Study on the development of the public transmission network around Goéland until 2030

Master of Science Thesis by
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ABSTRACT

The project was performed in RTE (“Réseau de Transport d’Electricité”), the French Transmission System Operator (TSO) within the Network Optimisation and Development Service (SDOP) that has to plan and direct the development of the regional transmission network (225 and 63 kV). The goal was to carry out a study on the development of the power transmission network until 2030 in a context of increasing demand, in order to match power need in the future. Thus, it consists into the determination of the different constraints (transmission capacity constraints, short-circuit current limitations, voltage stability constraints, environmental constraints…) that might appear in the area of study in the medium-term (2020) and long-term (2030). These constraints were analyzed with the determination of the causes and the calculation of the seriousness (for example power cut and not distributed energy) of the aforementioned constraints. The next step consists in the analysis of several technical and economical solutions to satisfy these constraints. Then, the study results in an investment plan from 2007 to 2030 including the solutions, their costs and their years of investment. Finally, this work was presented, explained and approved by the regional management of RTE.

This master thesis report is divided into four parts: a brief presentation of RTE is given, then the context of study and a prediction of the long-term behaviour of the electrical market are presented, followed by the technical issues and the general tools of the study and finally the consistent results related to the study are explained.

A chart of confidentiality was signed not to transmit the results outside of the company. This report is based on an existing grid, even though the names of the substations have been changed for the sake of confidentiality.
ACKNOWLEDGEMENTS

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I am grateful to Mr Joseph Alarcon, manager of the Network Study Unit and supervisor of my internship and Mr Frédéric Grand, engineer in this Unit, who gave time from their crowded schedules to answer my questions.

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# INTRODUCTION

The purpose of the grid is to transfer electric energy from the generation sources to the final consumer. Since electricity cannot be stored and as supply and demand are both subject to unforeseeable contingencies, it is impossible to guarantee that demand can be satisfied. RTE is a public service company responsible for operating, maintaining and developing the French electricity transmission network. RTE must keep the risk of shortfall occurring to a socially and economically level. In order to reach these objectives, the transmission grid development should be planned in advance.

The aim of this project is to detect the constraints on the 63kV power transmission grid by 2030 in a context of increasing consumptions and to find technical and economical solutions to solve these issues. The development of the transmission network must be anticipated quite early in order to fit to the long-term behaviour of the electrical market and to ensure safety. The goal is to optimize the system and to have the best performance at the lowest price in a long-time perspective.

The study was done in several steps (Figure 1.1) in order to reach the objectives [1].

![Step-by-step description of the study](image)

*Figure 1.1: Step-by-step description of the study*
As regards to the methodology, several simulating tools were used during the project. The core of the work was the analysis of the results from the simulation of the network. The electrical grid was simulated with the software PLATINE developed by the R&D centre of RTE. Moreover, the cost evaluation of the different constraints was realized by using the tool VALORIS in order to find the best economical solution and the plan of investments.

Within the study, two meetings with the project team were organised. The project team is composed of an estimated ten people from different Services: the Service of Customers Relationship, the Service of Prevision, the Group of Engineering and Maintenance of the Network and the Groups of Operation of Transportation. The aim of these meetings was to have several points of view concerning the results of the study. The first meeting was held the 2nd of October to present the project and the first results. The goal was to gather comments and suggestions from the project team towards these results. The second meeting was held the 12th of November to present the final results. The completed project was presented on the 12th of December 2007 to the regional direction of RTE for approval. Finally, a written report of the study was realized.
2 PRESENTATION OF RTE

RTE will be shortly presented from an overview of the European electricity market to a focus on the service where this master thesis was realized.

2.1 European electricity market

Electricity cannot be stored and automatic control systems are used to maintain the balance between generation and consumption. A neutral and independent actor maintains the balance at all times: the transmission system operator (TSO).

The European electric system is composed of 27 interconnected countries and has 4 synchronous zones (Scandinavia, United Kingdom, Ireland and Continental Europe).

2.2 Creation and roles of RTE

EDF was created after the Nationalisation Law of April 1946. EDF was a national public company that was dealing with the production, transmission and distribution of electricity. In 1996, a European directive opens the European market up to competition (Figure 2.1). Following the law of the 10 February 2000, RTE was created the 1st of July 2000. Since 1st of September 2005, RTE has been a state-owned limited company, a subsidiary of the EDF Group [7].

![Figure 2.1: Roles of RTE in the deregulated market of energy](Image)

Figure 2.1: Roles of RTE in the deregulated market of energy
RTE has a public service mission and must serve the national territory and interconnections with neighbouring countries in a rational way and provide non-discriminatory connections and access to the network based on public access tariffs, regardless of the distance between suppliers and consumers. RTE promotes the fluidity of exchanges and works with other TSOs to develop interconnection capacities [8].

Close relations are hold between RTE, the French Energy Regulator (CRE) and the Minister for Energy. The CRE approves investments programs and rules of RTE and determines access tariffs. The tariffs are identical throughout the territory regardless the distance. The Minister for Energy approves tariffs, development plans and specifications concerning the transmission network.

The market was opened to competition gradually. First, it was opened for professional customers the 1st of July 2004. Three years later, it was opened for private customers (the 1st of July 2007).

2.3 French electricity network

In an electric power system, the purpose of the grid is to transfer electric energy from the generation sources to the consumers. Such power system has a hierarchical structure depending on the voltage level. The 400kV network is built over long distances on national scale and is connected to the transmission grids of the neighbouring countries. Then, on a regional scale, the electricity is distributed to the distributors or the big industrial customers trough the 225kV, 90kV, 63kV and 45kV sub-transmission grids over shorter distances. These sub-transmission grids are used as a link between the transmission grids and the distribution grids to the final consumers.

The French network is one of the most important network in Europe with more than 100 000km of very high and high voltage network. In December 2006, the transmission installations were composed of 21 000km of 400kV lines, 26 000km of 225kV lines and 53 000km of 150, 90, 63 and 45kV lines owned by RTE. The French electrical consumption added up to 480TWh in 2006.

Several actors use the network: energy producers (nuclear, hydraulic, thermal, cogeneration, wind power…) who inject power in the network, energy distributors (20kV) who distribute power to local consumers and small industrials, big industrial customers and trading companies of energy (Powernext). Powernext is the electricity exchange that promotes the fluidity of the market at the best price.
2.4 Organisation of RTE

RTE is separated into two operational departments: the Power System Unit (SE) and the Electricity Transmission unit (TE) within 7 regional units coordinated by a central system (Figure 2.2). 7 300 persons are working in the regional systems and 1000 persons in the central system.

The chairman of the executive board is Mr Maillard.

Figure 2.2: National organisation of RTE
RTE is composed of 7 regional systems (Figure 2.3): Normandy-Paris, Northeast, East, West, Southwest, Southeast, Rhône-Alpes Auvergne. They manage the regional network of 225kV, 90kV and 63kV.

Figure 2.3: RTE and its 7 regional systems

This master thesis was carried out in SERAA that is the Power System unit (SE) in the Rhône-Alpes Auvergne regional unit (RAA).
2.5 RTE in Rhône-Alpes Auvergne

RTE in Rhône-Alpes Auvergne is divided into two regional units: the Electricity Transmission unit (TERAA) and the Power System unit (SERAA).

TERAA is made of several Groups that maintain the network, repair the failures, control the security of the system and develop engineering process.

SERAA encompasses four Services (Figure 2.4). The Service of Customers Relationship manages customers’ contracts and invoices. The Service of Operation balances in real time the production and consumption. The Prevision Service prepares operations on the network in the short-term and medium-term to maintain a secure system. Finally, the Service of Development and Optimisation of the Network (SDOP) makes studies in the short-term on customers’ connections and in the long-term on network developments. This service proposes technical projects to develop the network and propositions of investments. The master thesis took place in this service.

![Figure 2.4: Organizations in SERAA](image)
3 CONTEXT OF THE STUDY

3.1 Introduction

The study deals with the upcoming period 2007 to 2030 divided into two stages: 2007-2020 (medium-term) and 2020-2030 (long-term). This study concerns a non-linear meshed network, with interactions between the lines. The area of study is the power transmission grid between the three transformer substations of Chouette (substation 1 = S1) (400/63kV), Alouette (substation 8 = S8) (225/63kV) and Sittelle (substation 14 = S14) (225/63kV). This study deals with the 63kV network composed of the following electrical substations of Faisan (substation 2 = S2), Verdier (substation 4 = S4), Goéland (substation 5 = S5), Hirondelle (substation 6 = S6), Roitelet (substation 7 = S7), Alouette (substation 8 = S8), Martinet (substation 10 = S10), Moineau (substation 11 = S11) and Tourterelle (substation 15 = S15) in addition to the industrial consumers in Aigrette (substation 3 = S3), Buse (substation 12 = S12) and Chardonneret (substation 16 = S16).

A general overview of the network is necessary to realize the study. The main characteristics of the transmission grid are described.

The three transformer substations are situated in Chouette (S1) with 2 transformers 400/63kV of 240MVA each, in Alouette (S8) with 2 transformers 225/63kV of 100MVA each and in Sittelle (S14) with 2 transformers 225/63kV of 70MVA each and 1 transformer 225/63kV of 100MVA.

A branch line (in red in the Figure 3.1) is situated between Roitelet (S7) and one junction point on the line Hirondelle (S6) – Alouette (S8). This branch line is open in Roitelet (S7). A branch line is easy to build and has only 3 circuit breakers (at the three extremities: Alouette (S8), Hirondelle (S6) and Roitelet (S7)). To operate this system one out of the three circuit breakers should be open [9].

![Figure 3.1: Diagram of a branch line](image)

The high voltage production is made by two hydraulic power plants run-of-the-river in Caille (S9) and Serin (S13).
The 63kV network is operated with one electric node in Chouette (S1), two electric nodes in Sittelle (S14) and Alouette (S8) (Figure 3.2). Sittelle (S14) and Alouette (S8) are operated with two nodes in order to respect the limitation in short-circuit current \(I_{sc}\) of the substation materials or structures.

The technical characteristics of the transmission lines are given by GIMR (the Group of Engineering and Maintenance of the Network). It corresponds to the length of the lines, the materials, the section, the building year and the Maximal Intensity in Steady State (IMAP). The \(P_{MAP}\) is the maximal power flow that can be transmitted into a line without overloading. The Figure 3.2 shows the \(P_{MAP}\) of the lines in summer and winter (\(P_{MAPsummer} < P_{MAPwinter}\)).

![Figure 3.2: Power transmission network of the study with \(P_{MAP}\) characteristics](image)

A growth in electricity demand is observed in the area of study due to the development of the industrial areas and the proximity of two major French cities and an airport.
The study will be based on the prediction of the long-term behaviour in the area of study in terms of production and consumption.

3.2 Consumption forecasts

The electrical consumption depends on two variables: time and temperature. The most important one is the time with several variation cycles during the year: an annual cycle with a consumption peak in January and a trough in August, a weekly cycle with a decrease in consumption on weekends and a daily cycle with a decrease during the night. Then, the outside temperature affects the residential consumption. Consumptions increase in winter with lower temperatures (use of heating systems) and in summer with higher temperatures (use of air-conditioning systems).

A special computer forecasting software, based on temperature data and historical records of the previous year, builds up a prevision for the next years.

3.2.1 Method to calculate consumption forecasts

The consumption hypotheses are calculated for three periods of the year: winter (from the 10th November to the 20th of April), interseason (from the 20th of April to 10th of May and from the 20th of September to 10th of November) and summer (from the 10th of May to the 20th of September).

The study will focus more on the winter season due to the critical hypotheses during this season.

Moreover, there are two behaviours concerning the consumption. First, the residential consumption with a dependency on the outside temperature corresponds to the demand of the distributors for individuals (in winter, the demand increases when the temperature decreases). Then, the consumption with an independency on the outside temperature corresponds to the industrials demand (the temperature does not influence the level of production).
First, the consumption forecasts will be calculated for the winter season. The method of calculation is different for consumptions with a dependency on temperature and for consumptions with an independency on temperature.

For consumptions with a temperature dependency

\[ P_{9N} = \text{consumption at 9am of this day} \]

\[ P^{*}_{9N} = \text{normalized consumption} \]

\[ P^{*}_{9N \text{adapted}} \]

\[ P^{*}_{\text{maxN}} = \text{maximal consumption} \]

\[ P^{*}_{\text{tmbN}} \]

**Figure 3.3: Calculation of consumption forecasts with a temperature dependency**

For consumptions with a temperature independency

\[ P_{9N} = P^{*}_{9N} = \text{consumption at 9am of this day} \]

\[ P^{*}_{\text{maxN}} \]

\[ P^{*}_{\text{tmbN}} \]

**Figure 3.4: Calculation of consumption forecasts with a temperature independency**
Here is the list to explain the Figures 3.3 and 3.4.

1. Choice of the day of reference

The day of reference should correspond to a high load day with industrial consumption. An underestimation of hypotheses of consumption can be problematic for the study.

For the winter season, it corresponds to a day in January (high load) and a Tuesday or Thursday (industrial consumption). Then, the day chosen is when the temperature of the day \( T_j \) is the closest to the normal temperature \( T_n \) which is the temperature taken for normalization. The normal temperature \( T_n \) is calculated by an average of temperature over the last 30 years.

2. Calculation of \( P_{9N} \)

\( P_{9N} \) is the consumption of this day of reference at 9 o’clock.

3. Calculation of \( P^*_{9N} \)

\( P^*_{9N} \) is the normalization in temperature of \( P_{9N} \). \( P^*_{9N} \) is calculated with the gradient’s method (3.1) and corresponds to the consumption at 9 o’clock in condition of normal temperature.

The gradient \( g \) (MW/°C) represents the variation in consumption due to the temperature.

\[
P^*_{9N} = P_{9N} \times \left(1 + g \times (T_n - T_j)\right)
\]

(3.1)

In case of consumption independent on temperature, the gradient \( g=0 \).

4. Calculation of \( P^*_{9N\text{adapted}} \)

\( P^*_{9N\text{adapted}} \) corresponds to the adjustment of \( P^*_{9N} \) with the curve of reference. This curve is calculated with the value \( P^*_{9N\text{-}1} \) (value of the previous year) and the level of growth in consumption noticed during the year.

5. Calculation of \( P^*_{\text{max}N} \)

\( P^*_{\text{max}N} \) corresponds to the maximal normalized value of consumption within the day of reference (consumption at the rush hour).

This hour is different between residential and industrial consumptions.

The residential consumption depends on temperature.

\[
P^*_{\text{max}N} = K_{1a} \times P^*_{9N}
\]

(3.2)

\( K_{1a} \) is the coefficient to calculate \( P^*_{\text{max}N} \) from \( P^*_{9N} \) for the residential consumption.
For industries, the consumption does not depend on temperature.

\[ P_{\text{max}N}^* = K_{1b} \cdot P_{\text{9}N}^* \]  

(3.3)

\[ K_{1b} \] is the coefficient to calculate \( P_{\text{max}N}^* \) from \( P_{\text{9}N}^* \) for industries.

\section{Calculation of \( P_{\text{mb}N} \)}

\( P_{\text{mb}N} \) corresponds to the maximal value of consumption at the temperature \( T_{\text{mb}} \). This minimal temperature (\( T_{\text{mb}} \)) occurs in average one day a year. This represents the extreme conditions (very high consumption) which can appear with a very low occurrence.

\[ P_{\text{mb}N} = P_{\text{max}N}^* \cdot (1 + g \cdot (T_n - T_{\text{mb}})) = P_{\text{max}N}^* \cdot K_2 \]  

(3.4)

\[ K_2 \] is the coefficient to calculate \( P_{\text{mb}N} \) from \( P_{\text{max}N}^* \).

\section{Calculation of \( P_{\text{maxN}, N+1}, P_{\text{maxN+2}, N+1}, P_{\text{mbN+1}, N+1}, P_{\text{mbN+2}, N+1} \)}

From the values \( P_{\text{max}N}^* \) and \( P_{\text{mb}N} \) of the year of study \( N \), it is possible to calculate the values \( P_{\text{maxN+1}}, P_{\text{maxN+2}, N+1}, P_{\text{mbN+1}, N+1}, P_{\text{mbN+2}, N+1} \) of the following years (\( N+1, N+2, N+3 \)) with the TCMA \( N \) (Estimated Annual Level of Growth for the year \( N \)).

\[ P_{\text{maxN+1}, N+1} = P_{\text{maxN}, N}^* \cdot (1 + \text{TCMA}_{N+1}) \]  

(3.5)

\[ P_{\text{mbN+1}, N+1} = P_{\text{mbN}, N}^* \cdot (1 + \text{TCMA}_{N+1}) \]  

(3.6)

These values are estimations of the future consumptions and are calculated with estimated level of growth (TCMA).

Then, the consumption forecasts are calculated in interseason and in winter.

In interseason, \( P_{\text{max}N}^* \) and \( P_{\text{mb}N} \) are calculated in the same ways as in winter. However, there is no extreme condition in temperature in interseason (\( T_{\text{mb}} \)).

So, \( P_{\text{max}N}^* = P_{\text{mb}N} \)  

(3.7)

In summer, \( P_{\text{max}N}^* \) and \( P_{\text{mb}N} \) are calculated in the same ways as in interseason \( P_{\text{max}N}^* = P_{\text{mb}N} \). Moreover, the consumption is not depending on the temperature \( P_{\text{9}N}^* = P_{\text{9}N} \).

So, \( P_{\text{max}N}^* = K_{1a} \cdot P_{\text{9}N}^* = K_{1a} \cdot P_{\text{9}N} = P_{\text{max}N} \)  

(3.8)
3.2.2 Verification of the consumption forecasts calculated

The study is based on these forecasts of consumption. Thus, the coherency of the results ($P_{\text{maxN}}$ and $P_{\text{minN}}$) should be checked. This verification is realized with the comparison between the values calculated and the values observed in real time (for a high load day).

Let’s take an example with the calculation of the value for Goéland. For Goéland, the value observed in real time was amazingly higher than the value calculated of 51.2MW for the winter season. After an analysis, here is the explanation: the 4th of January, the day of reference in 2007, is a day during the Christmas break when some industries are closed.

A way of verifying was to normalize the consumption value $P_{\text{gn}}$ (3.1) of not only the day of reference but also for all Tuesday or Thursday during winter. This analysis was realized for the year 2007 (Figure 3.5) and for the year before (Figure 3.6). These curves (Figures 3.5 and 3.6) show the influence of the day of reference chosen for the substation Goéland. On 4th of January 2007 (reference for the year 2007 showed with a red circle on the Figure 3.5), the consumption did not correspond to a high load day contrary to the 14th of January which was one of the highest load day of the previous year (showed with a red circle on the Figure 3.6). That explains the underestimated value for Goéland calculated with the day of reference in 2007. A value of 57.5MW seems to be a coherent value for Goéland in 2007 and was taken for the study.

All the other values in the different substations seemed coherent.

![Figure 3.5: $P_{\text{g9}}$ normalized in Goéland (S5) for the winter season 2006/2007](image-url)
3.2.3 Consumption forecasts in the study

In the study, the consumption forecasts ($P_{\text{max}}^*$) for the winter season is 385MW in 2007, 467MW in 2020 and 522MW in 2030.
The Figure 3.7 shows the evolution of the total consumption in the area of study. The consumption is growing because the place of study is situated in a developing area close to two major cities and one airport. Moreover, a slight decrease of the curves between the year 2015 and 2016 is explained by the end of the nuclear power plant decommissioning in Martinet (S10) in 2015 (end of overloading).

In the study, consumption forecasts are used in the network simulations in order to detect two kinds of constraints.

The « **N constraint** » corresponds to normal conditions of the grid, that is to say when all the lines and transformers are working (no outage = complete grid). They are calculated with the extreme hypotheses ($P_{\text{tmb}}$) corresponding to very high consumption (a very cold day). The aim is to provide a secure system even in very high level of consumption with a low occurrence.

The « **N-1 constraint** » corresponds to the grid with one outage (one line or one transformer is broken). They are calculated with $P_{\text{max}}^*$ corresponding to the maximal consumption for a high load day. If any element of the transmission grid fails for whatever reason, it must be possible to transport electricity via another part of the network or to provide power from another generating unit. This rule is taken into account in studies of possible future network developments.

The values of $P_{\text{max}}^*$ and $P_{\text{tmb}}$, used in the study, are given in the annex ($K_{1a} = 1.04$, $K_{1b} = 1$ and $K_2 = 1.26$ in winter). In this study, the time of maximal consumption during the day is 2pm and the minimal temperature $T_{\text{mb}} = -7.7^\circ C$.

The TCMA (Annual Level of Growth) between 2007 and 2030 are given below:

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<thead>
<tr>
<th>TCMA</th>
<th>2007-2012</th>
<th>2013-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERDIER (S4)</td>
<td>2.10%</td>
<td>1.20%</td>
</tr>
<tr>
<td>FAISAN (S2)</td>
<td>2.30%</td>
<td>1.20%</td>
</tr>
<tr>
<td>HIRONDELLE (S6)</td>
<td>2.00%</td>
<td>1.20%</td>
</tr>
<tr>
<td>GOELAND (S5)</td>
<td>2.50%</td>
<td>1.20%</td>
</tr>
<tr>
<td>ROITELET (S7)</td>
<td>1.70%</td>
<td>1.20%</td>
</tr>
<tr>
<td>ALOUETTE (S8)</td>
<td>1.90%</td>
<td>1.20%</td>
</tr>
<tr>
<td>MARTINET (S10)</td>
<td>1.30%</td>
<td>1.20%</td>
</tr>
<tr>
<td>MOINEAU (S11)</td>
<td>1.40%</td>
<td>1.20%</td>
</tr>
<tr>
<td>TOURTERELLE (S15)</td>
<td>2.00%</td>
<td>1.20%</td>
</tr>
</tbody>
</table>

*Table 3.1: TCMA for each node*

The TCMA between 2007 and 2012 is calculated for each substation considering the future specificities and the future projects. The TCMA between 2012 and 2020 is set to 1.2% for the area of study.
A specific point in the study is the power limitation of 60MW in Goéland (S5). It is a contractual limitation between RTE and the distributor for this specific substation. Consequently, the total load in Goéland should not exceed 60MW (sum of the power flow in this node).

Generally, RTE takes in charge the different investments to develop the network. However, this is not the case when the contractual power is exceeded.

In this context, we will study two scenarios (chapter 5) regarding the hypothesis of consumption.

In the scenario 1, the load in Goéland (S5) does not exceed the contractual limiting value of 60MW. A part of the load is transferred to Hirondelle (S6) that is the closest and the easiest substation to transfer the load (5.5).

In the scenario 2, the load in Goéland (S5) exceeds the contractual limiting value of 60MW. None of the load is transferred to Hirondelle (S6). In that case the customer (distributor) has to pay for the violations of the constraints that is to say the additional investments realized for this scenario (5.6).

Consequently, the load in Goéland (S5) is higher in the scenario 2 than in the scenario 1 and the load in Hirondelle (S6) is higher in scenario 1 than in scenario 2.

After the consumption forecasts the production forecasts will be studied.

### 3.3 Production forecasts

In a power system, there are two kinds of production.

First, HTA (medium voltage) generation corresponds to decentralized production often operated by independent producers like wind power, thermal power, cogeneration or small hydro power… In this study, the main HTA production is situated in Goéland (S5).

Then, HTB (high voltage) generation corresponds to centralized production, mainly hydraulic power plants.

In this study, there are two hydraulic power plants run-of-the-river. The maximal power in Caille (S9) is 66MW and in Serin (S13) is 44MW. A run-of-the-river power plant has no reservoir, so the available generation capacity is determined by the water flow at the site of the plant. The generation depends on the water flow. The generation is nearly constant within the day but fluctuates within the year. Both plants are situated on the same river. Consequently, they have synchronous behaviour. Average values of generation are calculated for each season and used for the network simulations. Besides, for a specific season, the value taken for year N+1 will be the same as the value taken for year N.
4 TECHNICAL ISSUES AND GENERAL TOOLS OF THE STUDY

From the consumptions and generations forecasts, the software PLATINE will detect the different constraints on the network. These constraints can be of several kinds: thermal constraints, short-circuit constraints, voltage drop constraints, mechanical constraints and environmental constraints.

4.1 Simulation tool

PLATINE is a software used by engineers to study the power transmission network. It simulates the network at different time frame in the future [10].

The data base in PLATINE comes from the official Data Base on a national level. These data takes into account not only the existing equipments but also the future equipments already decided.

A complete description of the lines is given with the maximal current level, the length, the resistance, the reactance and the tension level. A description of the electrical characteristics of the generation and production units is memorized. Besides, this software takes into accounts all the consumption and production forecasts at every nodes of the network from 2008 to 2030.

For each specific study, a special file is created with the consumption and production forecasts calculated for each substation in the area of study.

From this file, the electrical transmission network is simulated with PLATINE. This simulation gives the direction and the value of the power flow on each line, the short-circuit current level of each node, the quantity of losses on each line, the percentage of overloading on each line… It is possible to modify some hypotheses of the network and to compare several simulations.
4.2 Technical issues: five constraints

4.2.1 Thermal constraints

At all times, RTE must ensure that the flow current in the transmission facilities (overhead lines, underground cables and transformers) stay within a set threshold for thermal reason (Joule effect). Overloading leads to degradations of the thermal insulation or creates safety problems [2].

Firstly, for overhead lines, the conductors should not exceed a limiting temperature. The distance between the cable and the ground decreases \( H_2 \leq H_1 \) when the temperature in the line increases \( T_2 \geq T_1 \) (Figure 4.1). For the sake of security, the cable should not be under a certain height [3].

When the temperature of the conductors in the line increases, the size of the conductor increases and the line is closer to the ground. A certain distance between the ground and the cable must be maintained, this leads to a temperature limitation and consequently to a transmission capacity limitation.

\[ T_1(\degree C) \]
\[ T_2(\degree C) \]
\[ H_2 \]
\[ H_1 \]

\textit{Figure 4.1: Thermal constraints on overhead lines}

The temperature in the conductors depends not only on the current in the line (Joule effect) but also on the outdoor conditions (temperature, wind, season…). The determination of the maximal temperature of a line, gives the IMAP (Maximal Current in Steady State). This value is specific to each component and season (winter, interseason and summer). The IMAP is higher in winter (low temperature) than in summer (high temperature). For 90kV lines, temporary overloads are not tolerated.

Then for underground cables, the maximal current flow in the cable is limited to avoid degradation of the conductor. There are three kinds of current limitations. The IMAP\(_c\) is the maximal intensity in steady state, the IMAP\(_m\) is the maximal intensity for long overloading (less than three weeks), this value is taken for reference during maintenance and reparations and the IMAX\(_sh\) is the maximal current for short overloading (less than one hour).
Finally, for transformers, it is necessary to prevent temperature rise in the transformers caused by physical effects like Joule losses, magnetic losses or eddy current losses. Consequently, a maximal current level is allowed in the transformers. There are three kinds of current limitations.

IS is the maximal current in steady state. In is the nominal current in steady state in the secondary part of the transformer.

\[
\text{In winter, } IS = 1.25 \times In \\
\text{In summer, } IS = 1.15 \times In
\]

\[IS_{20}\] is the maximal current for short overloading (less than 20 minutes).

\[IS_{20} = 1.5 \times In\]

If the current is between \(In\) and \(IS_{20}\), then a temporary overloading is possible for 20 minutes. However, if the current crossing the transformer exceeds \(IS_{20}\), then a final tripping is observed.

From the calculation of the transmission capacities for the different lines and transformers in the network, the thermal constraints can be detected. The detection of the thermal constraints is realized both in normal condition N (all the lines and the transformers are working) and in N-1 condition (one outage: one line or one transformer is out of work).

The following rules are used in power system planning to detect the thermal constraints.

In normal condition N, a tripping (loss of the component) is observed if the current exceeds the IMAP for a line, the IMAPc for an underground cable or In for a transformer.

In N-1 condition (when one line or one transformer is out of work), a tripping (loss of the component) is observed if the current exceeds the IMAP for a line, the IMAPd or IMAXlh for an underground cable and IS or \(IS_{20}\) for a transformer.

The detection of the different constraints (N and N-1) is given by the simulating tool PLATINE.
Table 4.1: Maximal current level allowed

The maximal power flow capacity is often given in MW (P_{MAP}).

\[
P_{MAP} = \sqrt{3} * U * \text{IMAP} * \cos \phi
\]

(4.4)

With \( U = 63kV \) and \( \cos \phi = 0.95 \).

4.2.2 Short-circuit constraints

In power system planning, not only the short-circuit current should be limited in order to avoid equipment deterioration, but also the short-circuit current should be high enough to guarantee a good quality of power towards perturbation [4].

The software COURCIRC of Platine calculates the short-circuit current at every substation.

This parameter played an important role in this study. First, Sittelle (S14) and Alouette (S8) should be operated with two nodes in order to reduce the short-circuit current at each node. Then, the short-circuit current limit for the materials and structure of the substation Faisan (S2) should not be exceeded, consequently several ring openings are made to respect this limitation.
4.2.3 Voltage drop constraints

The voltage drop between a voltage source and a substation must be under 16% (in N or N-1 conditions). The voltage source gives Un+8%. Consequently, for a 63kV network, the voltage should be over 63 * 1.08 * (1 − 0.16) = 57kV. With the impedance values (R and X), a special software is able to calculate the voltage drop.

In this study, there was no voltage drop constraint.

4.2.4 Mechanical safety and constraints regarding the state of the current network

Several rehabilitations are necessary considering the characteristics of the grid that is to say the age of the components, the material used and the temperature of operation. For safety reasons, the materials of the grid should respect some norms.

4.2.5 Environmental constraints

The study considers the environmental constraints of the study place: location of rivers, lakes or mountains, location of cities, roads or railways, city development plans and location of environmental reserves.

For instance, when a new line is built, the environmental reserves should be avoided and underground cables are preferable close to cities.

Five kinds of constraints can be detected on a transmission grid. In this study, the major constraints regard the short-circuit current and the thermal constraints but not the voltage levels. Moreover, some old lines should satisfy the mechanical constraints. Finally, the environmental constraints should be considered during the choice of solutions.
In a power transmission network development, the current network is optimized in order to minimize the different constraints. A network diagram of reference is obtained. From this optimised network, constraints will be detected, a cost will be associated to each of them and technical and economical solutions will be chosen to satisfy the constraints. In this study, the constraints only regard power consumption and short-circuit intensity and not voltage level.

5.1 Step 1: Determination of the network diagram of reference

From consumption and production forecasts and also technical characteristics of the grid, a network diagram of reference is chosen. It corresponds to the best operating plan of the grid which minimizes the number of constraints. This diagram is chosen by analysing the different network simulations with PLATINE. This diagram should respect operating constraints (short-circuit current and voltage drop) and should provide a good quality of power for the customer. In addition, the N constraints are minimized. Then, the N-1 constraints are minimized in a second level of priority.

In order to minimize the number of constraints, ring openings were realized. They are several possibilities for that [5].

The choice of the optimised network diagram is made in several steps. First, from the meshed network, ring openings are operated to respect the short-circuit constraints. Then, N thermal constraints were minimized. The final step is the minimization of N-1 thermal constraints. The constraints are detected with the software PLATINE.

This work resulted into two network diagrams of reference, one for study period between 2007 and 2020 (Figure 5.4) and a second one for the study period between 2020 and 2030 (Figure 5.5). Indeed, in 2020 a second transformer will be added in Mésange, this project has a high influence in the study and modifies the network diagram of reference.
These diagrams represent the “frozen” strategies, it corresponds to the optimization of the current network (when no improvement is realized on the network) for the periods 2007-2020 and 2020-2030.

**Figure 5.4: Optimized network diagram between 2007 and 2020**

The lines Tourterelle (S15) - Moineau (S11), Hirondelle (S6) - junction point, Faisan (S2) - Verdier and Goéland (S5) - Roitelet (S7) are open to minimize the number of constraints.
The lines Tourterelle (S15) - Moineau (S11), Hirondelle (S6) - junction point, Mésange - Chouette (S1) and Goéland (S5) - Roitelet (S7) are open to minimize the number of constraints.

### 5.2 Step 2: Detection of the constraints

The level of constraints will be calculated from these network diagrams of reference. It only corresponds to thermal constraints as the diagrams of reference were chosen to respect short-circuit current limitations.

Both scenario 1 \( P_{\text{max Goéland}}^* = 60\,\text{MW} \) and scenario 2 \( P_{\text{max Goéland}}^* > 60\,\text{MW} \) will be studied.

The thermal constraints are described by overloading coefficients of a line. This is the ratio between the current flow and the IMAP (maximal current allowed in the line). A constraint is detected when this coefficient is above 0.98. The value 0.98 (and not 1) is taken to include the losses in the line.

Two kinds of thermal constraints are detected: N constraints (calculated with the complete network without outage) and N-1 constraints (calculated with the network with one outage when one transformer or one line is out of work).
N constraints are detected on the line Chouette (S1) - Tourterelle (S15) and on one transformer in Alouette (S8) (in red on Figure 5.6).

Serious N-1 constraints are detected on the line Chouette (S1) - Tourterelle (S15), Chouette (S1) - Faisan (S2), Verdier (S4) - Goéland (S5) and Roitelet (S7) - junction point (in yellow on Figure 5.6).
5.3 Step 3: Seriousness of the thermal constraints

After the detection of different constraints, the seriousness of each of them is calculated with the probability of constraint, the unserved power $P_c$ that is the power cut due to a fault and the unserved energy $END$ that is the energy that could not be delivered due to the capacity limitation in the power system [11]. Then, a cost is associated to these values.

This probability $p_{N-1}$ is defined in N-1 conditions and corresponds to the probability of unavailability of a component (line or transformer).

$$p_{N-1} = \frac{n \times h}{8760}$$  \hspace{1cm} (5.1)

Where 8760 is the number of hours during one year, $n$ is the average annual frequency of fault (how many times a year a fault is expected for a specific material) and $h$ is the average duration of the fault. For a line, the parameters $n$ and $h$ depend on the age, the technology, the level of tension, the kind (underground cable or overhead lines), the length and number of cells of a line.

The probability $p_N$ corresponds to the probability to be in N conditions when all the lines and transformers are available. This probability is approximate to 1 because $p_{N-1} \ll 1$.

$$p_N = 1$$  \hspace{1cm} (5.2)

Each constraint is linked with a place of breakdown, that is to say the place where the load may be cut due to the constraint. For that, the network is simulated with PLATINE after the fault (without the broken component) and the most overloading line or transformer is open and so on (opening the component with the higher overloading coefficient) until a certain amount of substations is no longer fed. These substations represent the place of breakdown (Figure 5.7).

Figure 5.7: Determination of the place of breakdown
Pg is Available Transfer Capacity (ATC) that is to say the guaranteed power of a place of breakdown. This is the maximal power (in the place concerned by the fault = place of breakdown) the network is able to transmit without violating any constraints.

When a constraint occurs, load recovery is done by the Service of Operation.

In N conditions, when all the electrical equipments are available, the constraint can be anticipated and the clearance of the fault is done with load shedding in the place of the breakdown until the transmission in the line is under the maximal transmission capacity (IMAP).

In N-1 conditions, the breakdown of one component can not be anticipated and the load recovery is done in several steps. After the breakdown, all the power of the place of breakdown is cut, this is the unserved power (Pc). Then, just after the fault, a certain quantity of power P0 is restored with automatisms in the place of the breakdown. Finally, after the operations (opening lines, closing lines and disconnecting load) during h0 hours, the power P is available while the fault is being fixed (during h hours).

In N-1 conditions, it is possible to define the unserved power Pc, the power that is cut after the breakdown in the place of the failure and the unserved energy (END).

\[ END_{beforeoperation} = (P_c - P_0) \times h_0 \]  
\[ END_{afteroperation} = (P_c - P) \times (h - h_0) = (P_c - P) \times h \]  

Where h0 corresponds to the duration of operations for load recovery and h corresponds to the duration of reparation of the broken component.

Figure 5.8: Load recovery in N-1 conditions
The load duration curve is obtained from the real load curve and states how often a given load level will be exceeded during a given time period [12].

Figure 5.9: Determination of the load duration curve from the real load curve.

The load duration curve gives the number of hours \( H_1 \) during one year when the power is above a certain power \( P_g \).

In this study, the unavailability probability was calculated for the different components. Moreover, for each constraint, the place of breakdown, the solutions for load recovery and the residual constraints were determined. Some examples will be given (Table 5.1 and 5.2).

<table>
<thead>
<tr>
<th>Line</th>
<th>n (average annual frequency of fault)</th>
<th>h (average duration of fault)</th>
<th>p (probability of unavailability) (5.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chouette (S1) - Hirondelle (S6)</td>
<td>0.23</td>
<td>16</td>
<td>4.2\text{*e-4}</td>
</tr>
<tr>
<td>Chouette (S1) - Goéland (S5)</td>
<td>0.56</td>
<td>86</td>
<td>5.5\text{*e-3}</td>
</tr>
<tr>
<td>Chouette (S1) – Faisan2 (S2)</td>
<td>0.19</td>
<td>23</td>
<td>5.0\text{*e-4}</td>
</tr>
<tr>
<td>Chouette (S1) - Verdier (S4)</td>
<td>0.19</td>
<td>16</td>
<td>3.5\text{*e-4}</td>
</tr>
<tr>
<td>Alouette (S8) - Roitelet (S7)</td>
<td>0.29</td>
<td>20</td>
<td>6.6\text{*e-4}</td>
</tr>
<tr>
<td>Sittelle (S14) - Tourterelle (S15)</td>
<td>0.25</td>
<td>19</td>
<td>5.4\text{*e-4}</td>
</tr>
<tr>
<td>Chouette (S1) - Tourterelle (S15)</td>
<td>0.28</td>
<td>20</td>
<td>6.4\text{*e-4}</td>
</tr>
</tbody>
</table>

Table 5.1: Level of unavailability of the lines in the study
The annual average frequency of fault increases with the length of line. Moreover, the average duration of fault increases in case of underground cable (for example the line Chouette (S1) – Goéland (S5)).

The probability of unavailability ($p$) is used to calculate the seriousness of each constraint. This value is higher in N conditions ($p_N = 1$) than in N-1 conditions ($p_{N-1}$ is around e-3 and e-4).

<table>
<thead>
<tr>
<th>Failure</th>
<th>Constraint in 2030</th>
<th>Place of breakdown</th>
<th>Solution for load recovery</th>
<th>Residual constraint after operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alouette (S8) – Roitelet (S7)</td>
<td>Roitelet (S7) – junction point (1.44)</td>
<td>Roitelet (S7)</td>
<td>Close line Goéland (S5) – Roitelet (S7)</td>
<td>No (P=Pc)</td>
</tr>
<tr>
<td>Sittelle (S14) – Tourterelle (S15)</td>
<td>Chouette (S1) – Tourterelle (S15) (1.14)</td>
<td>Tourterelle (S15) + Chardonneret (S16)</td>
<td>Load shedding</td>
<td>Yes</td>
</tr>
<tr>
<td>Loss of one transformer of 70 MVA in Sittelle (S14)</td>
<td>Chouette (S1) – Tourterelle (S15) (1.16)</td>
<td>Tourterelle (S15) + Chardonneret (S16) + Buse (S12) + Martinet (S10) + Moineau (S11)</td>
<td>1 node in Sittelle (S14) and 2 nodes in Tourterelle (S15)</td>
<td>No (P=Pc)</td>
</tr>
<tr>
<td>Chouette (S1) – Faisan2 (S2)</td>
<td>Chouette (S1) – Faisan1 (S2) (1.33)</td>
<td>Faisan (S2) + Aigrette (S3) + Verdier (S4) + Goéland (S5)</td>
<td>Open a switch in Faisan (S2) (sharing of the load)</td>
<td>No (P=Pc)</td>
</tr>
<tr>
<td>Chouette (S1) – Goéland (S5)</td>
<td>Goéland (S5) - Verdier (S4) (1.02)</td>
<td>Goéland (S5)</td>
<td>Open disconnector in Goéland (S5) (sharing of the load)</td>
<td>Yes</td>
</tr>
<tr>
<td>Chouette (S1) – Verdier (S4)</td>
<td>Chouette (S1) – Faisan (S2) (1.07)</td>
<td>Goéland (S5) + Verdier (S4) + Aigrette (S3) + Faisan (S2)</td>
<td>Open line Goéland (S5) – Verdier (S4)</td>
<td>No (P=Pc)</td>
</tr>
<tr>
<td>Chouette (S1) – Hirondelle (S6)</td>
<td>Short power cut in Hirondelle (S6)</td>
<td>Hirondelle (S6)</td>
<td>close Hirondelle (S6) – junction point + open junction point - Roitelet (S7)</td>
<td>No (P=Pc)</td>
</tr>
</tbody>
</table>

*Table 5.2: N-1 constraints in winter 2030 (scenario 1)*

The seriousness of the constraint depends on the probability of unavailability, the size of the place of breakdown and the residual constraint after the solutions. Then, the cost of each constraint can be calculated.
5.4 Step 4: Cost of the constraints

The cost of the constraints will be written \( \Gamma \). It corresponds to the sum (7.4) of unserved power cost \( (\Gamma_c) \) and unserved energy cost \( (\Gamma_{\text{END}}) \) \[12\].

\[
\Gamma = \Gamma_c + \Gamma_{\text{END}} \tag{5.5}
\]

5.4.1 Normal conditions (N)

In N conditions, load shedding is planned in order to satisfy the constraints. This constraint is foreseen in advance and there is no power cut, so \( \Gamma_c = 0 \). The cost only corresponds to the unserved energy cost \( (\Gamma_{\text{END}}) \) after load shedding.

\[
\Gamma = \Gamma_{\text{END}} = V_i \times W \tag{5.6}
\]

Where \( V_i = 9 \, \text{€/kWh} \) and \( W = \text{END} \) during one year

\[
W = p_i \times S_g = S_g \tag{5.7}
\]

\( P_g \) is the ATC, the maximal power that the network is able to feed in normal condition without having constraint.

![Figure 5.10: Load duration curve in N conditions](image)

5.4.2 Incident conditions (N-1)

First, the cost of unserved power cost \( (\Gamma_c) \) is calculated.

\[
\Gamma_c = V_B \times P_c \tag{5.8}
\]

where \( V_B = 1 \, \text{€/kW} \)

\[
P_c = n \times \frac{\int_{t=0}^{8760} P(t)dt}{\int_{year}^{8760} dt} = \frac{n}{8760} \int_{t=0}^{8760} P(t)dt \tag{5.9}
\]
Then the cost of unserved energy due to the breakdown ($\Gamma_{END}$) is calculated.

$$\Gamma_{END} = VL(Em) \times W$$  \hspace{2cm} (5.11)

The cost VL is between 9 and 20€/kWh depending on the seriousness of the incident (Em) that is the average END of an incident.

During operation of load recovery (during $h_0$ hours), the power $P_0$ is available in the place of breakdown (Figure 5.8).

$$W_{before\_operation} = n \times \frac{h_0}{8760} \times S_0 = p_0 \times S_0$$  \hspace{2cm} (5.12)
After operation of load recovery until the clearance of the fault (during $h_r$ hours) the power $P_r$ is available in the place of breakdown.

$$W_{after\_operation} = n \frac{h_r}{8760} \cdot S_r = p_r \cdot S_r$$

From (5.1), $p_0 + p_r = p_{N-1}$  \hspace{1cm} (5.13)

We can conclude from (5.5):

$$\Gamma_N = \Gamma_{END}$$

$$\Gamma_{N-1} = \Gamma_c + \Gamma_{END\_before\_operation} + \Gamma_{END\_after\_operation}$$

The calculation is made with the software VALORIS [13].
5.4.3 Study results for the scenario 1: calculation of the cost of constraints

The N constraint in the area of Tourterelle (S15) appears in 2020 and increases much more rapidly than the N-1 constraints (Figure 5.15). N-1 constraints have a linear growth compared to the exponential growth of N constraints (Figure 5.16).
The failure is more important in scenario 2 than in scenario 1 (Figure 5.17).
5.5 Step 5: Strategy of reinforcement for the scenario 1

At this step, the different constraints and their costs are determined. Then, these constraints will be satisfied with economical strategy of reinforcements. The search for the best strategy is made in several steps [6]. First, for each constraint, a brainstorming of strategies is made in cooperation with the project team. Then, the best strategy considering technical and economical points of view is chosen. The economical profitability is calculated with comparison of the investment cost towards the profit on the diminution of the constraints.

In power system planning, two indicators are used to evaluate the performance of an investment.

The first indicator is the RBC (Profit Divided by Cost).

\[
RBC = \frac{\Gamma_{\text{after investment}} - \Gamma_{\text{before investment}}}{C_{\text{investment}}}
\]  

(5.15)

Where \( C_{\text{investment}} \) is the investment cost.

RBC is the ratio of the benefice provide by an investment over the cost of this investment. An investment is profitable if RBC>8% (rate of actualisation). This indicator gives the optimal year of investment.

The second indicator is the BEI (Profit for one Euro Invested).

The BEI is another indicator to evaluate the profitability of an investment in the future within the next 10 years. A BEI is positive if the investment is paid back within the next ten years.

To invest in the year \( n \), in the year \( n+1 \) the requirements are RBC>8% and BEI>0.

Then, in power system planning, the comparison of strategy is made with present value cost. The year of reference is 2007. The rate of actualisation is 8% a year. That is to say, 1 euro now has the same worth of 1.08 euro next year. If an investment of I euros is made in 2007+n years. Then, the present value cost (in 2007) is

\[
I \left( \frac{1}{1+8\%} \right)^n
\]
5.5.1 Strategy in the area of Tourterelle (S15): two nodes substation

The substation in Tourterelle (S15) will be renovated in 2010 (Figure 5.18). It is interesting to take this opportunity to satisfy the constraints on the line Chouette (S1) – Tourterelle (S15). The idea is to control the power flow between Chouette (S1) and Sittelle (S14) in an optimised way. The solution is to operate Tourterelle (S15) with two nodes with one part of the load of Tourterelle (S15) fed by Chouette (S1) and another part by Sittelle (S14) (Figure 5.20). In that way, it is easier to control the power flow.

The solution is to add a circuit breaker at one extremity (red square in the Figure 5.19) and a bus bar to join the two extremities of the substation Tourterelle (S15). The circuit breaker is closed in normal conditions. Then, it is possible to open one of the switches to operate Tourterelle (S15) with two nodes. In order to optimise the power flow on the line, 2/3 of the load in Tourterelle (S15) should be fed by Chouette (S1) and 1/3 of the load by Sittelle (S14).

This solution is quite cheap and the thermal constraints (N and N-1) are satisfied. The only remaining constraint is the short break-time in case of failure on the line Chouette (S1) – Tourterelle (S15).

Moreover, there is flexibility with different load sharing (one node or two nodes with 2/3 of the load fed by Chouette (S1) and 1/3 of the load by Sittelle (S14) or two nodes with 1/3 of the load fed by Chouette (S1) and 2/3 of the load by Sittelle (S14)).

Besides, this solution decreases the short-circuit current and enables to close the line between Faisan (S2) and Verdier (S4) (which was open to respect the limitation in short-circuit current).

The economic indicators (RBC>8% and BEI>0 in 2011) give the year of investment in 2010.

![Figure 5.18: Substation of Tourterelle (S15) before 2010](image)
Another strategy is to build a new overhead line. This solution satisfies all the thermal constraints. However, this solution is very expensive and the profitability is not shown before 2020 (RBC>8% and BEI>0 in 2021).
5.5.2 Strategy in the area of Faisan (S2): ACSS cable

The strategy chosen is to change the conductors of the line Chouette (S1) – Faisan (S2). The ACSS cable (Aluminium Conductor Steel Supported) is a low dilation cable with a higher maximal current level than for classical cable. This cable has the capacity to increase the power flow of more than 30%. This solution will be adapted to our case. The estimation of the cost is 50% of the cost for a new line. Moreover, the electrical impedance is similar to classical cable. Thus, the losses for the same current will not change and the short-circuit current in Faisan (S2) will not increase.

<table>
<thead>
<tr>
<th>Année</th>
<th>RBC</th>
<th>BEI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>3,9%</td>
<td>-25,6%</td>
</tr>
<tr>
<td>2010</td>
<td>5,7%</td>
<td>-14,1%</td>
</tr>
<tr>
<td>2011</td>
<td>7,8%</td>
<td>5,7%</td>
</tr>
<tr>
<td><strong>2012</strong></td>
<td><strong>10,4%</strong></td>
<td><strong>25,8%</strong></td>
</tr>
<tr>
<td>2013</td>
<td>12,3%</td>
<td>45,9%</td>
</tr>
</tbody>
</table>

*Table 5.3: Economic indicators for the Strategy in Faisan (S2) (RBC and BEI)*

Economic indicators (RBC>8% and BEI>0 in 2012) give the date of investment in 2011 (Table 5.3).

Another strategy is to build a new underground cable (in red in Figure 5.21). This solution satisfies the thermal constraint. However, this solution is very expensive and the profitability is not shown before 2030 (RBC>8% in 2030).

*Figure 5.21: Underground cable between Chouette (S1) and Faisan (S2)
Another solution is to add an inductance in series in the line Chouette (S1) – Faisan (S2) that leads to an increase of the line impedance. This solution is interesting not only because the sharing of power flow between parallel lines is improved (indeed the limiting line has a low power flow capacity with a low impedance so the sharing of power flow was not optimised) but also because the short-circuit current in Faisan (S2) is reduced due to the higher impedance of the line. However, this solution was not chosen because the cost is higher and the profitability is shown in 2015 (RBC>8% and BEI>0 in 2016). Moreover, this solution demands place on the substation and produces noise.

The best solution in the area is the ACSS cable.

5.5.3 Strategy in the area of Hirondelle (S6): second line Chouette (S1) - Hirondelle (S6)

In the first scenario, there is a transfer of load from Goëland (S5) to Hirondelle (S6). Consequently, it is necessary to reinforce the substation of Hirondelle (S6). Besides, Hirondelle (S6) is only fed by one substation Chouette (S1).

Currently, a second line from Chouette (S1) exists but is not used. Two more cells and terminations in Chouette (S1) and in Hirondelle (S6) should be added to create a second Chouette (S1) – Hirondelle (S6) (in red in Figure 5.22).

This low cost solution will lead to a reduction in losses and in short and medium power cuts. The profitability is shown in 2013 (RBC>8% and BEI>0 in 2014).
5.5.4 Strategy in the area of Roitelet (S7)

The strategy will be done in two steps in Roitelet (S7) (in 2012 and in 2020).

**Figure 5.23: Step one of the strategy in Roitelet (S7)**

The first step is to replace 3km of the old line (Roitelet - junction point) with a thin section of $147\text{mm}^2$ by a shorter line (1.3km) with a bigger section of $228\text{mm}^2$ (in red in Figure 5.23) for an estimated cost of 850k€. Economic profitability is not shown but this renovation is due to mechanical constraints (6.2.4).

**Figure 5.24: Step 2 of the strategy in Roitelet (S7)**

The second step is the rehabilitation of the line between Hirondelle (S6) and Alouette (S8) from 1924. The estimated renovation cost is higher than the cost of removal. Moreover, the network does not need the line between Hirondelle (S6) and the junction point (dotted line in Figure 5.24) to provide a secure system. Consequently, the removal of the line between Hirondelle (S6) and the junction point is an economical solution. For this area, it is important to have an assessment of the accurate cost of renovation and removal before taking a decision for the line between Hirondelle (S6) and the junction point. Besides, the other part of the line between Alouette (S8) and the junction point is necessary to have a secure network and should be renovated.
5.5.5 **Strategy for the transformers in Alouette (S8) and in Sittelle (S14)**

N constraints appear at the end of the period of study on the transformers in Alouette (S8). The solution is to replace the two 100MVA transformers by two 170MVA transformers. The estimated cost of this solution is $1900 \times 2 = 3800\,\text{€}$. This solution will be profitable in 2025.

N constraint appears at the end of the period of study on one transformer in Sittelle. The solution is to replace one 70MVA transformer by one 170MVA transformer. The estimated cost of this solution is $1900\,\text{€}$. However, the constraint is larger than the area of study. So, the exact date of profitability will be studied in another study.

5.5.6 **Residual constraints in 2030**

After all these strategies, most of the constraints have been satisfied. Very low residual constraints are remaining (Figure 5.25). The remaining constraints are not serious enough to be valued.

![Winter 2030 Scenario 1 Constraints N-1](image)

Figure 5.25: Residual constraints in winter 2030 for the scenario 1
5.6 Step 6: Strategy of reinforcement for the scenario 2

5.6.1 Residual constraints in 2030

In scenario 2, all the same strategies as in scenario 1 will be applied, except the one in the area of Hirondelle (S6). Indeed, in this scenario 2, the limiting power in Goéland (S5) is exceeded and there is no load transfer from Goéland (S5) to Hirondelle (S6). The load in Hirondelle (S6) is less important as in the scenario 1. The constraints are not important enough to justify the second line Chouette (S1) – Hirondelle (S6).

A major constraint on the line Verdier (S4) - Goéland (S5) is remaining due to the high load in Goéland (S5) (Figure 5.26). The load in Goéland (S5) is higher for the scenario 2 than for the scenario 1.

Figure 5.26: Residual constraints in winter 2030 for the scenario 2

5.6.2 Strategy in the area of Goéland (S5)

The solution to satisfy thermal constraints on the line Verdier (S4) - Goéland (S5) is to build a new line between Chouette (S1) and Goéland (S5). For that, the existing and not used line between Chouette (S1) and Hirondelle (S6) will be used and extended by an underground cable to Goéland (S5) (Figure 5.27).
The total cost of investment for the scenario 2 is higher than for the scenario 1. Consequently, the scenario 1 has higher probability to be chosen. But the final decision will be taken by the customer (the distributor).
CONCLUSION

This study shows the complexity of a non linear electricity transmission network. As the electricity cannot be stored and the equilibrium between production and consumption must be ensured in real time, it is necessary to understand this meshed network with its main characteristics and the influence of different parameters. A constraint which is not anticipated can lead to a blackout and causes major damages. The easiest solution is to use load shedding but this causes power cut and not distributed energy. In this context, the work of RTE is to anticipate the future constraints and to find economical solutions to avoid or minimize them in order to maintain a safe power system.

The goal of the project was to study a specific 63kV transmission grid by 2030 and to find the best strategy to satisfy the constraints. A long-term investment plan was determined with the best technical and economical solutions. The variety of the solutions with a two node substation, new conductors in a line, new lines, line removal, new transformers and the sharing of the solutions within the overall timescale, made this study very complete and interesting. This thesis work was achieved in time and the long-term investment plan was presented and approved by the regional managers of RTE the 12th of December. On a next step, the different investments of the study will be divided into different projects. For each project, a project leader and a project team will be chosen to realize it.

Long-term studies must take account of many uncertainties. Some assumptions are made to simplify the study and to make it solvable in a certain period of time. First, the production forecasts are made on average values. However, for run-of-the-river power plants, generation fluctuates directly with water flow and low generation level can appear. Moreover, the consumption forecasts are realized by a complex analysis. However, the behaviour of the consumer cannot be predicted accurately and can change with a variation of the electricity price or government policies all the more so, as new concerns about the development of renewable energy, CO2 emission permit and energy conservation are emerging. Moreover, the disturbances in the surrounding network have not been considered very deeply. However, in this meshed network, a disturbance may spread to the whole system. To conclude, this study focuses on a long-term investment plan for the system and some investments can be anticipated or delayed depending on the changes in the assumptions.
## ANNEX: POWER IN THE DIFFERENT SUBSTATIONS

Annex: Consumption forecasts in winter, interseason and summer

<table>
<thead>
<tr>
<th>SCENARIO 1</th>
<th>2007</th>
<th></th>
<th></th>
<th>2020</th>
<th></th>
<th></th>
<th>2030</th>
<th></th>
<th></th>
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<tr>
<td></td>
<td>WINTER</td>
<td>INTERSEASON</td>
<td>SUMMER</td>
<td>WINTER</td>
<td>INTERSEASON</td>
<td>SUMMER</td>
<td>WINTER</td>
<td>INTERSEASON</td>
<td>SUMMER</td>
</tr>
<tr>
<td></td>
<td>$P_{max}$ (MW)</td>
<td>$P_{imb}$ (MW)</td>
<td>$P_{max}$ (MW)</td>
<td>$P_{max}$ (MW)</td>
<td>$P_{imb}$ (MW)</td>
<td>$P_{max}$ (MW)</td>
<td>$P_{max}$ (MW)</td>
<td>$P_{imb}$ (MW)</td>
<td>$P_{max}$ (MW)</td>
</tr>
<tr>
<td>VERDIER</td>
<td>26.2</td>
<td>33</td>
<td>18</td>
<td>16</td>
<td>34.1</td>
<td>43</td>
<td>24.4</td>
<td>21.9</td>
<td>38.5</td>
</tr>
<tr>
<td>FAISAN</td>
<td>60.1</td>
<td>63.2</td>
<td>38.8</td>
<td>36.1</td>
<td>64.3</td>
<td>81</td>
<td>60.5</td>
<td>46.2</td>
<td>72.4</td>
</tr>
<tr>
<td>HIRONDELLE</td>
<td>10.9</td>
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<td>12.1</td>
<td>10.0</td>
<td>23.2</td>
<td>29.2</td>
<td>14.9</td>
<td>13.3</td>
<td>26.1</td>
</tr>
<tr>
<td>GOELAND</td>
<td>69.9</td>
<td>75.3</td>
<td>47</td>
<td>43.2</td>
<td>76.5</td>
<td>96.4</td>
<td>61.1</td>
<td>56.3</td>
<td>87.6</td>
</tr>
<tr>
<td>ROITELET</td>
<td>37.2</td>
<td>46.2</td>
<td>30.5</td>
<td>26.5</td>
<td>44.8</td>
<td>66.5</td>
<td>37.2</td>
<td>32.3</td>
<td>50.4</td>
</tr>
<tr>
<td>ALOUETTE</td>
<td>60.8</td>
<td>76.7</td>
<td>48</td>
<td>46.2</td>
<td>75.4</td>
<td>95</td>
<td>60.5</td>
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<td>85.2</td>
</tr>
<tr>
<td>MARTINET</td>
<td>30.7</td>
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<td>20.9</td>
<td>10.9</td>
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<td>36.3</td>
<td>19.7</td>
<td>10.0</td>
<td>32.4</td>
</tr>
<tr>
<td>MUINEAU</td>
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<td>10.6</td>
<td>11</td>
<td>19.7</td>
<td>24.8</td>
<td>12.2</td>
<td>13.1</td>
<td>22.2</td>
</tr>
<tr>
<td>TOUTERELLE</td>
<td>48.5</td>
<td>61.6</td>
<td>33.4</td>
<td>31.5</td>
<td>60.1</td>
<td>75.7</td>
<td>41.3</td>
<td>39.1</td>
<td>67.9</td>
</tr>
</tbody>
</table>

| SCENARIO 2 |           |           |           |          |           |           |          |           |           |
|            | WINTER   | INTERSEASON | SUMMER    |          | WINTER   | INTERSEASON | SUMMER    |          | WINTER   | INTERSEASON | SUMMER    |
|            |          |           |           |          |          |           |           |          |          |           |           |
|            | $P_{max}$ (MW) | $P_{imb}$ (MW) | $P_{max}$ (MW) |          | $P_{max}$ (MW) | $P_{imb}$ (MW) | $P_{max}$ (MW) |          | $P_{max}$ (MW) | $P_{imb}$ (MW) | $P_{max}$ (MW) |
| HIRONDELLE | 18.8     | 23.8      | 12.1      | 10.8     | 39.7      | 50.1      | 28.2     | 26.5       | 53.9      | 67.9      | 40.2      | 37        |
| GOELAND    | 69.8     | 75.3      | 47        | 43.2     | 60.0      | 75.6      | 47       | 43.0       | 60.0      | 75.6      | 47        | 43        |

Annex: Consumption forecasts in winter, interseason and summer.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Signification</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACSS</td>
<td>Aluminium Conductor Steel Supported</td>
</tr>
<tr>
<td>ATC</td>
<td>Available Transfer Capacity</td>
</tr>
<tr>
<td>BEI</td>
<td>Profit for Euro Invested</td>
</tr>
<tr>
<td>CRDM</td>
<td>Regional Committee of Direction</td>
</tr>
<tr>
<td>CRE</td>
<td>French Energy Regulatory Commission</td>
</tr>
<tr>
<td>EDF</td>
<td>“Electricité de France”: major company of electricity production and distribution in France</td>
</tr>
<tr>
<td>END</td>
<td>Energy Not Distributed = Unserved Energy</td>
</tr>
<tr>
<td>GIMR</td>
<td>Group of Engineering and Maintenance of the Network</td>
</tr>
<tr>
<td>HTA</td>
<td>Medium Voltage</td>
</tr>
<tr>
<td>HTB</td>
<td>High Voltage</td>
</tr>
<tr>
<td>IMAP</td>
<td>Maximal Current in Steady State</td>
</tr>
<tr>
<td>RAA</td>
<td>Rhône-Alpes Auvergne</td>
</tr>
<tr>
<td>RBC</td>
<td>Ratio Benefice over Cost</td>
</tr>
<tr>
<td>RTE</td>
<td>“Réseau de Transport d’Electricité”: French TSO and owner of the public power transmission network</td>
</tr>
<tr>
<td>SDOP</td>
<td>Network Optimization and Development Department</td>
</tr>
<tr>
<td>SE</td>
<td>Power System unit</td>
</tr>
<tr>
<td>SERAA</td>
<td>Rhône-Alpes Auvergne Power System unit</td>
</tr>
<tr>
<td>TCMA</td>
<td>Medium Annual Growth Level</td>
</tr>
<tr>
<td>TE</td>
<td>Electricity Transmission unit</td>
</tr>
<tr>
<td>TERAA</td>
<td>Rhône-Alpes Auvergne Electricity Transmission unit</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
</tbody>
</table>
REFERENCES

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  [1] RTE, "M000- Methodology for a network study" ("M000- Conduite d’une étude décisionnelle : Cas général"), 2003