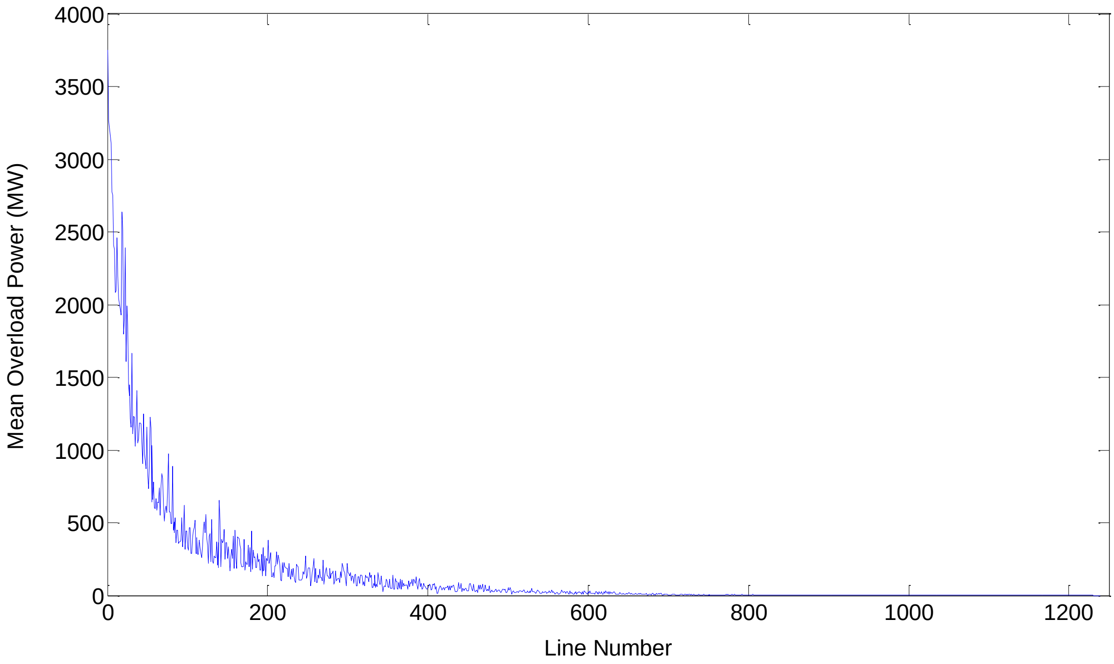

Figure 16: Mean Power Overload, Descending Order of F.W.M.E.

- Cumulative power in descending order of Frequency Weighted Mean Energy:

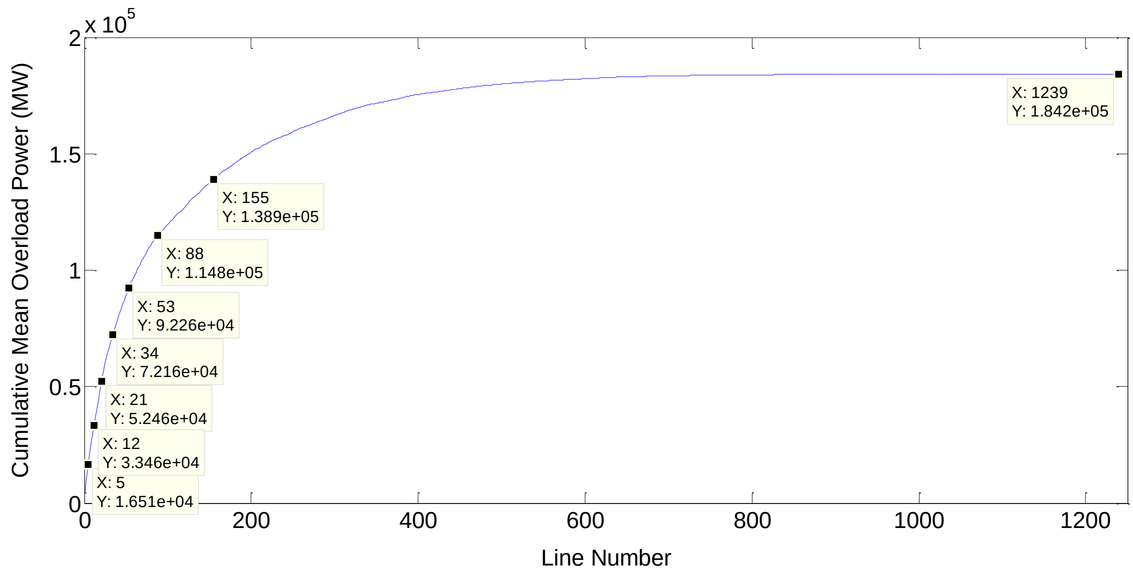

Figure 17: Cumulative Mean Power Overload, Descending Order of F.W.M.E.

3.3. Frequency Weighted Mean Energy

The following diagrams were represented to study the viability of the application of the Frequency Weighted Mean Energy Selection criterion. In the following diagrams the relationship between the frequency at which the lines experience overload and the magnitude of the latter were represented:

- Overload frequency rate in descending order of overload magnitude:

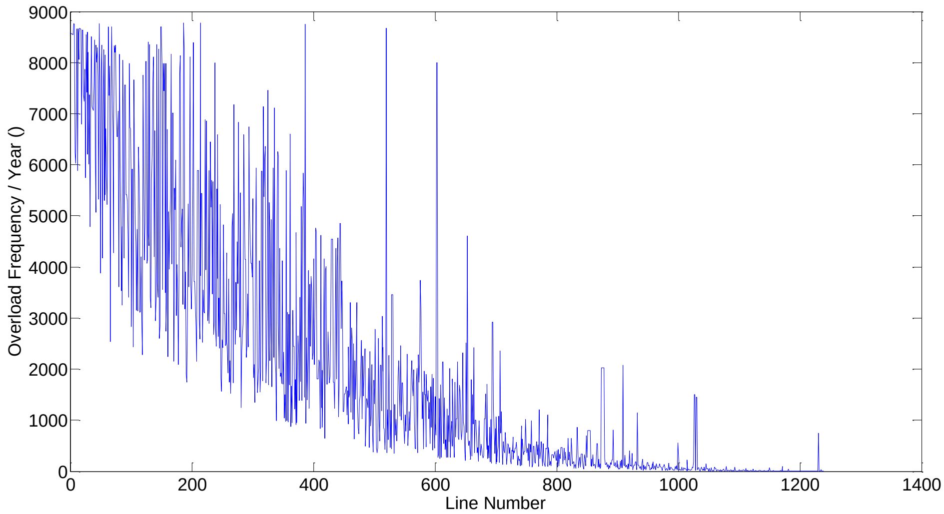

Figure 18: Overload Frequency Rate, Descending Order of Power Overload

- Overload Magnitude in descending order of overload frequency rate:

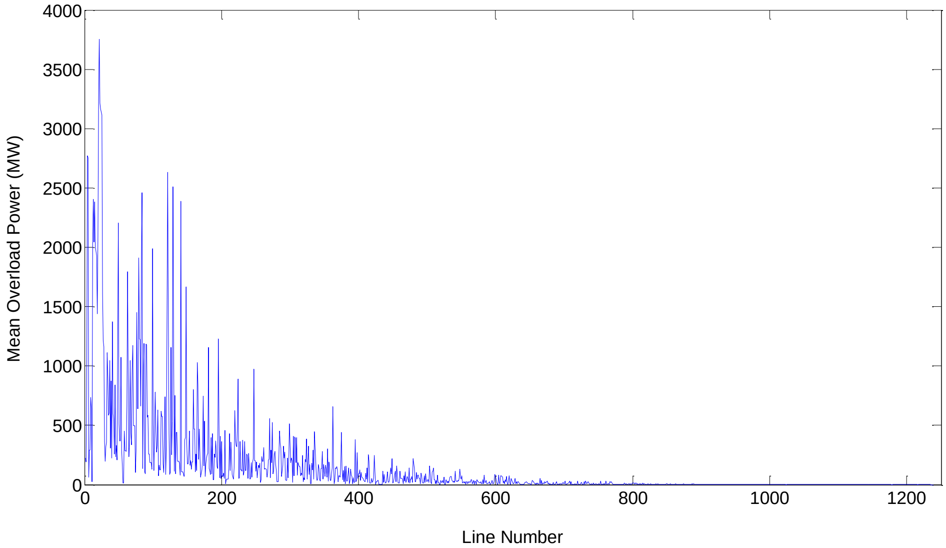

Figure 19: Power Overload in Descending Order of Frequency Overload Rate

- Mean overload magnitude as a function of overload frequency rate when the lines are ordered in decreasing order of Frequency Weighted Mean Energy:

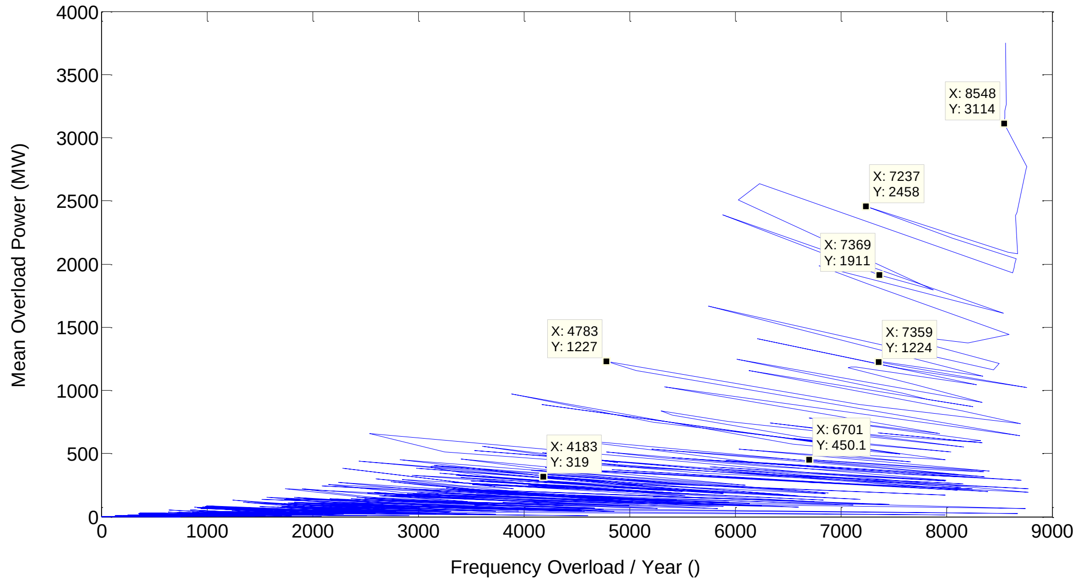

Figure 20: Mean Power Overload, As a Function of Overload Frequency Rate, Decreasing Order of F.W.M.E.

The next two diagrams represented show the Frequency Weighted Mean Energy of all the lines in a decreasing order and in a cumulative manner:

- Frequency Weighted Mean Energy in decreasing order:

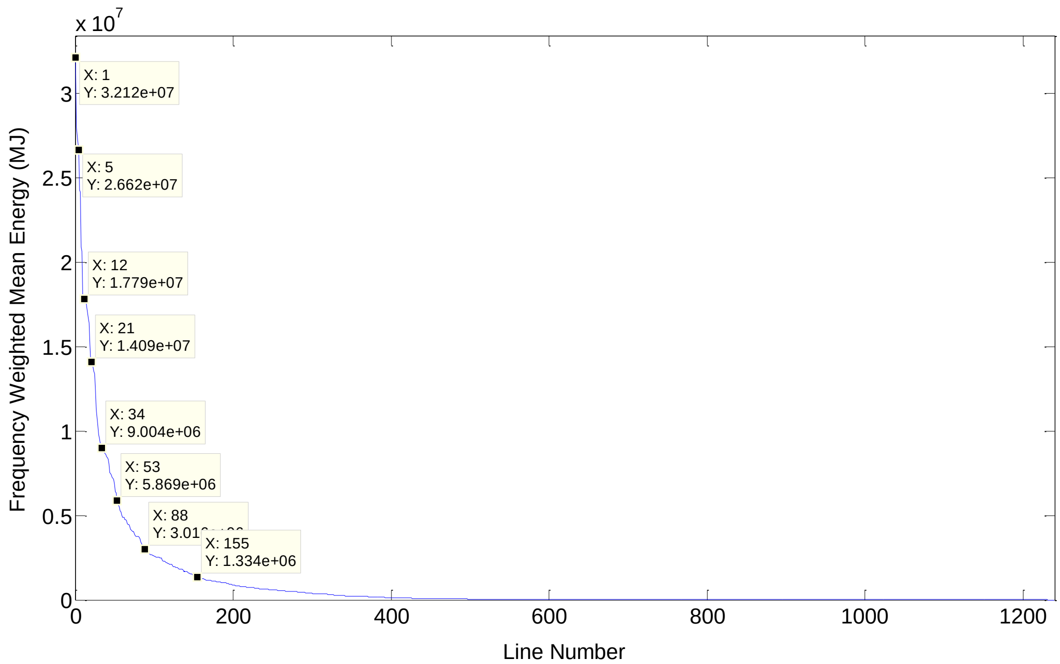

Figure 21: F.W.M.E., Decreasing Order

- Cumulative Frequency Weighted Mean Energy:

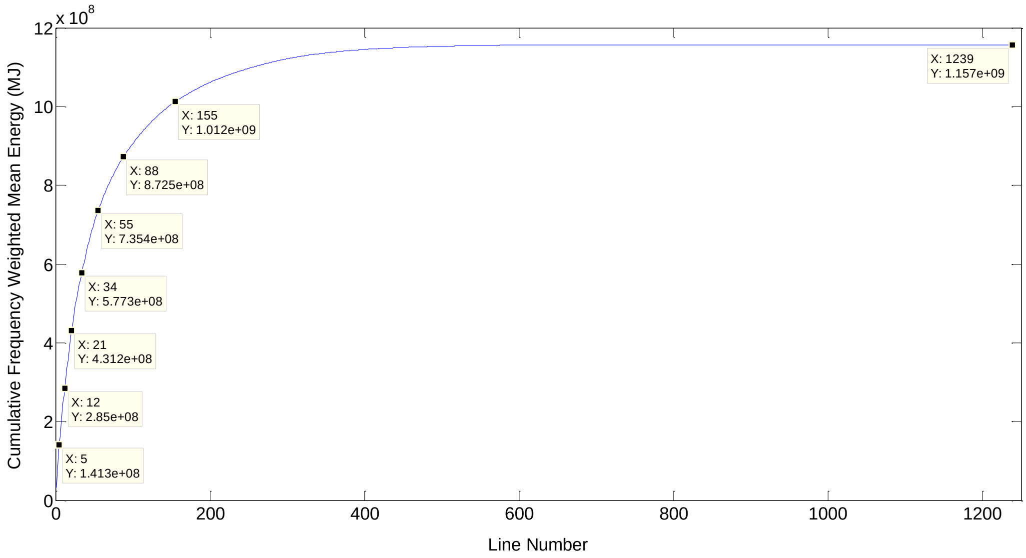

Figure 22: Cumulative F.W.M.E., Decreasing Order

3.4. Total Line Length to Upgrade

The following diagrams show the length of the candidate lines to be upgraded in a descending order, in a decreasing order of Frequency Weighted Mean Energy and in a cumulative way:

- Length of lines in descending order of Frequency Weighted Mean Energy:

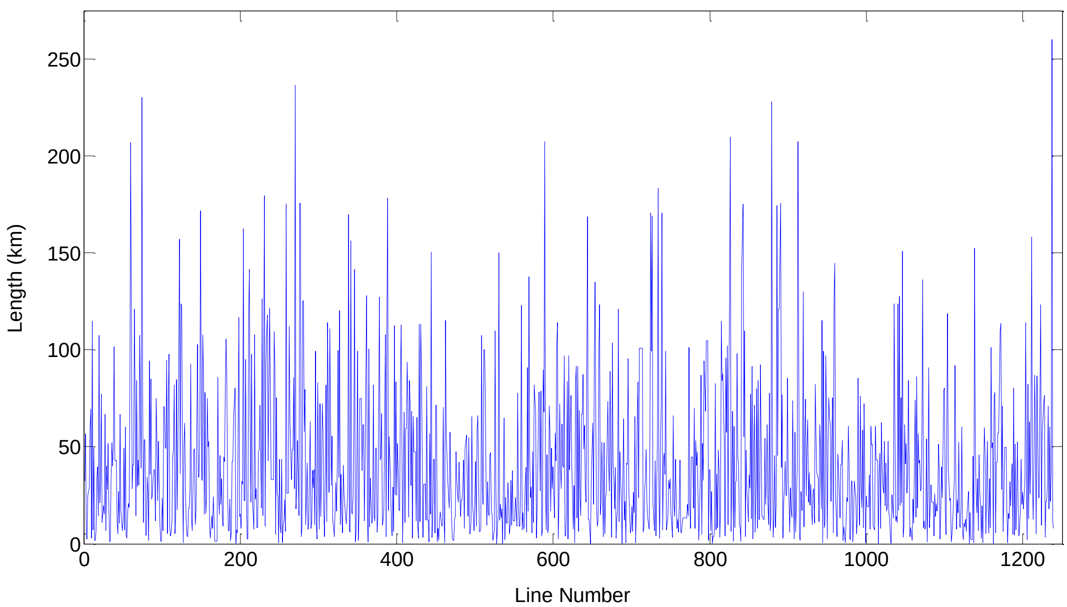

Figure 23: Line Length, Descending Order of F.W.M.E.

- Cumulative total length in descending order of Frequency Weighted Mean Energy:

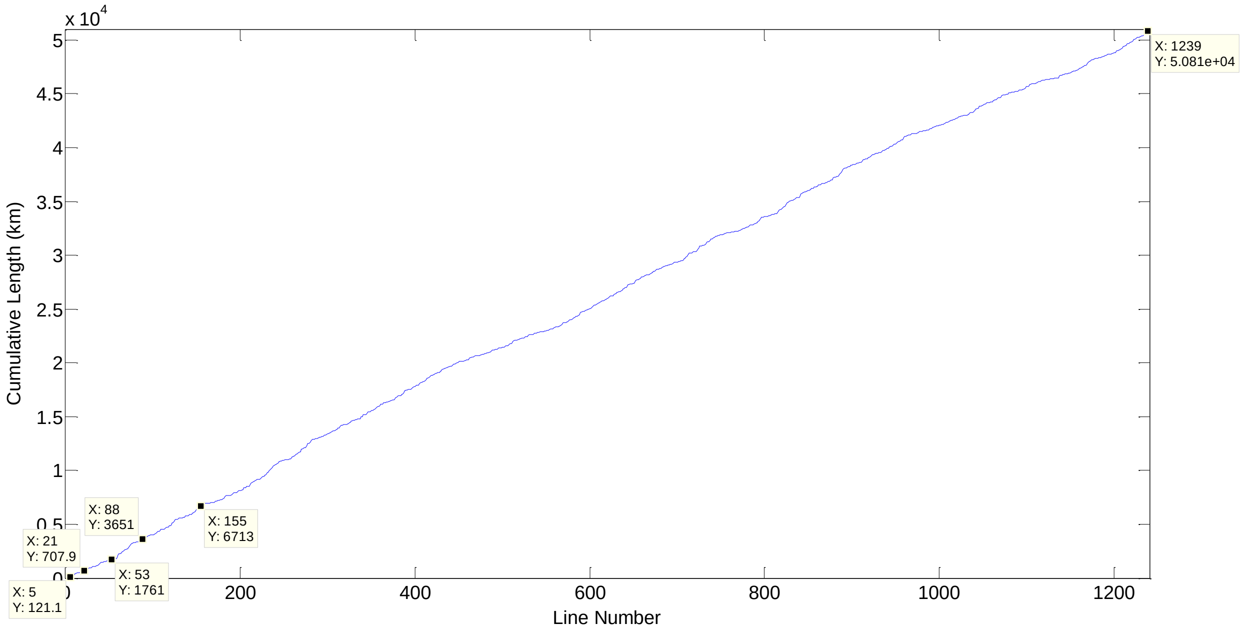

Figure 24: Cumulative Total Upgrade Length, Descending Order of F.W.M.E.

3.5. Upgrade Plan Investment

The investment necessary for the upgrade plans was calculated using the upgrade cost and the length of each the respective lines and is represented below in a descending order of Frequency Weighted Mean Energy, and in a cumulative way in descending and ascending order of Frequency Weighted Mean Energy. This process was repeated applying the upgrade level of mean, mean + standard deviation and maximum power overload of each line throughout the 8784 hours being simulated.

a. Mean Overload Power Upgrade:

- Cost in decreasing order of Frequency Weighted Mean Energy:

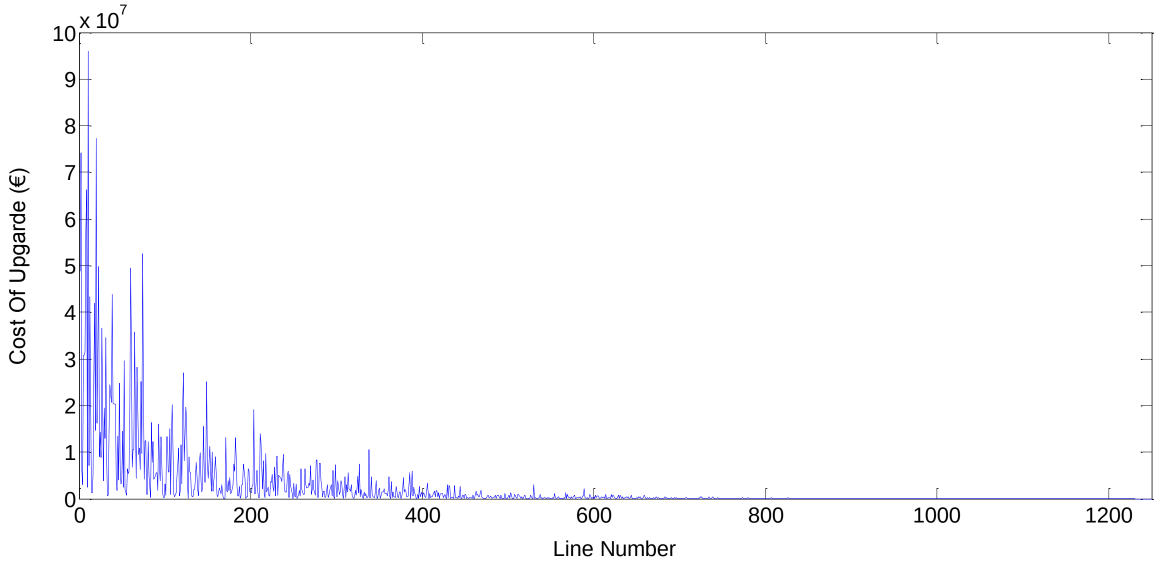

Figure 25: Cost of Mean Power Overload Upgrade, Decreasing Order of F.W.M.E.

- Cumulative cost in decreasing order of Frequency Weighted Mean Energy:

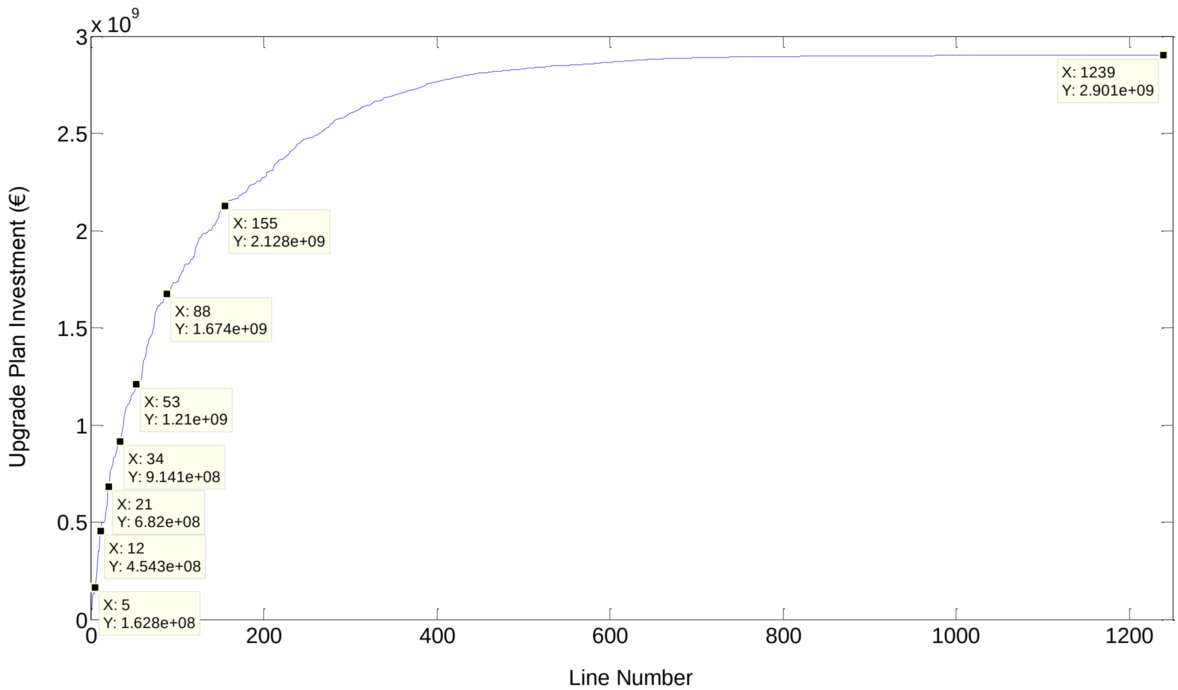

Figure 26: Cumulative Cost of Mean Power Overload Upgrade, Decreasing Order of F.W.M.E.

- Cumulative Cost in order in ascending order of Frequency Weighted Mean Energy:

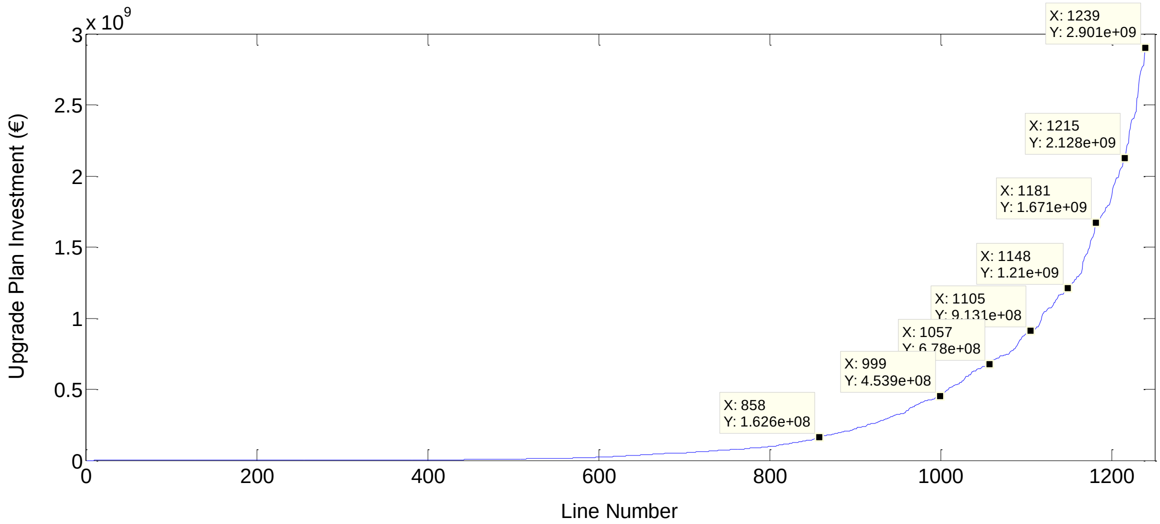

Figure 27: Cumulative Cost of Mean Power Overload Upgrade, Ascending Order of F.W.M.E.

b. Mean + Standard Deviation of Overload Power Upgrade:

- Cost in descending order of Frequency Weighted Mean Energy:

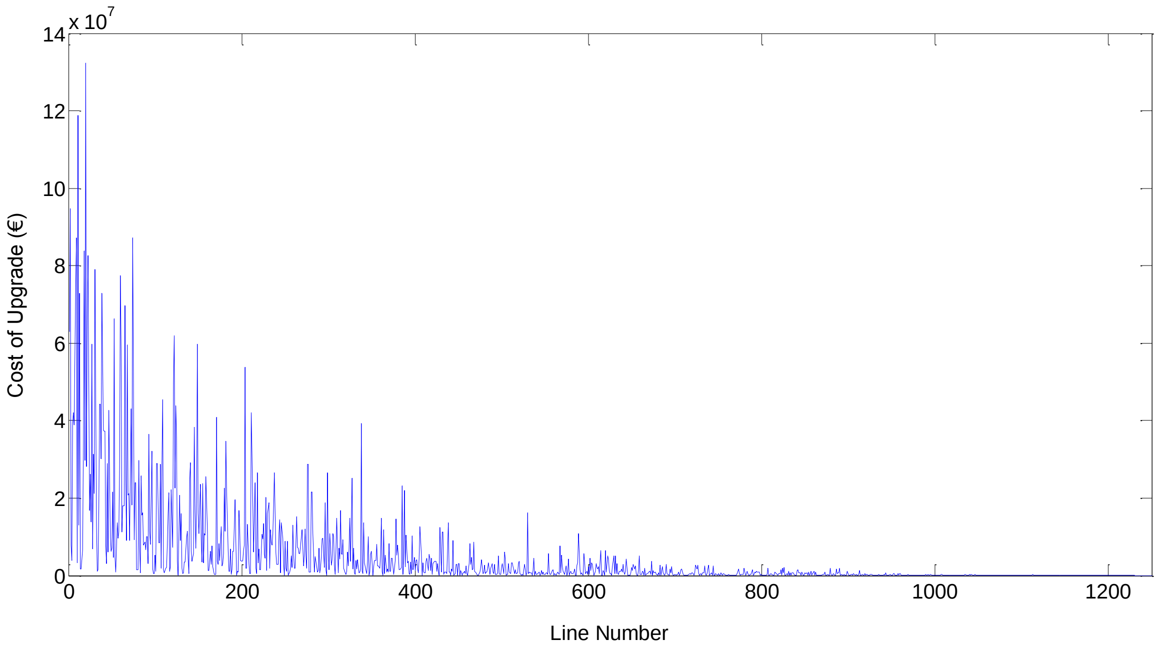

Figure 28: Cost of Mean+S.D. Power Overload Upgrade, Decreasing Order of F.W.M.E.

- Cumulative cost in descending order of Frequency Weighted Mean Energy:

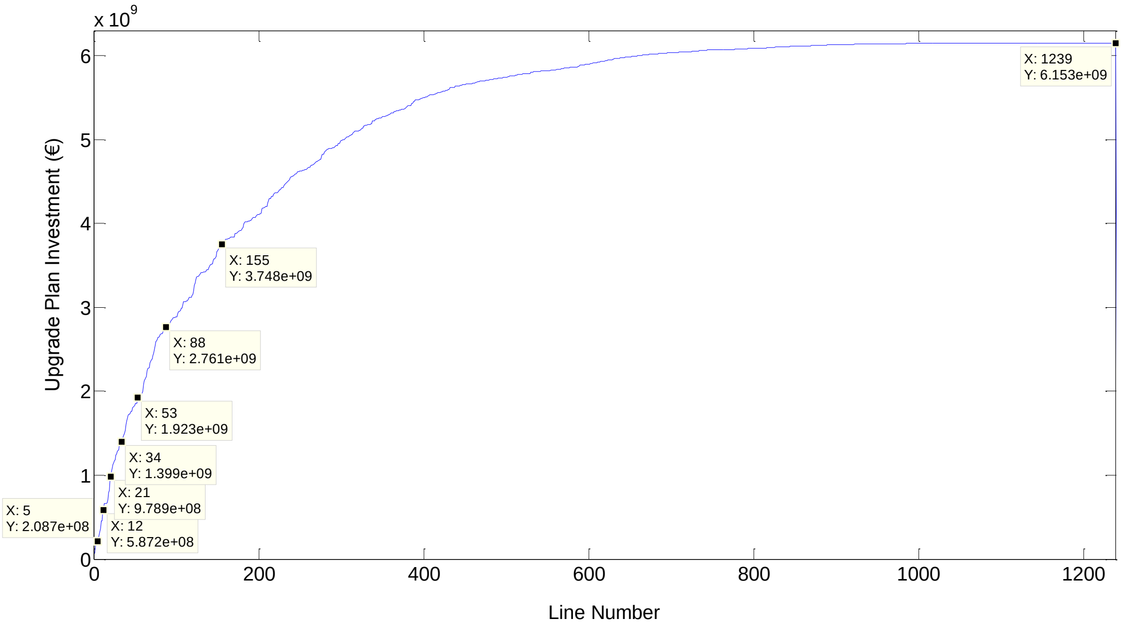

Figure 29: Cumulative Cost of Mean+S.D Power Overload Upgrade, Decreasing Order of F.W.M.E.

- Cumulative cost in ascending order of Frequency Weighted Mean Energy:

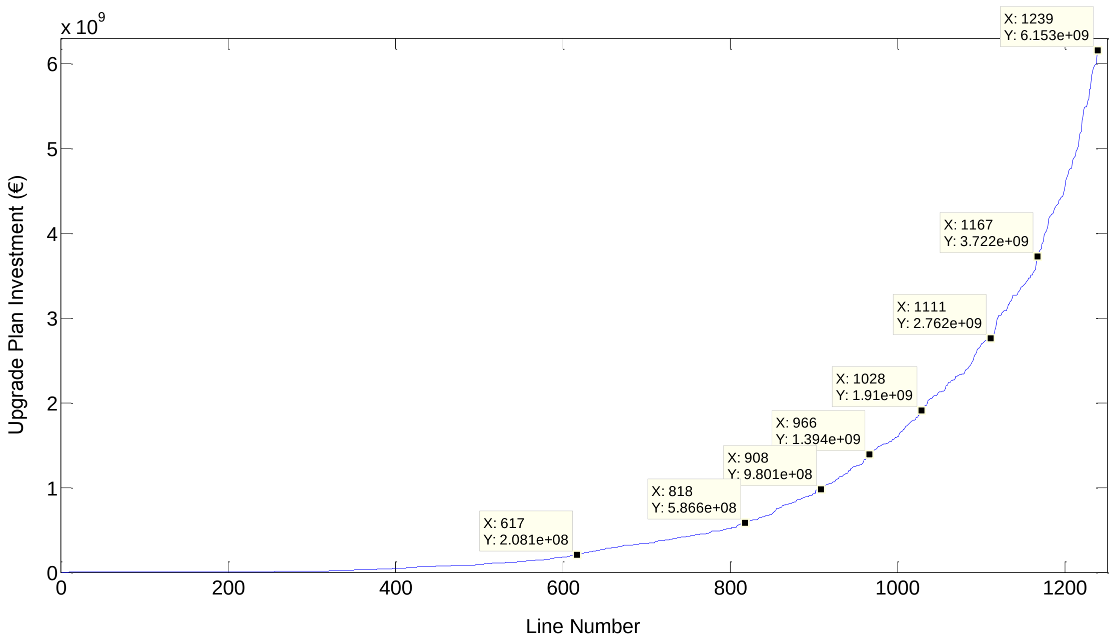

Figure 30: Cumulative Cost of Mean+S.D Power Overload Upgrade, Ascending Order of F.W.M.E.

c. *Maximum Overload Power Upgrade:*

- Cost in decreasing order of Frequency Weighted Mean Energy:

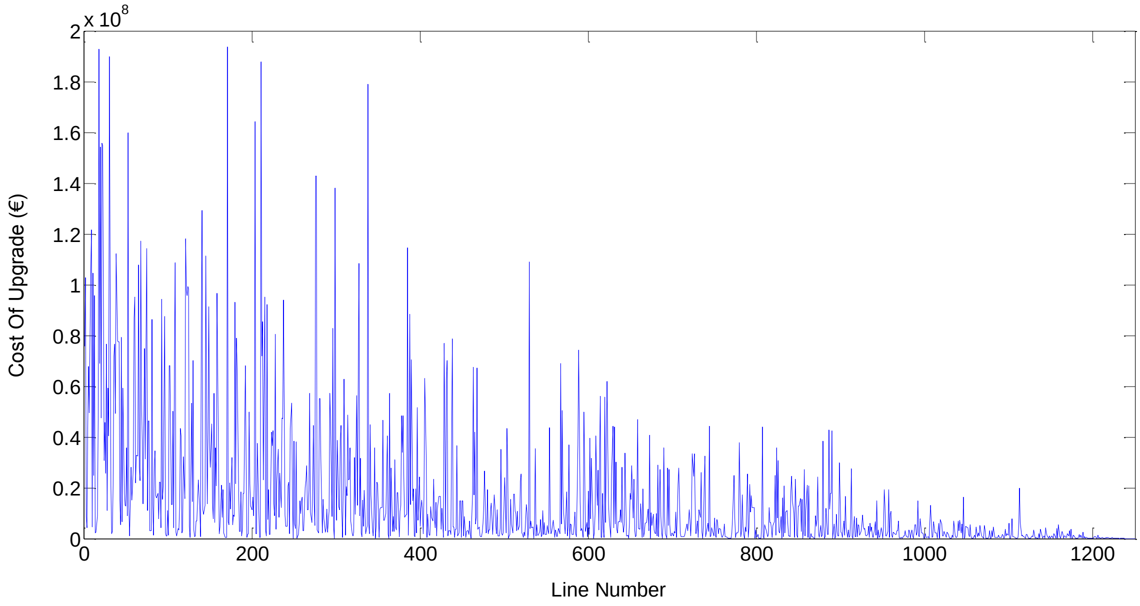

Figure 31: Cost of Maximum Power Overload Upgrade, Decreasing Order of F.W.M.E.

- Cumulative cost in decreasing order of Frequency Weighted Mean Energy:

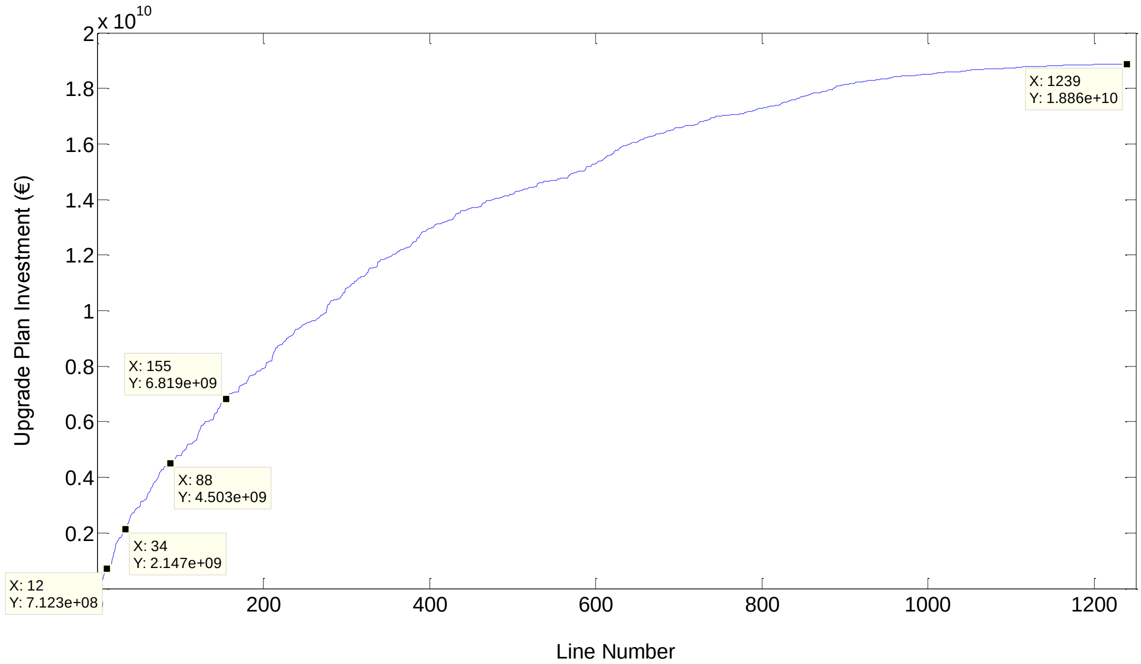

Figure 32: Cumulative Cost of Maximum Overload Upgrade, Decreasing Order of F.W.M.E.

- Cumulative cost in ascending order of Frequency Weighted Mean Energy:

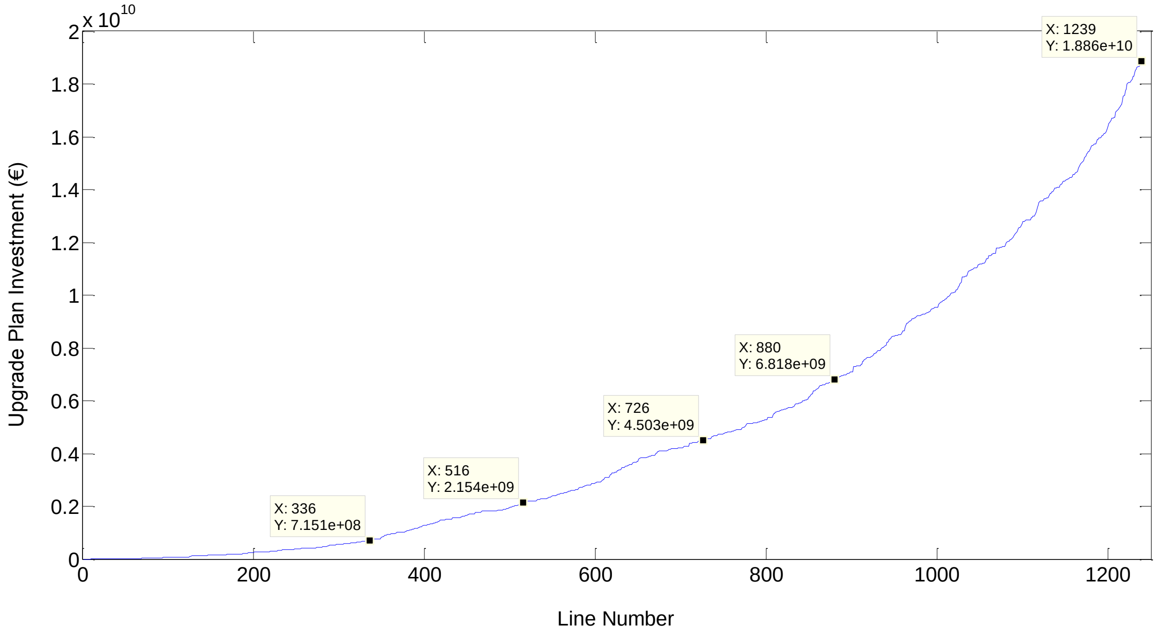

Figure 33: Cumulative Cost of Maximum Power Overload Upgrade, Ascending Order of F.W.M.E.

3.6. Study of Upgrade Plans Based on Frequency Weighted Mean Energy Preference

3.6.1. Mean Overload Power Upgrade

Table 3: Upgrade Plan Results, Mean Overload Power Upgrade

Nº Lines	Cumulate F.W.M.E. (MJ)	Tot. Length (km)	Cost of Upgrade (€ billion)	Curtailed Renewable Energy (MW)			Total Reduction Curtailed Renewable Energy (MWh)
				PV	Wind	Total	
5	1.416e+08	121.1	0.1628	2.7756e+05	7.8718e+06	8.1494e+06	-36.8056
12	2.85e+08	431.5	0.4543	2.7564e+05	7.7244e+06	8.0001e+06	-1.4932e+05
21	4.312e+08	707.9	0.6820	2.7616e+05	7.7464e+06	8.0226e+06	-1.2683e+05
34	5.773e+08	1081	0.9141	2.2791e+05	6.7289e+06	6.9568e+06	-1.1926e+06
53	7.354e+08	1761	1.210	1.7339e+05	5.0259e+06	5.1993e+06	-2.9501e+06
88	8.725e+08	3651	1.674	1.7616e+05	4.9585e+06	5.1347e+06	-3.0147e+06
155	1.012e+09	6713	2.128	2.1090e+05	4.8503e+06	5.0612e+06	-3.0881e+06

Below, the evolution of the investment made for the application of the upgrade plan and the money saved with the reduction of the curtailed renewable energies can be observed for all the upgrade plans studied when a mean overload power upgrade level is employed:

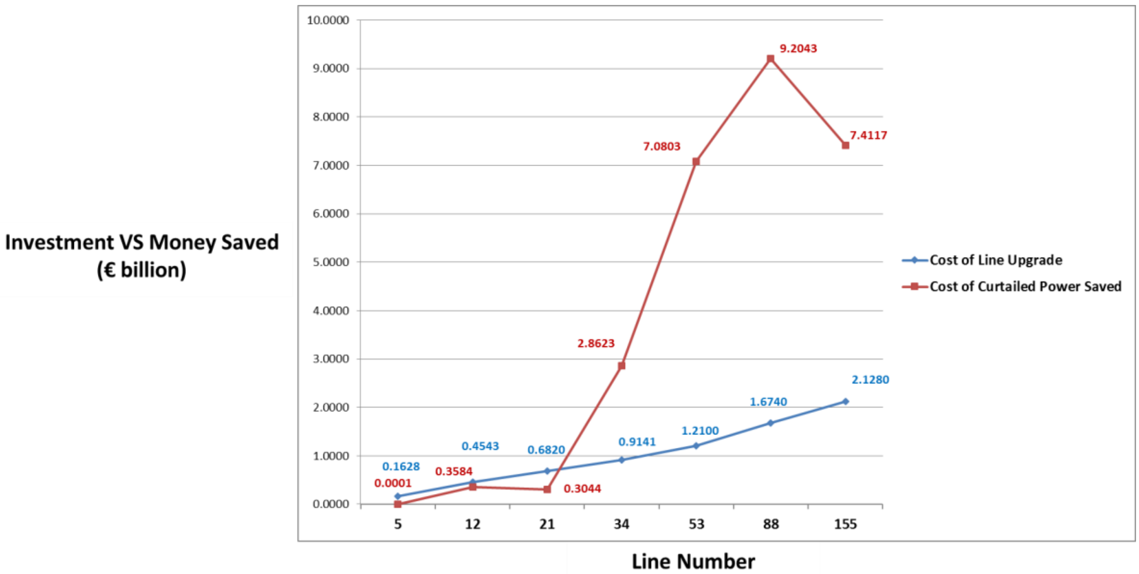

Figure 34:Investment vs. Money Saved With Curtailment Reduction, Mean Overload Power Upgrade Plan

3.6.2. (Mean + Standard Deviation) Overload Power Upgrade

Table 4: Upgrade Plan Results, Mean + Standard Deviation Overload Power Upgrade

Nº Lines	Cumulate F.W.M.E. (MJ)	Tot. Length (km)	Cost of Upgrade (€ billion)	Curtailed Renewable Energy (MW)			Total Reduction Curtailed Renewable Energy (MWh)
				PV	Wind	Total	
5	1.416e+08	121.1	0.2087	2.7756e+05	7.8717e+06	8.1494e+06	-36.8056
12	2.85e+08	431.5	0.5872	2.7564e+05	7.7245e+06	8.0001e+06	-1.4932e+05
21	4.312e+08	707.9	0.9789	2.7615e+05	7.7465e+06	8.0226e+06	-1.2680e+05
34	5.773e+08	1081	1.399	2.1852e+05	6.5184e+06	6.7369e+06	-1.4125e+06
53	7.354e+08	1761	1.923	1.3985e+05	4.2342e+06	4.3741e+06	-3.7754 e+06
88	8.725e+08	3651	2.761	1.4627e+05	4.1680e+06	4.3143e+06	-3.8351e+06
155	1.012e+09	6713	3.748	1.8779e+05	3.9841e+06	4.1719e+06	-3.9775e+06

Below, the evolution of the investment made for the application of the upgrade plan and the money saved with the reduction of the curtailed renewable energies can be observed for all the upgrade plans studied when a mean + standard deviation overload power upgrade level is employed:

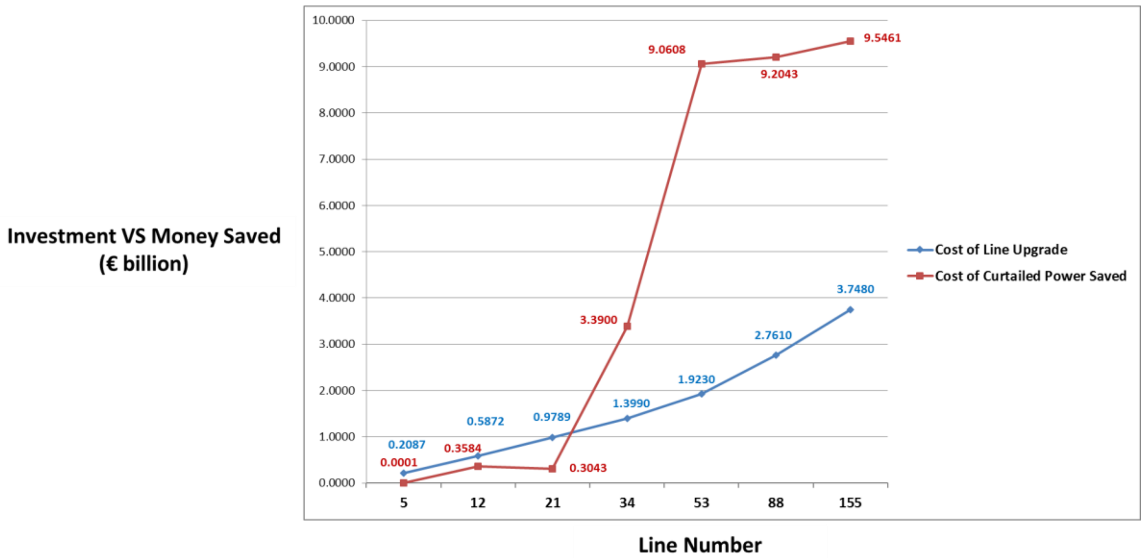

Figure 35: Investment vs. Money Saved With Curtailment Reduction, Mean+ S.D. Overload Power Upgrade Plan

3.6.1. Maximum Overload Power Upgrade

Table 5: Upgrade Plan Results, Maximum Overload Power Upgrade

Nº Lines	Cumulate F.W.M.E. (MJ)	Tot. Length (km)	Cost of Upgrade (€ billion)	Curtailed Renewable Energy (MW)			Total Reduction Curtailed Renewable Energy (MWh)
				PV	Wind	Total	
5	1.416e+08	121.1	0.2344	2.7756 e+05	7.8718 e+06	8.1494 e+06	-36.8056
12	2.85e+08	431.5	0.7123	2.7564 e+05	7.7245 e+06	8.0001 e+06	-1.4932e+05
21	4.312e+08	707.9	1.3320	2.7615 e+05	7.7465 e+06	8.0226 e+06	-1.2680e+05
34	5.773e+08	1081	2.1470	2.1852 e+05	6.5184 e+06	6.7369 e+06	-1.4125e+06
53	7.354e+08	1761	3.1250	1.3875 e+05	4.2286 e+06	4.3673 e+06	-3.7821e+06
88	8.725e+08	3651	4.5030	1.4424e+05	4.1629e+06	4.3071e+06	-4.3067e+06
155	1.012e+09	6713	6.8190	1.8664 e+05	3.9777 e+06	4.1644 e+06	-3.9851e+06

Below, the evolution of the investment made for the application of the upgrade plan and the money saved with the reduction of the curtailed renewable energies can be observed for all the upgrade plans studied when a maximum overload power upgrade level is employed:

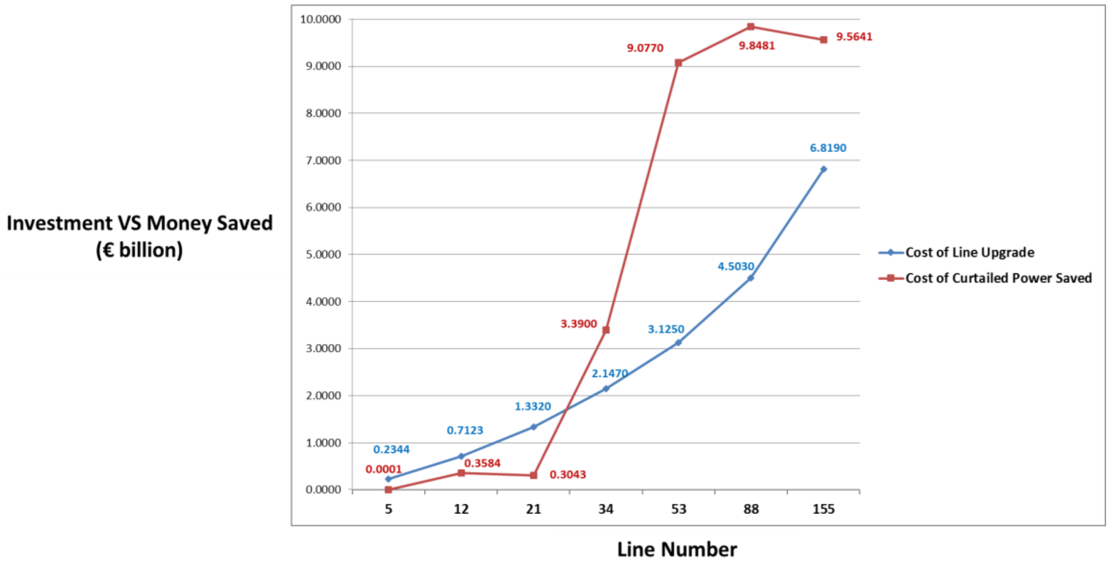

Figure 36: Investment vs. Money Saved With Curtailment Reduction, Maximum Overload Power Upgrade Plan

3.6.2. Comparison Upgrade Plans with Mean and Maximum Overload Power Upgrade

Table 6: Revenue of Upgrade Plans; Mean, Mean + Standard Deviation and Maximum Power Upgrade

	Cost of Line Upgrade (€ billion)			**Cost of Curtailed Power Saved (€)**			**Revenue (€ billion)**		
Upgrade Level / Nº lines Upgraded	**Mean**	**Mean + S.D.**	**Max**	**Mean**	**Mean + S.D.**	**Max**	**Mean**	**Mean + S.D.**	**Max**
5	0.1628	0.2087	0.2344	88333.4248	88333.4206	88333.4205	-0.1627	-0.2086	-0.2343
12	0.4543	0.5872	0.7123	3583.6380e+05	3583.6381e+05	3583.6381e+05	-0.0959	-0.2288	-0.3539
21	0.6820	0.9789	1.332	3043.9973e+05	3043.2596e+05	3043.2596e+05	-0.3776	0.3043	-1.0277
34	0.9141	1.399	2.147	2862.3071e+06	3389.9927e+06	3389.9927e+06	1.9482	1.9910	1.2430
53	1.210	1.923	3.125	7080.3475e+06	9060.8454e+06	9077.0281e+06	5.8703	7.1378	5.9520
88	1.674	2.761	4.503	9204.2949e+06	9204.2949e+06	9848.1373e+06	7.5303	6.4433	5.3451
155	2.128	3.748	6.819	7411.6617e+06	9546.1019e+06	9564.1342e+06	5.2837	5.7981	2.7451

The graph below represents the revenue each upgrade plan produces after the lifetime of the lines; as said previously, considered in this project to be 40 years:

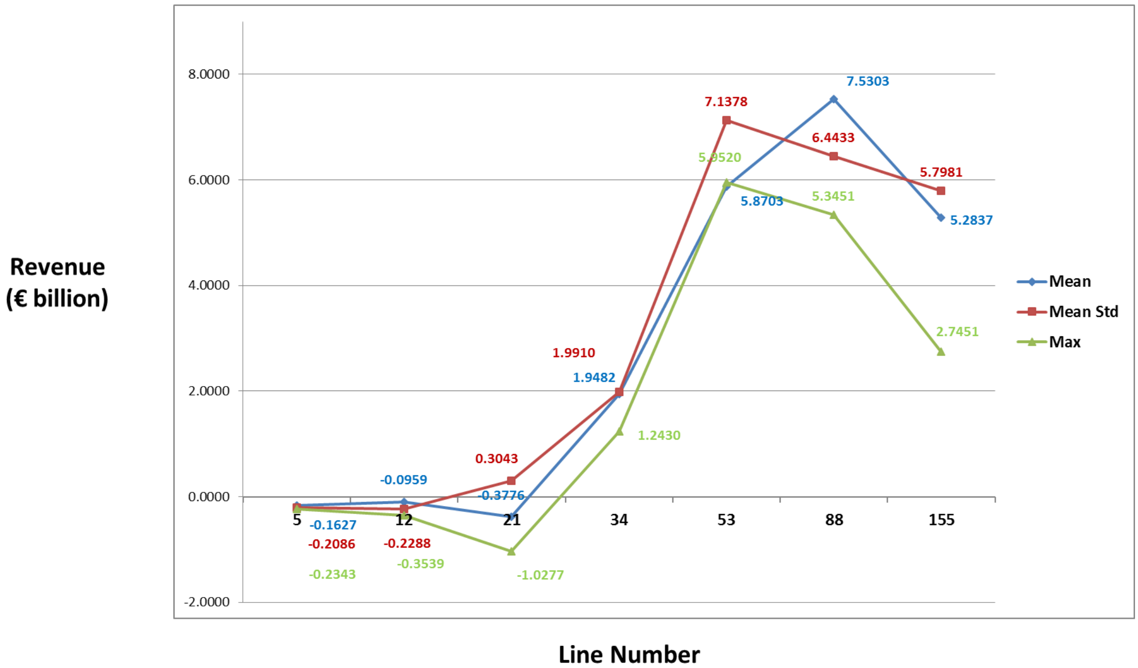

Figure 37: Revenue, Upgrade Plans

The next graph shows the reduction in the renewable energy curtailed for all upgrade plans being considered in comparison to the original European Transmission System without any modifications:

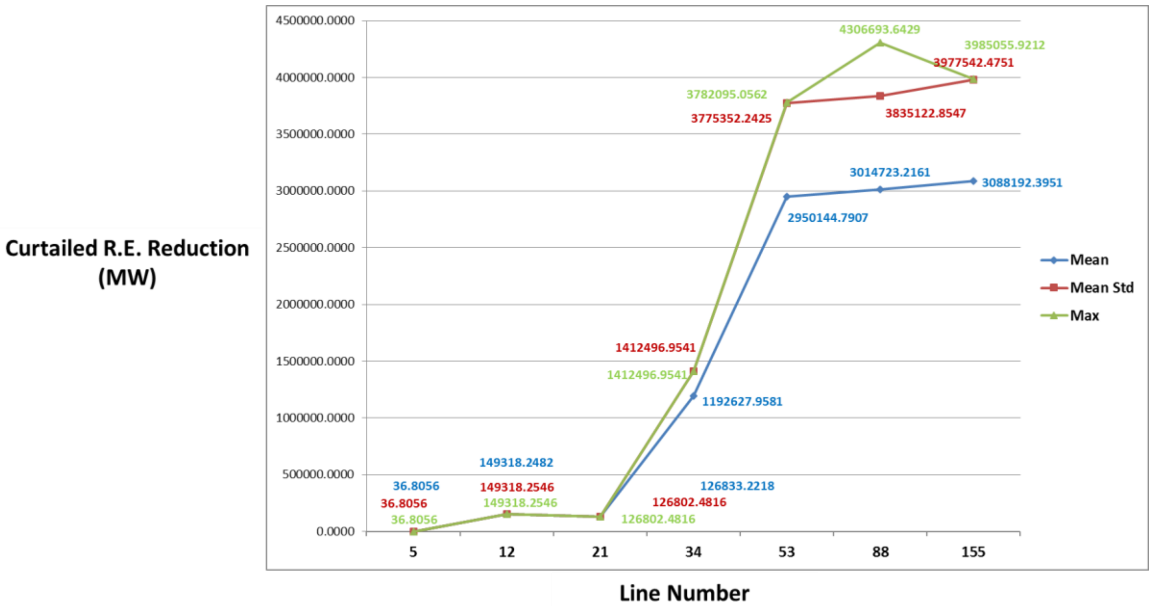

Figure 38: Reduction of Curtailed R.E. Power, Upgrade Plans

ANALYSIS AND INTERPRETATION OF RESULTS

1. Analysis Criteria for Preference Order

In this section, the use of the Frequency Weighted Mean Energy as a preference criterion to order the lines to be included in an upgrade plan will be analyzed and the explanation for the decision of its application will be exposed. To do this, firstly the results obtained from the Simulation of the European Transmission System with the application of soft limits and the following representations shown in the results section will be used.

As mentioned previously the Frequency Weighted Mean Energy is the result of the product of the frequency at which each line is overloaded throughout a year and its mean power overload magnitude during the 8784 hours simulated. This parameter was created to upgrade first those lines that are overloaded most frequently and with the highest overload power. In other words, those that cannot transport the highest quantities of energy and contribute in a larger degree to the curtailment of renewable energies.

As it can be seen in Figure 17 and Figure 23, when the lines are setup in descending order of Frequency Weighted Mean Energy, although both the mean power overload and the frequency rate at which it occurs for every line is not continuously decreasing, it follows a descending trend. As a result, both can be maximized at the same time as the Frequency Weighted Mean is maximized. The Figure 26 and Figure 27 also help to show this be representing the relationship between these two variables, and how as one decreases, the other one tends to do so at the same time.

Moreover, the mean power overload was represented as a function of the overload frequency rate for every line after being ordered from higher to lower Frequency Weighted Mean Energy on Figure 28. This graph shows the way this variable maximizes the weighted mean,and when after adding one line, if the frequency decreases, the mean overload power will increase to comppensate and vice versus.

In addition, as it can be seen on Figure 32, the length of the lines that are being selected for the tested upgrade plans are maintained within a range when ordered in descending succession of Frequency Weighted Mean Energy, and do not have an increasing or decreasing trend. As a result, it has been considered that the line length does not oppose any negative effect to the ordering of the lines in this manner. On the one hand, the cost used was €400/km/MW [27], and therefore, we can focus on the upgrade power level of the lines when adjusting the cost of their upgrade. On the other hand, the energy saved from the reduction in curtailment will only depend on the frequency and magnitude of overload of the lines, and the price of the renewable energy used, €60/MWh [27], does not depend on the length.

As a result of the two previous criteria that have been considered and the output they have produced, it was considered to combine both to obtain a more powerful criterion. When selecting those lines with the highest curtailed power along a year, the consideration of the number of hours into which it is divided is not considered.

As a result, if a large total overload power is result of a continuous curtailment extended uniformly in time or by contrast, it is caused by a high overload power peak during a short period of time cannot be distinguished. The same way, when basing the selection criteria on the frequency of overload, the quantity at which it occurs is ignored.

Consequently, the variable Frequency Weighted Mean Energy was created by multiplying the frequency rate of overload and the mean overload power across each line during the 8784 hours simulated. At first, by simply multiplying these two variables, the maximization of both parameters can't be assured, as a high result of the product may be a consequence of only one of the variables being large.

The priority set for line upgrade using this variable is the maximization of both the overload frequency rate and the magnitude of energy overload, and therefore the maximization of the Frequency Weighted Mean Energy. Therefore, to observe the degree and rate of variation between the lines and to serve as a reference for the creation of the line upgrade plans that will be tested and analyzed; the lines were ordered from higher to lower Frequency Weighted Mean Energy.

2. Analysis Mean, Mean + Standard Deviation and Maximum Overload Power Upgrade Plans

Firstly, from the results obtained after the simulation of the European Transmission System with the application of the upgrade plans selected, it can be observed from Table 6 and the graph shown on Figure 37 that the best upgrade plans lie between the upgrade of 34 and 88 lines for the mean + standard deviation and the maximum levels of upgrade, while for the mean power upgrade level, it is between the 53 and the 155 line plan, as the maximum revenues lie respectively within these ranges. After this point, although the revenue is still positive, the new lines added to the plan have a higher cost of upgrade than the money saved from the reduction in curtailed renewable energy they cause and therefore, reduce the total revenue.

Furthermore, the plan studied that achieved the highest revenue was that with the mean overload power upgrade level and 88 lines included in the plan, and was of € 7.5303 billion. The mean + standard deviation power upgrade level showed the highest revenues until an upgrade of 53 lines, while the maximum power upgrade level never showed the highest revenue in any upgrade plan. This is due to its high investment costs it demands, with which the money saved with the reduction in renewable energy curtailed can never compete.

In addition, the 5, 12 and 21 line upgrade plans with mean and maximum overload power upgrade and for 5 and 12 line upgrade plans for mean + standard deviation power upgrade, the revenue has shown to be negative. This can be caused by a 'chain reaction' of the connection of the lines. Some of the lines that suffer the highest curtailment are those that connect transmission systems of different countries, with very large capacities and few connected loads during most of their length.

As a result, although the transmission capacity of a line is increased significantly, it will only increase the energy it actually transmits if the successive components to which it is connected can also transport it; as Kirchoff's Law states, the current must be constant across the circuit. Therefore, either the loads to which the upgraded line is connected can make use of this energy or the successive lines connected to it at either ends must also be able to transmit the new energy fed into the system. The results is that, with the first line being upgraded, the revenue will be negative, as the system cannot make out of the increase in capacity while the cost of the upgrade will stay constant, no matter how much power it is able to transport. However, as successive lines that are closely linked to this line are also upgraded, more closed circuits will increase their total capacity and renewable energy generator will be able to transmit more energy into the system. The renewable energy curtailed will therefore decrease and increase its competitiveness with the cost of upgrade; until as seen in the results on Table 6, the revenue becomes positive. For better understanding, the following figure shows how if the red line is upgraded, if the loads can't make use of this energy and the other lines connected to it at both ends don't have enough capacity to transport the upgraded power, the reduction in the curtailment will not be as large as desired and the revenue may remain negative until these bottlenecks are reduced.

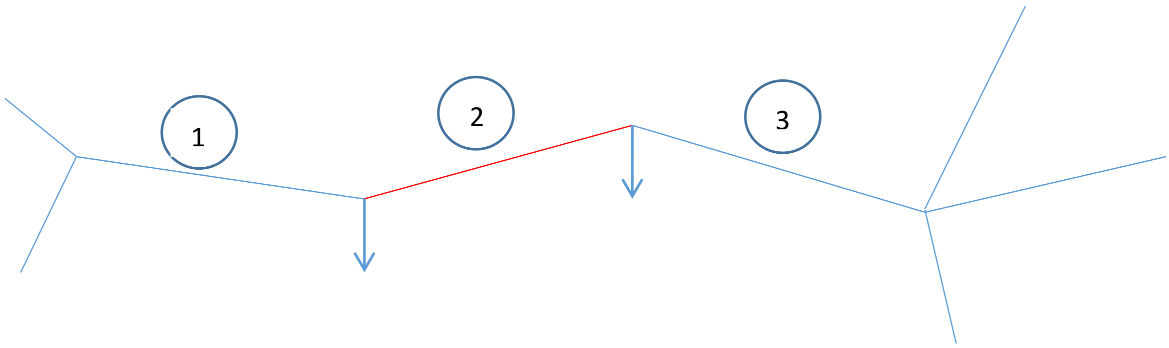

Figure 39: Illustration Situation of Higher R.E. Curtailment with More Lines Upgraded

Furthermore, an interesting fact was encountered when simulating the upgrade plans of 12 and 21 lines. Although there is an increase in the number of lines upgraded in the system, and therefore the total capacity of transporting energy, and although the cost of photovoltaic and wind sources of energy is always lower than any other source of energy, the renewable energy curtailed increases. The explanation found for this phenomenon is that the line upgraded is in such a strategic location that it contributes to the integration of energy from a conventional generator instead of a renewable source of energy.

If the next line(s) to be upgraded is (are) purely connected to generators, or if at the end of the line, there are at least two conventional generators, but some considerably cheaper than the others, the system operators will find the cheapest energy input by favoring the cheapest of them. Although there may also be renewable energy generators connected to that line, if those specific generators do not experience curtailment throughout the year, the cheapest conventional generators will take advantage of the situation and make use of the larger transmission capacity. Furthermore, as the new energy that is being fed into the grid has a positive cost, the revenue will become more negative. The most significant difference in renewable energy curtailment between the 12 line upgrade plan and the 21 line upgrade plan was found to be in hour 2792.

The following diagram shows a possible situation that could cause this phenomenon:

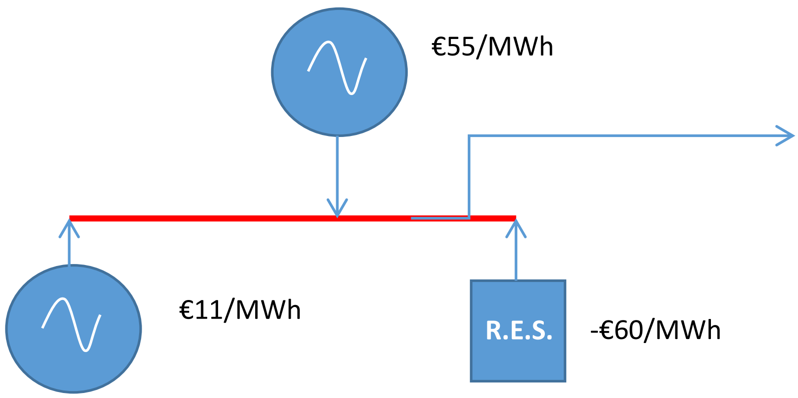

Figure 40: Illustration Situation of Higher R.E. Curtailment with More Lines Upgraded

This effect can also be observed in the following Figure 41 and Figure 42. The addition of lines 14 and 15 produce a sudden increase in the ratio Frequency Weighted Mean Energy versus Cost, therefore, the infeed of energy into the system is greater. At the same time, the curtailed renewable energy increases, proving that the new energy fed into the system has to come from conventional generators.

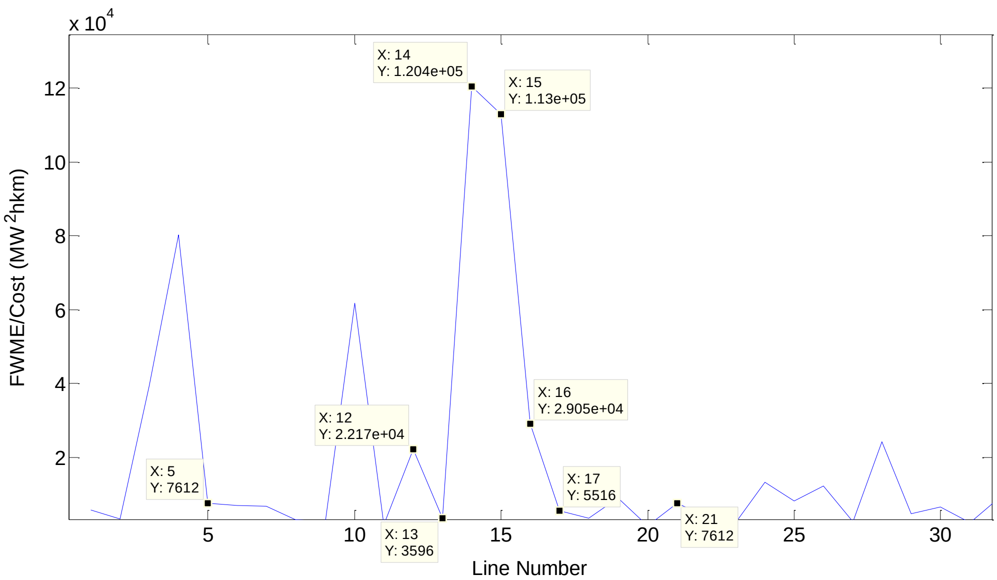

Figure 41: Ratio FWME/Cost of Upgrade, Mean Power Upgrade Level

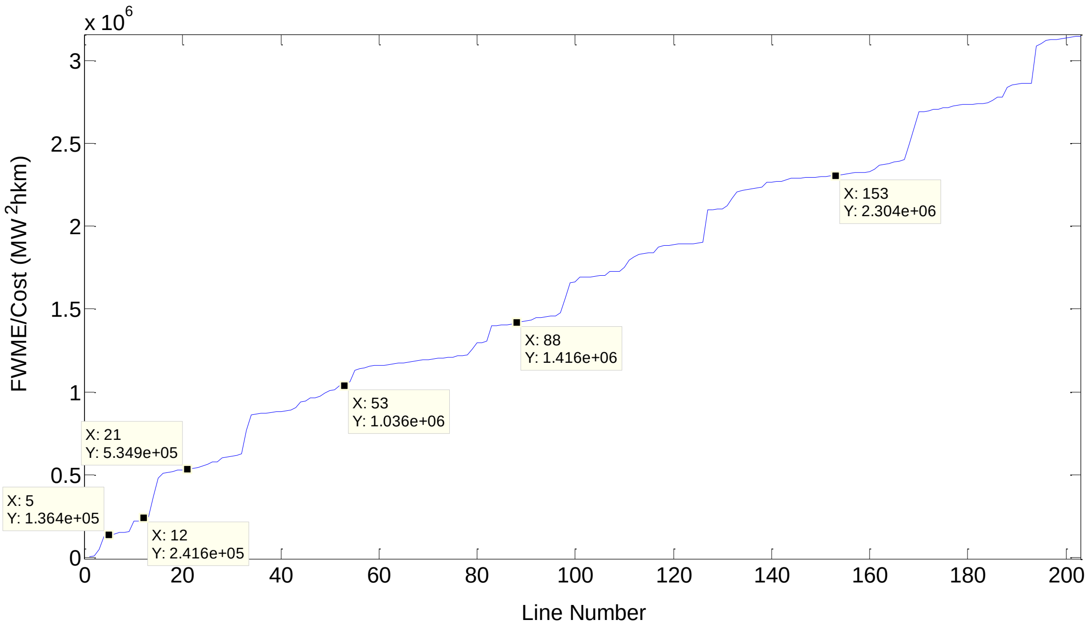

Figure 42: Cumulative Ratio FWME/ Cost of Upgrade, Mean Power Upgrade Level

Zoom:

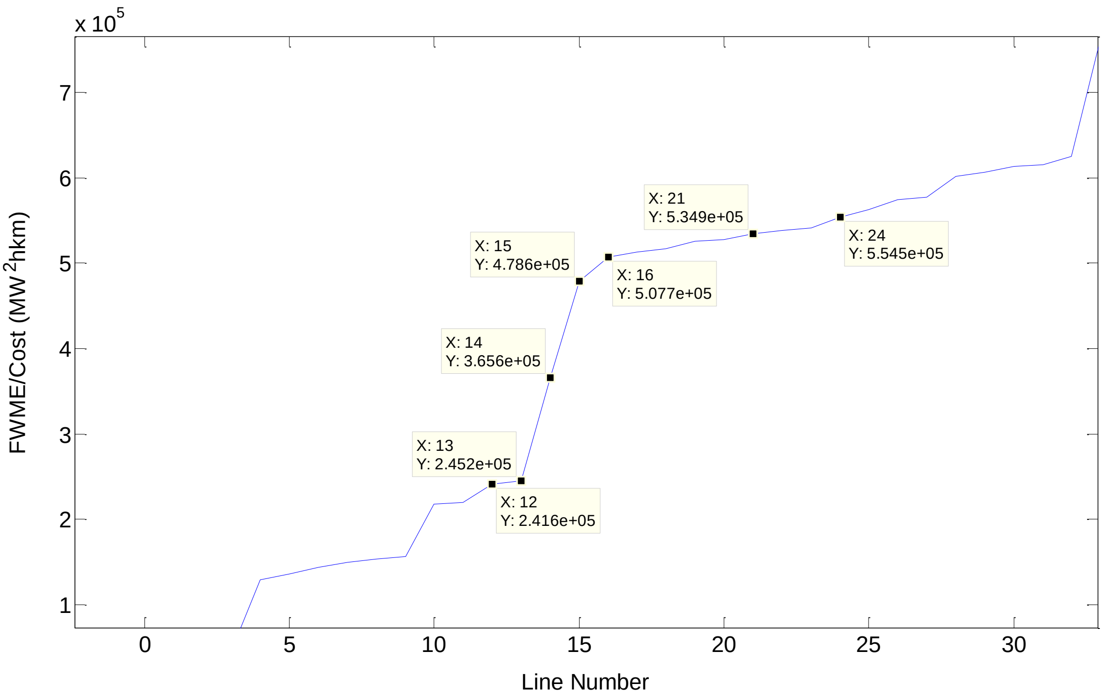

Figure 43: Zoom Cumulative Ratio FWME/ Cost of Upgrade, Mean Power Upgrade Level

These events however shift the configuration of the transmission system, as the available energy proceeding from conventional generators and their location changes. The succeeding upgrade plans should take this into consideration, as in reality the European Transmission System model will be different from the upgrade of these lines onwards.

Also, when comparing the power upgrade level for each of the upgrade plans, it can be observed that there is not a unique grade that stays to have the highest revenues as the number of lines included in the successive upgrade plans. As a result, no general trends can be made out of this study to decide which the best upgrade power for each plan is. However, the highest

SUMMARY, CONLUSIONS AND RECOMMENDATIONS

1. Summary and Conclusions

From all the plans studied, the best upgrade plan found, that offered the highest revenue was the plan with the mean overload power upgrade level and 88 lines upgraded. The revenue has a value of € 7.5303 billion.

Until further simulations are formulated, it can be concluded from the results obtained that the best upgrade plans lie between the upgrade of 34 and 88 lines for the mean + standard deviation and the maximum levels of upgrade, while for the mean power upgrade level, it is between the 53 and the 155 line plan, as the maximum revenues lie respectively within these ranges.

Furthermore, in relation to the power level of upgrade, although no general trends could be found and further investigation is necessary to find the power that best suites the power magnitude and frequency of overload and for the lines, it can be observed that the mean + standard deviation power upgrade level showed the highest revenues until an upgrade of 53 lines. The maximum power upgrade level, however, never showed the highest revenue in any upgrade plan. This is due to its high investment costs it demands, with which the money saved with the reduction in renewable energy curtailed can never compete.

It was also concluded that to be able to obtain positive revenues, a minimum number of lines (minimum higher than 12 in the case of mean + standard deviation power upgrade level and at least higher that 21 lines in the case of mean and maximum overload power upgrade) must be included in the upgrade plan. The exact minimum number of lines requires the performance of further simulations.

It is important to highlight, that when the selection criteria of Frequency Weighted Mean Energy is applied, the addition of new lines does not always contribute to a reduction in the renewable energy curtailed, and special care must be taken when the curtailment increases. If the revenue still increases, it means that the new lines upgraded contribute to the integration of energy from a conventional generator instead of a renewable source of energy. The configuration of the transmission system is varied and the available energy proceeding from conventional generators and their location changes.

2. Recommendations

Firstly, all the data used to create a network upgrade strategy is based on predictions of how the model of the European Power Transmission System, the price of the electricity, the weather conditions, the load model and the dispatch model will be in the year 2030. However, although each one in different degrees, they are very hard to predict due to economic and political reasons among others. As a result, to obtain more exact results, more simulations should be performed using other possible situations. This includes:

- More weather conditions: Instead of using the weather model of a specific year due to the small variability and unpredictability of it, a larger number of recent years could be compared and with the resultant mean, create the weather model.
- More electricity prices: this parameter is especially difficult to predict. It is a very volatile variable that can vary very abruptly with political issues, the discovery of larger quantities of exploitable fossil fuels, such as petrol or new discoveries in technological devices that can improve the efficiency of energy extraction among others. The result of such changes affects our model through a variation in the prices of the power to be curtailed that is used in the soft limits and then in the line upgrade algorithm. The number of lines and the selection of which should be upgraded could affected severely. By using different prices, different scenarios will be studied and a wider range of possibilities can be considered. The European Grid Study 2030/2050 suggest to consider 3 cents, 5 cents and 10 cents per kWh, depending on different levels of integration of renewable sources of energy.
- Different Objectives: Instead of focusing on the economic aspect in the selection of the lines to be included in the upgrade plan other motivations can be found. An example is the increase in the stability of the system or how concentrated in one area the lines being studied are. If many lines in the same area are excluded during the selection process, that area may have problems in the supply of energy that can lead to social, industrial and economic aspects of a population.
- Other combinations of criteria: Similarly to how the criteria related to power overloaded and the frequency at which the lines are overloaded were combined to maximize both at the same time, other combination of different criteria could be studied. This way, the number of benefits obtained from applying the project could be increased.

- Other combination criteria/objectives: After applying the different strategies to select the lines to be upgraded, the combination of them with limitations on other aspects other than the ones that have been studied in this project would enrich the investigation. It would help to have a better understanding and more realistic study of the lines that can be upgraded inside the set limitations.
- Application of other techniques to upgrade transmission lines: As it was mentioned at the beginning of this project, there are other ways of increasing the power transport capacity. The efficiency and effectiveness of this project could be improved if different approaches were combined. An example would be to apply a Dynamic Line Rating before upgrading the electric grid so that the extension of the lines affected by an increase in power capacity is broader.
- Include price of transformer upgrade: In this project, the cost of the necessary upgrading of transformers has been considered negligible in comparison to the cost of the upgrade of the lines, however, for more precise calculation, this cost should also be included in the future.
- Upgrade plans with a selection of the best lines in the market: In this project, the cost of the new HVAC lines to be installed was considered as constant at €400/km/MW. However, for future upgrade plans, different HVAC OHL with different characteristics could be applied for better economic results. A source to obtain the different lines available in the market is the database Standard Power of Lines Irene 40 [18].

Other optimization approaches:

- KKT multipliers: When applying the extension toggle_softlims, the output data structures also include the Kuhn-Tucker multipliers on the soft limits constraints. This method is a theoretical model that is applied to obtain qualitative results applicable for example to the maximization of revenue that is dependent on a minimum profit condition.

APPENDIX

1. Implementation Line Upgrade Algorithm Over a Year

```
function [ resultsStruct ] = qslfHernandez(startHour,endHour)

tstart=tic

    %Quasi-Stationary Load Flow without reserves

        %load PV and Wind Data for regions
        load('\\C:\Thesis\Matlab\regPVHourList.mat');
        load('\\C:\Thesis\Matlab\regWindHourList.mat');
        load('\\C:\Thesis\Matlab\model2030.mat');
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        mpc=mpcHernandez;


        %Negative cost of renewable generators
        mpc.gencost(860:end,5)=-60;

        mpcOriginal=mpc;

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        [nPV,~]=size(mpcRenewPV.gen(:,1));
        [nWind,~]=size(mpcRenewWind.gen(:,1));
        nGen=length(mpc.gen(:,1))-nWind-nPV;

        %initialise variables
        simRes.convergence=[];

        simRes.genDisp(1:nGen,1)=mpc.gen(1:nGen,1);

        simRes.pvDisp(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.windDisp(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.avPV(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.avWind(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.busLoad(:,1)=mpc.bus(:,1);
        simRes.lineFlow(:,1:2)=mpc.branch(:,1:2);
        simRes.lineFlow(:,3)=mpc.branch(:,6);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



    %start time series load flow

        for hourCount=startHour:endHour

            hourCount
            %update bus loads
            mpc.bus(:,3)=busLoadList(:,hourCount+1);

            %update pv and wind gens

mpc.gen(nGen+1:nGen+nPV,9)=
mpcOriginal.gen(nGen+1:nGen+nPV,9).*regPV15MinList(mpcRenewPV.region(:,1),hourCount,1);

mpc.gen(nGen+nPV+1:nGen+nPV+nWind,9)=
mpcOriginal.gen(nGen+nPV+1:end,9).*regWind15MinList(mpcRenewWind.region(:,1),hourCount,1);

            %run hourly opf 1
            results=rundcopf(mpc,mpoption(mpoption,'out.all',0,'opf.dc.solver','GLPK'));
```

```
            simRes.convergence(hourCount,1)=results.success;

            simRes.genDisp(:,hourCount+1)=results.gen(1:nGen,2);

            simRes.pvDisp(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,2);
            simRes.windDisp(:,hourCount+1)=results.gen(1+nGen+nPV:end,2);

            simRes.avPV(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,9);
            simRes.avWind(:,hourCount+1)=results.gen(1+nGen+nPV:end,9);

            simRes.busLoad(:,hourCount+1)=results.bus(:,3);
            simRes.lineFlow(:,hourCount+3)=results.branch(:,16);

        end

    simRes.curtPV=[mpc.gen(1+nGen:nGen+nPV,1),(simRes.avPV-simRes.pvDisp)];
    simRes.curtWind=[mpc.gen(1+nGen+nPV:end,1),(simRes.avWind-simRes.windDisp)];

    simRes.time=toc(tstart);

    saveName=strcat('simRes_NoS_NoUp_',num2str(startHour),'_',num2str(endHour),'.mat');
    save(saveName,'simRes','-v7.3');

    resultsStruct=simRes;


end
```

2. Application of Soft Limits Algorithm

```
% APPLICATION OF SOFT LIMITS FUNCTION


function [ resultsStruct ] = qslfHernandez(startHour,endHour)

tstart=tic

    %Quasi-Stationary Load Flow without reserves

        %load PV and Wind Data for regions
        load('\\nas.ads.mwn.de\ga26ved\Desktop\FINAL\Matlab\regPVHourList.mat');
        load('\\nas.ads.mwn.de\ga26ved\Desktop\FINAL\Matlab\regWindHourList.mat');
        load('\\nas.ads.mwn.de\ga26ved\Desktop\FINAL\Matlab\model2030.mat');
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        %Activation os SoftLims
        mpc=mpcHernandez;
        mpc=toggle_softlims(mpcHernandez,'on');

      Making the lines match in branch and line length so can be associated
for i=1:length(lineLength(:,1))

    %If node1 and node 2 the same (same line)
    tempIndex=find((eq(mpc.branch(:,1),(lineLength(i,1)))&
eq(mpc.branch(:,2),(lineLength(i,2))))==1);

    %The grid update cost is the length of THAT line * 400/MW/km
    %/(365*24*40)for hourly cost of upgrade
    for j=1:length(tempIndex(:,1))
        mpc.softlims.cost(tempIndex(j,1),1)=(lineLength(i,3))*400/(24*365*40);
    end

end

        % Input cost of renewable generators
        mpc.gencost(860:end,5)=-60;

        mpcOriginal=mpc;

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        [nPV,~]=size(mpcRenewPV.gen(:,1));
        [nWind,~]=size(mpcRenewWind.gen(:,1));
        nGen=length(mpc.gen(:,1))-nWind-nPV;

        %initialise variables
        simRes.convergence=[];

        simRes.genDisp(1:nGen,1)=mpc.gen(1:nGen,1);

        simRes.pvDisp(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.windDisp(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.avPV(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.avWind(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.busLoad(:,1)=mpc.bus(:,1);
        simRes.lineFlow(:,1:2)=mpc.branch(:,1:2);
        simRes.lineFlow(:,3)=mpc.branch(:,6);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %start time series load flow

%         mpc.

        for hourCount=startHour:endHour

            hourCount
            %update bus loads
            mpc.bus(:,3)=busLoadList(:,hourCount+1);
```

```
            %update pv and wind gens

mpc.gen(nGen+1:nGen+nPV,9)=
mpcOriginal.gen(nGen+1:nGen+nPV,9).*regPV15MinList(mpcRenewPV.region(:,1),hourCount,1);

mpc.gen(nGen+nPV+1:nGen+nPV+nWind,9)=
mpcOriginal.gen(nGen+nPV+1:end,9).*regWind15MinList(mpcRenewWind.region(:,1),hourCount,1);

            %run hourly opf 1
            results=rundcopf(mpc,mpoption(mpoption,'out.all',0,'opf.dc.solver','GLPK'));


            simRes.convergence(hourCount,1)=results.success;

            simRes.genDisp(:,hourCount+1)=results.gen(1:nGen,2);

            simRes.pvDisp(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,2);
            simRes.windDisp(:,hourCount+1)=results.gen(1+nGen+nPV:end,2);

            simRes.avPV(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,9);
            simRes.avWind(:,hourCount+1)=results.gen(1+nGen+nPV:end,9);

            simRes.busLoad(:,hourCount+1)=results.bus(:,3);
            simRes.lineFlow(:,hourCount+3)=results.branch(:,16);

            %Include softlimit overload MW in results output
            simRes.softlimsdata(:,hourCount)=results.softlims(:,1);

        end

    simRes.curtPV=[mpc.gen(1+nGen:nGen+nPV,1) , (simRes.avPV-simRes.pvDisp)];
    simRes.curtWind=[mpc.gen(1+nGen+nPV:end,1) , (simRes.avWind-simRes.windDisp)];

    simRes.time=toc(tstart);

    saveName=strcat('simRes_NoS_NoUp_',num2str(startHour),'_',num2str(endHour),'.mat');
    save(saveName,'simRes','-v7.3');

    resultsStruct=simRes;

end
```

3. Management Output of Application of Soft Limits Algorithm

```
% MANAGEMENT OF OUTPUT DATA FROM SIMULATION OF EUROPEAN TRANSMISSION SYSTEM WITH
APPLICATION OF SOFT LIMITS

new_table=zeros(7785,30); %Initialize table of data

% SUM OVERLOAD ENERGY IN ONE YEAR
% FREQUENCY OVERLOAD IN ONE YEAR
% MAXIMUM POWER OVERLOAD IN ONE YEAR

%For every line and hour
for j=1:7783
    for i=1:8784

        % SUM Overload energy one line during one year(MW)
        new_table(j,1)=new_table(j,1)+results.softlimsdata(i).overload(j,1);
        % Total overload energy all lines all hours (MW)
        new_table(7785,1)=new_table(7785,1)+results.softlimsdata(i).overload(j,1);

        % Frequency overloaded in one year
        if results.softlimsdata(i).overload(j,1)>0 %If overloaded
            new_table(j,2)= new_table(j,2)+1;
        end

        % Maximum power overload per line in one year (MW)
        if results.softlimsdata(i).overload(j,1)>new_table(j,3)
            new_table(j,3)= results.softlimsdata(i).overload(j,1);
        end
    end
end

% Total Mean Overload power all lines all hours (MW)
tot_mw_mean_upgrade= new_table(7785,1)/8784;


% TOTAL COST OF UPGRADING PLAN
% PROBABILITY LINE OVERLOADED
% FREQUENCY WEIGHTED MEAN ENERGY

% for every line
for j=1:7783

% SUM Overload energy with maximum power overload during one year(MW)
new_table(7785,3)= new_table(7785,3) + new_table(j,3);

% TOTAL COST OF UPGRADING PLAN
              % strategytable(j,3) MAX OVERLOAD POWER UPGRADE

new_table(j,4)=
new_table(j,4)+results.softlimsdata(1).cost(j,1)*40*365*24*(new_table(j,3));

new_table(7785,4)=
new_table(7785,4)+results.softlimsdata(1).cost(j,1)*40*365*24*(new_table(j,3));

              % strategytable(j,1)/8784 MEAN OVERLOAD POWER UPGRADE

new_table(j,5)=
new_table(j,5)+results.softlimsdata(1).cost(j,1)*40*365*24*(new_table(j,1)/8784);

new_table(7785,5)=
new_table(7785,5)+results.softlimsdata(1).cost(j,1)*40*365*24*(new_table(j,1)/8784);

% PROBABILITY LINE OVERLOADED
            new_table(j,6) = new_table(j,2)/8784*100;

% FREQUENCY WEIGHTED MEAN ENERGY
            new_table(j,7) = new_table(j,2)*new_table(j,1)/8784;

end
```

```
% LINE LENGTH

for i=1:length(lineLength(:,1))

    %Match index and length - If node1 and node2 the same (same line)
tempIndex=find((eq(mpcHernandez.branch(:,1),(lineLength(i,1)))&
eq(mpcHernandez.branch(:,2),(lineLength(i,2))))==1);

    for j=1:length(tempIndex(:,1))
        if new_table(tempIndex(j,1),2)>=1
            new_table(tempIndex(j,1),9)=lineLength(i,3);
        end
    end

end

% TOTAL LENGTH
new_table(7785,9)=0; %Initialize variable

for j=1:7783
    new_table(7785,9)=new_table(7785,9)+new_table(j,9);
end


% RES CURTAILED
RES_curt=0; %Initialize variable
RES_tot=0; %Initialize variable

% for every node and hour
for i=1:5750
    for j=3:8786
        % RES curtailed in one year
        RES_curt = RES_curt + results.curtPV(i,j) + results.curtWind(i,j);
        RES_tot = RES_tot + results.pvDisp(i,j-1) + results.windDisp(i,j-1);
    end
end

RES_curt_Perc = RES_curt/RES_tot*100;
```

4. Mean Overload Power Upgrade Algorithm:

```
function [ resultsStruct ] = qslfHernandez(startHour,endHour)

tstart=tic

    %Quasi-Stationary Load Flow without reserves

        %load PV and Wind Data for regions
        load('\\C:\Thesis\Matlab\regPVHourList.mat');
        load('\\C:\Thesis\Matlab\regWindHourList.mat');
        load('\\C:\Thesis\Matlab\model2030.mat');
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        mpc=mpcHernandez;


        %Negative cost of renewable generators
        mpc.gencost(860:end,5)=-60;

        mpcOriginal=mpc;


% UPGRADE MEAN

for j=1:155
    a=new_table(j,30);


        %MeanOv.
        mpc.branch(a,6)=mpc.branch(a,6)+new_table(j,1)/8784;

end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        [nPV,~]=size(mpcRenewPV.gen(:,1));
        [nWind,~]=size(mpcRenewWind.gen(:,1));
        nGen=length(mpc.gen(:,1))-nWind-nPV;

        %initialise variables
        simRes.convergence=[];

        simRes.genDisp(1:nGen,1)=mpc.gen(1:nGen,1);

        simRes.pvDisp(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.windDisp(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.avPV(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.avWind(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.busLoad(:,1)=mpc.bus(:,1);
        simRes.lineFlow(:,1:2)=mpc.branch(:,1:2);
        simRes.lineFlow(:,3)=mpc.branch(:,6);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %start time series load flow

%           mpc.

        for hourCount=startHour:endHour

            hourCount
            %update bus loads
            mpc.bus(:,3)=busLoadList(:,hourCount+1);

            %update pv and wind gens


mpc.gen(nGen+1:nGen+nPV,9)=
mpcOriginal.gen(nGen+1:nGen+nPV,9).*regPV15MinList(mpcRenewPV.region(:,1),hourCount,1);

mpc.gen(nGen+nPV+1:nGen+nPV+nWind,9)=
mpcOriginal.gen(nGen+nPV+1:end,9).*regWind15MinList(mpcRenewWind.region(:,1),hourCount,1);
```

```
            %run hourly opf 1
            results=rundcopf(mpc,mpoption(mpoption,'out.all',0,'opf.dc.solver','GLPK'));


            simRes.convergence(hourCount,1)=results.success;

            simRes.genDisp(:,hourCount+1)=results.gen(1:nGen,2);

            simRes.pvDisp(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,2);
            simRes.windDisp(:,hourCount+1)=results.gen(1+nGen+nPV:end,2);

            simRes.avPV(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,9);
            simRes.avWind(:,hourCount+1)=results.gen(1+nGen+nPV:end,9);

            simRes.busLoad(:,hourCount+1)=results.bus(:,3);
            simRes.lineFlow(:,hourCount+3)=results.branch(:,16);

        end

    simRes.curtPV=[mpc.gen(1+nGen:nGen+nPV,1) , (simRes.avPV-simRes.pvDisp)];
    simRes.curtWind=[mpc.gen(1+nGen+nPV:end,1) , (simRes.avWind-simRes.windDisp)];

    simRes.time=toc(tstart);

    saveName=strcat('simRes_mean155_',num2str(startHour),'_',num2str(endHour),'.mat');
    save(saveName,'simRes','-v7.3');

    resultsStruct=simRes;

end
```

5. Mean + Standard Deviation of Overload Power Upgrade Algorithm:

```
function [ resultsStruct ] = qslfHernandez(startHour,endHour)

tstart=tic

    %Quasi-Stationary Load Flow without reserves

        %load PV and Wind Data for regions
        load('\\C:\Thesis\Matlab\regPVHourList.mat');
        load('\\C:\Thesis\Matlab\regWindHourList.mat');
        load('\\C:\Thesis\Matlab\model2030.mat');
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        mpc=mpcHernandez;

        %Negative cost of renewable generators
        mpc.gencost(860:end,5)=-60;

        mpcOriginal=mpc;


% UPGRADE STD

for j=1:21
    Pow_Up = mean(Ov_perH) + std(Ov_perH);

    mpc.branch(new_table(j,30),6) = mpc.branch(new_table(j,30),6)+ Pow_Up(j);
end

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        [nPV,~]=size(mpcRenewPV.gen(:,1));
        [nWind,~]=size(mpcRenewWind.gen(:,1));
        nGen=length(mpc.gen(:,1))-nWind-nPV;

        %initialise variables
        simRes.convergence=[];

        simRes.genDisp(1:nGen,1)=mpc.gen(1:nGen,1);

        simRes.pvDisp(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.windDisp(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.avPV(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.avWind(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.busLoad(:,1)=mpc.bus(:,1);
        simRes.lineFlow(:,1:2)=mpc.branch(:,1:2);
        simRes.lineFlow(:,3)=mpc.branch(:,6);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %start time series load flow

%         mpc.

        for hourCount=startHour:endHour

            hourCount

            %update bus loads
            mpc.bus(:,3)=busLoadList(:,hourCount+1);

            %update pv and wind gens

mpc.gen(nGen+1:nGen+nPV,9)=
mpcOriginal.gen(nGen+1:nGen+nPV,9).*regPV15MinList(mpcRenewPV.region(:,1),hourCount,1);

mpc.gen(nGen+nPV+1:nGen+nPV+nWind,9)=
mpcOriginal.gen(nGen+nPV+1:end,9).*regWind15MinList(mpcRenewWind.region(:,1),hourCount,1);

            %run hourly opf 1
results=rundcopf(mpc,mpoption(mpoption,'out.all',0,'opf.dc.solver','GLPK'));

            simRes.convergence(hourCount,1)=results.success;
```

```
            simRes.genDisp(:,hourCount+1)=results.gen(1:nGen,2);

            simRes.pvDisp(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,2);
            simRes.windDisp(:,hourCount+1)=results.gen(1+nGen+nPV:end,2);

            simRes.avPV(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,9);
            simRes.avWind(:,hourCount+1)=results.gen(1+nGen+nPV:end,9);

            simRes.busLoad(:,hourCount+1)=results.bus(:,3);
            simRes.lineFlow(:,hourCount+3)=results.branch(:,16);

        end

    simRes.curtPV=[mpc.gen(1+nGen:nGen+nPV,1) , (simRes.avPV-simRes.pvDisp)];
    simRes.curtWind=[mpc.gen(1+nGen+nPV:end,1) , (simRes.avWind-simRes.windDisp)];

    simRes.time=toc(tstart);

    saveName=strcat('simRes_std21_',num2str(startHour),'_',num2str(endHour),'.mat');
    save(saveName,'simRes','-v7.3');

    resultsStruct=simRes;

end
```

6. Maximum Overload Power Upgrade Algorithm:

```
function [ resultsStruct ] = qslfHernandez(startHour,endHour)

tstart=tic

    %Quasi-Stationary Load Flow without reserves

        %load PV and Wind Data for regions
        load('\\C:\Thesis\Matlab\regPVHourList.mat');
        load('\\C:\Thesis\Matlab\regWindHourList.mat');
        load('\\C:\Thesis\Matlab\model2030.mat');
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        mpc=mpcHernandez;

        %Negative cost of renewable generators
        mpc.gencost(860:end,5)=-60;

        mpcOriginal=mpc;


for j=1:53
    a=new_table(j,30);

        % MaxOv.
        mpc.branch(a,6)=mpc.branch(a,6)+new_table(j,3);
end

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        [nPV,~]=size(mpcRenewPV.gen(:,1));
        [nWind,~]=size(mpcRenewWind.gen(:,1));
        nGen=length(mpc.gen(:,1))-nWind-nPV;

        %initialise variables
        simRes.convergence=[];

        simRes.genDisp(1:nGen,1)=mpc.gen(1:nGen,1);

        simRes.pvDisp(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.windDisp(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.avPV(1:nPV,1)=mpc.gen(1+nGen:nGen+nPV,1);
        simRes.avWind(1:nWind,1)=mpc.gen(1+nGen+nPV:end,1);

        simRes.busLoad(:,1)=mpc.bus(:,1);
        simRes.lineFlow(:,1:2)=mpc.branch(:,1:2);
        simRes.lineFlow(:,3)=mpc.branch(:,6);
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %start time series load flow

%          mpc.

        for hourCount=startHour:endHour
            j
            hourCount
            %update bus loads
            mpc.bus(:,3)=busLoadList(:,hourCount+1);

            %update pv and wind gens

mpc.gen(nGen+1:nGen+nPV,9)=
mpcOriginal.gen(nGen+1:nGen+nPV,9).*regPV15MinList(mpcRenewPV.region(:,1),hourCount,1);

mpc.gen(nGen+nPV+1:nGen+nPV+nWind,9)=
mpcOriginal.gen(nGen+nPV+1:end,9).*regWind15MinList(mpcRenewWind.region(:,1),hourCount,1);

            %run hourly opf 1
            results=rundcopf(mpc,mpoption(mpoption,'out.all',0,'opf.dc.solver','GLPK'));


            simRes.convergence(hourCount,1)=results.success;
```

```
            simRes.genDisp(:,hourCount+1)=results.gen(1:nGen,2);

            simRes.pvDisp(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,2);
            simRes.windDisp(:,hourCount+1)=results.gen(1+nGen+nPV:end,2);

            simRes.avPV(:,hourCount+1)=results.gen(1+nGen:nGen+nPV,9);
            simRes.avWind(:,hourCount+1)=results.gen(1+nGen+nPV:end,9);

            simRes.busLoad(:,hourCount+1)=results.bus(:,3);
            simRes.lineFlow(:,hourCount+3)=results.branch(:,16);

        end

    simRes.curtPV=[mpc.gen(1+nGen:nGen+nPV,1) , (simRes.avPV-simRes.pvDisp)];
    simRes.curtWind=[mpc.gen(1+nGen+nPV:end,1) , (simRes.avWind-simRes.windDisp)];

    simRes.time=toc(tstart);

    saveName=strcat('simRes_max53_',num2str(startHour),'_',num2str(endHour),'.mat');
    save(saveName,'simRes','-v7.3');

    resultsStruct=simRes;

end
```

7. Complementary Graphs for Further Analysis

7.1. Application of Soft Limits

Sample graphs of arbitrary line 10 during the 8784 hours simulated:

- Overload Cost:

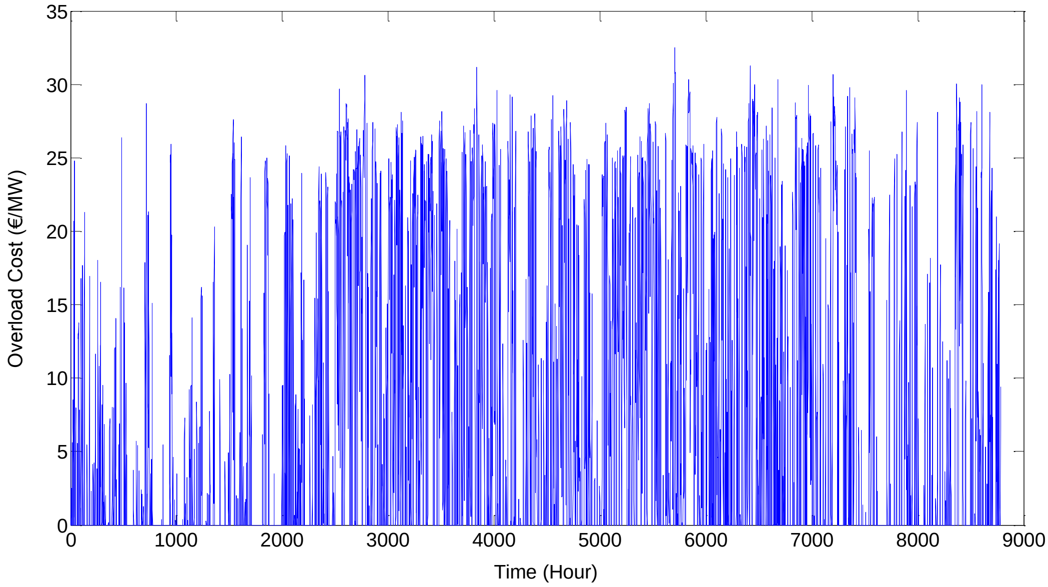

Figure 44: Output of Soft Limit Application: Overload Cost, Line 10, All Hours

- Overload:

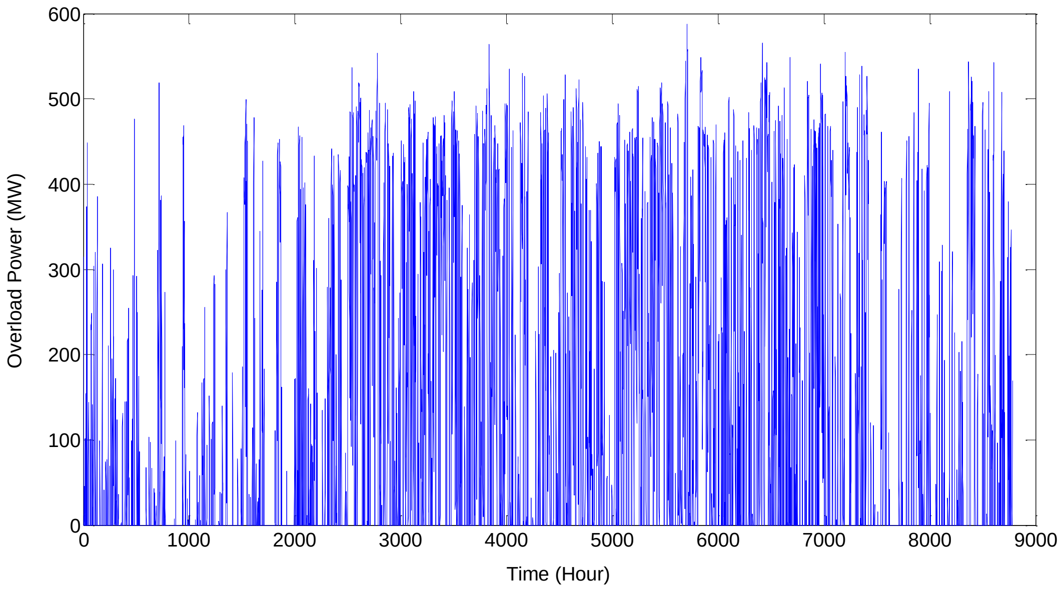

Figure 45: Output of Soft Limit Application: Overload, Line 10, All Hours

<u>Sample graphs of all the lines for the arbitrary hour 3905:</u>

- Overload Cost:

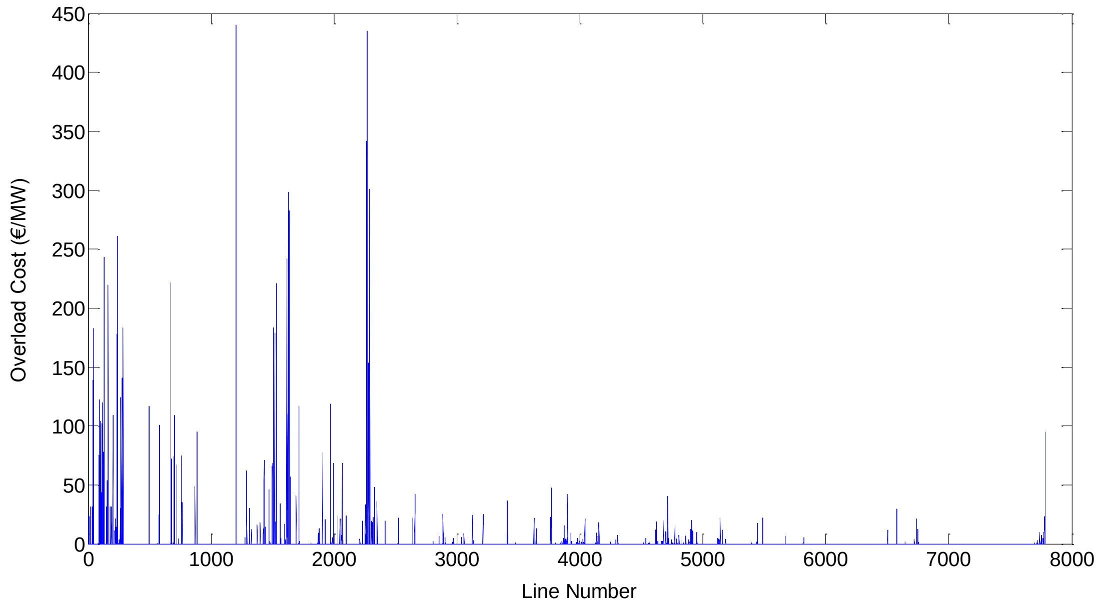

Figure 46: Output of Soft Limit Application: Overload Cost, All Lines, Hour 3905

- Overload:

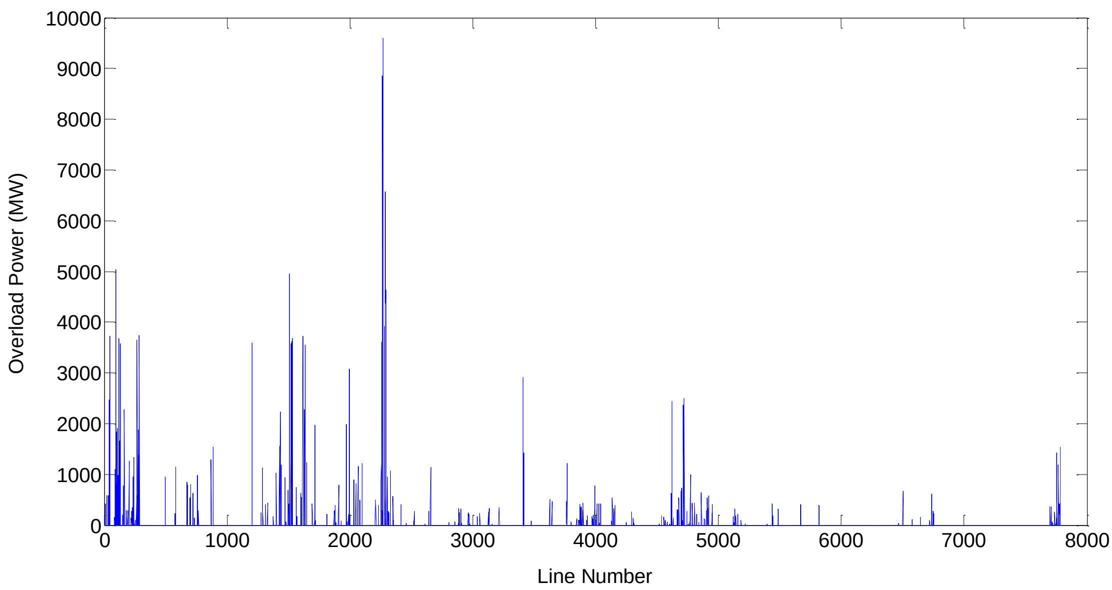

Figure 47: Output of Soft Limit Application: Overload Power Magnitude, All Lines, Hour 3905

7.2. Relationship Preference Order Criteria

a. Magnitude of Energy Overload

- Maximum overload power of each line in descending order:

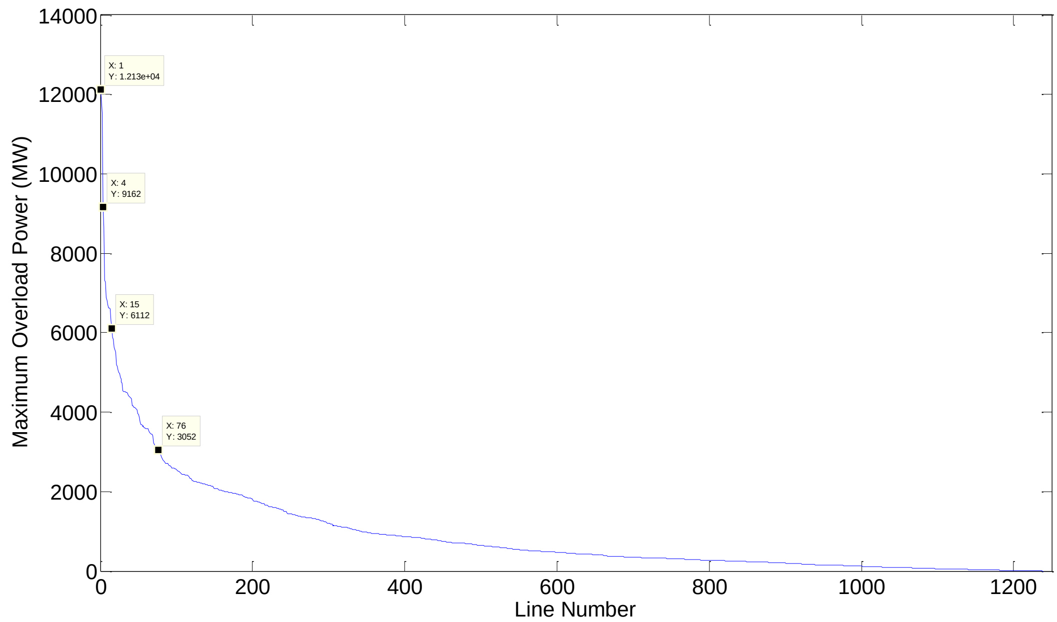

Figure 48: Maximum Power Overload, Descending Order

- Cumulative maximum power overload in descending order of maximum power overload of each line:

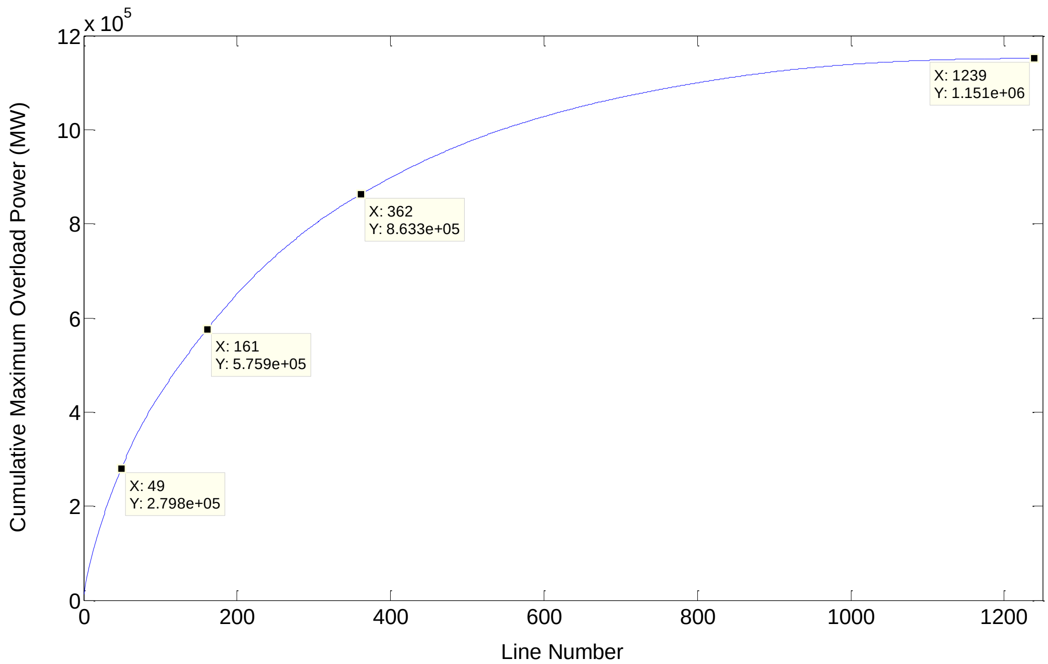

Figure 49: Cumulative Maximum Power Overload, Descending Order of Maximum Power Overload

- Mean overload power of each line in descending order:

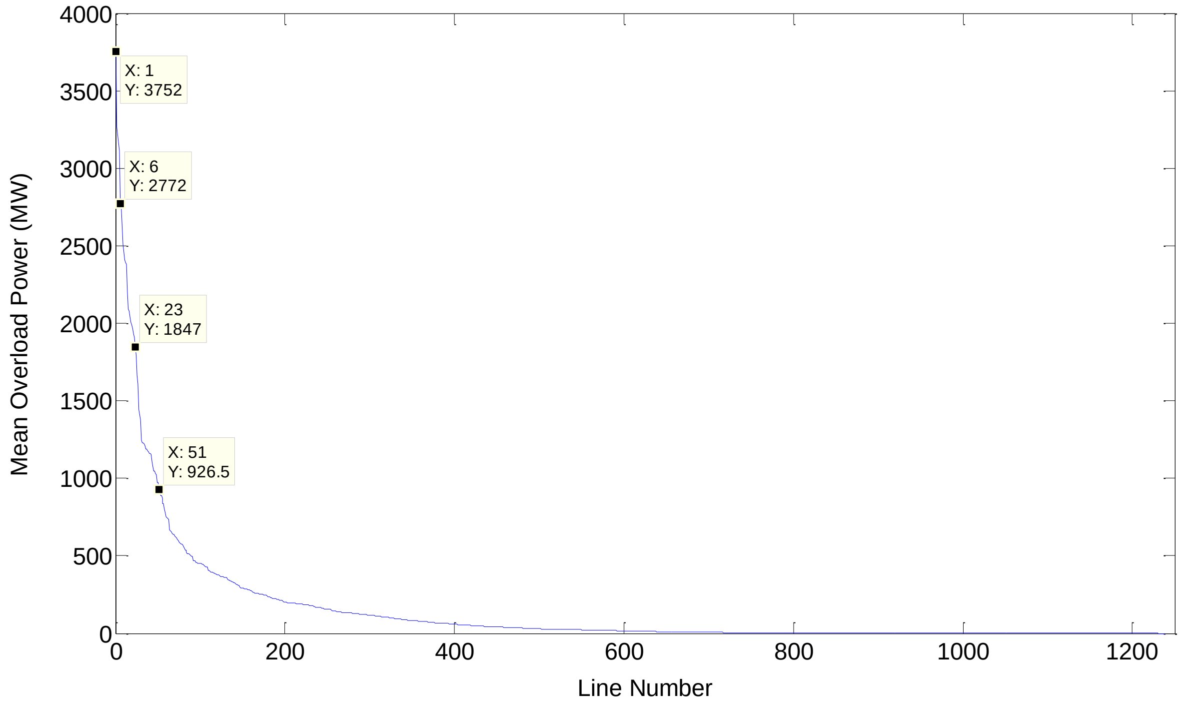

Figure 50: Mean Power Overload, Descending Order

- Cumulative mean overload power in descending order:

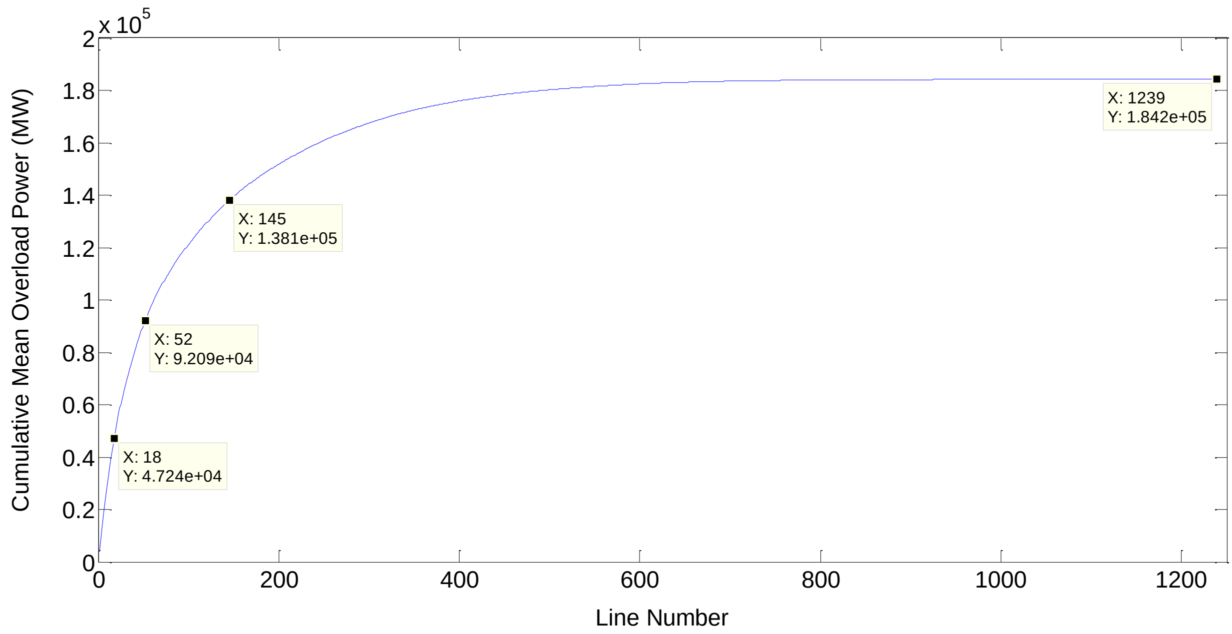

Figure 51: Cumulative Mean Power Overload, Descending Order

b. *Total Line Length to Upgrade*

- Length of lines in descending order:

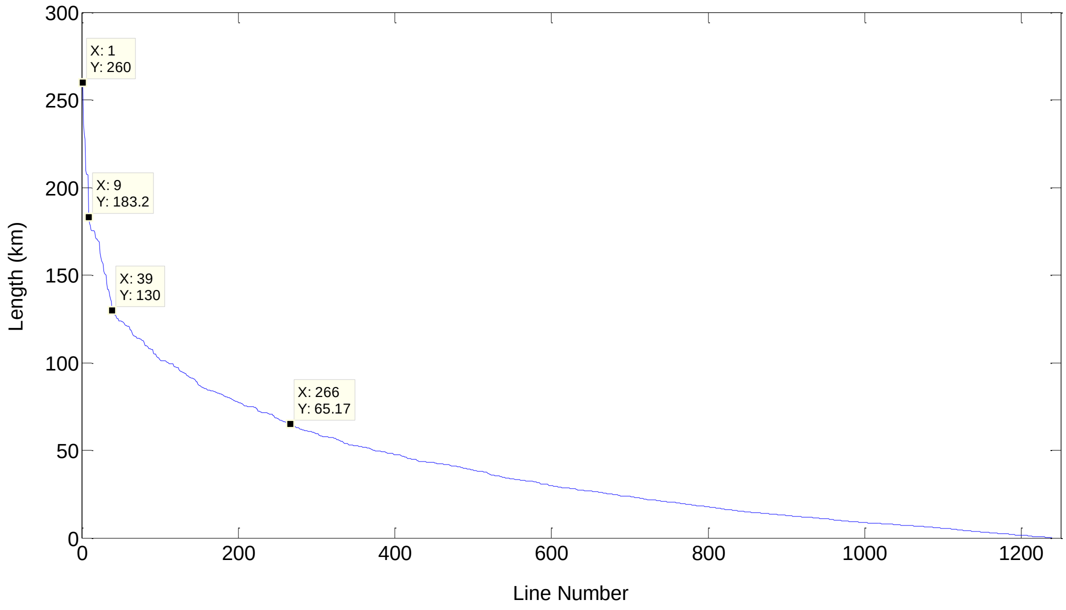

Figure 52: Line Length, Descending Order

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