ANALYSIS OF ALTERNATIVES FOR THE INTEGRATED GENERATION AND TRANSMISSION EXPANSION PLANNING WITH SECURITY CONSTRAINTS

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Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Engenharia Elétrica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia Elétrica.

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ANÁLISE DE ALTERNATIVAS PARA O PLANEJAMENTO INTEGRADO DA EXPANSÃO DE GERAÇÃO E TRANSMISSÃO COM CRITÉRIOS DE SEGURANÇA

Lucas Yukio Okamura Ribeiro

Fevereiro/2023

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Programa: Engenharia Elétrica

O planejamento da expansão de sistemas de potência consiste em selecionar o conjunto de geradores e linhas de transmissão a ingressarem ao sistema que garanta o atendimento pleno à demanda futura a mínimo custo. Além disso, o sistema expandido deve respeitar critérios de segurança operativa preestabelecidos para não comprometer o atendimento a carga na ocorrência de falhas na geração e/ou transmissão que o sistema está sujeito.

Usualmente, devido à alta complexidade do problema, as expansões de geração e transmissão são realizadas de forma separada, em que primeiro se calcula o plano de expansão de geração e depois o plano de expansão de transmissão, considerando fixa as decisões de geração previamente definidas. Devido a esta abordagem hierárquica, a solução final apresenta custos mais elevados quando comparado a uma solução totalmente integrada, onde as expansões são calculadas simultaneamente e o trade-off entre investir em geradores que requerem um alto grau de investimento em transmissão e geradores mais próximos dos centros de carga pode ser representado.

Esta dissertação propõe alternativas para o planejamento integrado da expansão de geração e transmissão com o critério de segurança N-1 na transmissão, buscando uma solução equilibrada em termos de qualidade e tempo computacional requerido. Todas as alternativas propostas são aplicadas e avaliadas em dois estudos de casos, um com dimensões reduzidas em termos de rede e outro representando o sistema elétrico Chileno.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

ANALYSIS OF ALTERNATIVES FOR THE INTEGRATED GENERATION AND TRANSMISSION EXPANSION PLANNING WITH SECURITY CONSTRAINTS

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Fevereiro/2023

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The expansion planning of power systems consists of selecting the set of generators and transmission lines to enter the system that meets the future demand at minimum cost. In addition, the expanded system must comply with pre-established operational security criteria, so it does not compromise the fulfillment of the load in the occurrence of failures in the generation and transmission that the system is subject to.

Usually, due to the high complexity of the problem, the generation and transmission expansion planning are carried out separately, in which the generation expansion plan is first calculated and then the transmission expansion plan, considering fixed the previously defined generation decisions. Due to this hierarchical approach, the final solution reaches higher costs when compared to a fully integrated solution, where the expansions are calculated simultaneously, and the trade-off between investing in generators that require a high degree of investment in transmission and generators closer to load centers can be represented.

This dissertation proposes alternatives for the integrated generation and transmission expansion planning with the N-1 security criterion in the transmission, seeking a balanced solution in terms of quality and computational time required. All proposed alternatives are applied and evaluated in two case studies, one with reduced dimensions in terms of network and the other representing the Chilean electrical system.

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1 Introduction

1.1 Objectives and relevance of this work

1.1.1 Expansion planning problem

The expansion planning problem arises from the necessary changes in power systems due to the demand growth, requiring the addition of new generators and transmission circuits to meet it [1]. The decisions during the planning process consist of selecting the best generators and transmission routes that ensure the demand fulfillment in the future with minimum cost for the society. Usually, this decision-making process is represented by a large optimization problem that aims to minimize the total costs produced by investing and operating the expanded system, subjected to economic, operating, environmental, security, and energy policy constraints.

In several countries, the methodology applied to the generation and transmission (G&T) expansion planning is generally based on a hierarchical procedure with two steps. First, the generation expansion planning is performed without assessing the necessary network reinforcements. Next, fixing the generation expansion plan obtained in the first step, the transmission expansion planning is calculated to obtain the necessary investments in the grid to meet the demand under the operating limits.

By dividing the optimization problem into two smaller problems, this approach contributes to reducing the complexity of the optimization process. Also, most power sectors have an unbundled generation market, where private players decide on the expansion, but transmission expansion planning is still a centralized decision process. So, as the G&T expansion decisions are taken separately, the hierarchical approach seems more adequate for the planning.

However, planning the generation and transmission expansion separately leads to suboptimal solutions in terms of costs to society. Adding generators far from the load centers, which at first glance may seem a cheaper decision, leads to further reinforcements in the transmission system to connect them to the demand, which can culminate in a total cost higher than investing in closer generators.

This trade-off, which cannot be assessed when the expansion planning is performed disjointly, has become more relevant in recent years. The leading generation expansion sources, in power systems worldwide, are the variable renewable energy

(VRE) plants, such as utility-scale solar PV and wind, typically located far from the load centers.

The figure below shows a forecast of the world's total installed capacity per technology until 2027:

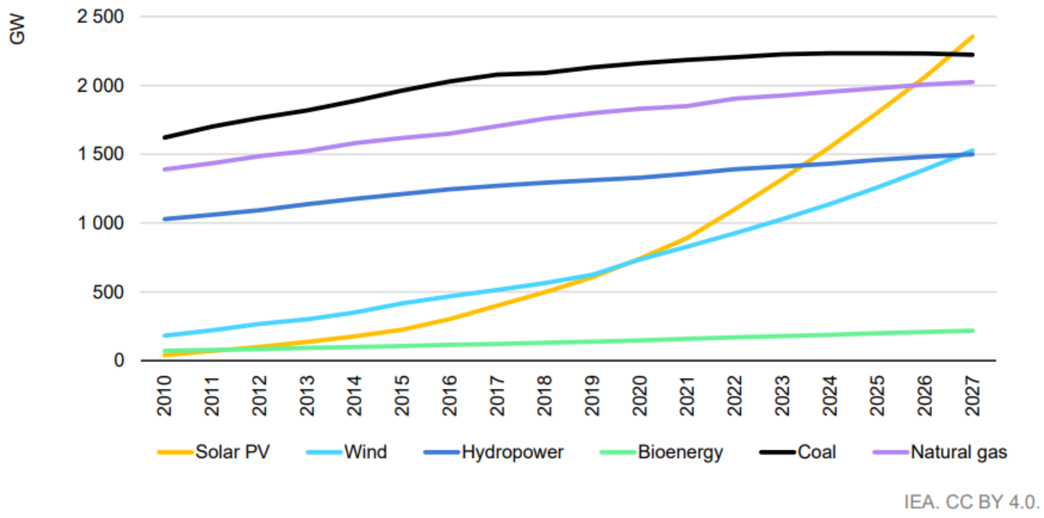

Figure 1 - Cumulative installed capacity per technology worldwide [2]

Solar PV is expected to have the largest global installed capacity among other sources in 2027. Moreover, the wind power installed capacity will almost triplicate in 10 years (from 2018 to 2027) [2].

This expectation is boosted by the rapid increase of net zero greenhouse gas (GHG) emissions pledges, established by many governments worldwide. In 2021, the European Union, together with 44 countries, established to meet a net zero emission target [3]. Consequently, the expansion of renewable power plants is foreseen to increase even more in the future years, reaching more than 60% of the global generation matrix, as presented in the figure below:

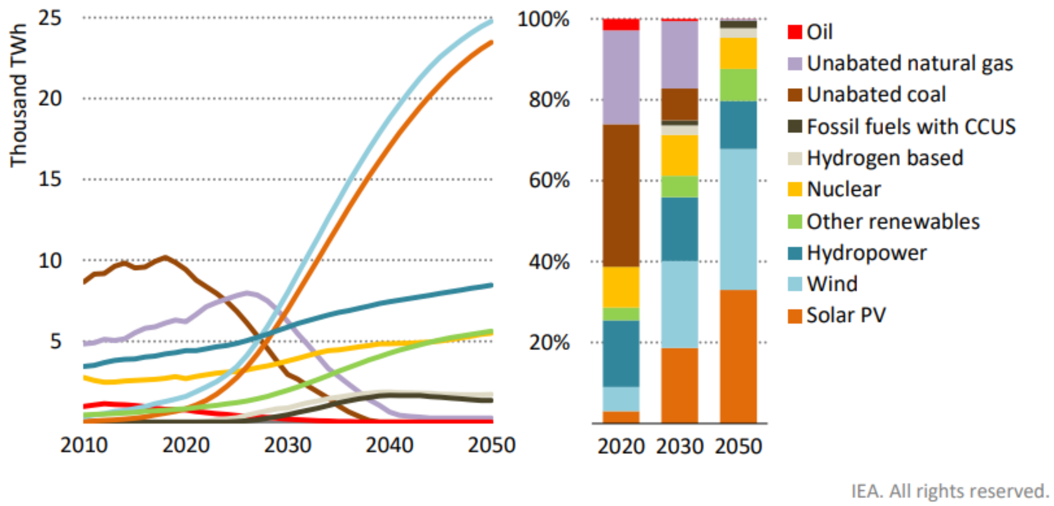

Figure 2 - Global electricity generation by source with net-zero emissions [3]

In addition, the different construction times between the VRE plants (usually three years) and the transmission lines (usually five years) [4] harm the coordination of the expansions when treating them separately. Depending on the length of the transmission line, the construction time is even higher than five years, which challenges even more this coordination.

Thus, this trend increases the importance of the transmission reinforcements in expansion planning. An alternative is to consider expanding the generation system and transmission network in the same optimization problem. In this way, the trade-off between investing in more competitive generators, such as VRE plants, and plants more likely of installing near load centers, such as thermal plants, can be evaluated accordingly.

Such an approach can be directly applied in a vertical environment, as the generation and transmission investment decisions are taken centrally. Furthermore, transmission planners may use this concept of integrated planning in an unbundled electric system for “anticipative planning,” in which they could project how grid reinforcements change the incentives for private generating companies to invest [5],[6]. An example of the application of this anticipative strategy is the “Estudos Proativos de Transmissão" made by the Brazilian expansion planning company (EPE) [4], which intends to anticipate the transmission planning to accommodate the generation prospects.

Nevertheless, the optimization problem considering an integrated approach becomes more extensive as the number of constraints and variables of the problem increases significantly, which can cause an exponential growth in the computational time to solve the problem [6]. Also, some network constraints may enhance the complexity of the problem and disturb the solution process.

This dissertation's main objective is to propose alternatives for integrated generation and transmission expansion planning, taking into account the trade-off between the quality of the solution and the computational effort needed in the optimization process. Those alternatives use two distinct planning methodologies, which, combined sequentially, produce final G&T expansion plans. The first calculates the optimal expansion planning contemplating simultaneously generation and transmission investment variables, with the possibility to make simplifications in some operating constraints. The second, in turn, consists of an optimization model for exclusively transmission expansion planning, that complements the transmission investment decisions taken in the first approach if any simplification was applied.

Afterwards, the expansion plans resulted by the proposed alternatives can be compared against each other in terms of solution quality and CPU performance.

1.1.2 Security constraints

Power systems are subject to failures in their components (generating units, transmission lines, transformers, etc.) that can disrupt their operation and even compromise the complete demand fulfillment. In the operation planning, measures to ensure the proper functioning of the system, increasing its reliability and robustness to failures, are common. Also, the system's expansion planning must include further investments to maintain adequate levels of reliability in future operations.

The reliability criteria used in the expansion and operating planning can be classified as deterministic, probabilistic, or economic. The economic criteria represent the insufficiency in meeting the demand with economic terms, such as deficit costs. The probabilistic, in turn, considers the probability of occurring failures to quantify reliability indexes (targets) through stochastic simulations [7].

The deterministic criteria do not consider the outage uncertainties and are typically represented by the N-1, N-2, or N-k criteria. In the N-1, the planned system must support any single contingency in the network without any load shedding or violation of operating constraints. Although this criterion is considered conservative, as do not take into account the probabilities of occurring the contingencies, it is simple to implement and vastly used in many countries, such as Brazil [7].

However, combining the integrated G&T expansion planning approach and security constraints in the same optimization problem is challenging, as the complexity of the problem rises considerably.

Another objective of this dissertation is to propose a method to include security constraints that represent the N-1 criterion for the transmission network during the integrated expansion planning process. The method is incorporated into the proposed alternatives for the G&T expansion planning, ensuring that the final plans meet the N-1 security constraint.

1.2 Organization of the dissertation

This document is organized as shown in Table 1. Chapter 2 reviews the literature for integrated G&T expansion planning. The methodology is divided into three Chapters. Chapter 3 presents the integrated expansion planning methodology, while Chapter 4 shows another methodology exclusively for the transmission expansion planning. Finally, Chapter 5 proposes alternatives for integrated planning using the methods presented in the two previous Chapters. Chapter 6 explores the proposed alternatives in two study cases with different dimensions, and Chapter 7 concludes the dissertation.

Table 1: Chapter organization

Chapter	Description
2	Literature Review
3	Integrated Generation and Transmission Expansion Planning Problem
4	Transmission Expansion Planning Problem
5	Generation and Transmission Expansion Planning Alternatives
6	Case Studies
7	Conclusions
8	References

2 Literature Review

In the literature, most of the proposed methodologies treat Generation Expansion Planning (GEP) and Transmission Expansion Planning (TEP) separately due to the high computational complexity of solving both jointly [8]. Historically, the first models that co-optimized generation and transmission expansion were developed in the 1960s. However, these early approaches have a very simplified representation of constraints, such as considering the network without the effects of the second Kirchhoff law [5].

Many complex methodologies that coordinate the GEP and TEP were developed recently, motivated by the points raised in the last section. Those are described in more detail below.

2.1 Representing market aspects

Many electrical systems worldwide have a deregulated generation market. It means that the generation planning decision, once made centrally in the past, is now taken by private companies. So, it is interesting to consider some aspects of the market in the expansion planning models, and coordination with the TEP becomes essential as it must anticipate these generation decisions.

The main objective of expansion planning in a deregulated system is to maximize the total revenue of the companies or the social welfare. Unlike a regulated market, where the primary purpose is to minimize the total costs, as the decisions are centrally taken. In both approaches, the constraints imposed by the independent system operators (ISO), such as reliability criteria and reserve margin, must also be considered [9].

To accommodate all those aspects, it is common to formulate the co-optimization of GEP and TEP with a multi-level optimization problem, in which coordination is established by iterative methods [5]. Some examples are described below.

ROH *et al.* [10] propose a market-based coordination for expanding the generation and transmission systems that consists of an iterative process between the generation, transmission companies, and the ISO. The companies decide their capacity investments by solving a mixed integer linear programming problem aiming to maximize their profit based on marginal prices and capacity payments calculated by the ISO. The method then enters a first loop, in which the ISO solves an optimal linear flow to calculate security violations and feedback on the investment problems with capacity signals. After ending the first loop, the second starts: the ISO solves a dispatch problem considering the actual investments and bid generation prices submitted by the generation companies, calculating new values of marginal costs for the first step.

In a later work [11], the same authors enhance the methodology by representing uncertainty in the load growth and availability of generation and transmission equipment. Here the scenarios are generated by a Monte Carlo method, where the generation unit outages, transmission line outages, and load growth are sampled considering a normal distribution. After that, a scenario reduction technique is applied, and the ISO's optimization problems are solved deterministically for each scenario (Benders cuts are formulated based on expected values of the marginal costs).

JENABI *et al*. [12] present a bi-level model. The first level represents a centralized transmission operator that can calculate the optimal transmission expansion, aiming for maximum social welfare or profit. On the other hand, the second level represents a generation market and calculates the optimal generation expansion, maximizing the total social welfare. The two-level problem is rewritten into a single problem with equilibrium constraints, linearizing the KKT conditions of the second problem and adding to the first as constraints.

The methodology proposed in [13] models a mixed-integer bi-level problem. The objective of the upper-level problem is to calculate the optimal capacity expansion of generators, transmission, and fuel transportation assets, maximizing the total welfare. At the lower level, the individual interests of each agent (generator companies, fuel suppliers, and the ISO) are modeled by unique optimization problems. The generator companies aim to maximize their profits, the ISO wants to maximize social welfare, and fuel suppliers seek to minimize transportation costs. In the end, the whole optimization is formulated into a single mathematical program with equilibrium constraints (MPEC), where the lower-level optimization represents the complementary constraints by applying KKT conditions. Also, some reformulation techniques are presented to solve the problem in a reasonable computational time.

HESAMZADEH *et al.* [14],[15] built a mathematical structure consisting of a multi-level optimization problem, where the generator's operation and expansion decisions are represented through a Nash equilibrium problem in the first levels. The Nash equilibrium with the highest social cost is selected for the TEP problem (lower level), which aims to minimize the social costs. This multi-level problem is solved using a hybrid bi-level genetic algorithm strategy.

BARINGO and CONEJO [16] present a bi-level model focused on wind generation and transmission expansion planning. The model has an upper-level problem, representing the planner, which aims to minimize total costs subject to investment constraints, and a set of lower-level problems that illustrate the market's clearing, seeking to maximize social welfare under operational conditions. This bi-level model is converted to a single-level MPEC problem using a primal-dual formulation, and non-linear constraints are linearized, finally turning it into a mixed integer linear programming (MILP) problem.

BARINGO [17] presents a set of optimization models to calculate optimal wind power expansion plans in another work. One of them addresses the importance of considering jointly the transmission expansion planning needed to accommodate wind power generation. In this model, the problem is formulated in two levels, where the first seeks to minimize the investment in wind power and transmission and operating costs subjected to investment constraints. The second represents the day ahead market clearing under different demand and renewable production conditions, aiming to maximize the total social welfare. This bi-level problem is converted to an MPEC, replacing the lower-level problem with its primal, dual constraints and strong duality equality. Ultimately, all non-linearities are treated by adding integer variables, converting the problem into a MILP.

MOTAMEDI *et al*. [18] propose a methodology to calculate a "robust" transmission expansion plan based on different generation expansion plan scenarios. The method is divided into two steps. The first consists of solving the expansion of the generation market using a bi-level problem, where the generation companies aim to maximize their profits, and the ISO intends to maximize the social welfare subjected to operating constraints. This bi-level problem is solved using agent-based and search-based algorithms, producing a set of generation expansion scenarios. In the second step, a predefined set of transmission expansion plans is considered. For each generation expansion scenario and transmission expansion plan pair, market clearing quantities are determined after solving a similar problem to the one formulated in the first step. Finally, the robust transmission plan is selected using a criterion of minimizing the maximum regret.

In [19],[20], JIN *et al.* developed a three-level model, where the first calculates the optimal TEP (centralized decision), and the second represents the individual expansion planning of the generation companies, which seek to maximize their profits. Finally, the third formulates the problem of market operation where the generation companies bid their quantities and prices, and the ISO operates the system. The last two problems are rewritten into a single for each generation company using optimal conditions. A hybrid method is proposed to solve the whole problem. The methods of Diagonalization (solving each problem iteratively to find the Nash Equilibrium) and Complementary Problem formulation (formulating the tri-level problem in a single equilibrium problem with equilibrium constraints) are used iteratively.

Following the three-level proposal, [21] presents a very similar formulation. This work reduces all levels into a single problem, and non-linearities are linearized using the Fornuby-Amat formulation. So, in the end, it turns into a MILP problem. On the other hand, [22] has a similar approach but does not mention the linearization of non-linear constraints. In addition, it compares a model with a 100% G and T centralized decision and another with a T expansion decision without the feedback of the expansion and operation of the generation system, showing that the proposed model obtains a result between these other two.

2.2 Centralized decision models

In other research, the authors propose centrally co-optimizing the GEP and TEP. So, the primary purpose of these optimization problems is to minimize the system's total costs, subject to investment, operating, and security constraints.

GU et al. [23] present a model in which generation and transmission expansion problems are solved separately. Benders decomposition is applied to each problem, dividing them into a master (investment) subproblem and two slave subproblems, one to decide the unit commitment of the plants and another to determine the dispatch. The coordination between them is done iteratively, and the optimal solution is reached if the difference between subsequent iterations is less than a defined tolerance. In their case study, using a modified IEEE 24-bus system, they show that this coordination between the generation and transmission problems caused a 4.3% reduction in the total expansion cost concerning the case without coordination.

PEREIRA *et al*. [24] decompose the G&T expansion problem into two optimization subproblems: investment and operation. These subproblems are solved iteratively, where the investment subproblem decides which/when plants and transmission lines must enter into operation. The operation subproblem receives those decisions, calculates the optimal operation of the entire system, and feeds back the investment problem with Benders cuts. This process is repeated until a convergence criterion is met. The authors demonstrate that the network can be represented by a transportation model or a complete DC power flow model in this algorithm and apply these two representations in a simplified Brazilian southern system.

GRAEBER *et al*. [25] analyze the benefits of a regional integrated expansion planning of the southern African countries instead of the traditional national planning. To do so, the authors present an optimization model, which calculates the minimum cost G&T expansion plan formulating a MILP that considers investments, operating, and emissions costs. Also, demand-side management projects are modeled.

Different from other approaches, KÜÇÜKYAZICI *et al.* [26] suggest a heuristic method is used to solve the problem, requiring human interaction in decision-making. At each iteration, critical paths are evaluated, and new transmission candidates are defined.

Some authors address the fuel infrastructure inside the expansion problems. In [27],[28], multiobjective optimization problems are presented to calculate the generation and transmission expansion planning, aiming to minimize the total investment and operating costs, CO2 emissions, fuel importation, and exposure to fuel price volatility. Many algorithm techniques generate non-dominant solutions, clustered using K-means and ranked afterward using the AHP method.

UNSIHUAY-VILA *et al*. [29],[30] consider expanding natural gas infrastructure into the integrated G&T problem. The proposed model seeks to minimize the total annualized investment and operation costs subject to constraints related to the natural gas and electric system, all represented in a single problem. Relevant cost reduction is demonstrated when solving the problem with an integrated approach.

SHARAN and BALASUBRAMANIAN [31] also include fuel transportation in the expansion planning. In this research, exciting comparisons are made by applying the method in some study cases. It shows the importance of considering Kirchhoff's second law constraints on the network as the power flows change significantly. Also, it highlights the benefit of the integrated generation and transmission solution instead of the hierarchical solution (indicating a 21% reduction in total costs).

Other aspects are also considered together with the expansion of G&T. In [32], the problem is formulated into a single MILP with CO2 emissions constraints and demand-side management projects. Storage devices can also be represented, as in [33].

2.2.1 Uncertainty treatment

GEP and TEP are naturally affected by uncertainties. Some of them have more impact in the long-term, such as economic growth, which directly influences demand growth, investment costs, and governmental policies. Others are more relevant in the short-term, such as hydro inflows, renewable energy production, and equipment outages [5]. In addition to [11], the methodologies described below incorporate some of those uncertainties in the expansion planning task to find expansion plans that are robust and adaptable to possible future scenarios.

LOPEZ *et al*. [34] propose a method to calculate the optimal generation and transmission expansion plan considering uncertainties in the demand forecast and the risk aversion of the planner. The method solves a non-linear stochastic optimization problem, where the objective function minimizes the sum of investment in new equipment (generation plants and transmission lines) and the expected value operation cost of new and existing plants. The operating constraints, in turn, contemplate different demand forecast scenarios. Furthermore, they formulate probabilistic constraints to express equipment availability. The mean-variance Markovitz theory is applied to include a risk aversion factor.

LIU *et al*. [35] present an integrated GEP and TEP model representing uncertainty through a scenario tree. The investment decision is calculated in a higher time resolution (tree nodes) than the operating decisions (tree branches), which are optimized in an hourly or sub-hourly resolution, allowing the representation of renewable production variability, ramp constraints, and short-term storage devices. Due to the complexity of the problem, an algorithm based on Progressive Hedging is used to solve it.

MUNOZ *et al*. [36] propose a model for a stochastic GEP and TEP, considering uncertainties in the demand forecast, water inflows, and renewable production. To cut down the size of the problem, the number of scenarios is reduced using the k-means clustering technique. The MILP formulated is solved using progressive hedging, decomposing the problem by scenario. Also, Jensen inequality is used to compute lower bounds. In another work, MUNOZ *et al.* [37] develop a method for solving GEP and

TEP together in two steps. The first uses clustering and stratified sampling techniques to compute upper and lower bounds, and the second uses an "enhanced" Benders decomposition to reduce even more the gap between the lower and upper bounds found in the first step.

In [38], uncertainties in the load forecast and costs (emissions, fuel, and transmission) are incorporated into the planning. The MILP problem is formulated into two steps. The first calculates the generation and transmission capacity additions without accounting for uncertainties, and the second operates the system to minimize total costs considering the uncertainties. Affine adjustable decision rules are used to make the problem computationally tractable, and affine uncertainties models are used to capture data correlation.

CAMPODÓNICO *et al.* [39] propose a methodology considering uncertainty in hydro inflows. The method consists of a Benders decomposition scheme, where the master problem calculates the optimal investments in generation and interconnections. The slave problem operates the plan using an SDDP algorithm and sends feedback to the investment problem at each iteration.

FERREIRA *et al.* [40] incorporate the uncertainty in the implementation times of transmission lines into the TEP, aiming a better coordination with the GEP. A MILP problem is formulated where scenarios of implementation times are contemplated, considering that their probability distributions are known, in addition to other operating scenarios.

CARVALHO et al. [41] present minimax-cost and minimax-regret approaches to solve the TEP problem considering uncertainty in the market-based generation expansion. Macro-scenarios, represented by different generation expansion plans, are considered in those approaches, and the transmission investment decisions are determined by MILP problems considering those scenarios. Also, the transmission decisions are divided into immediate and future decisions. The former is applied to all macro-scenarios, as must begin immediately, and the latter can vary according to the macro-scenarios.

2.3 Reliability criteria

Some researchers incorporate reliability criteria in decision-making to ensure that the future supply system can always meet the demand. The most common strategies are to include the reliability target as a constraint or represent it directly on the objective function, using some reliability indexes, such as the Loss of Load Probability (LOLP) and expected energy not supplied (EENS) [9]. Another approach, explored in a few works, is to include security constraints in the G&T optimization, such as the N-1 criterion.

2.3.1 Reliability indexes

PANTOŠ [42] presents a method for integrated generation, transmission, and natural gas infrastructure expansion planning considering multiple load growth scenarios and equipment outages. The quasi-Monte Carlo technique generates those scenarios, and a scenario reduction is applied afterward. After that, the method formulates the problem decomposing it into a master problem, a MILP, and decides the investment in equipment and a subproblem for a reliability check. This subproblem, in turn, is also decomposed into a master problem, which performs a reliability check only in the power system considering a LOLP target and a lower subproblem that checks the feasibility of the natural gas system. These inner and outer loops are solved by Benders decomposition.

AGHAEI *et al.* [43] propose a MILP formulation of the GEP and TEP problem considering reliability criteria. The EENS considering simple contingencies in generation and transmission is represented by an operating constraint. The model seeks to minimize it together with investment and the expected value of operating costs, which have probabilities due to forced outage of the components. Non-linear constraints are linearized.

KHOADEI and SHAHIDEHPOUR [44] present a model that considers microgrids as candidates, modeled as controllable loads. The method is decomposed into two problems: the first represents the planning and the operating problem, solved by Benders decomposition, and the second is a reliability subproblem, which performs a Monte-Carlo simulation (scenario reduction is applied to avoid excessive computational burden) and checks if the EENS is below a defined target. If not, feasibility cuts are generated for the planning problem. In [45], the EENS index is represented by a target as well, but the problem is solved using a non-dominant sorting genetic algorithm and Fuzzy Satisfying techniques.

ROUHANI *et al.* [46] present a heuristic approach to calculate the GEP and TEP, considering distributed generation as candidates and reliability criteria. The GEP and TEP problems are formulated separately but are solved iteratively until the generation and transmission expansion plan stay the same between consecutive iterations. WASP, MATBAL, and LINGO software are used.

KHOADEI *et al.* [47], in another work, formulate a MILP that represents extra operation constraints such as unit commitment, emission budgets, and hydro storage. This module iterates with a reliability module, which checks for each year of the study horizon the LOLE (loss of load expectation). If the value is below the predefined target, the module feedbacks the planning model with Benders cuts.

In similar works, ALIZADEH and JADID [48],[49] also apply Benders decomposition to solve the integrated G&T expansion planning problem. Furthermore, a reliability check involving the K-means clustering technique is used at the end of the process, feedbacking the expansion planning problem with any reliability criteria that are violated.

2.3.2 N-1 representation

TOR *et al.* [50] propose a formulation that decomposes the problem into one master problem and two subproblems. The master problem calculates the investment plan minimizing the total investment cost of new generation and transmission assets, subject to investment constraints. The first subproblem performs a security check, applying the N-1 criteria. If the criterion is violated, Benders cut are generated to the master problem, and the process is repeated until the criterion is met. After that, the second subproblem is solved, calculating the optimal dispatch, and feeding back the first problem with Benders cuts.

SEPASIAN *et al.* [51] formulate a problem considering fuel availability restrictions and N-1 criteria in the transmission. To solve it, a heuristic process is used in which all transmission candidates are first considered built, and the generation expansion is calculated, solving a linear optimization problem. Then, the candidate circuits are removed one by one, and another generation expansion planning is performed for each removal. Performance indexes are calculated based on the total costs and constraint violations, and the expansion with the best performance is chosen. If the configuration selected is not the base case (with all circuits built), the entire process is repeated, starting with the selected configuration. This process stops when the starting configuration provides the best performance compared with the removal ones.

BARATI *et al*. [52] incorporate the expansion of the exploration/transportation of natural gas into the problem. Firstly, the generation expansion plan is optimized through a minimum cost criterion. Then, the development of infrastructure related to natural gas and transmission is optimized, considering the generation expansion plan calculated in the previous step. In the transmission expansion planning, the N-1 criterion is represented. This final plan (transmission + natural gas infrastructure) feeds back to the generation expansion planning problem. The process is solved using a Genetic Algorithm and repeated until the algorithm reaches convergence.

RODRIGUEZ *et al.* [53] propose a methodology for the TEP, including capacitor expansion, AC power flow equations and N-1 criterion. The problem is divided into an investment and operating sub-problems, which are solved in an iterative way by a combination of Genetic Algorithm and Random Mutation Hill-Climbing techniques.

2.4 Network formulation

In the methodologies presented in this section, there are different ways to represent the network constraints inside the optimization problem. Some utilize the transportation model [23],[24][25],[26],[28],[29],[30],[35],[38],[39],[46] which consists in a simplified DC power flow representation that disregards the Kirchhoff voltage law (KVL) among the network constraints. Others [18],[45] decide to represent the KVL only for existing transmission lines (not for the candidates).

The most common representation [54] used is the complete DC power flow model, but in the case of expansion planning problems, the disjunctive model is applied to preserve the linearity of the optimization problem [10],[11],[12],[13],[17],[19],[20],[24],[31],[32],[33],[36],[40],[42],[43],[44],[47],[50]. Both Kirchhoff laws (current and voltage) are represented in this formulation, but for the candidates, a disjunctive formulation is used to linearize the KVL constraint.

Finally, some works represent the AC power flow formulation [14],[15],[16],[27],[34],[48],[49],[51],[52],[53], which implies non-linear constraints and requires non-linear optimization techniques to solve the problem.

Those different linear formulations will be explored in more detail in the following sections.

3 Integrated Generation and Transmission Expansion Planning Problem

3.1 Introduction

The main objective of expansion planning is to decide on a set of generators and transmission circuits to be commissioned that minimizes the total cost of the power system in the long term. The total cost can be split into two components: (i) investment and (ii) operating cost. The first component represents the sum of the annualized investment cost in generation and transmission. The second, in turn, depends on the dispatch decision, representing the sum of costs related to fuel consumption of thermal plans and penalizations for not meeting the foreseen demand.

Thus, the dispatch decision significantly affects the expansion decision and must be well represented in the expansion planning problem. Before moving to the formulation of the expansion problem, the next section will cover some aspects related to the operating problem.

3.2 Operating Problem

3.2.1 Hydrothermal dispatch

Most power systems are mainly composed of hydro and thermal power plants. In recent years, non-conventional renewable power plants, such as wind and solar, are also participating in the generation mix.

The dispatch problem consists of determining each plant's generation in all stages that minimize total operating cost. Supposing that the non-conventional renewable plants already have a predefined generation setpoint based on a forecast, and the thermal plants have direct operating costs related to their fuel consumption. In that case, the problem seems straightforward to solve by ranking the thermal plants from the cheapest to the most expensive and dispatching them until reaching the system net demand (demand minus the total renewable generation).

However, the presence of hydro plants with storage makes the dispatch problem more complex. Since hydro plants can transfer water from one period to the next, it is unclear whether the plant should store water in the reservoir for future use or use it promptly. Immediate dispatch of hydro plants means lower immediate operating costs. Still, it could cause high future costs with the generation of expensive thermal plants that could be avoided if water were stored, as the future hydrology is uncertain. On the other hand, not dispatching hydro plants can save unnecessary water if the following period is very humid, leading to water spillage in the future. The figure below illustrates this dilemma.

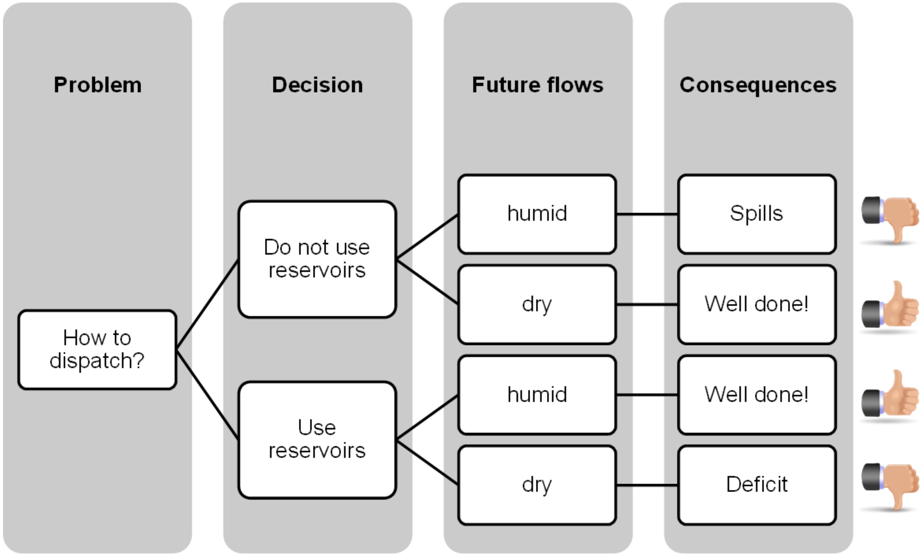

Figure 3 - Hydrothermal dispatch dilemma

The problem becomes even more complex when considering the uncertainty related to VRE production in the future.

Disregarding the uncertainties and the transmission network (single-node representation) by now, the hydrothermal dispatch problem can be formulated as follows:

$$Min \sum_{t=1}^{T}\left(\sum_{j\in J_T} c_{j,t}g_{j,t} + \delta r_t\right) \tag{3.1}$$

s.t.

$$\sum_{j\in J_T,J_R} g_{j,t} + \sum_{i\in J_H} \rho_j u_{j,t} + r_t = d_t \qquad \forall t = 1, \dots T \tag{3.2}$$

$$v_{j,t+1} = v_{j,t} + a_{j,t} - u_{j,t} - s_{p_{j,t}} + \sum_{m\in \Pi_j} (u_{m,t} + s_{p_{m,t}}) \qquad \forall j \in J_H, \forall t = 1, \dots T \tag{3.3}$$

$$v_{j,t+1} \le \overline{v_j} \qquad \forall j \in J_H, \forall t = 1, \dots T \tag{3.4}$$

$$u_{j,t} \le \overline{u_j} \qquad \forall j \in J_H, \forall t = 1, \dots T \tag{3.5}$$

$$g_{j,t} \le \overline{g_j} \qquad \forall j \in J_T, \forall t = 1, \dots T \tag{3.6}$$

Where:

$c_{j,t}$	Operating cost of thermal plan j in stage t
$g_{j,t}$	Generation of plant j in stage t
ρ_j	Production coefficient of hydro plant j
$u_{j,t}$	Turbined outflow of hydro plant j in stage t
$a_{j,t}$	Water inflow of hydro plant j in stage t
δ	Deficit cost
r_t	Deficit in stage t
d_t	Demand in stage t
$v_{j,t+1}$	Final storage of hydro plant j in stage t
$v_{j,t}$	Initial storage of hydro plant j in stage t
$s_{p\,j,t}$	Spilled outflow of hydro plant j in stage t
Π_j	Set of hydro plants immediately upstream of hydro plant j
$\overline{v_j}$	Maximum storage of hydro plant j
$\overline{u_j}$	Maximum turbined outflow of hydro plant j
$\overline{g_j}$	Maximum generation of thermal plant j
J_H	Set of hydro plants
J_T	Set of thermal plants
J_R	Set of renewable plants
T	Number of stages

The objective function (3.1) aims to minimize the sum of the operating cost of the thermal plants, subject to a set of constraints: load balance of the system (3.2), water balance of each hydro plant (3.3), storage (3.4) and turbined outflow (3.5) limits of the hydro plants, and generation limit for the thermal plants (3.6). In this problem, the renewable generation is predetermined.

Depending on the dimensions of the system and the number of stages, the size of the problem makes it computationally intractable. So, decomposing the large problem into several smaller one-stage subproblems is a fair approach to solve the problem. However, to keep the coherence in the time-coupled decisions between the stages, it is necessary to approximate a function that represents the future costs related to the dispatch decision in each stage. This function is called the Future Cost Function (FCF) and is illustrated in the figure below.

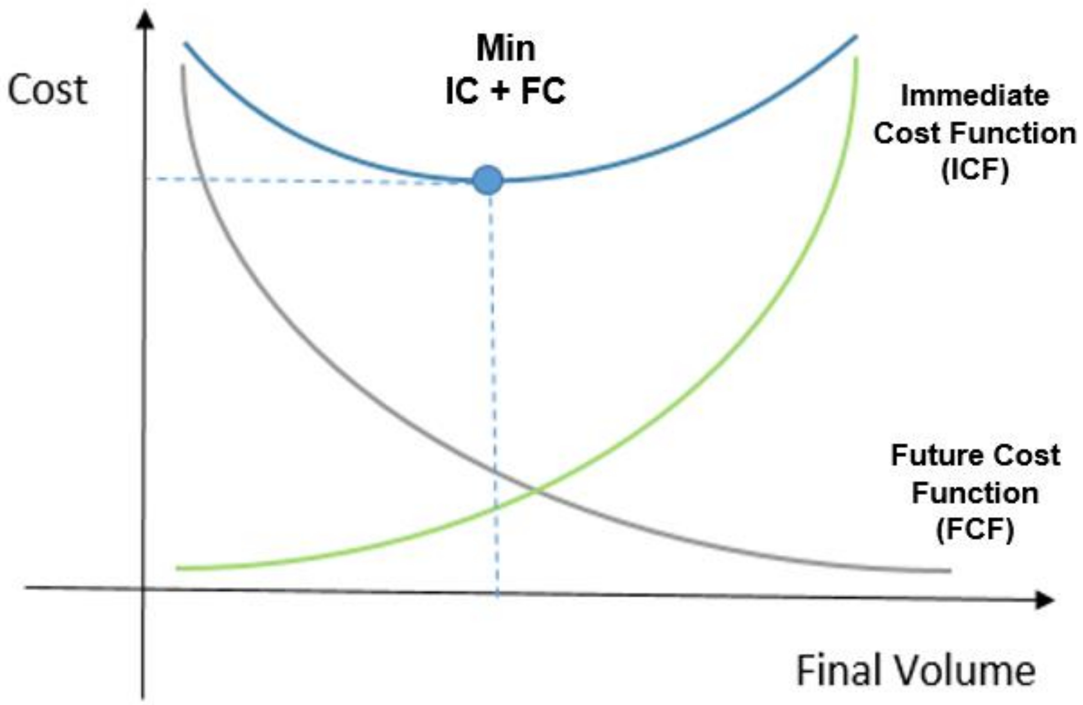

Figure 4- Immediate and future cost functions

After approximating the FCFs, it is possible to evaluate the trade-off between using the water in the current stage or in the future stages. So, the one-stage subproblems can be solved forward in time, minimizing the sum of the immediate cost function (ICF), that represents the operating cost of the current stage, and the FCF. The following formulation illustrates the one-stage dispatch problem, for stage t:

$$Min \sum_{j\in J_T} c_j g_{j,t} + \delta r_t + FCF_t \tag{3.7}$$

s.t.

$$\sum_{j \in J_T, J_R} g_{j,t} + \sum_{i \in J_H} \rho_j u_{j,t} + r_t = d_t \tag{3.8}$$

$$v_{j,t+1} = v_{j,t} + a_{j,t} - u_{j,t} - s_{p_{j,t}} + \sum_{m \in \Pi_j} (u_{m,t} + s_{p_{m,t}}) \qquad \forall j \in J_H, \tag{3.9}$$

$$v_{j,t+1} \leq \overline{v_j} \qquad \forall j \in J_H \tag{3.10}$$

$$u_{j,t} \leq \overline{u_j} \qquad \forall j \in J_H \tag{3.11}$$

$$g_{j,t} \leq \overline{g_j} \qquad \forall j \in J_T \tag{3.12}$$

Where $\sum_{j \in J_T} c_j g_j + \delta r_t$ represents the ICF of stage t and FCF_t, the future cost function of stage t.

One technique used to approximate those functions is Dual Dynamic Programming (DDP), based on Benders decomposition theory. It consists of an iterative method for building approximations of the FCF around interesting storage states defined by the method itself. Different from conventional Dynamic Programming, which approximates the FCF by discretizing and interpolating the state space (leading to an exponential increase in the computational effort with the number of state variables), the DDP iteratively creates linear segments around those interesting storage states, using the information of the operating cost and the FCF derivatives with respect to the storage level of each hydro plant (known as water values).

The iterative method of DDP can be divided into two phases:

- The Forward phase consists of solving all stages from the first to the final stage T, passing the calculated storage levels of the current problem to the problems of subsequent stages. It generates the “interesting” storage points of the reservoirs at each stage, considering the current approximation of their FCFs.
- The algorithm reverses the direction when the T stage is solved, starting the Backward phase. In this phase, it adds linear segments around the interesting storage points generated in the Forward phase to update the approximation of the FCF of each stage. That is, dual variables are calculated in the problem associated with stage $t+1$ and sent to stage t as constraints that relate the marginal variation of the total operating cost from stage $t+1$ to stage T with the marginal variation of the primal solution provided by stage t.

This Forward-Backward process repeats until a convergence criterion is satisfied.

Moreover, inside the one-stage optimization problem, it is possible to have a representation of different levels of demand and renewable generation as input, even in hourly granularity, to capture their natural variability that exist inside a stage that usually represents an entire month or week.

3.2.2 Incorporating uncertainties

Using a single hydrological scenario in the optimization of a hydrothermal dispatch is risky. For example, if a wet scenario is considered in the optimization, but the actual scenario is dry, the system storage may become very low and provoke energy shortage. On the other hand, considering a dry scenario during the optimization, when the actual is wet, the reservoir system will fill up and even spill water, resulting in a too-conservative dispatch. This logic can be applied to other sources of uncertainties, such as VRE production.

Once the stochastic models that capture the statistical behavior of hydrology (or VRE production) can be estimated, it is possible to generate as many scenarios of natural inflows and VRE production as needed by the Monte Carlo method to represent this variability. Furthermore, the Stochastic Dual Dynamic Programming (SDDP) method can be applied to consider those synthetic scenarios in the determination of optimal dispatch under uncertainty.

SDDP is very similar to the deterministic DDP described in the previous section. In the forward phase, multiple scenarios are considered, and the solution is similar to various deterministic DDP problems. However, the Backward phase presents some differences, as the approximated FCFs must now capture the uncertainty in the future operation. For that, more scenarios are contemplated in this phase. The figure below illustrates how the scenarios are generated in both phases:

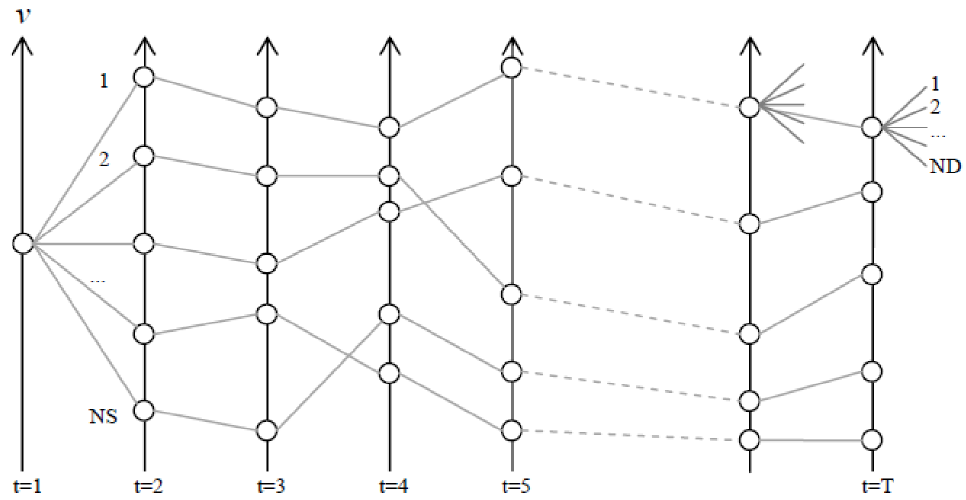

Figure 5 - SDDP scenario structure

At each stage t, NS states (storage levels) are calculated by the forward operating simulation based on a set of NS scenarios. During backward recursion, at each stage t and scenario $s_f = 1, \dots, NS$, the scenarios are discretized once more in ND realizations. The coefficients used to build the Benders cut associated with the problem of stage t and scenario s_f are equal to the average of dual variables calculated for the ND operating problems.

For more information about the SDDP algorithm, please refer to [55], [56].

3.2.3 Network representation

The power systems are also composed of transmission networks responsible for transferring the energy generated by the power plants to their consumers. Transmission networks impose additional constraints that may limit the dispatch of some plants, so it is essential to represent them in the problem formulation.

The DC power flow model is used to represent these constraints instead the non-linear power flow, as the linearized model provides a fair approximation of the real power flows in the high voltage network and avoids non-convergence problems prevalent in non-linear models. Also, reactive power support can be assessed afterward due to its "local" nature (shunt compensation) and is less relevant in terms of investment cost. So, at this step, the reactive power flows will be neglected.

3.2.3.1 Kirchhoff Current Law (KCL)

The KCL, also known as first Kirchhoff law, represents the power balance in each bus of the system, that is, the sum of the power flow that arrives in the bus plus the total generation connected to the bus must be equal to the sum of power flows leaving the bus plus its total load. Considering just a single stage, this constraint can be defined as follows:

$$\sum_{j \in \Phi_i} (g_j + \rho_j u_j) + \sum_{k \in \Omega_i^+} f_k - \sum_{k \in \Omega_i^-} f_k + r_i = d_i \qquad \forall i \in I \qquad (3.13)$$

Where:

Φ_i	Set of generators connected to bus i
Ω_i^+	Set of circuits which the terminal bus i is the TO bus
Ω_i^-	Set of circuits which the terminal bus i is the FROM bus
f_k	Power flow in circuit k
d_i	Demand in bus i
r_i	Deficit in bus i
I	Set of buses
K	Set of circuits

f_k can assume positive and negative values, where the former indicates a power flow in the direction FROM-TO and the latter in the direction TO-FROM. To simplify the notation let us convert this constraint into matrix form, assuming at most one thermal generator connected to each bus:

$$-Sf + g + r = d \qquad (3.14)$$

Where S is the incidence matrix of dimension IxK, which represents the connections of the circuits to the buses. The k-th column of the matrix consists of zeros in all positions except for those lines corresponding to terminal buses of the k-th circuit (1, whether it is FROM bus and -1, otherwise). f is the K-dimensional power flow vector. g, d, and r are the I-dimensional generation, load, and deficit vector, respectively.

3.2.3.2 Kirchhoff Voltage Law (KVL)

According to the KVL, also recognized as second Kirchhoff law, the power flow in the transmission lines follows non-linear equations subjected to the voltage levels at their terminal buses. The linearization of those equations results in a direct relationship between the active power flow and the angle difference between the terminal buses, as presented below:

$$f_k = \gamma_k \Delta\theta_k \qquad \forall k \in K \qquad (3.15)$$

Where:

γ_k Suceptance of circuit k

$\Delta\theta_k$ Angular difference between the terminal buses of circuit k

Using the matrix expression:

$$f = |\gamma| S^T \theta \qquad (3.16)$$

Where $|\gamma|$ is the MxM diagonal matrix, which contains the circuit's susceptance, and θ is the I-dimensional bus angle vector. The superscript T denotes the transpose operation.

3.2.3.3 Power flow limits

The power flow in each circuit is limited to its capacity:

$$-\bar{f} \leq f \leq \bar{f} \qquad (3.17)$$

Where $\bar{f}$ denotes the K-dimensional vector of maximum capacities of the circuits.

3.2.3.4 Problem formulation with network constraints

Adding the constraints mentioned above into the one-stage dispatch problem results in the following matrix formulation:

$$Min\ C^T g + \delta r \qquad (3.18)$$

s.t.

$$-Sf + g + r = d \tag{3.19}$$

$$f - |\gamma| S^T \theta = 0 \tag{3.20}$$

$$-\bar{f} \leq f \leq \bar{f} \tag{3.21}$$

$$g \leq \bar{g} \tag{3.22}$$

Where C denotes the I-dimensional vector of operating costs and $\bar{g}$ the I-dimensional vector of generation capacity at each bus.

It is important to note that no explicit variable represents the losses in the transmission lines in the above formulation. In a simplified way, it is assumed that losses are represented in the demand as an additional load (input data) since it typically represents a low percentage of total demand.

However, there are no methodological impediments in representing losses explicitly in the problem, only requiring a linear representation, since they are quadratic in relation to the power flow in the lines, to maintain the linearity of the dispatch problem.

3.2.3.5 Compact formulation

The constraints (3.19) to (3.21) are linear and could be included in the dispatch problem. However, depending on the size of the network, the number of decision variables corresponding to the vectors θ and f may increase significantly. This problem can be avoided by rewriting the KCL and KVL constraints only in terms of the decision vector g, which was already showed up in the single-node formulation.

Using the equation (3.20) in (3.19):

$$-B\theta + g + r = d \tag{3.23}$$

Where $B = S\gamma S^T$ is the susceptance matrix with dimension IxI. After eliminating the row and column in B that corresponds to the reference bus, as the matrix has a rank $I - 1$:

$$\tilde{\theta} = \tilde{B}^{-1}(\tilde{g} + \tilde{r} - \tilde{d}) \tag{3.24}$$

Where $\sim$ indicates the matrix and vectors without the reference bus (voltage angle equals to 0). To simplify the notation, null rows and columns are added in the position of the reference bus into the matrix and vectors of equation (3.24), resulting in:

$$\theta = B^{-1}(g + r - d) \tag{3.25}$$

Replacing (3.25) with (3.20):

$$f = \beta(g + r - d) \tag{3.26}$$

Where $\beta = \gamma S B^{-1}$ is the sensitivity matrix with dimension. KxI. Each element β_{ki} represents the variation in the power flow of circuit k with respect to a variation in the generation of bus i. The elements related to the reference bus are equal to zero, as the generation in this bus is implicitly calculated from the total load balance of the remaining buses, represented by the following equation:

$$e^T(g + r) = e^T d \tag{3.27}$$

Where e denotes an I-dimensional unitary vector.

Finally, the one-stage dispatch problem can be formatted as follows:

$$Min\ C^T g + \delta r \tag{3.28}$$

s.t.

$$-\bar{f} \leq \beta(g + r - d) \leq \bar{f} \tag{3.29}$$

$$g \leq \bar{g} \tag{3.30}$$

$$e^T(g + r) = e^T d \tag{3.31}$$

While the complete network formulation, with the explicit representation of the KCL and KVL constraints, presents $J + 2I + K$ decision variables and $I + 2K + J$ constraints, the compact formulation reduces those numbers to $J + I$ decision variables and $J + K + 1$ constraints. Consequently, the computational complexity of the problem decreases significantly.

Regarding the matrix structure, the sensitivity matrix β is highly dense, which may affect the computational efficiency of the algorithm. However, a relaxation strategy can be used to enhance efficiency, as described in the flowchart below:

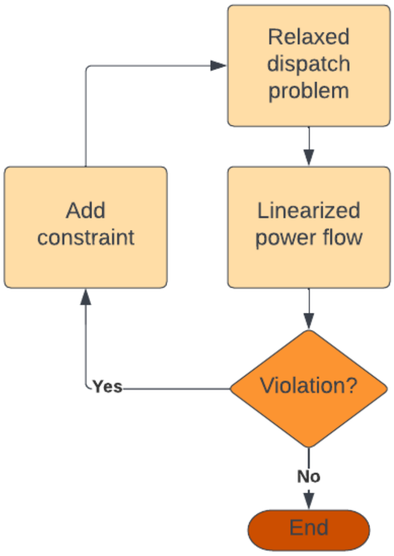

Figure 6 - Relaxation scheme

Initially, the problem is solved without considering the flow limit constraints (3.29). After that, the linearized power flow is used to check if any power flow is above the circuit's capacities. If so, only the rows of β corresponding to violated circuits are calculated and added to the list of constraints, and the problem is solved again. This process is repeated until all circuits are operating under their capacities. This relaxation structure contributes to the computational efficiency of the algorithm.

3.2.3.6 N-1 security constraint

The N-1 criterion is a well-known security constraint that imposes that the solution for the optimal dispatch must not violate the operating constraints whether any single contingency occurs in the system. In this work, only the contingencies in the transmission network will be considered.

Every single contingency configures a new network topology. To represent this constraint in the problem, the sensitivity matrices considering all single contingencies in the network must be calculated and added as constraints into the dispatch problem.

Let β_n denote the sensitivity matrix considering the single contingency n and N, the number of single contingencies. The dispatch problem can be written as follows:

$$Min\ C^T g + \delta r \tag{3.32}$$

s.t.

$$-\bar{f} \leq \beta(g + r - d) \leq \bar{f} \tag{3.33}$$

$$-\overline{f_e} \leq \beta_n(g + r - d) \leq \overline{f_e} \qquad \forall n \in N \tag{3.34}$$

$$g \leq \bar{g} \tag{3.35}$$

$$e^T(g + r) = e^T d \tag{3.36}$$

Where $\overline{f_e}$ denotes the vector of emergency capacities (normally the circuits can operate above their nominal capacities for a short time in emergency situations, such as a contingency situation). The representation of the N-1 criterion notably increases the number of constraints in the problem. However, the same relaxation strategy may be applied in this case. Only the rows of β and β_n corresponding to the violated circuits are calculated and added iteratively to the list of constraints. Also, in this case, the linearized power flow must be performed for each network topology configuration (base case and single contingencies).

3.3 Expansion Problem

In addition to the variables and constraints present in the dispatch problem, the expansion planning optimization problem contains variables and constraints related to the investment in new generation and transmission assets. Considering a purely thermal system without transmission network, for the sake of simplicity, the multi-stage expansion planning problem is formulated as follows:

$$Min \sum_{t=1}^{T} \left(\sum_{j \in J_{TC}} p_{j,t} x_{j,t} + \sum_{j \in J_T} c_{j,t} g_{j,t} + \delta r_t \right) \tag{3.37}$$

s.t.

$$\sum_{j \in J_T} g_{j,t} + r_t = d_t \qquad \forall t = 1, \dots T \tag{3.38}$$

$$g_{j,t} \leq \overline{g_J} \sum_{\tau=1}^{t} x_{j,\tau} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \tag{3.39}$$

$$g_{j,t} \leq \overline{g_J} \qquad \forall j \in J_{TE}, \forall t = 1, \dots T \tag{3.40}$$

$$x_{j,t} \in \{0,1\} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \tag{3.41}$$

$$\sum_{t=1}^{T} x_{j,t} \leq 1 \qquad \forall j \in J_{TC} \tag{3.42}$$

Where:

$p_{j,t}$	Investment cost of thermal plan j in stage t
$x_{j,t}$	Investment decision of plant j in stage t
J_{TE}	Set of existing thermal plants
J_{TC}	Set of candidate thermal plants

$J_T = J_{TC} \cup J_{TE}$

The objective function incorporates the investment costs in new generation plants in addition to the operating and deficit costs, aiming to minimize the total cost of the system. The operating limits of the candidate plants are represented by the constraint (3.39), which is multiplied by the term $\sum_{\tau=1}^{t} x_{j,\tau}$. This term, due to constraints (3.41) and (3.42), is equal to 1 in stages from t to T, if project j is decided to commit at stage t, and 0 at stages from 1 to $t-1$.

Since the problem now presents integer variables ($x_{j,t}$), it is characterized as a MILP problem unlike the linear programming problems shown in the previous sections. Furthermore, this structure naturally suggests the use of decomposition schemes to solve the problem as the operating constraints depend on the investment decisions. First, the investment decision is taken and after, the dispatch problem can be solved by fixing those decisions.

The Benders decomposition technique will be applied to solve this problem in this work. The following section describes it in more detail.

3.3.1 Benders decomposition

As mentioned above, the expansion planning problem can be decomposed into an investment subproblem and an operating subproblem. The figure below presents the iterative process between the solution of both subproblems:

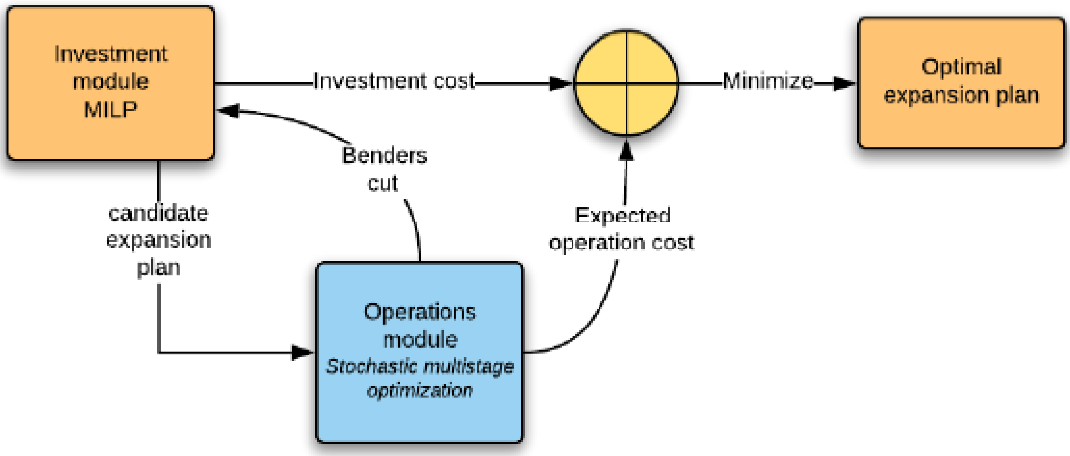

Figure 7- Decomposition scheme

The investment module aims to minimize the sum of the investment costs and an approximation of the operating cost. This approximation is represented by a piecewise linear function built by the Benders cuts generated by the operation module. At each iteration, the investment subproblem is solved and the investment decisions are sent to the operation module.

The operation module, in turn, calculates the multi-stage optimal dispatch, considering the investment decisions made by the previous module. This problem is solved using the SDDP algorithm, described in section 3.2. So, all aspects related to time coupling dispatch decisions, uncertainty in the hydrology and VRE production, and intra-stage variability of the demand and VRE are considered during the expansion planning.

From the dual variables (Lagrange multipliers) of the operating constraints and the value of the objective function, Benders cut are calculated and sent back to the master problem (investment module). Those cuts represent a linear approximation of the expected value of the operating cost due to different investment decisions. Over the course of the iterations this approximation improves, and the investment module can establish better investment decisions.

The investment subproblem can be formulated as follows:

$$Min \sum_{t=1}^{T} \sum_{j \in J_{TC}} p_{j,t} x_{j,t} + \alpha \tag{3.43}$$

s.t.

$$\alpha \geq w(x^{\mu}) - \sum_{t=1}^{T} \sum_{j \in J_{TC}} \left(\overline{g_J} \sum_{\tau=t}^{T} \pi_{j.\tau}^{\mu} \right) \left(x_{j,t} - x_{j,t}^{\mu} \right) \qquad \forall \mu = 1, \dots v \qquad (3.44)$$

$$x_{j,t} \in \{0,1\} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \qquad (3.45)$$

$$\sum_{t=1}^{T} x_{j,t} \leq 1 \qquad \forall j \in J_{TC} \qquad (3.46)$$

Where:

α	Approximation of the operating cost
$w(x^{\mu})$	Value of the objective function of the operating problem at the μ-th iteration
$\pi_{j,\tau}^{\mu}$	Dual variable associated with the constraint (3.49) of candidate j in stage t at the μ-th iteration
$x_{j,t}^{\mu}$	Investment decision at the μ-th iteration for candidate j in stage t
v	Current iteration

And the operation sub problem is illustrated below:

$$w(x^{v}) = Min \sum_{t=1}^{T} \left(\sum_{j \in J_T} c_{j,t} g_{j,t} + \delta r_t \right) \qquad (3.47)$$

s.t.

$$\sum_{j \in J_T} g_{j,t} + r_t = d_t \qquad \forall t = 1, \dots T \qquad (3.48)$$

$$g_{j,t} \leq \overline{g_J} \sum_{\tau=1}^{t} x_{j,\tau}^{v} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \qquad (3.49)$$

$$g_{j,t} \leq \overline{g_J} \qquad \forall j \in J_{TE}, \forall t = 1, \dots T \qquad (3.50)$$

Where:

$x_{j,\tau}^{v}$	Investment decision at the v-th iteration for candidate j in stage t

The constraints (3.44) represent the Benders cuts generated at each iteration μ of the algorithm, composing the linear piecewise function α, which represents the approximation of the operating cost function. To demonstrate how these cuts are formulated, let us consider the generic formulation of the operating subproblem below:

$$w(x) = Min\ cy \tag{3.51}$$

s.t.

$$Ex + Fy \geq h \tag{3.52}$$

$$y \geq 0 \tag{3.53}$$

Where y denotes the vector of operating variables. E and F are generic matrix, h is the vector of bounds and c is the vector of operating costs. From the Linear Programming theory, the dual problem can be written as follows:

$$w(x) = Max\ \pi(h - Ex) \tag{3.54}$$

s.t.

$$\pi F \leq c \tag{3.55}$$

$$\pi \geq 0 \tag{3.56}$$

Where π represents the vector of dual variables (Lagrange multipliers associated with the constraints (3.52) of the primal problem). Also, from the Linear Programming theory, the optimal solution of both problems (primal and dual) coincides. Considering that π^b denotes a feasible solution to the dual problem, the optimal solution can be calculated by the following enumeration:

$$w(x) = Max\ \pi^b(h - Ex) \qquad \forall b = 1, \ldots B \tag{3.57}$$

Where B denotes the number of feasible solutions. Also, this can be rewritten as follows:

$$w(x) = Min\ \alpha \tag{3.58}$$

s.t.

$$\alpha \geq \pi^1(h - Ex) \tag{3.59}$$

$$\alpha \geq \pi^2(h - Ex) \tag{3.60}$$

$$\ldots$$

$$\alpha \geq \pi^B(h - Ex) \tag{3.61}$$

Where α is a scalar variable. Since α must be greater or equal than $\pi^b(h - Ex)$ for all feasible solutions and the objective function is to minimize α, the solution will be $Max\,\pi^b(h - Ex)$. The figure below illustrates this solution, showing that $w(x)$ is represented by a linear piecewise function:

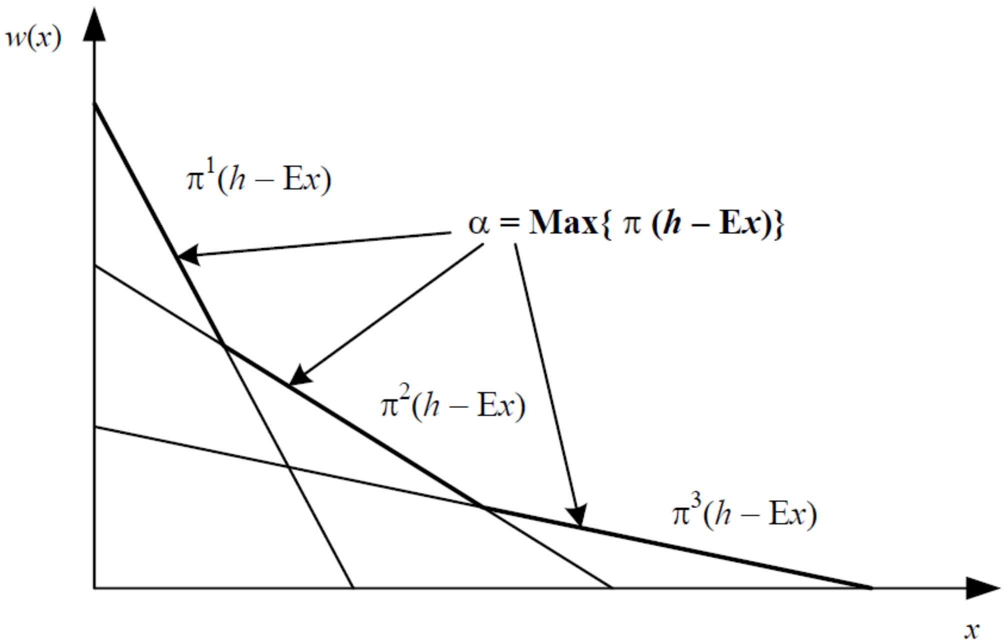

Figure 8 - Function w(x)

Therefore, the expansion problem $Min\,z(x) = c(x) + w(x)$, in which $c(x)$ is the total investment cost, can be reformulated as:

$$Min\,c(x) + \alpha \tag{3.62}$$

s.t.

$$\alpha \geq \pi^b(h - Ex) \qquad \forall b = 1, \dots B \tag{3.63}$$

$$x \in X \tag{3.64}$$

Where X denotes the set of feasible investment decisions. Using the equality of primal and dual solutions $w(x^v) = \pi^v(h - Ex^v)$ at v-th iteration, the constraint (3.63) can be rewritten as:

$$\alpha \geq w(x^v) - \pi^v E(x - x^v) \tag{3.65}$$

The constraint (3.65) is a generic representation of the Benders cuts (3.44). At each iteration of the algorithm, these cuts are generated and added to the investment problem, enhancing the approximation of the operating cost function α. Also, in each iteration, it is possible to calculate the upper and lower bounds of the optimal solution. As the objective function is to minimize the total cost, any feasible solution has a cost greater or equal to the optimal solution. So, the upper bound consist of the minimum total cost among the feasible solutions at the current iteration:

$$\bar{z} = Min\, z(x^{\mu}) \qquad \forall \mu = 1, \dots \nu \tag{3.66}$$

On the other hand, the lower bound is the total cost calculated by the investment problem because this problem is a relaxation of the original expansion problem ((3.37) to (3.42)), as the linear approximation of the operating cost underestimates the original function.

$$\underline{z} = \sum_{t=1}^{T} \sum_{j \in J_{TC}} p_{j,t} x^{\nu}{}_{j,t} + \alpha^{\nu} \tag{3.67}$$

The algorithm iterates until the difference between the upper and lower bounds is lower than a tolerance.

The operation subproblem illustrated by the equation (3.47) to (3.50) only represents thermal plants for didactic reasons. A real problem may have other generation elements, such as hydro and renewable plants, and the variables and constraints related to them must be represent in this problem as described in section 3.2.

As mentioned before, this subproblem is solved by the SDDP algorithm, which can incorporate uncertainties in the operating planning by considering multiple scenarios during the optimization. The Benders cut coefficients, in that case, will be equal to the average of the coefficients calculated for each scenario defined. In that way, uncertainties are also considered in the investment decision-making process.

The next section describes how to represent the network in both modules.

3.3.2 Network representation

To consider the transmission network in the expansion problem, the constraints described in section 3.2.3 must be added to the problem. Furthermore, to represent the possibility of investing in new circuits, the investment variable must be added together with the transmission constraints as follows:

$$Min \sum_{t=1}^{T} \left(\sum_{j \in J_{TC}} p_{j,t} x_{j,t} + \sum_{k \in K_C} p_{k,t} x_{k,t} + \sum_{j \in J_T} c_{j,t} g_{j,t} + \delta r_t \right) \tag{3.68}$$

s.t.

$$\sum_{j\in\Phi_i} g_{j,t} + \sum_{k\in\Omega_i^+} f_{k,t} - \sum_{k\in\Omega_i^-} f_{k,t} + \delta r_{i,t} = d_{i,t} \qquad \forall i \in I, \forall t = 1, \dots T \qquad (3.69)$$

$$g_{j,t} \leq \overline{g_J} \sum_{\tau=1}^{t} x_{j,\tau} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \qquad (3.70)$$

$$g_{j,t} \leq \overline{g_J} \qquad \forall j \in J_{TE}, \forall t = 1, \dots T \qquad (3.71)$$

$$f_{k,t} = \gamma_k \Delta\theta_{k,t} \qquad \forall k \in K_E, \forall t = 1, \dots T \qquad (3.72)$$

$$f_{k,t} = \gamma_k \Delta\theta_{k,t} \sum_{\tau=1}^{t} x_{k,\tau} \qquad \forall k \in K_C, \forall t = 1, \dots T \qquad (3.73)$$

$$-\overline{f_k} \leq f_{k,t} \leq \overline{f_k} \qquad \forall k \in K_E, \forall t = 1, \dots T \qquad (3.74)$$

$$-\overline{f_k} \sum_{\tau=1}^{t} x_{k,\tau} \leq f_{k,t} \leq \overline{f_k} \sum_{\tau=1}^{t} x_{k,\tau} \qquad \forall k \in K_C, \forall t = 1, \dots T \qquad (3.75)$$

$$x_{j,t} \in \{0,1\} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \qquad (3.76)$$

$$x_{k,t} \in \{0,1\} \qquad \forall k \in K_C, \forall t = 1, \dots T \qquad (3.77)$$

$$\sum_{t=1}^{T} x_{j,t} \leq 1 \qquad \forall j \in J_{TC} \qquad (3.78)$$

$$\sum_{t=1}^{T} x_{k,t} \leq 1 \qquad \forall k \in K_C \qquad (3.79)$$

Where:

$x_{k,t}$	Investment variable for the transmission candidate k in stage t
$p_{k,t}$	Investment cost of circuit k in stage t
K_C	Set of candidate circuits
K_E	Set of existing circuits

$K = K_C \cup K_E$

The constraints (3.73) and (3.75) represent the second Kirchhoff law and the operating limits for the transmission candidates, respectively. The presence of the investment variable $x_{k,t}$ in the constraint (3.73) results in a non-linearity, as it multiplies another decision variable ($\Delta\theta_{k,t}$), and the problem becomes non-linear and non-convex. The application of Benders decomposition might not be recommended in that case because the cuts generated may exclude some feasible regions of the problem, including the region containing the optimal solution.

To bypass this issue, the constraint (3.73) can be replaced by the disjunctive formulation as follows:

$$-M_k\left(1-\sum_{\tau=1}^{t}x_{k,\tau}\right)\leq f_{k,t}-\gamma_k\Delta\theta_{k,t}\leq M_k\left(1-\sum_{\tau=1}^{t}x_{k,\tau}\right)\qquad \forall k\;\epsilon\;K_C,\forall t=1,\dots T \qquad (3.80)$$

Where $M_k\approx\infty$. When the investment variable $\sum_{\tau=1}^{t}x_{k,\tau}$ is equal to 1, the constraint turns to the second Kirchhoff equation (3.72). Otherwise, as M_k is a huge positive number, the constraint will be relaxed, and the angular difference between the terminal buses will not be constrained by a non-existing circuit.

Applying the Benders decomposition in the problem presented above, the Benders cuts generated in each iteration are formulated as follows:

$$\alpha\geq w(x^v)-\sum_{t=1}^{T}\left(\sum_{j\in J_{TC}}\left(\overline{g_J}\sum_{\tau=t}^{T}\pi_{\tau,j}^{v}\right)\left(x_{j,t}-x_{j,t}^{v}\right)\right.$$
$$\left.+\sum_{k\in K_C}\left(M_k\sum_{\tau=t}^{T}\pi_{\tau,k}^{v,\gamma}-\overline{f_k}\sum_{\tau=t}^{T}\pi_{\tau,k}^{v,f}\right)\left(x_{k,t}-x_{k,t}^{v}\right)\right) \qquad (3.81)$$

Where:

$\pi_{\tau,k}^{v,\gamma}$	Dual variable related to the constraint (3.80) at iteration v
$\pi_{\tau,k}^{v,f}$	Dual variable related to the constraint (3.75) at iteration v
$x_{k,t}^{v}$	Investment decision at the v-th iteration for candidate k in stage t

Although the disjunctive formulation keeps the linearity of the KVL constraints for the candidates and enables Benders decomposition to solve the problem, the disjunctive constants M_k will also compose the Benders cuts. It makes the algorithm ill-conditioned, given the huge values of these constants, perturbing the convergence process. BINATO *et al* [57] proposes to calculate the smallest value for the disjunctive constant based on the reactance of the shortest path between the terminal buses of the circuit, to reduce this effect (this calculation is presented in the Annex A). Moreover, this work will explore alternatives to bypass this representation, as described later in Chapter 5.

Note that when applying the decomposition on the expansion problem, the operation module will always receive defined values of the investment variables, so it is not necessary to differentiate between existing and candidate elements. Consequently, the constraints related to candidates not added to the systems (such as the disjunctive constraints) can be neglected.

However, for building the Benders cuts, the dual variables of those constraints are needed. To solve this issue, the Lagrange multipliers associated with them can be calculated implicitly, based on the relationship between available multipliers, as shown in [1].

3.3.3 Integrated generation and transmission formulation

Joining the network representation to the decomposed formulation, results in the following integrated generation and transmission expansion planning problem (for the sake of the explanation, only thermal generators are being represented):

Investment subproblem:

$$Min \sum_{t=1}^{T}\left(\sum_{j\in J_{TC}} p_{j,t}x_{j,t} + \sum_{k\in K_C} p_{k,t}x_{k,t}\right) + \alpha \tag{3.82}$$

s.t.

$$\alpha \geq w(x^{\mu}) - \sum_{t=1}^{T}\left(\sum_{j\in J_{TC}}\left(\overline{g_J}\sum_{\tau=t}^{T}\pi_{\tau,j}^{v}\right)\left(x_{j,t}-x_{j,t}^{v}\right) + \sum_{k\in K_C}\left(M_k\sum_{\tau=t}^{T}\pi_{\tau,k}^{v,\gamma} - \overline{f_k}\sum_{\tau=t}^{T}\pi_{\tau,k}^{v,f}\right)\left(x_{k,t}-x_{k,t}^{v}\right)\right) \quad \forall\mu = 1,\dots v \tag{3.83}$$

$$x_{j,t} \in \{0,1\} \qquad \forall j \in J_{TC}, \forall t = 1,\dots T \tag{3.84}$$

$$\sum_{t=1}^{T} x_{j,t} \leq 1 \qquad \forall j \in J_{TC} \tag{3.85}$$

$$x_{k,t} \in \{0,1\} \qquad \forall k \in K_C, \forall t = 1,\dots T \tag{3.86}$$

$$\sum_{t=1}^{T} x_{k,t} \leq 1 \qquad \forall k \in K_C \tag{3.87}$$

Operating subproblem:

$$w(x^{v}) = Min \sum_{t=1}^{T} \left(\sum_{j \in J_T} c_{j,t} g_{j,t} + \delta r_t \right) \tag{3.88}$$

s.t.

$$\sum_{j \in \Phi_i} g_{j,t} + \sum_{k \in \Omega_i^{+}} f_{k,t} - \sum_{k \in \Omega_i^{-}} f_{k,t} + \delta r_{i,t} = d_{i,t} \qquad \forall i \in I, \forall t = 1, \dots T \tag{3.89}$$

$$g_{j,t} \leq \overline{g_J} \qquad \forall j \in J_{TE}, \forall t = 1, \dots T \tag{3.90}$$

$$g_{j,t} \leq \overline{g_J} \sum_{\tau=1}^{t} x_{j,\tau} \qquad \forall j \in J_{TC}, \forall t = 1, \dots T \tag{3.91}$$

$$f_{k,t} = \gamma_k \Delta\theta_{k,t} \qquad \forall k \in K_E, \forall t = 1, \dots T \tag{3.92}$$

$$-M_k \left(1 - \sum_{\tau=1}^{t} x_{k,\tau} \right) \leq f_{k,t} - \gamma_k \Delta\theta_{k,t} \leq M_k \left(1 - \sum_{\tau=1}^{t} x_{k,\tau} \right) \qquad \forall k \in K_C, \forall t = 1, \dots T \tag{3.93}$$

$$-\overline{f_k} \leq f_{k,t} \leq \overline{f_k} \qquad \forall k \in K_E, \forall t = 1, \dots T \tag{3.94}$$

$$-\overline{f_k} \sum_{\tau=1}^{t} x_{k,\tau} \leq f_{k,t} \leq \overline{f_k} \sum_{\tau=1}^{t} x_{k,\tau} \qquad \forall k \in K_C, \forall t = 1, \dots T \tag{3.95}$$

The compact formulation can be applied to save computational time if all network constraints are being represented, as described in section 3.2.3.5. However, when some constraints are neglected, as presented in Chapter 5, the complete formulation must be applied.

4 Transmission Expansion Planning Problem

4.1 Introduction

This Chapter presents the methodology for the transmission expansion planning problem, considering that the generation expansion planning decisions are already taken, and dispatch scenarios are available for the expanded generation system. Also, a solution strategy is presented based on heuristics and Benders decomposition.

This methodology can be used to complement the results obtained by the one explained in the previous Chapter in cases where some simplifications on the network representation were considered to reduce the problem's complexity. In the next Chapter, some alternatives of integrated generation and transmission expansion planning sequentially using those two methodologies are proposed.

4.2 Problem formulation

Considering a single scenario and stage, for the simplicity of notation, the transmission expansion planning problem can be formulated as follows:

$$Min \sum_{k \in K_C} p_k x_k + \rho * o(x) \tag{4.1}$$

The objective function is to minimize the total investment cost in new circuits plus a penalty for circuit overload, denoted as ρ. Usually, the value of ρ is high enough to avoid having any circuit overload at the final expansion plan. The function $o(x)$ represents an optimal power flow (OPF) problem, formulated as follows:

$$o(x) = Min \sum_{k \in K} \left(f_k^{\delta +} + f_k^{\delta -}\right) \tag{4.2}$$

s.t.

$$\sum_{k \in \Omega_i^+} \left(f_k + f_k^{\delta +}\right) - \sum_{k \in \Omega_i^-} \left(f_k + f_k^{\delta -}\right) = d_i - \sum_{j \in \Phi_i} g_j \tag{4.3}$$

$$f_k = \gamma_k \Delta\theta_k \qquad \forall k \in K_E \tag{4.4}$$

$$-M_k(1 - x_k) \leq f_k - \gamma_k \Delta\theta_k \leq M_k(1 - x_k) \qquad \forall k \in K_C \tag{4.5}$$

$$-\overline{f}_k \leq f_k \leq \overline{f}_k \qquad \forall k \in K_E \tag{4.6}$$

$$-\overline{f}_k x_k \leq f_{k,t} \leq \overline{f}_k x_k \qquad \forall k \in K_C \tag{4.7}$$

$$x_k \in \{0,1\} \qquad \forall k \in K_C \qquad (4.8)$$

$$f_k^{\delta+} \geq 0 \qquad \forall k \in K \qquad (4.9)$$

$$f_k^{\delta-} \geq 0 \qquad \forall k \in K \qquad (4.10)$$

Where $f_k^{\delta+}$ and $f_k^{\delta-}$ denote the circuit overload in the direction FROM bus to TO bus and vice versa, respectively.

In this formulation, the function $o(x)$ aims to minimize the total circuit overload of the system, and the values of the variables related to the generators dispatch $g_j, j \in J$, are known (input data). Once more, the KVL constraints for circuit candidates are represented by the disjunctive formulation where the constant M_k is calculated for each circuit applying the methodology described in Annex A.

The final expansion plan resulting from this formulation will be optimal for a single dispatch scenario. Ideally, the transmission expansion plan must be robust to different network setpoints, that can be represented by multiple dispatch scenarios. The following formulation takes that into account:

$$Min \sum_{k \in K_C} p_k x_k + \rho \sum_{s \in S} o_s(x) \qquad (4.11)$$

Where:

$$o_s(x) = Min \sum_{k \in K} \left(f_{k,s}^{\delta+} + f_{k,s}^{\delta-}\right) \qquad \forall s \in S \qquad (4.12)$$

s.t.

$$\sum_{k \in \Omega_i^+} \left(f_{k,s} + f_{k,s}^{\delta+}\right) - \sum_{k \in \Omega_i^-} \left(f_{k,s} + f_{k,s}^{\delta-}\right) = d_{i,s} - \sum_{j \in \Phi_i} g_{j,s} \qquad \forall i \in I \qquad (4.13)$$

$$f_{k,s} = \gamma_k \Delta\theta_{k,s} \qquad \forall k \in K_E \qquad (4.14)$$

$$-M_k(1 - x_k) \leq f_{k,s} - \gamma_k \Delta\theta_{k,s} \leq M_k(1 - x_k) \qquad \forall k \in K_C \qquad (4.15)$$

$$-\overline{f}_k \leq f_{k,s} \leq \overline{f}_k \qquad \forall k \in K_E \qquad (4.16)$$

$$-\overline{f}_k x_k \leq f_{k,s} \leq \overline{f}_k x_k \qquad \forall k \in K_C \qquad (4.17)$$

$$x_k \in \{0,1\} \qquad \forall k \in K_C \qquad (4.18)$$

$$f_{k,s}^{\delta+} \geq 0 \qquad \forall k \in K \qquad (4.19)$$

$$f_{k,s}^{\delta -} \geq 0 \qquad \forall k \in K \qquad (4.20)$$

Where subscript s denotes the variables for scenario s and S represents the set of dispatch scenarios. Note that the objective function intends to minimize sum of total the circuit overload of all scenarios, so the final transmission expansion plan will be robust for all of them.

4.3 Benders decomposition

The Benders decomposition will also be applied to solve the transmission expansion planning problem as the entire problem becomes intractable depending on the number of dispatch scenarios considered. The decomposition scheme is illustrated in the diagram below:

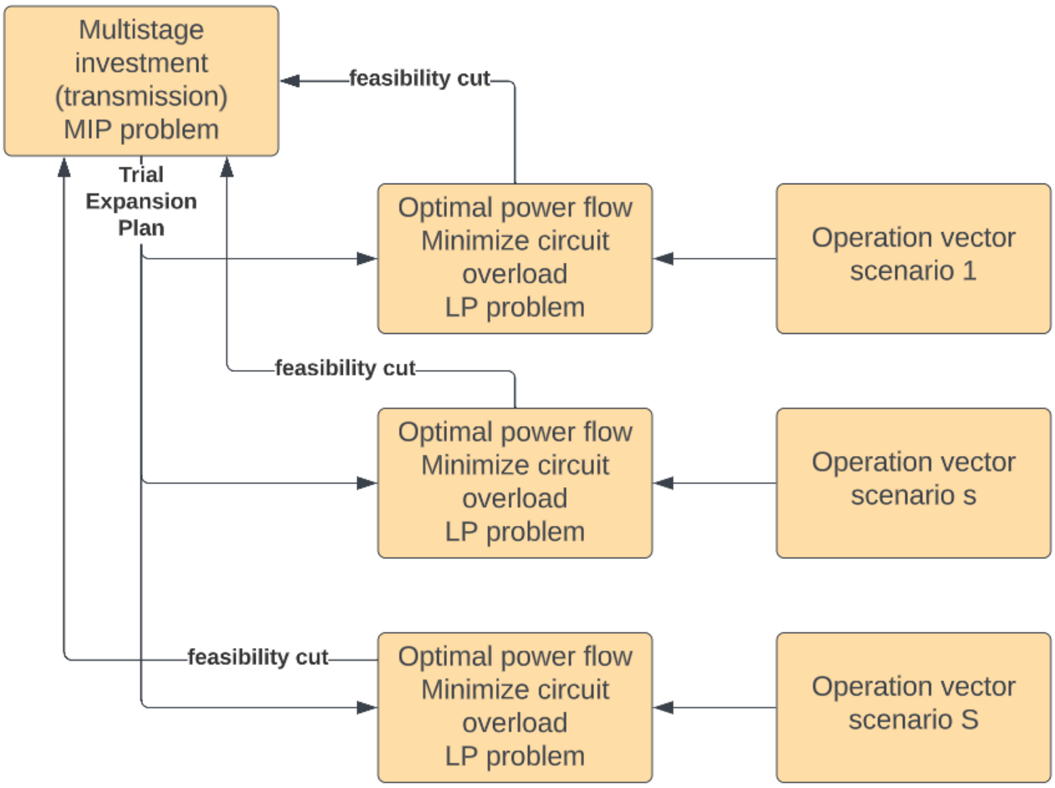

Figure 9- Benders decomposition for the transmission expansion problem

The problem is decomposed into an investment subproblem and a set of OPF problems, each contemplating one dispatch scenario. The investment problem is a mixed integer linear programming problem with the objective function (4.11) subjected to a set of constraints represented by Benders feasibility cuts, generated from the OPF problems ((4.12) to (4.18)). These feasibility cuts can be formulated as follows:

$$o_s(x^v) - \sum_{k \in K_C} \left(M_k \pi_{k,s}^{v,\gamma} - \bar{f}_k \pi_{k,s}^{v,f}\right)(x_k - x_k^v) \leq 0 \qquad \forall s \in S \tag{4.21}$$

Where:

$\pi_{k,s}^{v,\gamma}$	Dual variable related to the constraint (4.15) at iteration v, scenario s
$\pi_{k,s}^{v,f}$	Dual variable related to the constraint (4.17) at iteration v, scenario s
$z_s(x^v)$	Value of the objective function (4.12) at iteration v
x_k^v	Investment decision of circuit k at iteration v

So, the investment subproblem is formulated as follows:

$$Min \sum_{k \in K_C} p_k x_k \tag{4.22}$$

s.t.

$$o_s(x^\mu) - \sum_{k \in K_C} \left(M_k \pi_{k,s}^{\mu,\gamma} - \bar{f}_k \pi_{k,s}^{\mu,f}\right)(x_k - x_k^\mu) \leq 0 \qquad \forall s \in S, \mu = 1, \ldots, v \tag{4.23}$$

At each iteration, the investment (master) subproblem gives a trial transmission expansion plan to the OPF problems, which derive the feasibility cuts based on the OPF solutions, sending them back to the master problem. The coefficients of the Benders cuts capture the marginal effect on the total circuit overload for investing in a candidate circuit, improving the trial expansion plan over the iterations. The iteration process continues until the transmission expansion plan eradicate all circuit overloads in all dispatch scenarios.

Moreover, it is possible to represent a subset of dispatch scenarios inside the investment subproblem. In that case, the OPF constraints related to these dispatch scenarios are included:

$$Min \sum_{k \in K_C} p_k x_k + \rho \sum_{k \in K} \sum_{s \in S_I} \left(f_{k,s}^{\delta+} + f_{k,s}^{\delta-}\right) \qquad \forall s \in S_I \tag{4.24}$$

s.t.

$$o_s(x^\mu) - \sum_{k \in K_C} \left(M_k \pi_{k,s}^{\mu,\gamma} - \bar{f}_k \pi_{k,s}^{\mu,f}\right)(x_k - x_k^\mu) \leq 0 \qquad \forall s \in (S - S_I), \mu = 1, \ldots, v \tag{4.25}$$

$$\sum_{k \in \Omega_i^+} \left(f_{k,s} + f_{k,s}^{\delta+}\right) - \sum_{k \in \Omega_i^-} \left(f_{k,s} + f_{k,s}^{\delta-}\right) = d_{i,s} - \sum_{j \in \Phi_i} g_{j,s} \qquad \forall s \in S_I \tag{4.26}$$

$$f_{k,s} = \gamma_k \Delta\theta_{k,s} \qquad \forall s \in S_I, \forall k \in K_E \qquad (4.27)$$

$$-M_k(1 - x_k) \leq f_{k,s} - \gamma_k \Delta\theta_{k,s} \leq M_k(1 - x_k) \qquad \forall s \in S_I, \forall k \in K_C \qquad (4.28)$$

$$-\overline{f_k} \leq f_{k,s} \leq \overline{f_k} \qquad \forall s \in S_I, \forall k \in K_E \qquad (4.29)$$

$$-\overline{f_k} x_k \leq f_{k,s} \leq \overline{f_k} x_k \qquad \forall s \in S_I, \forall k \in K_C \qquad (4.30)$$

$$x_k \in \{0,1\} \qquad \forall k \in K_C \qquad (4.31)$$

$$f_{k,s}^{\delta+} \geq 0 \qquad \forall s \in S_I, \forall k \in K \qquad (4.32)$$

$$f_{k,s}^{\delta-} \geq 0 \qquad \forall s \in S_I, \forall k \in K \qquad (4.33)$$

Where S_I, denotes the set of dispatch scenarios represented in the investment subproblem ($S_I \in S$).

4.4 Solution strategy

The convergence of the Benders decomposition may take many iterations depending on the number of candidates and dispatch scenarios. One way to accelerate the convergence process is to solve the problem by applying a heuristic method in the first place that intends to solve it quickly but without ensuring that the final solution is optimal. Then, this suboptimal solution can be used as a "hot-start" to the Benders decomposition to accelerate its convergence. This heuristic method is described in the sequence.

4.4.1 Heuristic method

Initially, the OPF problems are solved for each dispatch scenario s without considering any transmission expansion. Then, the set of scenarios with the highest total circuit overload, named as S_C, is identified.

After that, a MILP is formulated contemplating only those critical scenarios and solved, resulting in a transmission expansion plan. Now, the OPF problems are solved considering the current expansion plan, and, if there are still some scenarios with circuit overload, these are ranked once again, S_C is updated, and a new MILP is solved. This iterative process continues until there is no scenario with circuit overload.

Furthermore, it is possible to calculate benders cuts at each iteration of the method and include them at the beginning of the decomposition method., boosting its convergence process.

Note that the investment decisions are fixed at each iteration, so the new iterations can only add more investment to the expansion plan. Once the heuristic method ends, the expansion plan may contain some redundant circuits due to the "greedy" nature of the solution process. Thus, to identify the redundancies, an OPF is solved for each scenario, removing each candidate at a time from the expansion plan in descending cost order. When a redundant circuit is found, it is eliminated from the expansion plan, and a new round of redundancy check is performed until no redundancies remain.

Even though the redundancies are eliminated, the heuristic method fails to ensure that the final expansion plan is optimal because the investment decisions of previous iterations are not reassessed (only eliminated if they are redundant). Therefore, the Benders decomposition is applied after the heuristic to calculate the optimal expansion plan.

4.4.2 Decomposition method

First, the expansion plan is reset and the investment subproblem is formulated. The solution of OPF for all scenarios, calculated in the first step of the heuristic method, is used to define the S_I dispatch scenarios, representing the most severe scenarios in terms of circuit overload. Thus, the investment subproblem is formulated as described in the equations (4.24) to (4.33).

After that, the benders cuts calculated at each iteration of the heuristic method is added to the investment subproblem and the iterative process begin.

All steps of the algorithm are detailed next

4.4.3 Algorithm steps

- Heuristic method:
    - Step 1: solve the OPF for all scenarios considering the current expansion plan. In case of having no circuit overload, go to step 4;

- Step 2: select the set S_C of critical scenarios and build the corresponding Benders cuts to be added to the investment problem in the decomposition method;
- Step 3: solve the transmission expansion planning by contemplating only the S_C scenarios and include the investment decisions to the network configuration. Go to step 1;
- Step 4: redundancy check, as described in section 4.4.1

- Decomposition method:
  - Step 5: reset the expansion plan an add the Benders cuts generated in step 2 to the investment subproblem;
  - Step 6: solve the investment subproblem representing the S_I scenarios and update the expansion plan;
  - Step 7: solve the OPF in each scenario in the subset $(S - S_I)$ considering the current expansion plan. If there is no circuit overload, stop. Otherwise, rank the scenarios, identify the S_C once more and add to the investment problem the Benders cuts corresponding to them.
  - Step 8: solve again the investment subproblem representing the S_I scenarios, update the expansion plan, and go to step 7.

Regarding the number of stages, considering many in the same optimization problem may make the problem computationally intractable. So, the problem described above is formulated for a single stage (normally this stage represents an entire year). If the expansion horizon is larger than a stage (year), this strategy is performed stage by stage, going forward in time and considering that the investment decisions of previous stages are fixed.

4.5 Generation deviation

Considering that the dispatch decisions are fixed during the transmission expansion planning, the resulting investment decisions may be too conservative as they accommodate exactly those setpoints. However, in some situations, minor deviations from the original setpoint may avoid some investment in new circuits without compromising the robustness of the expansion plan, resulting in a lower total cost than the solution without any deviation.

It is possible to represent this deviation in the transmission expansion planning problem, by including the variable g^{δ} in some constraints at the OPF problem:

$$o_s(x) = Min \sum_{k \in K} \left(f_{k,s}^{\delta+} + f_{k,s}^{\delta-} \right) + \delta^g \sum_{j \in J} \left| g_{j,s}^{\delta} \right| \qquad \forall s \in S \qquad (4.34)$$

s.t.

$$\sum_{k \in \Omega_i^+} \left(f_{k,s} + f_{k,s}^{\delta+} \right) - \sum_{k \in \Omega_i^-} \left(f_{k,s} + f_{k,s}^{\delta-} \right) + \sum_{j \in \Phi_i} g_{j,s}^{\delta} = d_{i,s} - \sum_{j \in \Phi_i} g_{j,s} \qquad (4.35)$$

$$f_{k,s} = \gamma_k \Delta\theta_{k,s} \qquad \forall k \in K_E \qquad (4.36)$$

$$-M_k(1 - x_k) \leq f_{k,s} - \gamma_k \Delta\theta_{k,s} \leq M_k(1 - x_k) \qquad \forall k \in K_C \qquad (4.37)$$

$$-\overline{f_k} \leq f_{k,s} \leq \overline{f_k} \qquad \forall k \in K_E \qquad (4.38)$$

$$-\overline{f_k} x_k \leq f_{k,s} \leq \overline{f_k} x_k \qquad \forall k \in K_C \qquad (4.39)$$

$$x_k \in \{0,1\} \qquad \forall k \in K_C \qquad (4.40)$$

$$f_{k,s}^{\delta+} \geq 0 \qquad \forall k \in K \qquad (4.41)$$

$$f_{k,s}^{\delta-} \geq 0 \qquad \forall k \in K \qquad (4.42)$$

$$\underline{g_j^{\delta}} \leq g_{j,s}^{\delta} \leq \overline{g_j^{\delta}} \qquad \forall j \in J \qquad (4.43)$$

Where:

$g_{j,s}^{\delta}$	Generation deviation of plant *j* in scenario *s*
$\underline{g_j^{\delta}}$	Lower bound for the generation deviation of plant *j*
$\overline{g_j^{\delta}}$	Upper bound for the generation deviation of plant *j*
δ^g	Generation deviation penalty

The same modifications are applied in the investment subproblem:

$$Min \sum_{k \in K_C} p_k x_k + \rho \sum_{k \in K} \left(f_{k,s}^{\delta+} + f_{k,s}^{\delta-} \right) + \frac{\delta^g}{n(S_I)} \sum_{j \in J} \left| g_{j,s}^{\delta} \right| \qquad \forall s \in S_I \qquad (4.44)$$

s.t.

$$o_s(x^{\mu}) - \sum_{k \in K_C} \left(M_k \pi_{k,s}^{\mu,\gamma} - \overline{f_k} \pi_{k,s}^{\mu,f} \right) \left(x_k - x_k^{\mu} \right) \leq 0 \qquad \forall s \in (S - S_I), \mu = 1, \dots, \nu \qquad (4.45)$$

$$\sum_{k\in\Omega_i^+}\left(f_{k,s}+f_{k,s}^{\delta+}\right)-\sum_{k\in\Omega_i^-}\left(f_{k,s}+f_{k,s}^{\delta-}\right)+\sum_{j\in\Phi_i} g_{j,s}^{\delta}=d_{i,s}-\sum_{j\in\Phi_i} g_{j,s} \qquad \forall s\,\epsilon\,S_I \qquad (4.46)$$

$$f_{k,s}=\gamma_k\Delta\theta_{k,s} \qquad \forall s\,\epsilon\,S_I,\forall k\,\epsilon\,K_E \qquad (4.47)$$

$$-M_k(1-x_k)\leq f_{k,s}-\gamma_k\Delta\theta_{k,s}\leq M_k(1-x_k) \qquad \forall s\,\epsilon\,S_I,\forall k\,\epsilon\,K_C \qquad (4.48)$$

$$-\overline{f_k}\leq f_{k,s}\leq\overline{f_k} \qquad \forall s\,\epsilon\,S_I,\forall k\,\epsilon\,K_E \qquad (4.49)$$

$$-\overline{f_k}x_k\leq f_{k,s}\leq\overline{f_k}x_k \qquad \forall s\,\epsilon\,S_I,\forall k\,\epsilon\,K_C \qquad (4.50)$$

$$x_k\in\{0,1\} \qquad \forall k\in K_C \qquad (4.51)$$

$$f_{k,s}^{\delta+}\geq 0 \qquad \forall s\,\epsilon\,S_I,\forall k\,\epsilon\,K \qquad (4.52)$$

$$f_{k,s}^{\delta-}\geq 0 \qquad \forall s\,\epsilon\,S_I,\forall k\,\epsilon\,K \qquad (4.53)$$

$$\underline{g_j^{\delta}}\leq g_{j,s}^{\delta}\leq\overline{g_j^{\delta}} \qquad \forall s\,\epsilon\,S_I,\forall j\,\epsilon\,J \qquad (4.54)$$

Where $n(S_I)$ denotes the number of elements in S_I and is included to maintain the order of magnitude of the total penalization cost for generation deviation between the investment subproblem (contemplates more than one dispatch scenario) and the OPF problems (represents only one scenario).

The application of these deviations will be explored as an alternative for the integrated generation and transmission expansion planning, presented in the next Chapter.

5 Generation and Transmission Expansion Planning Alternatives

5.1 Introduction

This Chapter proposes alternatives for integrated generation and transmission expansion planning based on the methodologies presented in the previous chapters. In each alternative, these methods are applied sequentially. In the first approaches, some network constraints will be simplified. But, as we go through the alternatives, the network representation will be improved, until reaching the full representation.

Moreover, the last alternatives are expected to present a slower convergence due to a more detailed representation of the network. The idea is to evaluate the trade-off between the quality of the solution and computational effort among all proposed alternatives.

5.2 Alternative 1 (A1) – Hierarchical approach

In the hierarchical approach, expansion planning is performed in two steps. The first step is calculating the generation expansion plan disregarding the network representation. The second consists of calculating the transmission expansion plan, considering the fixed generation expansion and dispatch decisions taken in the first step.

For the first step, the methodology presented in section 3.3 is applied, removing all variable or constraints related to the transmission network. The generation expansion plan and dispatch scenarios are produced as a result of this step. After that, the methodology of Chapter 4 is applied to calculate the transmission expansion plan. Finally, the SDDP methodology, described in section 3.2, is used for the operating simulation, considering the G&T expansion plan calculated in the previous steps. This final step is vital to validate the final expansion plan and calculate the actual operating costs.

The flowchart below illustrates this approach:

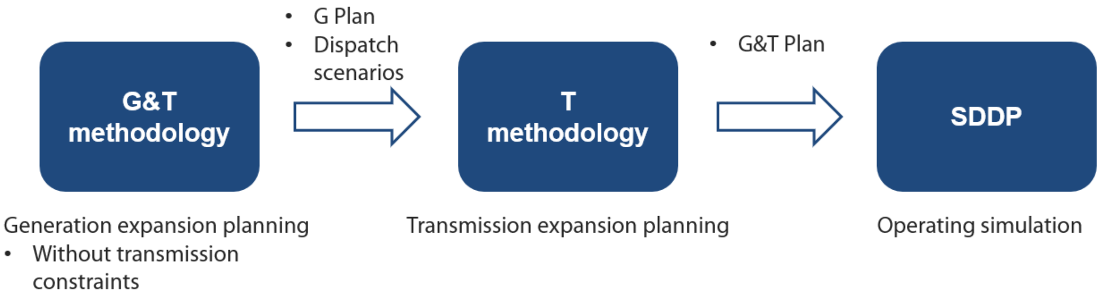

Figure 10 - A1 - Hierarchical approach

Note that the hierarchical approach differs from the integrated approach, as the generation decisions are not taken with network constraints. So, this alternative will be used as a benchmark for the following ones.

5.3 Alternative 2 (A2) – Generation deviation

This alternative is similar to A1. The only difference is that the generation deviation presented in section 4.5 is applied in the second step. This representation is expected to avoid some investment in the transmission network by minor adjustments in the dispatch scenarios produced by the first step, resulting in a lower total cost than the previous alternative. The flowchart below details the steps for this alternative:

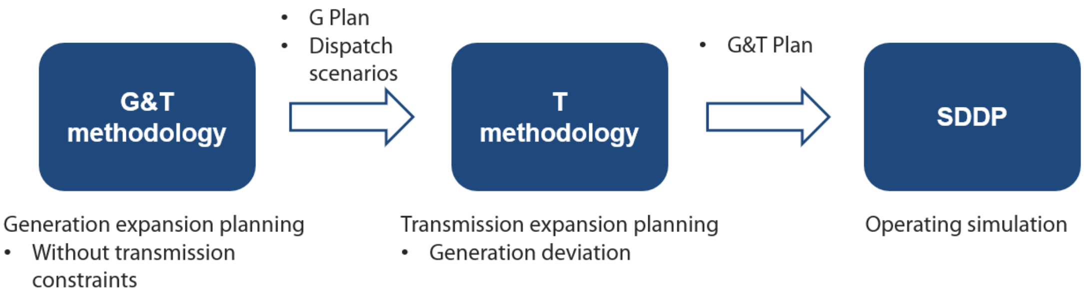

Figure 11- A2 - Generation deviation

5.4 Alternative 3 (A3) – Integrated approach without KVL constraints

This alternative introduces the integrated generation and transmission expansion planning in the first step. However, the network is simplified, and the constraints related to the second Kirchhoff law ((3.92) and (3.93)) are not represented. So, only the first Kirchhoff law (KCL) and the operating limits are included in the model.

The KVL constraints for circuit candidates, as discussed in section 3.3.2, may lead to a slower convergence in the Benders decomposition. So, eliminating these constraints facilitates the convergence process.

The G&T expansion plan calculated in the first step, by neglecting the KVL, may not comply with the complete network constraints. So, it is necessary to keep the second step, without simplifications in the network representation, to complement the initial transmission expansion plan with new circuits and make the final expansion plan meet all operating constraints. As always, the operating simulation is performed considering the final G&T expansion plan at the end, as described in the figure below:

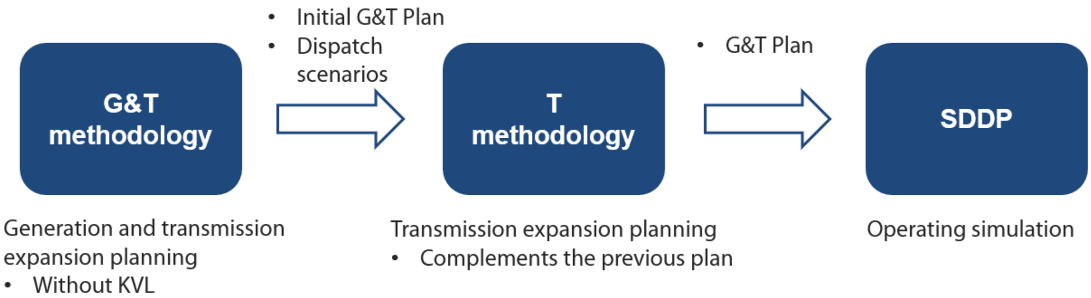

Figure 12 - A3 - Integrated approach without KVL

The presence of a representation of the network in the first methodology, even simplified, may result in a better expansion plan than the previous alternatives, in which the generation expansion is planned separately from the transmission expansion.

In this and in the next alternatives, the generation deviation is no longer represented in the second step.

5.5 Alternative 4 (A4) – Integrated approach without KVL constraints only for the circuit candidates

To enhance the network representation in the previous strategy without affecting the convergence process in the first step, this alternative represents the KVL constraints only for the existing circuits (only neglecting equation (3.93)). This strategy avoids the inclusion of the disjunctive formulation into the Benders decomposition, which tends to slow the convergence because of the disjunctive constant M_k.

Once again, the second step is necessary to complement the transmission expansion plan, and the SDDP is applied at the end considering the final G&T expansion plan, as presented below:

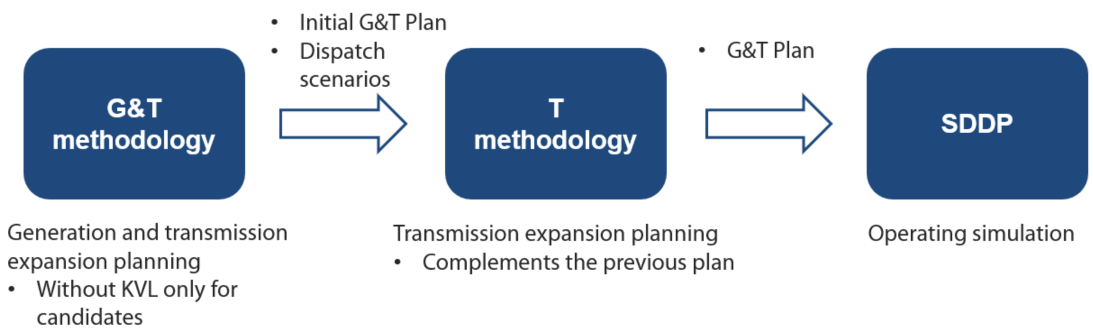

Figure 13 - A4 - Integrated approach without KVL for candidates

Despite not representing the KVL constraints for all circuits, the addition of these constraints for some circuits induces a higher computational effort to solve the problem compared to the previous approach.

5.6 Alternative 5 (A5) – Integrated approach without policy recalculation

The first step decomposes the problem into an investment and an operating subproblem. The latter is solved using the SDDP methodology, which decomposes the multi-stage hydrothermal dispatch problem into multiple one-stage problems. To keep the coherence of the reservoir operating along the stages, it approximates a future cost function for each one-stage problem. This approximation can be named by "policy" calculation.

The construction of new hydroelectric plants with big reservoirs is becoming more unlikely, given the current global concern about the environmental impact that this undertaking causes. So, depending on the type of candidates that are considered in the expansion planning (if there are not hydro plant projects on the list, for instance), it may be reasonable to assume that the operating policy of the reservoirs will remain mostly the same in the future years.

So, this alternative proposes to avoid recalculating the future cost functions at each iteration of the Benders decomposition in the first step. In this case, the future cost function must be given at the beginning of the optimization and will be fixed throughout the whole convergence process. Therefore, this strategy saves CPU time in the iterations of the first module.

Furthermore, the network constraints are totally represented and modeled by the compact formulation described in section 0, which reduces the network model's number of constraints and variables, contributing for the computational efficiency of the algorithm.

As the network is fully represented, applying the transmission expansion planning methodology is unnecessary after the first step. Still, the operating simulation at the end is necessary to calculate the future cost functions coherent with the final G&T expansion plan.

The flowchart below illustrates this strategy:

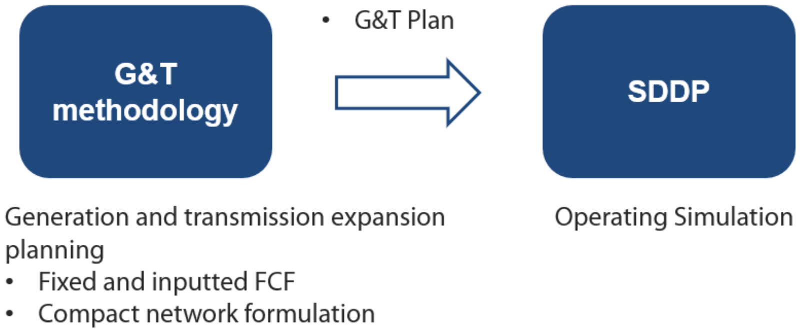

Figure 14 - Integrated approach without policy recalculation

5.7 Alternative 6 (A6) – Integrated approach

This final alternative proposes to apply the integrated generation and transmission expansion planning without any simplification in the formulation and solution of the optimization problem. Thus, further steps than the first module are dispensable, as described in the figure below:

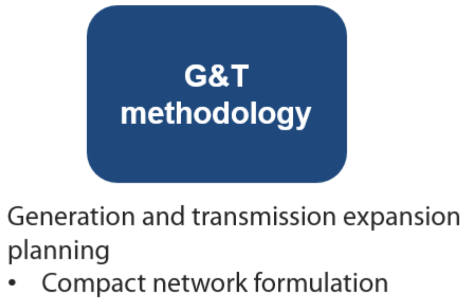

Figure 15 - Integrated approach

As this strategy consists of a completely integrated approach, it is foreseen that it will produce the expansion plan with the lowest total cost compared to the remaining alternatives. However, depending on the size of the system and the number of candidates, the convergence process may be disturbed.

5.8 N-1 security constraints

All the alternatives proposed above are not contemplating the N-1 security criterion in the transmission. Although the methodology does not impede representing this criterion in the strategies mentioned above, a different approach is recommended to include this criterion in the G&T expansion planning because the representation of it significantly increases the size of the optimization problem (as explained in section 3.2.3.6).

Given a generation and transmission expansion plan calculated by any alternative without considering the N-1 criterion, the expansion planning can be started once more, now contemplating this criterion in the optimization. The flowchart below describes the approach:

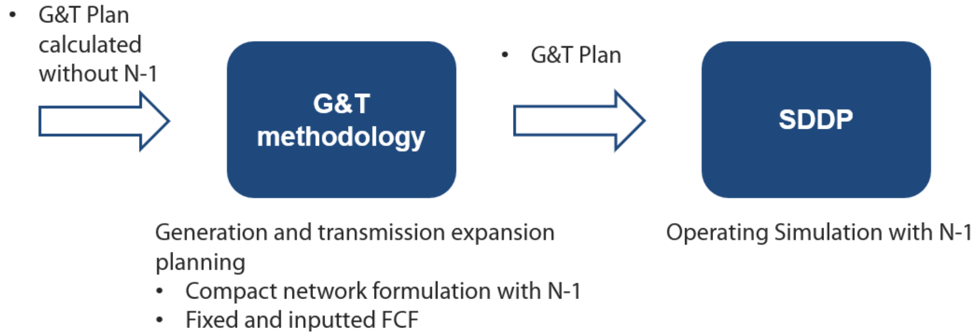

Figure 16 - Inclusion of the N-1 criterion

Thus, in this case, the first step will complement the G&T expansion plan with more investment in generation and transmission to accommodate the N-1 criterion. It is proposed to refrain from recalculating the future cost functions in this step to avoid convergence problems, as performed in A5. After that, the operating simulation is executed, considering the N-1 criterion as well.

In the next Chapter, all approaches present in this Chapter will be applied in two different case studies.

6 Case Studies

6.1 Introduction

This Chapter presents two case studies where the alternatives shown in the previous Chapter were applied to calculate the generation and transmission expansion plan. The first case consists of the Garver 6-bus systems with some modifications in the assumptions. The next is a representation of the Chilean power system. In both cases, the results obtained by each proposed alternative are compared and discussed.

For all steps presented in each alternative for the G&T expansion planning, the software OPTGEN [58] (methodology described in section 3.3), NETPLAN [59] (methodology described in Chapter 4), and SDDP [56] (hydrothermal dispatch optimization, described in section 3.2) were used.

6.2 Garver 6-bus

6.2.1 Assumptions

The system is composed of six buses, connected by six transmission lines, as shown in the diagram below:

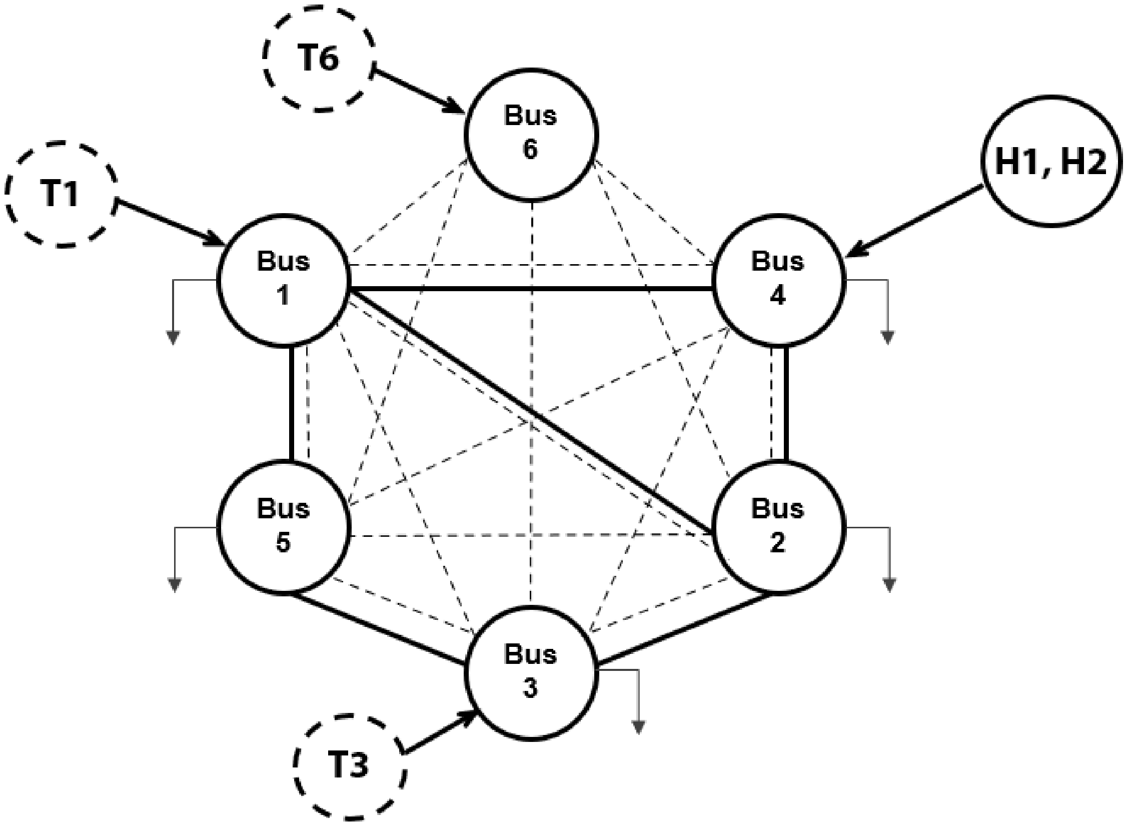

Figure 17 - Garver 6-bus

The solid lines point out the existing elements, and the dashed lines, the candidate elements.

6.2.1.1 Generation data

There are two existing hydro plants connected to bus 4 and three candidate thermal plants connected to buses 1, 3, and 6. The tables below present the characteristics of these plants:

Table 2 - Garver 6-bus - Thermal plants

Name	Existing/Candidate	Connection bus	Operating cost ($/MWh)	Investment cost ($/kW)	Installed capacity (MW)
T1	Candidate	1	14	900	230
T3	Candidate	3	12	800	420
T6	Candidate	6	10	700	600

T1 has the most expensive operating and investment cost, followed by T3 and T6. Although T6 is the cheapest thermal plant with the highest capacity, it is connected to an isolated bus.

Table 3 - Garver 6-bus - Hydro plants

Name	Existing/ Candidate	Connection bus	Mean production coefficient ($MW/m^3/s$)	Maximum turbined outflow (m^3/s)	Storage capacity (hm^3)	Initial storage (hm^3)	Installed capacity (MW)
H1	Existing	4	1.5	100	100	100	150
H2	Existing	4	1.5	100	-	-	150

Both hydro plants are connected to the same bus and have similar parameters. The only difference is that H1 has a reservoir, and H2 is a run-of-river plant. Concerning the hydro topology, H1 turbines and spills to H2, which, in turn, turbines and spills to the sea.

6.2.1.2 Transmission data

The transmission system has six existing lines with the following parameters:

Table 4 - Garver 6-bus - Existing lines

Name	Existing/ Candidate	FROM bus	TO bus	Reactance (%)	Capacity (MW)
1-2-1	Existing	1	2	4	100
1-4-1	Existing	1	4	6	80
1-5-1	Existing	1	5	2	100
2-3-1	Existing	2	3	2	100
2-4-1	Existing	2	4	4	100
3-5-1	Existing	3	5	4	100

Besides the terminal buses, the existing lines have different reactances, and line 1-4-1 has a lower capacity them the remaining circuits. Also, there is no existing circuit connecting bus 6 to other buses.

The candidates are defined for branch with the following parameters:

Table 5 - Garver 6-bus - Candidate lines

Name	Existing/ Candidate	FROM bus	TO bus	Reactance (%)	Capacity (MW)	Investment cost (M$)
1-2-2	Candidate	1	2	4	100	50
1-3-1	Candidate	1	3	3.8	100	45
1-4-2	Candidate	1	4	6	80	45
1-5-2	Candidate	1	5	2	100	50
1-6-1	Candidate	1	6	3.4	140	110
2-3-2	Candidate	2	3	2	100	50
2-4-2	Candidate	2	4	4	100	50
2-5-1	Candidate	2	5	3.1	100	50
2-6-1	Candidate	2	6	1.5	200	150
3-4-1	Candidate	3	4	5.9	82	46.1
3-5-2	Candidate	3	5	4	100	50
3-6-1	Candidate	3	6	2.4	200	150
4-5-1	Candidate	4	5	6.3	75	42.5
4-6-1	Candidate	4	6	3	100	150
5-6-1	Candidate	5	6	3	156	120

The candidate lines connecting bus 6 to other buses are the most expensive ones.

6.2.1.3 Additional data

The study horizon considered in this case study is one year, divided into 12 stages (months). For all months, the demand is presented below:

Table 6 - Garver 6-bus - Demand

Bus	Demand (MW)
1	80
2	240
3	40
4	160
5	240
6	0

Finally, there are deterministic water inflows considered exclusively in the hydro plant H1, as follows:

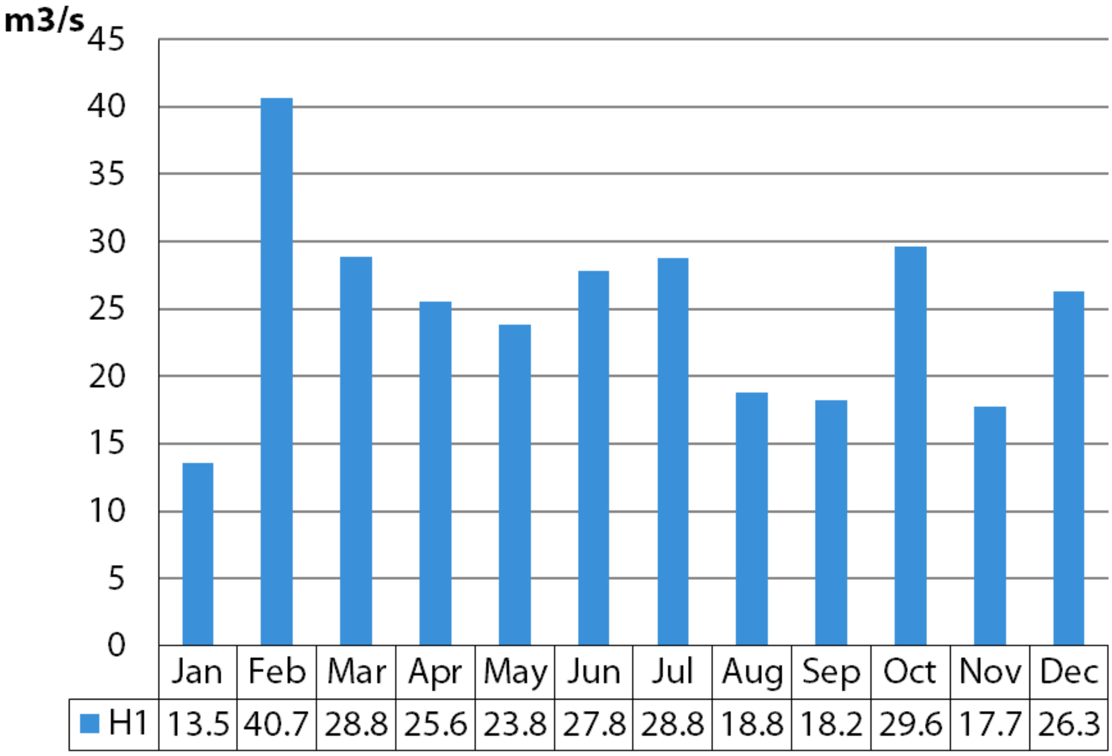

Figure 18 - Garver 6-bus - H1 water inflows

For H2, there are no incremental inflows considered (it only receives water from H1).

6.2.2 Results

6.2.2.1 Alternative 1

The figure below presents the expansion plan generated by alternative 1. The elements decided by the first step are highlighted in green, and the elements decided by the second step, in red.

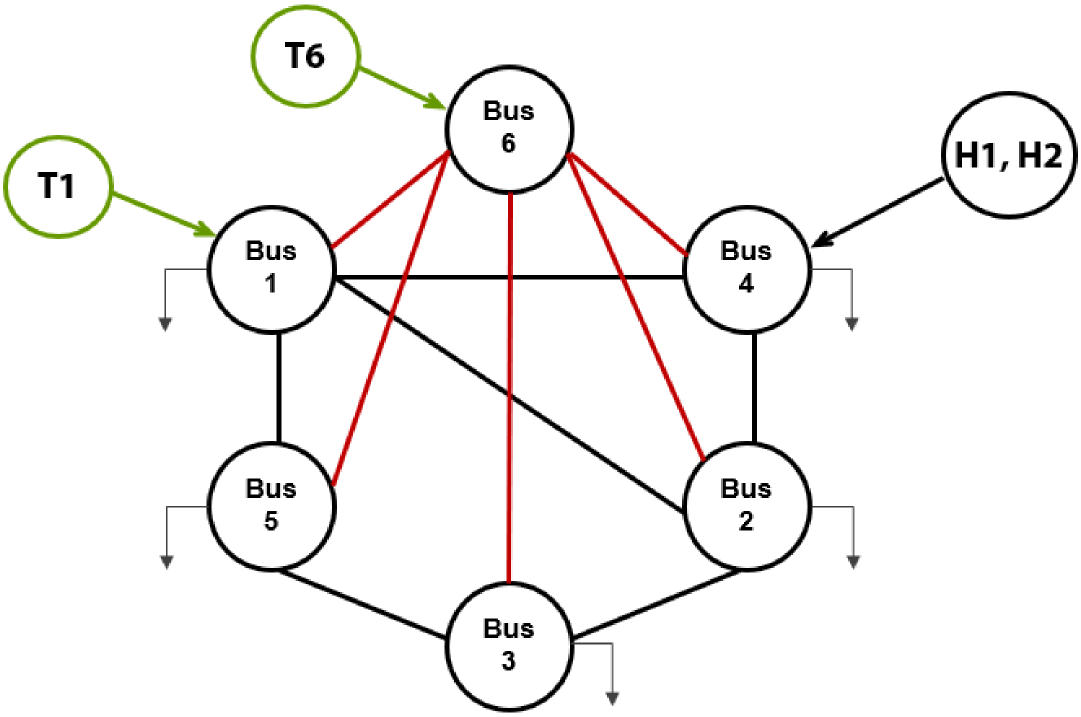

Figure 19 - Garver 6-bus - A1 expansion plan

The network constraints are not represented in the first step, so the model opted to invest in T6, in addition to T1, as it has the cheapest investment and operating costs. However, it caused further investments in transmission in the second step, in which all circuits connecting bus 6 to the remaining buses were selected by the model to accommodate the generation of T6. The generation setpoints were calculated without transmission constraints, so the model maximized the dispatch of T6.

6.2.2.2 Alternative 2

The representation of generation deviation in the transmission expansion planning is permitted in A2. In that case, the deviation limit was considered equal to 5%. The resulting expansion plan is presented below:

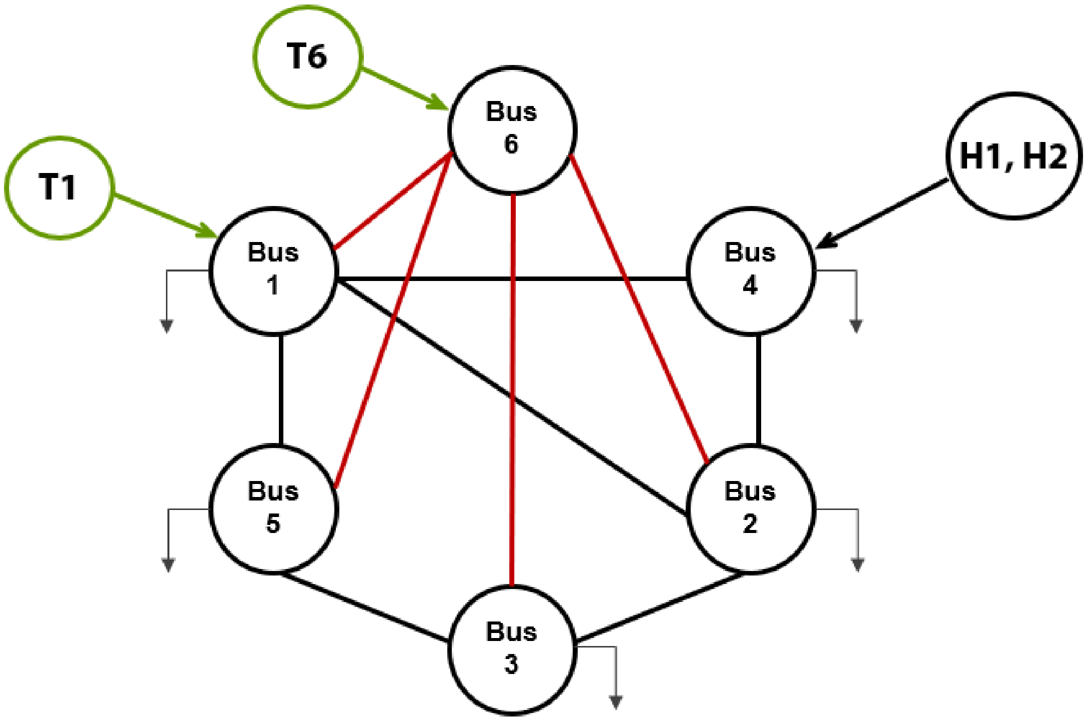

Figure 20 - Garver 6-bus - A2 expansion plan

The model saw benefit in modifying the generating setpoints, especially in reducing T6 to avoid the expansion of transmission line 4-6-1.

6.2.2.3 Alternative 3

In A3, the first step represents some constraints related to the network (first Kirchhoff law and operating limits) in the optimization. Also, at the same step, the expansion of generators and transmission elements is permitted. The resulting expansion plan is shown below:

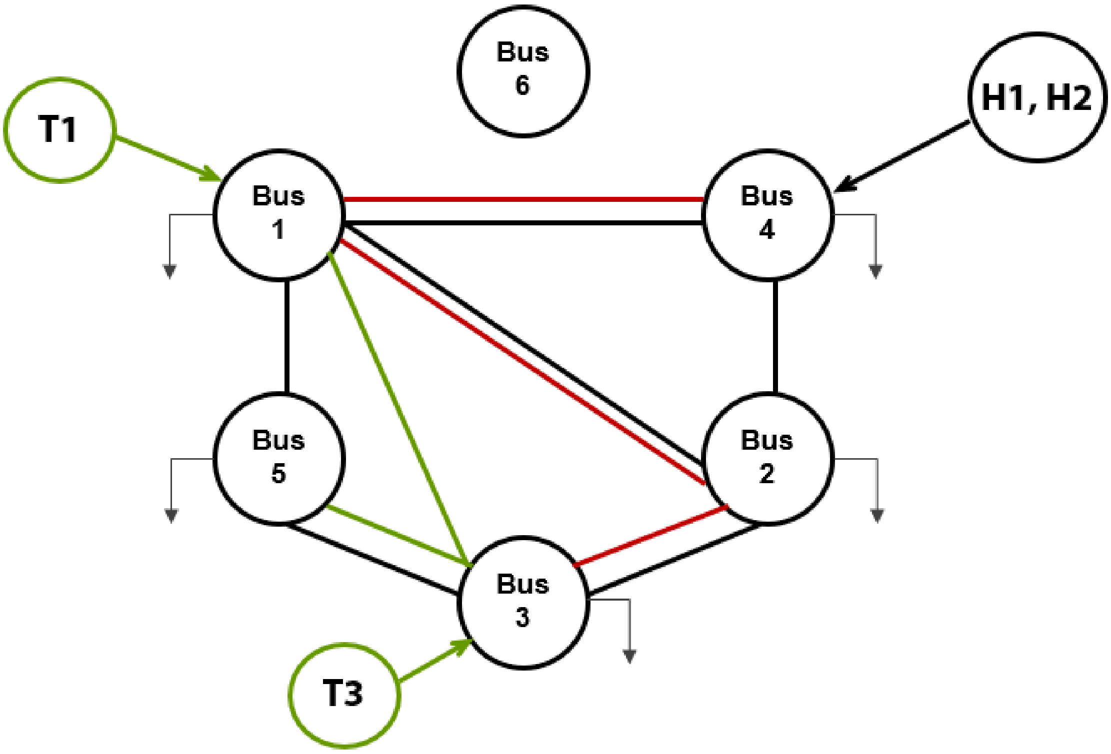

Figure 21 - Garver 6-bus - A3 expansion plan

The presence of those network constraints was sufficient to avoid the expansion of T6, which requires expansive reinforcements in the grid. To replace T6, T3 was selected.

The grid reinforcements highlighted in green were selected to accommodate the generation of the new generators. However, as the first step is not considering the KVL constraints, the investment in the lines in red was necessary to meet all network constraints in the second step.

6.2.2.4 Alternative 4

A4 adds the KVL constraints for existing circuits in comparison to A3. The presence of such constraints changed the decision in transmission reinforcements in the first step, removing the circuit 1-3-1 and including 2-3-2, as illustrated in the following figure:

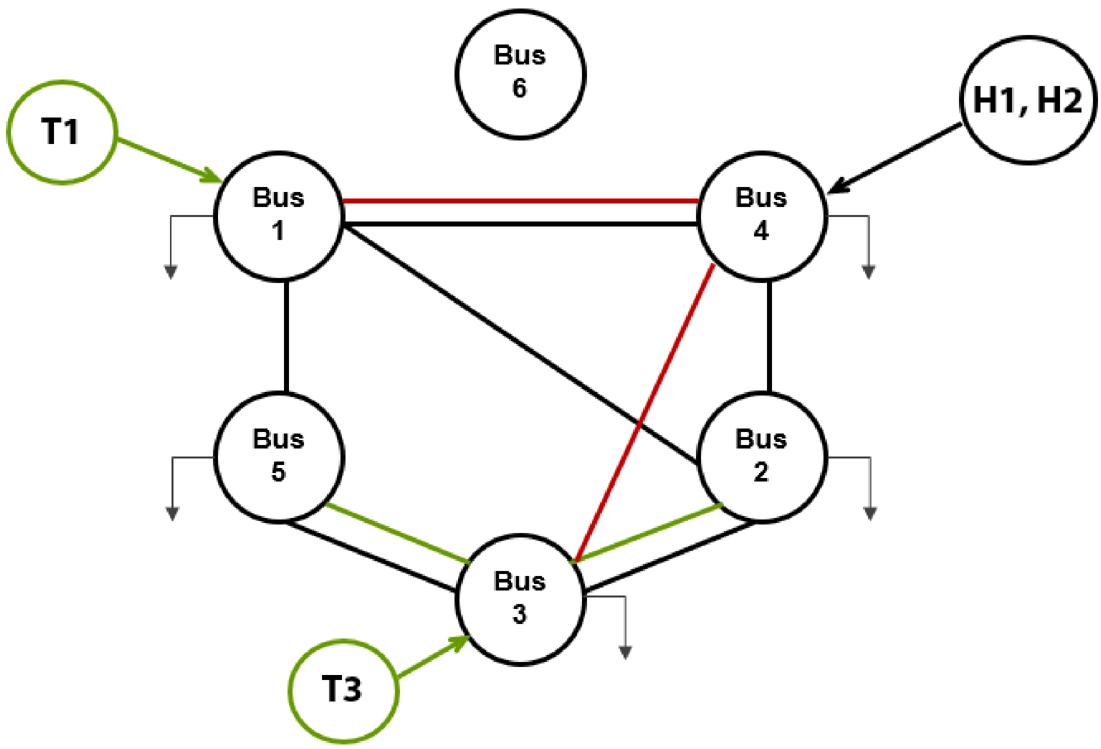

Figure 22 - Garver 6-bus - A4 expansion plan

Therefore, the transmission investment in the second step was reduced to two circuits (1-4-2 and 3-4-1), configuring a lower investment cost than the previous strategy.

6.2.2.5 Alternative 5

In A5, all network constraints are considered in the first step of the expansion planning. On the other hand, the FCFs are not recalculated at each iteration of the algorithm. In this case, the FCF resulting from the last step of A1 is used as an input to this strategy. The resulting expansion plan is presented in the figure below:

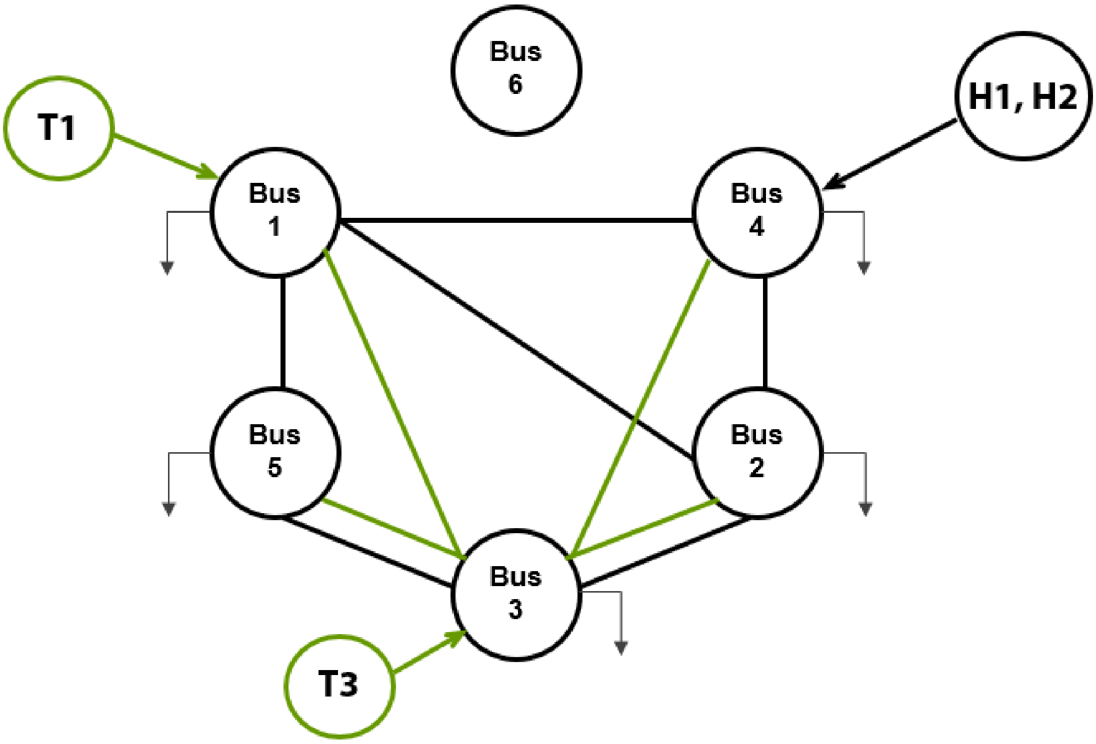

Figure 23 - Garver 6-bus - A5 expansion plan

The result was slightly different from the previous alternative, with minor changes in the selection of the candidate circuits. Circuit 1-4-2 is no longer in the final plan, substituted by circuit 1-3-1.

6.2.2.6 Alternative 6

A6 presents the optimal solution for the G&T expansion planning, as no simplifications are made during the optimization process. The figure below presents this solution:

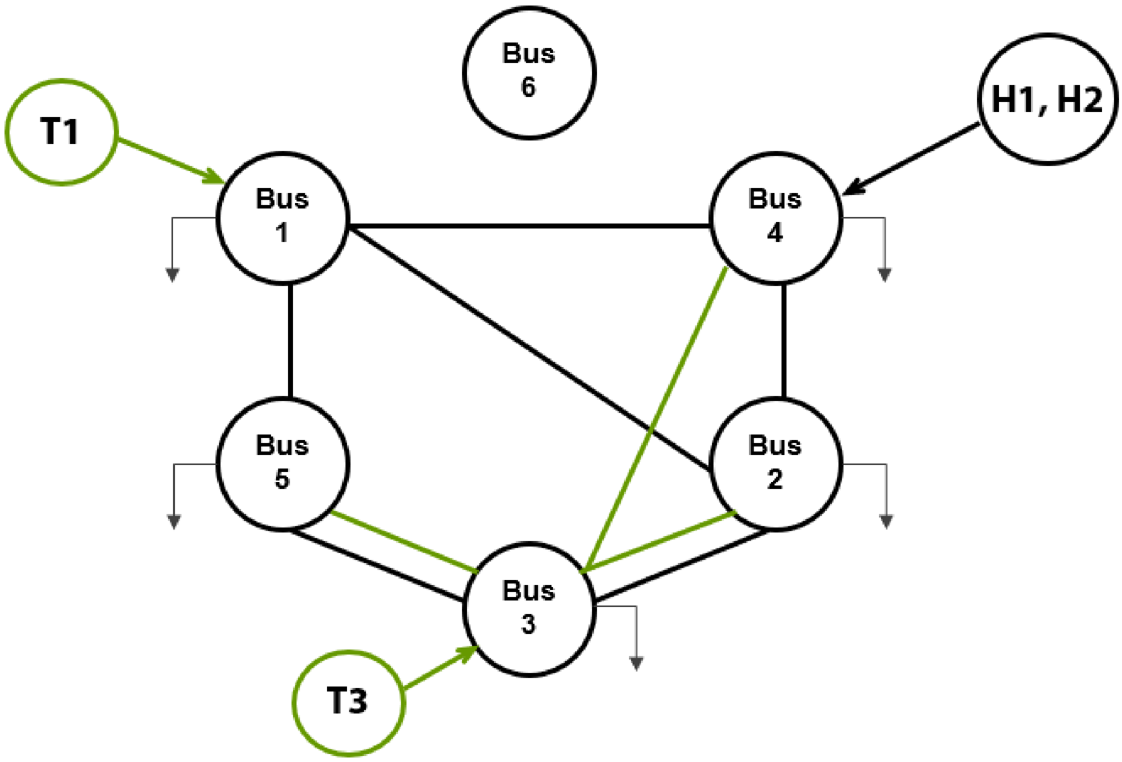

Figure 24 - Garver 6-bus - A6 expansion plan

The recalculation of the operating policy of the existing hydro plants at each iteration gave a more precise signal to the investment module about how the operating costs change with the investment decisions. Consequently, the model saw that removing circuit 1-3-1 from the expansion plan results in a lower total cost than the previous strategy.

6.2.2.7 Comparison

The following table compiles the expansion plan calculated by all alternatives:

Table 7 - Garver 6-bus - Expansion result

Alternative	Step 1	Step 2
1	T1 and T6	1-6-1, 2-6-1, 3-6-1, 4-6-1, and 5-6-1
2	T1 and T6	1-6-1, 2-6-1, 3-6-1, and 5-6-1
3	T1, T3, 1-3-1, and 3-5-2	1-2-2, 1-4-2, and 2-3-2
4	T1, T3, 2-3-2, and 3-5-2	1-4-2 and 3-4-1
5	T1, T3, 1-3-1, 2-3-2, 3-4-1, and 3-5-2	-
6	T1, T3, 2-3-2, 3-4-1, and 3-5-2	-

After calculating the final expansion plan, the third step was performed to calculate the optimal hydrothermal dispatch. The graph below shows the resulting total costs (the investment cost of the expansion plan plus the operating cost of all 12 stages) of all alternatives:

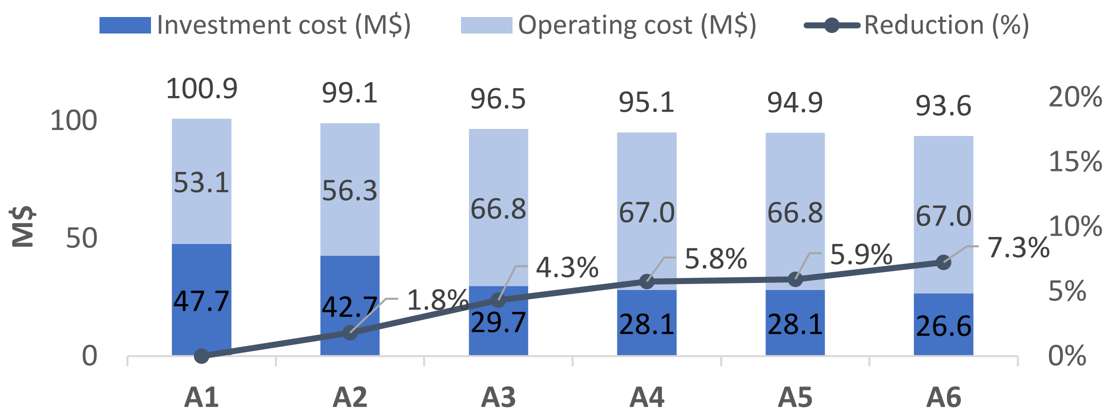

Figure 25 - Garver 6-bus - Total costs

From A1 to A6, the total cost reduces while the system constraints' representation is enhanced in the first expansion problem. Comparing with A1, A2 has a reduction of 1.8%, A3 4.3%, A4 and A5 almost 6% and A6, which represents the optimal solution, 7.3%.

The strategies from A3 to A6, which represent the network somehow during the first step, present a lower investment cost and higher operating costs compared to the hierarchical alternatives (A1 and A2). Despite that, the total costs are lower than these first strategies.

Regarding CPU performance, the graphs below illustrate the convergence process of the first step and the total CPU time.

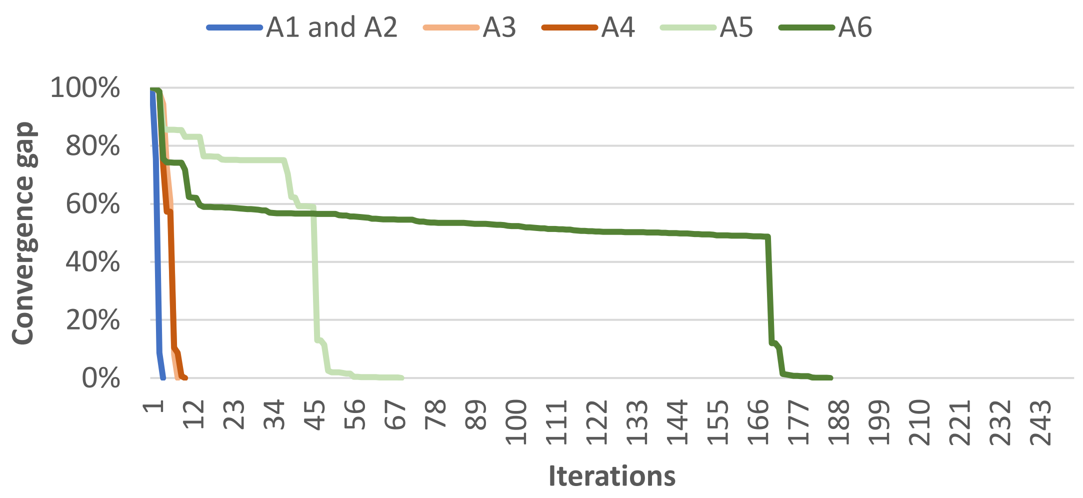

Figure 26 - Garver 6-bus – Convergence

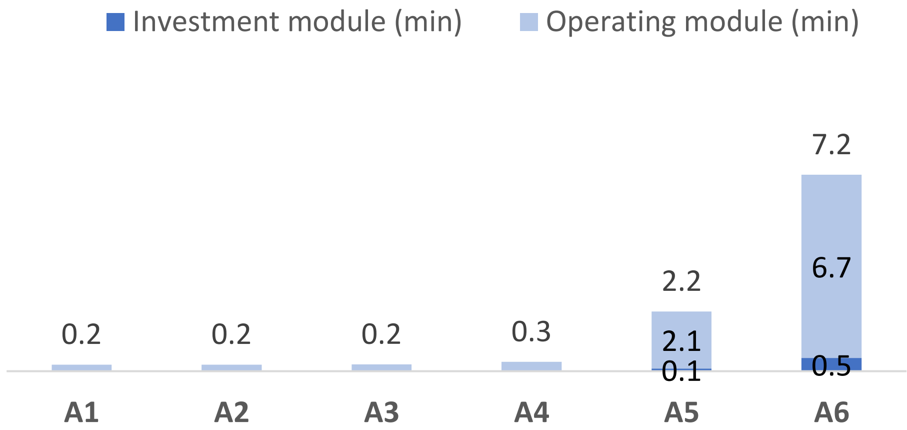

Figure 27 - Garver 6-bus - CPU time

Four iterations were sufficient for A1 and A2 to reach the gap of 0%. The following strategies, A3 and A4, took a few more iterations to converge (8 and 10, respectively), but the total CPU time was lower than 1 minute. When we look at the final alternatives, A5 and A6, the algorithm took more iterations (69 and 186, respectively) due to the disjunctive formulation. The latter, in turn, saved time in the operating module as the FCFs were not recalculated in each iteration.

In the second step, the number of dispatch scenarios was equal to 12 (one for each month). For both heuristic and decomposition methods, all dispatch scenarios were considered in the investment problems. As a result, the algorithm in all alternatives (from A1 to A4) took less than 5 seconds to find the solution, so it did not affect the numbers presented above.

Alternative 6 presents the best results, and despite having the highest CPU time, it is still negligible. However, this case study is too simple and not representative of an actual power system. Depending on the dimensions of the case, A6 may not have a satisfactory computational performance, and other alternatives may stand out with a better trade-off between solution quality and computational time. This behavior will be more evident in the subsequent case study.

6.2.2.8 N-1 security constraint

Two simulations were performed to consider the N-1 security constraints in the expansion planning optimization. The first considered the expansion plan resulted by A6 as fixed and calculated the investment additions to meet the N-1 criterion (named as "Complementary"). The second calculated the expansion plan without any starting point (named as "Complete").

Also, in this exercise, the number of transmission candidates was duplicated. So, each branch presented two candidates with the same parameters.

Both approaches resulted in the same expansion plan, illustrated below. The elements highlighted in blue are the additions compared to the plan calculated by A6.

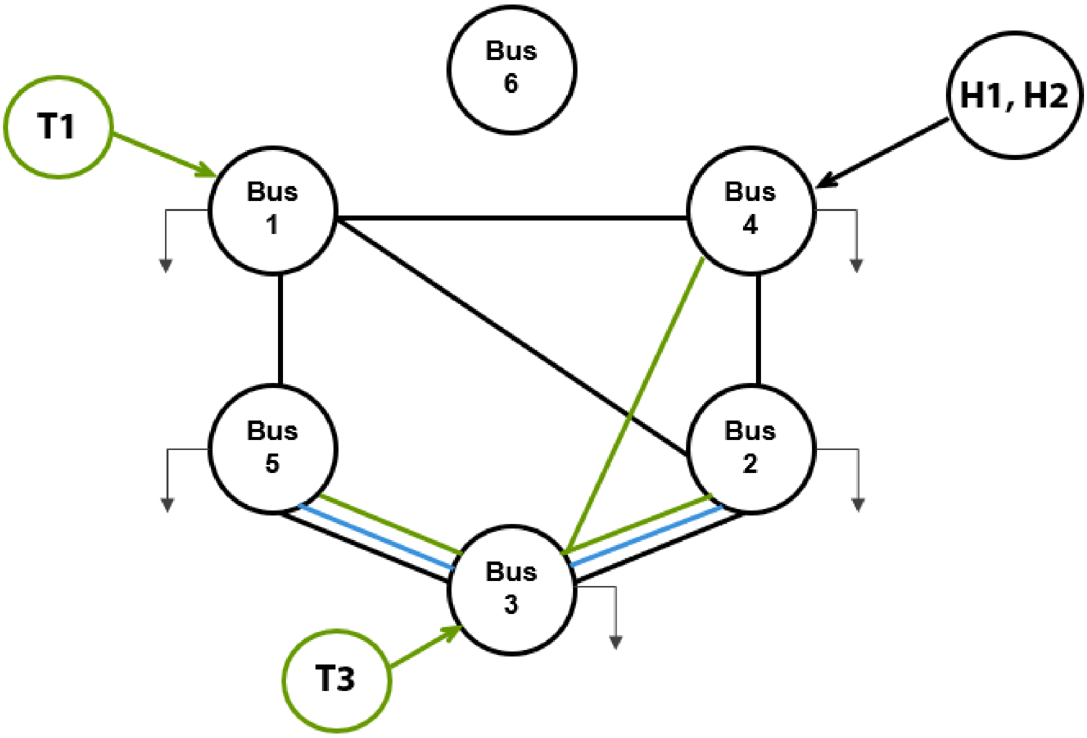

Figure 28 - Garver 6-bus - N-1 expansion plan

The expansion plan is summarized in the table below:

Table 8 - Garver 6-bus - N-1 expansion results

Simulation	Expansion without N-1 criterion	Expansion with N-1 criterion
Complementary	T1, T3, 2-3-2, 3-4-1, and 3-5-2	2-3-3 and 3-5-3
Complete	-	T1, T3, 2-3-2, 3-4-1, 3-5-2, 2-3-3, and 3-5-3

In terms of costs, the inclusion of the N-1 criterion raised the total costs by 3%, as shown below:

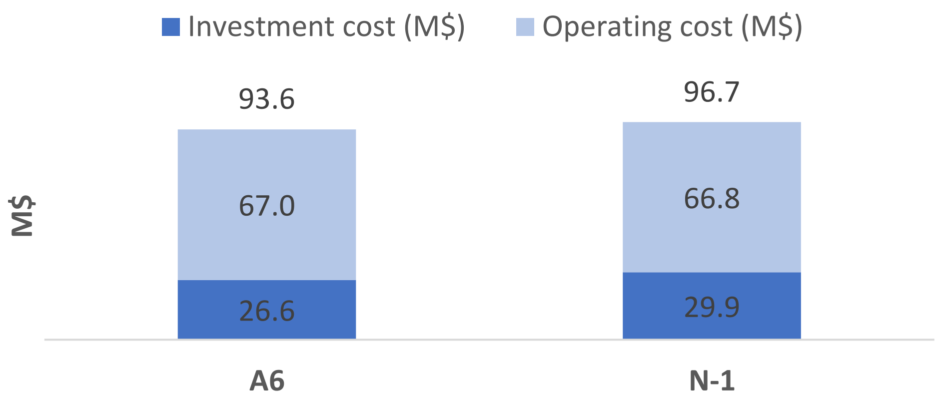

Figure 29 - Garver 6-bus - N-1 total cost

Looking at the computational performance, the charts below present the convergence process and the CPU time of the execution. For comparison purposes, the A6 expansion plan was recalculated considering the same number of candidates for the N-1 approaches.

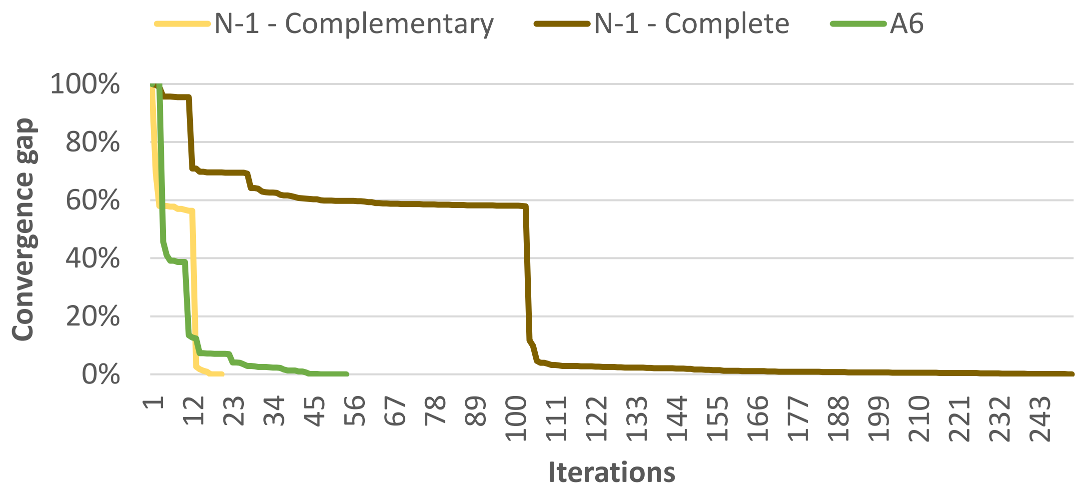

Figure 30 - Garver 6-bus - N-1 convergence

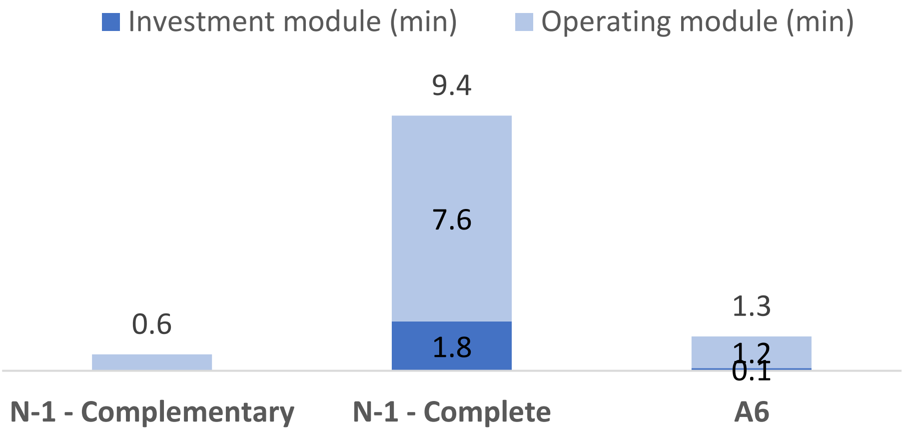

Figure 31 - Garver 6-bus - N-1 CPU time

The complementary approach took 20 iterations to reach the 0% gap, while the complete approach took 252 to find the optimal solution.

Even though both approaches reached the same solution, the complete approach took significantly more time (approximately 15 times) than the complementary approach. Anticipating the convergence performance when applying this methodology in larger systems, the complementary approach seems a good strategy to avoid computational burden during the optimization.

6.3 Chile

This representation of the Chilean power systems was built in the context of a study by PSR, in partnership with Moray consulting group, for the association of generators in Chile, during 2017 and 2018. Because it has realistic generation and transmission dimensions, and the study was public, this case was selected for this work. The following section presents the main assumptions of this case.

6.3.1 Assumptions

6.3.1.1 Generation data

The installed capacity of the Chilean power system in 2017 was 22 GW, for a peak demand of 10 GW. Fossil-fueled plants represent 54 % of total installed capacity (21 % coal, 20 % diesel, 13 % gas), followed by hydro (31 %), VRE (8 % of solar and 6 % of wind), and 2 % of other technology types.

The study horizon considered in the simulations is 2025 to 2030 (6 years). So, a fixed generation and transmission expansion plan from 2018 until 2024 is considered as input to the simulations. The following pie chart presents the installed capacity mix in 2024 in terms of GW and % of the total installed capacity:

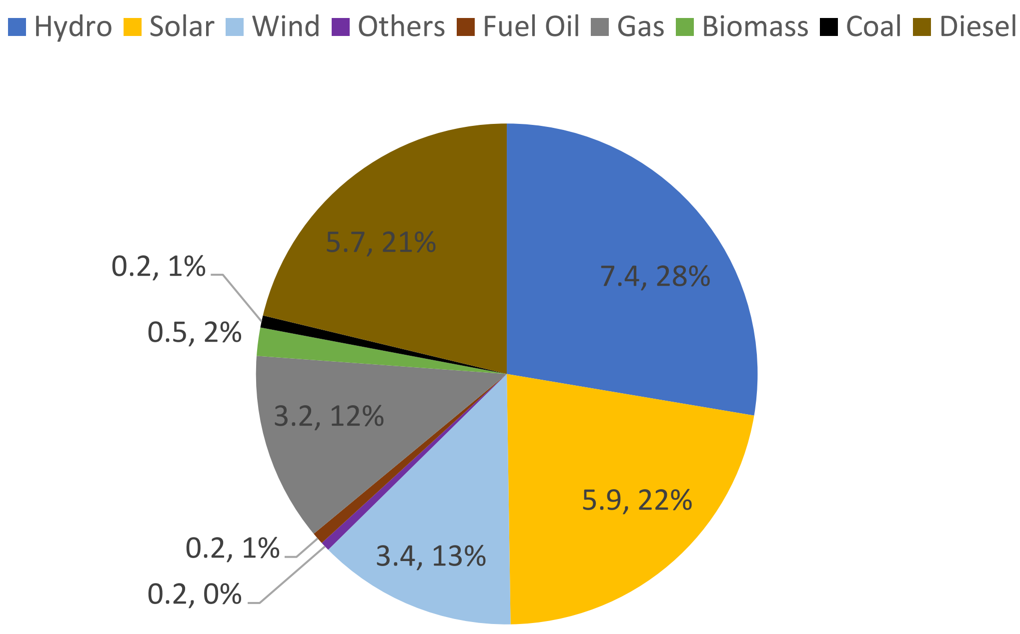

Figure 32 - Chile - Capacity mix in 2024

Regarding the demand, the graph below shows the demand forecast considered for the entire system, including the transmission losses:

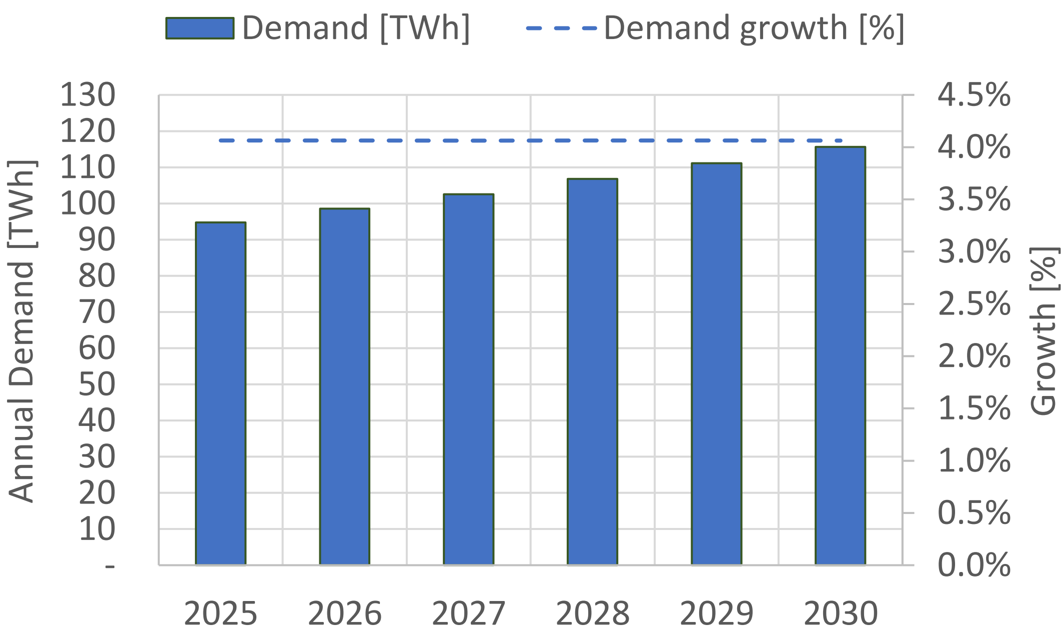

Figure 33 - Chile - Demand forecast

The demand is inputted at the model in hourly resolution for the entire study horizon. However, during the simulations, the demand is clustered into 13 blocks at each stage (month), using the K-means method. So, the model considers 13 levels of demand at each stage, with different lengths according to the clustering result. The following figure illustrates the clustering result for January:

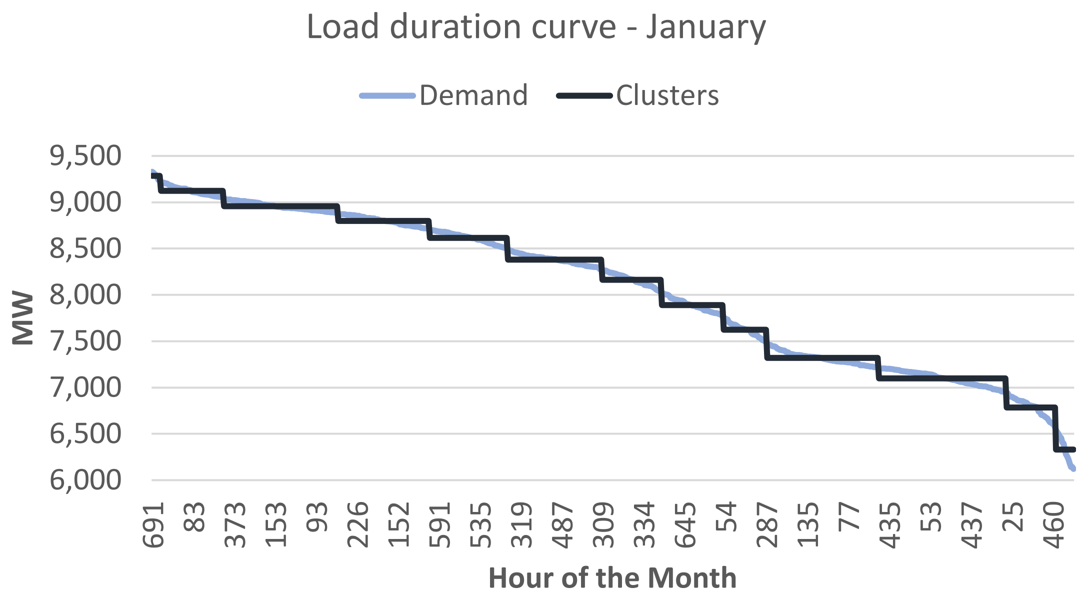

Figure 34 - Chile - Load duration curve

Candidate lists is composed by thermal plants (gas-fired) and VRE (wind and solar). The VRE candidates were created based on the projects that participated in past power supply auctions in Chile. The total capacity of VRE candidates considered during the study horizon (2025 to 2030) are 9.6 GW of solar (182 projects), primarily located in the country's northern region, and 7.1 GW of wind (81 projects), mainly in the Center and South regions. The figure below shows the geographical location of these candidates:

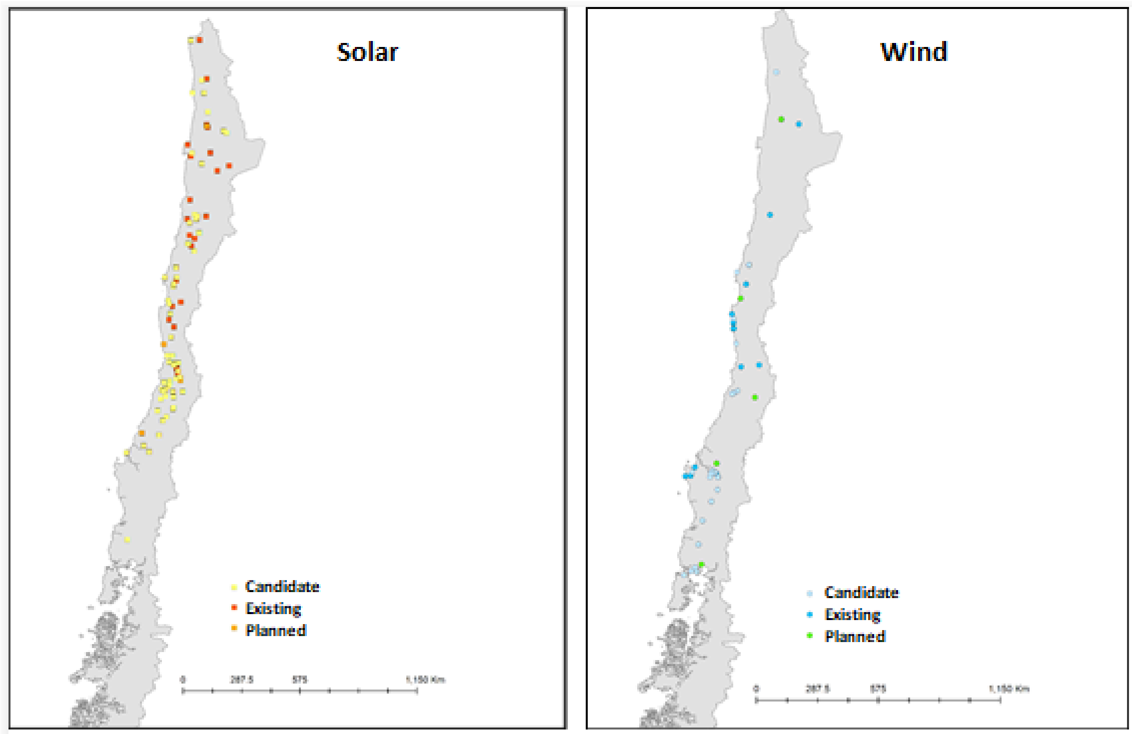

Figure 35 - Chile - VRE location

There is a slight decrease in the investment costs of wind over the years, as described in the graphs below:

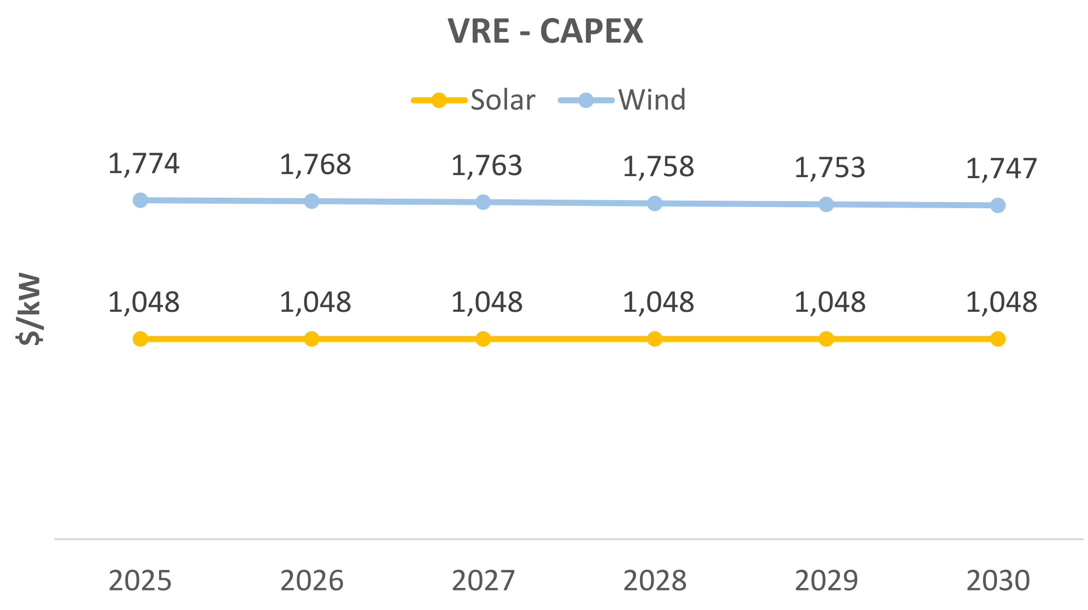

Figure 36 - Chile - VRE investment costs

In addition to the investment costs for the VRE projects illustrated above, fixed operating and maintenance costs are also represented in the investment decisions. For solar power plants, the annual fixed expenses related to operation and maintenance are 1.5% of the investment cost of the projects. For wind projects, the annual expenditure with operation and maintenance is 2% of investment costs. An annual discount rate of

5.7% is considered for all types of candidates to convert the investment costs into annualized costs.

The parameters related to the gas-fired thermal candidates are described below:

Table 9 - Chile - Thermal candidates

Candidate	Installed capacity (MW)	Minimum generation (MW)	Investment cost ($/kW)	Specific consumption (MMBTU/MWh)
OCGT	100	0	864	9.47
CCGT	250	100	1141	6.94

Two types of gas-fired candidates are represented. The opened cycle (OCGT) has lower investment costs, lower capacity, and higher operating costs. On the other hand, the combined cycle (CCGT) presents higher investment costs, higher capacity, and lower operating costs. No fixed operating and maintenance costs were considered for them.

When it comes to the operating costs, the following graphs present the price projections for the fuels consumed by the thermal plants (existing and candidates). To calculate the final operating costs, the individual specific consumption and costs related to fuel transportation and variable operating and maintenance, for each thermal plant, were contemplated.

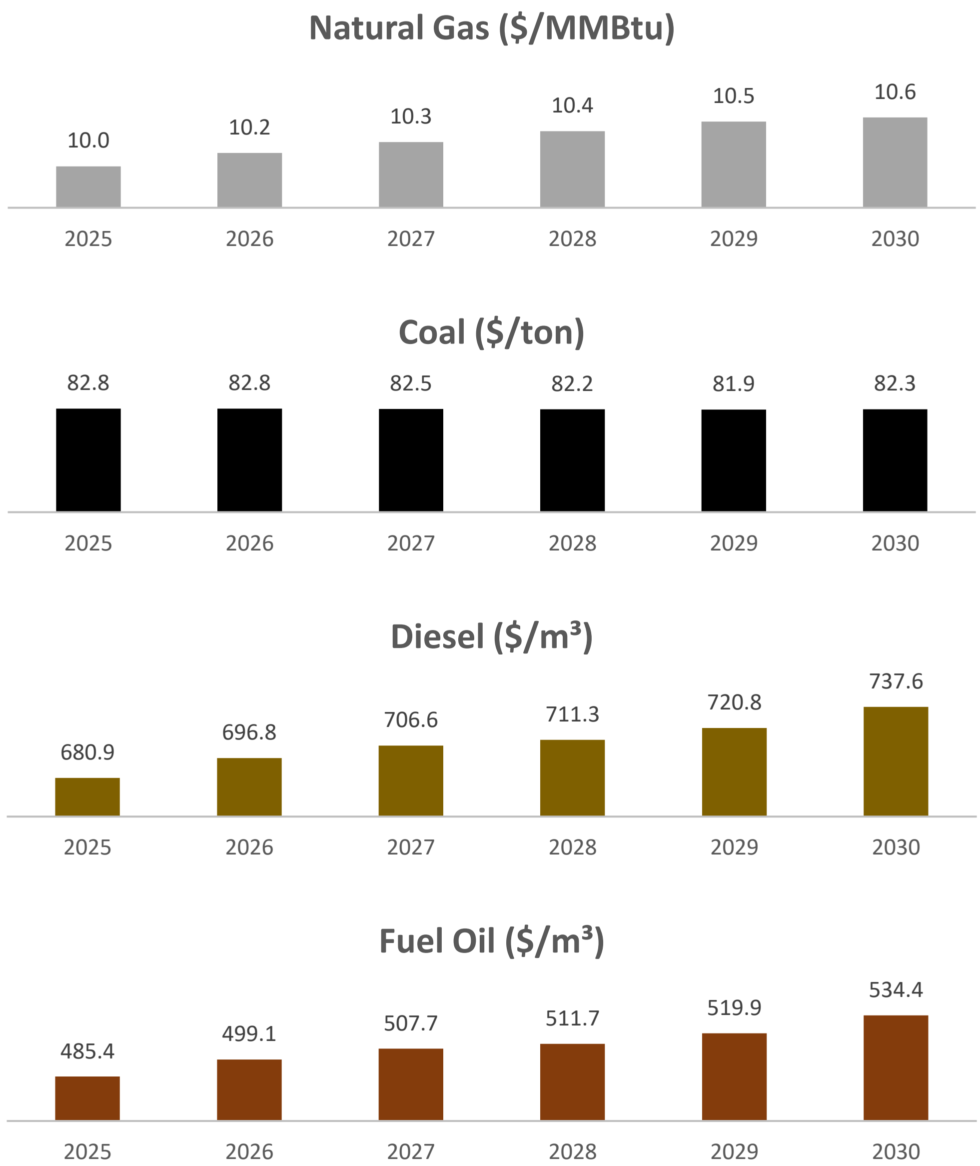

Figure 37 - Chile - Fuel price projections

6.3.1.2 Generation scenarios

The historical water inflow data, used as an input to the model, is 54 years long with monthly values. SDDP manages this information to generate the future inflow scenarios used in the expansion planning optimization, as described in [56]. The table below shows the total inflow energy calculated for the hydroelectric configuration of 2017, for each hydrological year, in ascended order.

Table 10 - Chile - Historical inflow

Ascending order	Inflow energy (GWh)	Year	Ascending order	Inflow energy (GWh)	Year	Ascending order	Inflow energy (GWh)	Year
1	19,464.8	1968	19	32,992.8	1974	37	39,945.4	1979
2	22,029.5	1998	20	33,805	1967	38	40,297.4	1984
3	22,784.3	1996	21	34,008.9	1969	39	40,914.7	1987
4	24,659.4	2012	22	34,202.3	1971	40	41,453.9	1966
5	26,259.1	2013	23	34,396.1	2009	41	41,597.2	1992
6	26,890.4	1962	24	35,028.8	2008	42	42,010.9	2005
7	27,062.3	2010	25	35,644	1985	43	42,075	1986
8	27,653.4	2007	26	35,823.2	1963	44	42,236.4	1997
9	27,717.7	2011	27	35,999.5	2003	45	42,277.4	1977
10	27,924.4	1999	28	36,588.1	1991	46	43,034.1	2001
11	28,238.5	1989	29	37,373.5	1975	47	43,612.2	1978
12	28,420.5	1960	30	37,464.6	1973	48	44,631.2	1993
13	28,507.1	1990	31	38,140.8	1995	49	45,849.3	2002
14	29,920.5	1970	32	38,174.3	1994	50	46,258.3	1965
15	30,052.3	1976	33	38,266	2000	51	46,406.1	2006
16	30,937.8	1964	34	38,945.3	1981	52	46,554	1982
17	31,312.4	1988	35	39,096.5	1983	53	47,992.6	1980
18	31,777.8	2004	36	39,260.1	1961	54	48,087.2	1972

In the case of wind and solar production, for both existing and candidate plants, a historical record was created through the following procedure: (i) from the geographical position of each plant, the wind and irradiation resource data were obtained considering a hourly historical window of 30 years (from the public Chilean database); (ii) these values were transformed into energy production values through a simulation model with some assumptions regarding the characteristics of the wind generator/PV panel; (iii) for the existing plants, using the actual measurement data of the equipment, a "scaling" of the energy production values was made; and (iv) PSR's Times Series Lab tool [60] was used to generate synthetic future scenarios of VRE production to match the water inflow scenarios.

In the end, 30 scenarios of VRE production and water inflow for all VRE and hydro plants were produced and considered in the expansion planning simulations. Note that for the VRE production, the scenarios are generated in hourly resolution (resulting in 8760 x 30 values of capacity factors of each VRE plant). As the demand was aggregated into 13 blocks, the VRE production followed the same aggregation, resulting in 13 x 12 x 30 capacity factors per year represented during the expansion planning optimization for each VRE plant (existing and candidate).

6.3.1.3 Transmission data

The Chilean system network represented has 315 buses. The following figure and table classify them into different voltage levels:

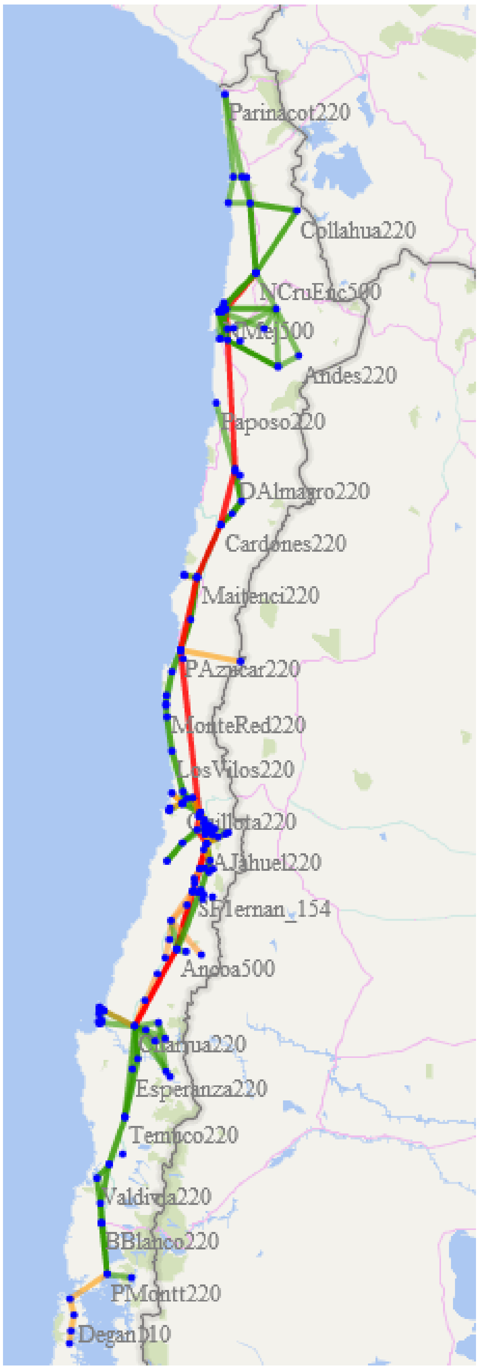

Figure 38 - Chile - Transmission network

Table 11 - Chile - Bus voltage

Voltage (kV)	Number of buses
< 38	38
110	74
154	29
220	150
345	2
500	22

The 220 kV lines are highlighted in green, 500 kV in red, and under 154 kV, in yellow. In total, the system has 471 existing circuits, of which 388 are transmission lines, and 83 are transformers.

Regarding the candidates, 128 projects are considered, of which 104 are transmission lines, and 24 are transformers. Investment costs vary depending on the level of voltage and length (for the transmission lines). The figure below illustrates the location of these projects:

Figure 39 - Chile - Transmission candidates

The Annex B presents more information about the transmission data.

6.3.2 Results

6.3.2.1 Base case

The following figures present the generation and transmission expansion plan calculated by the six alternatives. For A2, three simulations were executed, varying the maximum limit for the generation deviation (5, 10, and 15%). In A5, the future cost functions generated by A1 was used.

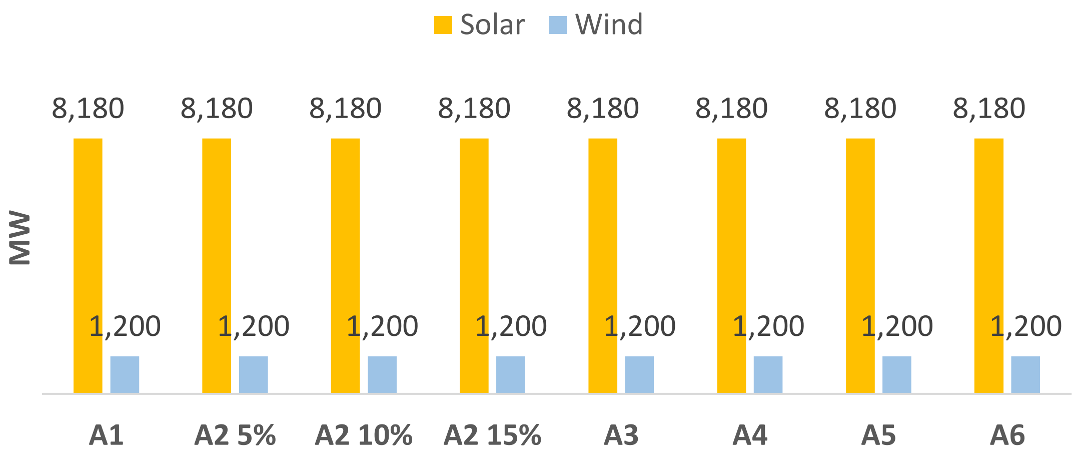

Figure 40 - Chile - Base case - Generation expansion plan

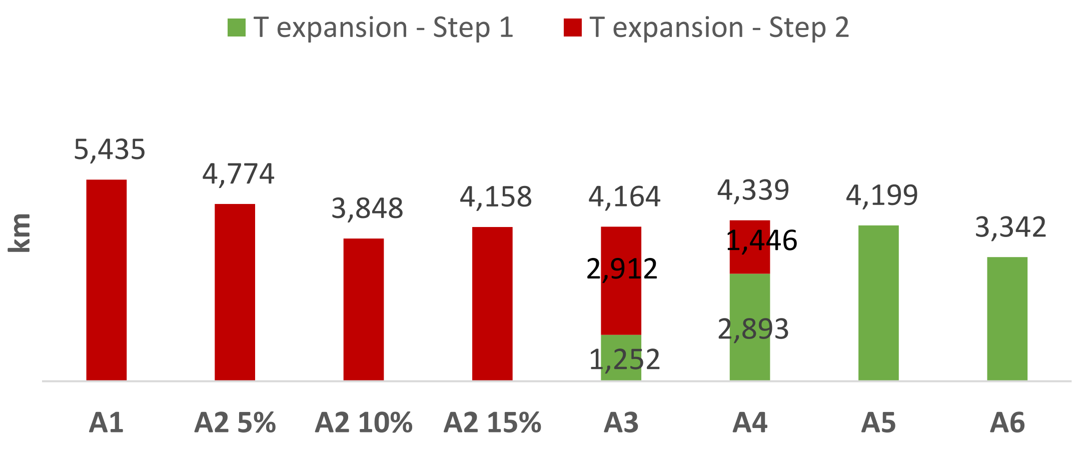

Figure 41 - Chile - Base case - Transmission expansion plan

The figure above presents the transmission expansion plan in terms of the total length (km) invested, divided by the decision taken in steps 1 and 2. In Figure 40, the generation expansion plans show that all alternatives invest only in VRE plants. Despite all alternatives invested in the same total capacity for wind (1.2 GW) and solar (8.18 GW), the expansion timing over the years was different. For instance, the figure below compares the capacity additions along the study horizon for A1 and A6.

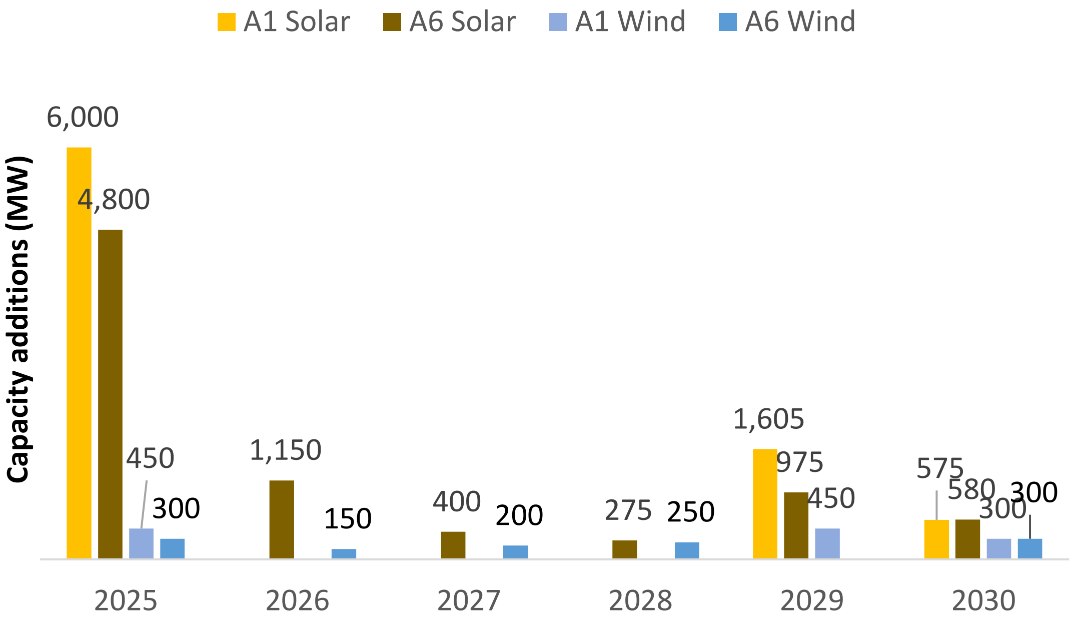

Figure 42 - Chile - Base case - A1 vs. A6

In A1, the investments were more concentrated in the first and last years, whereas, in A6, they were more diffused in the study horizon. This behavior, together with the differences in the transmission expansion plan, contributed to the differences in the total costs, as shown in the figure below.

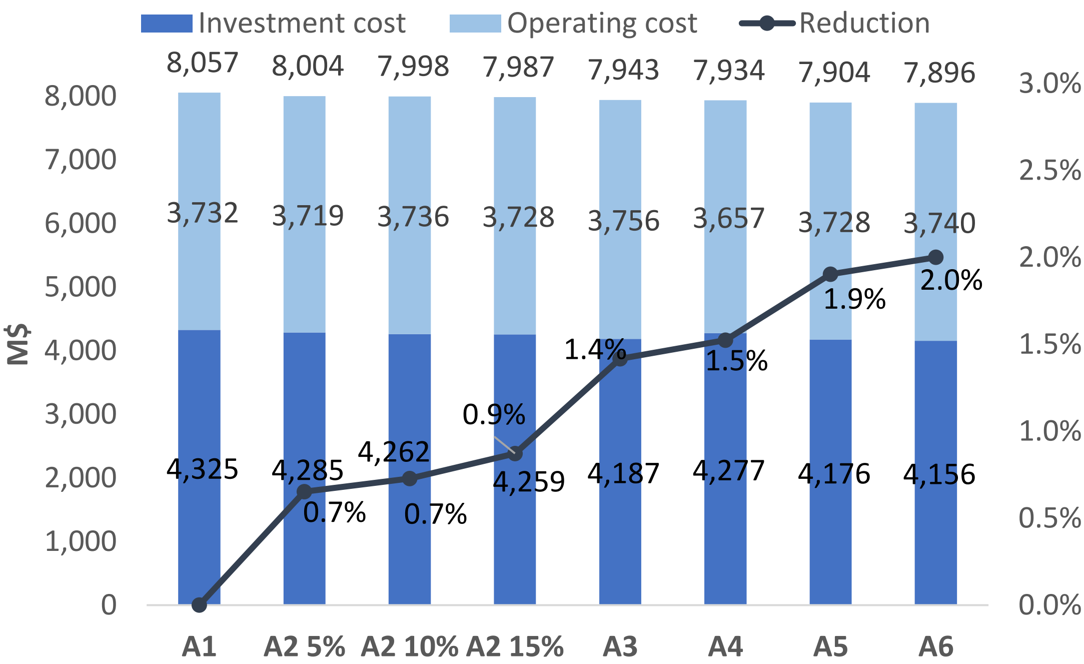

Figure 43 - Chile - Base case - Total costs

It is notable three levels of cost reduction. A2 simulations reduced the investment in transmission, leading to a total reduction of 0.7 to 0.9%. A better reduction showed up in the case with a higher generation deviation limit (15%).

The strategies allowed to invest in generators and circuits in the first step but simplifying some network constraints, presented a reduction of 1.4 to 1.5%. Finally, the strategies with full network representation in the first step reach a total reduction of 1.9-2%, representing approximately 160 million dollars.

To complement the graph above, Figure 44 shows the share of the investment and operating cost in the total cost. The latest strategies showed a slight decrease in the share of the investment cost, followed by an increase in operating costs.

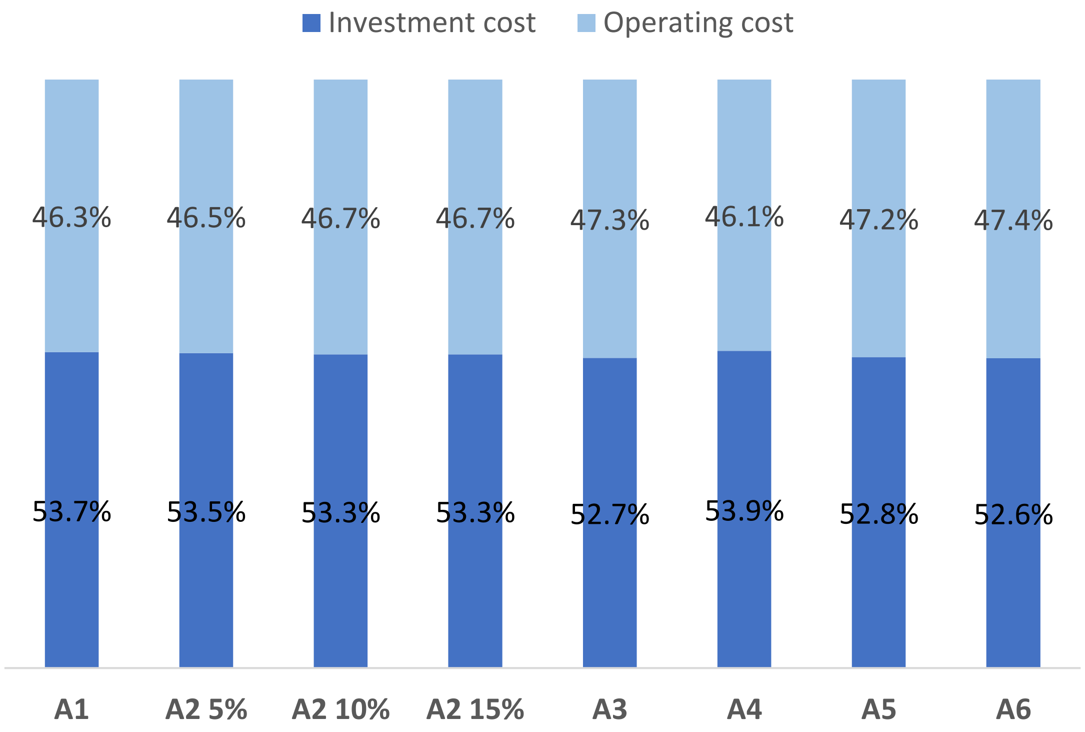

Figure 44 - Chile - Base case - Costs share

The convergence process and computational performance for step 1 are presented in the graphs below. All simulations were performed in cloud computing using a cluster with 64 processes. The convergence tolerance defined in the simulations was 1%.

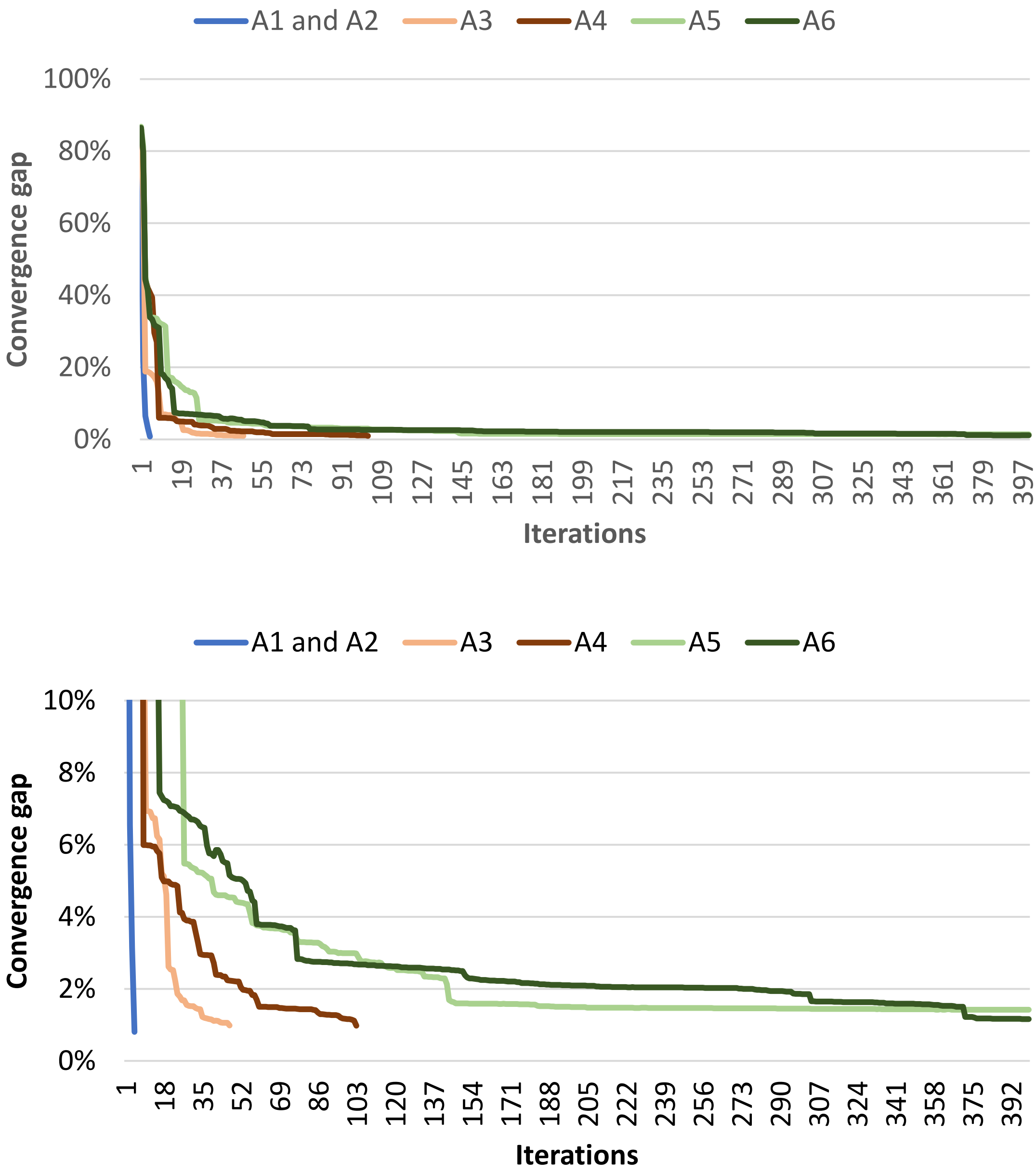

Figure 45 - Chile - Base case – Convergence step 1

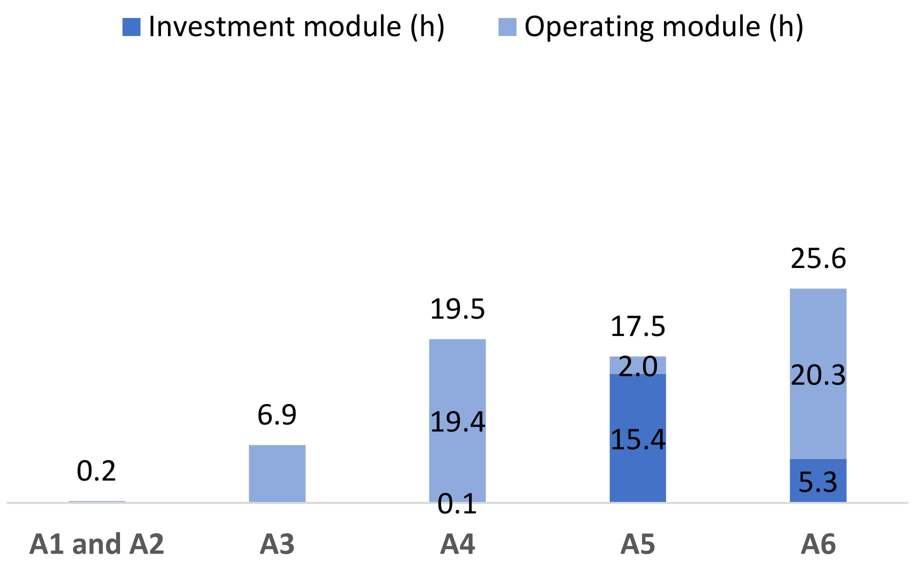

Figure 46 - Chile - Sensitivity case - CPU time step 1

In the first figure, the second graph is just a zoom in the y-axis of the first graph. A1/A2 took only five iterations to reach the convergence tolerance, followed by A3 (47) and A4 (103). Although the remaining alternatives reached the maximum number of iterations, defined as 400, the final gap was close to 1%.

Regarding the CPU time, there was a big difference comparing the cases with no representation of KVL constraints and the cases with partial or complete representation. Notably, A5 had a better CPU performance than A4, highlighting the effect of the compact network formulation and the fixed FCF.

In addition, the investment problem in A5 took more time than in A6, as the inputted FCF is not perfectly adequate for the case. On the other hand, the CPU time in the operating module is much shorter than A6 due to the fixed FCF.

In these cases, the CPU time in the second step had significant numbers, as described in Figure 47. The number of dispatch scenarios in each year of the horizon was equal to 4,860 (12 months x 13 load blocks x 30 generation scenarios). For the investment problem, 10 scenarios were selected.

All alternatives took around 5 to 8 hours to calculate the complementary transmission expansion plan, considering as fixed the plan calculated in the first step. In this step, the simulations were performed in a local computer with four processors (so they are not directly comparable to the CPU time results of the first step).

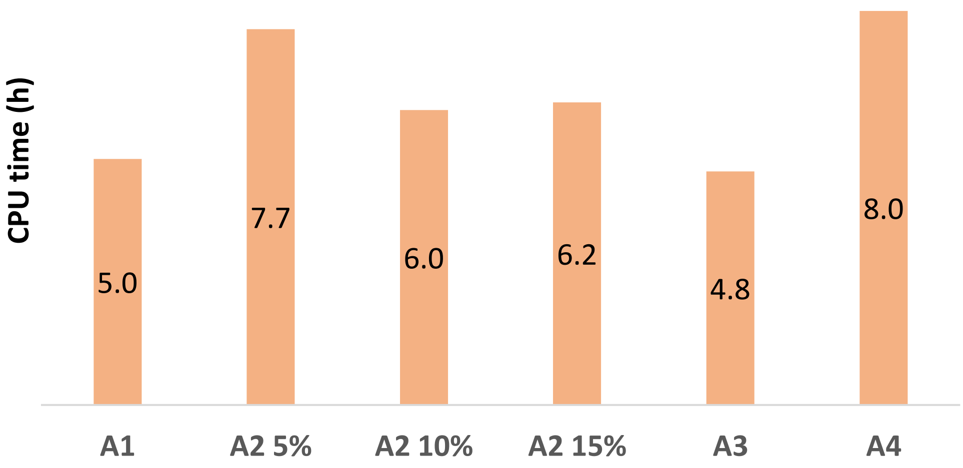

Figure 47 - Chile - Base case - CPU time step 2

6.3.2.2 Sensitivity case

The sensitivity case considers a reduction of 10% in the investment cost of wind plants and a 3-fold increase in investment costs of the circuits. The idea is to verify that with a change in the final expansion mix, the conclusions observed in the base case remain.

The resulting expansion plans are described below. There were differences in the total generation expansion plan, but the model insisted on investing only in VRE projects. A4, A5, and A6 presented higher investments in wind power than the remaining strategies. As mentioned in the assumptions section, most wind candidates are located in the south, where most of the system's demand is situated. So, the strategies with better transmission signals tend to have more wind power, as it requires fewer transmission reinforcements (sustained by the results presented in Figure 49).

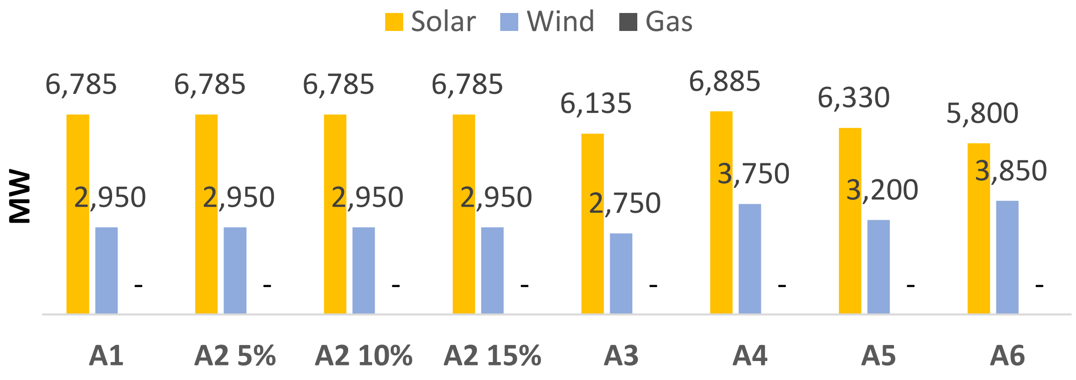

Figure 48 - Chile - Sensitivity case - Generation expansion plan

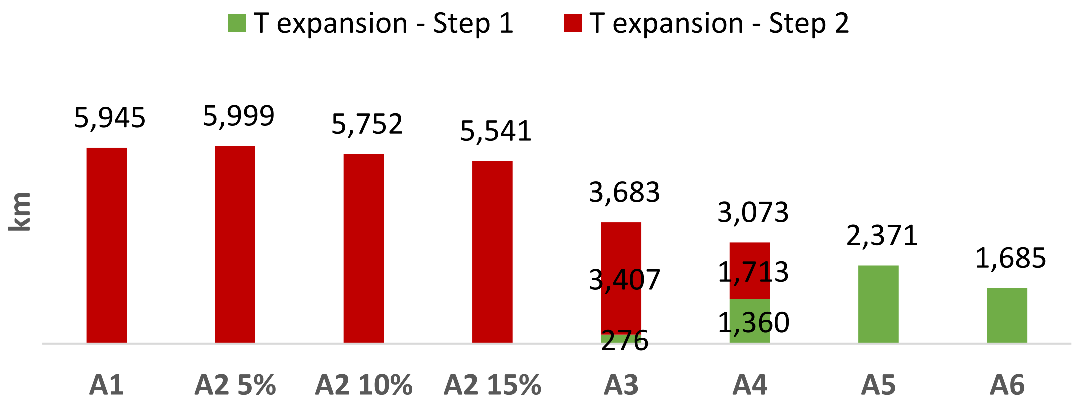

Figure 49 - Chile - Sensitivity case - Transmission expansion plan

The resulting total costs are described in the chart below:

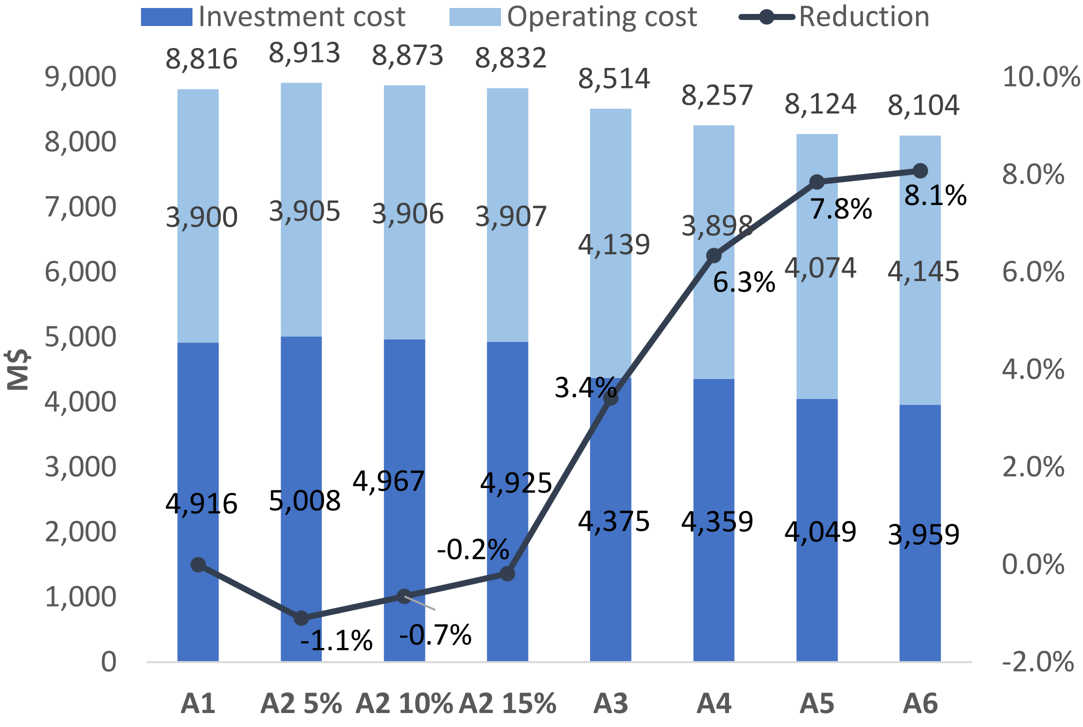

Figure 50 - Chile - Sensitivity case - Total costs

In this case, A2 simulations reduced the investment in transmission but caused an increase in the total cost of 0.2 to 1.1%. There is no guarantee of reducing the total cost, as the step 2 methodology is "myopic" to the future years when calculating the current year's transmission expansion plan. In other words, the method does not reassess the investment decisions made in past years when solving the current year. So, in the end, the final solution may not be optimal compared to a solution contemplating all years in the same optimization problem (which makes the problem intractable to solve).

On the other hand, the strategies allowed to reinforce the generation and transmission system in the first step, but with some simplification in the network constraints, presented a better result than the base case, reaching a reduction of 3.4% (A3) and 6.3% (A4). Finally, applying strategies with full representation of the network resulted in a total reduction of 7.8% and 8.1%, representing ~710 million dollars.

Regarding the share between investment and operating cost in the total cost, presented in chart Figure 51, the last strategies tended to reduce the investment cost, causing an increase in the operating cost but resulting in a lower total cost.

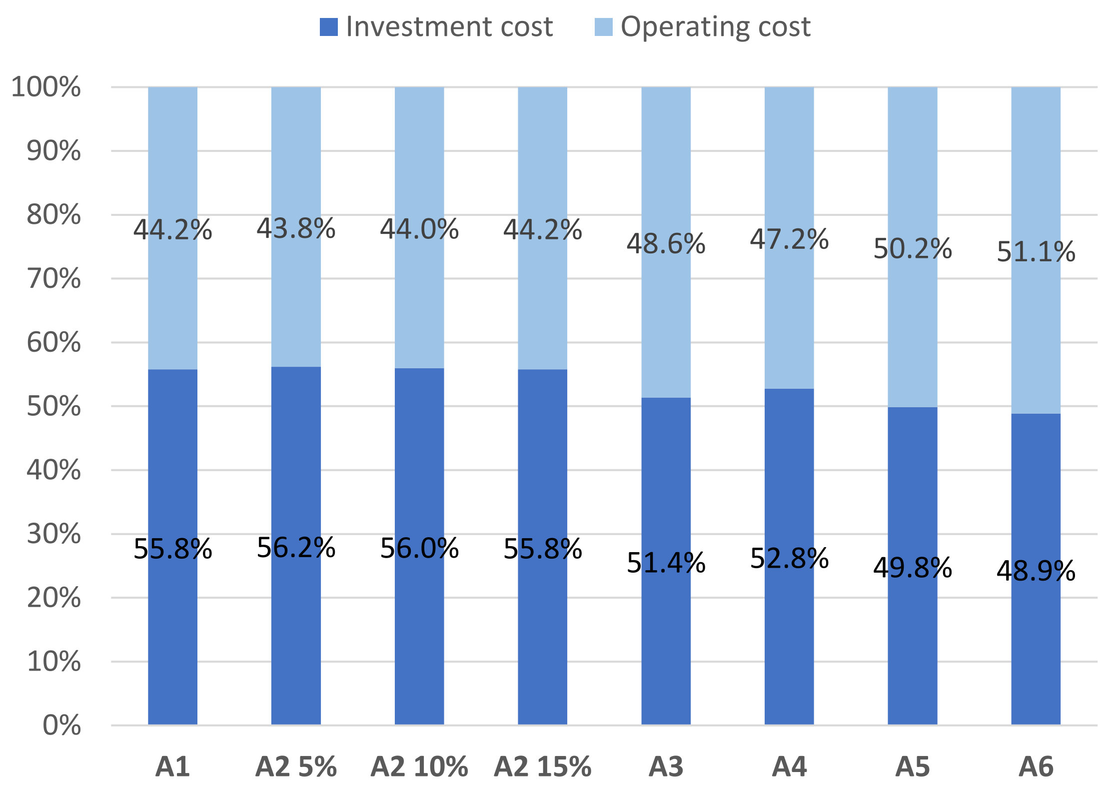

Figure 51 - Chile - Sensitivity case - Costs share

The convergence process and computational performance for step 1 are now presented in the graphs below for this sensitivity case:

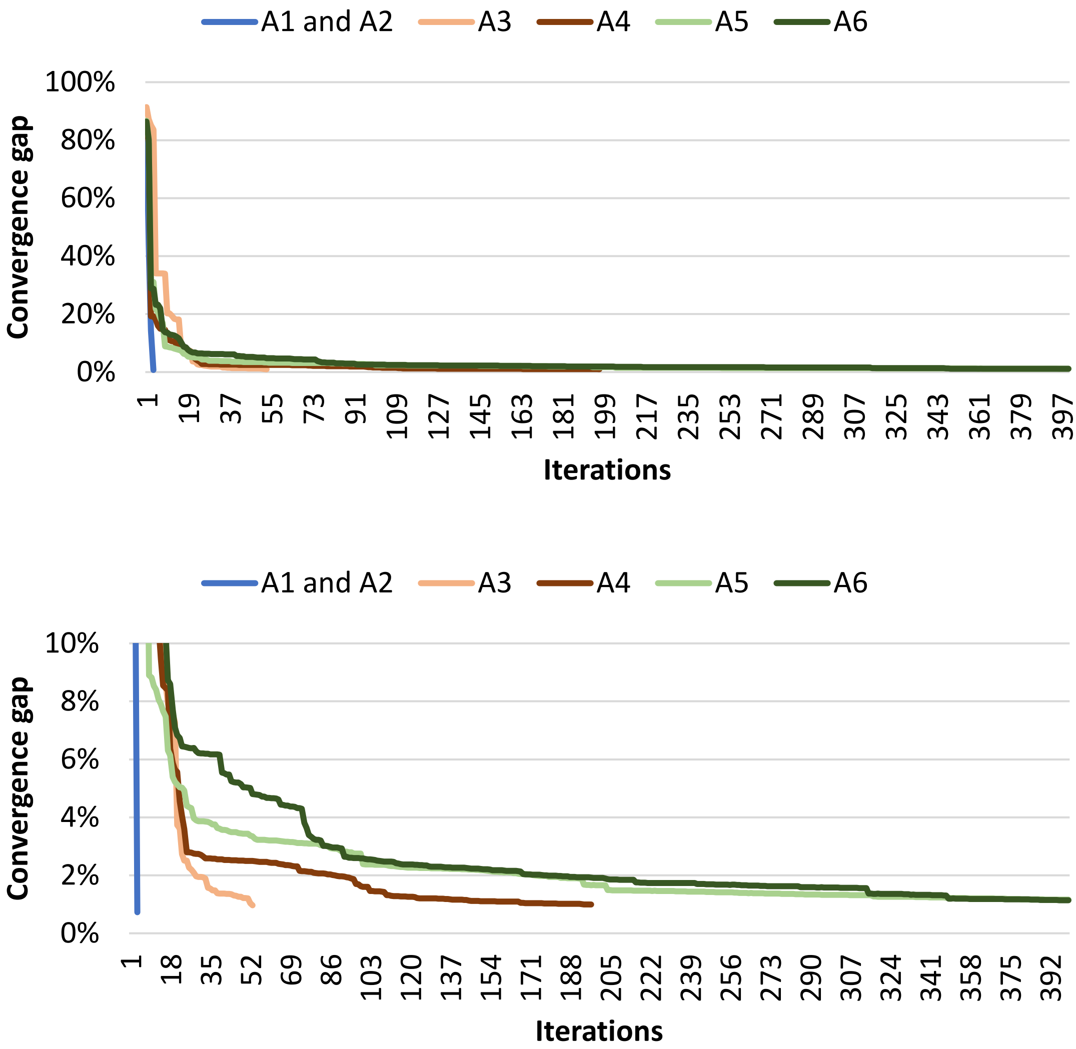

Figure 52 - Chile - Sensitivity case – Convergence step 1

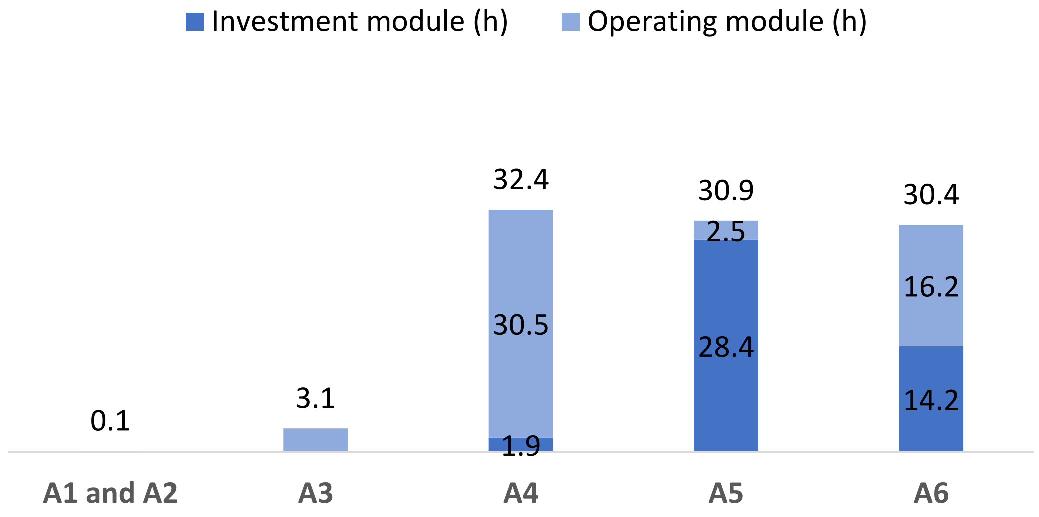

Figure 53 - Chile - Sensitivity case - CPU time step 1

A1/A2 remained to take a few iterations (4) to reach the convergence tolerance, followed by A3 (53), but A4 now is taking more iterations (193). Once more, the remaining alternatives reached the maximum number of iterations with a final gap close to 1%.

As a result of the increase in the number of iterations, A4 had the highest CPU time, followed by A5 and A6. Also, it is notable the same behavior was observed in the base case, with the investment problem in A5 taking more time than in A6 and the shorter CPU time by the operating module in A5 compared to A4 and A6.

Evaluating the CPU performance together with the expansion results for both base and sensitivity cases, the alternative A5 stands out against the others, reaching very close values of costs to the A6 and better computational performance. In the sensitivity case, the performance is similar to A6. However, seeing the convergence gap along the iterations, it is notable how fast this strategy reaches gaps close to the tolerance before A6. Moreover, although A5 takes the maximum number of iterations, the best solution is found at iteration 204 (4 hours of execution), different from A6, which takes 21 hours of execution to find the best solution at iteration 333.

Last, the CPU time in the second step is described below. The alternatives with generation deviation took more time than those without this feature to calculate the complementary transmission expansion plan, as the number of constraints increases in the optimization problem. Again, the simulations were performed in a local computer with four processors (so they are not directly comparable to the CPU time results of the first step). Here, the same execution parameters of the base case were used.

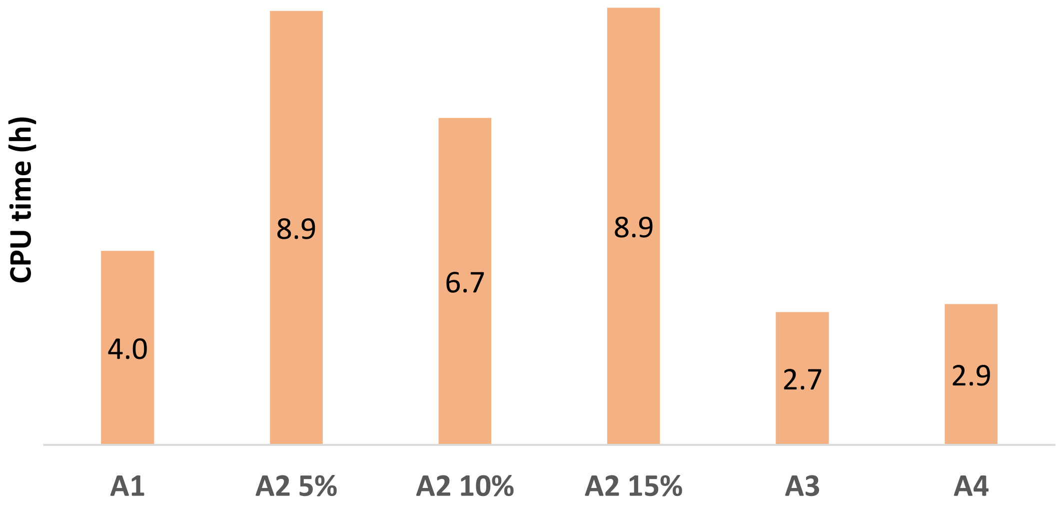

Figure 54 - Chile - Sensitivity case - CPU time step 2

6.3.2.3 N-1 security constraint

The simulations with N-1 security constraints in the transmission system were performed only in the sensitivity case. Once more, two executions were made, one considering the expansion plan calculated by A5 as a starting point for the N-1 expansion planning and the other with no fixed expansion plan.

Only the circuits with voltage level greater or equal to 154kV were selected for the contingency lists, which represents 480 circuits, summing existing and candidates. Also, when applying the single contingencies, the emergency capacity for each circuit is considered instead of the nominal capacity. In this case, the emergency capacity was considered 20% higher than the nominal capacity for all circuits. The results are shown next.

Starting with the convergence process, the chart below shows the result for both approaches:

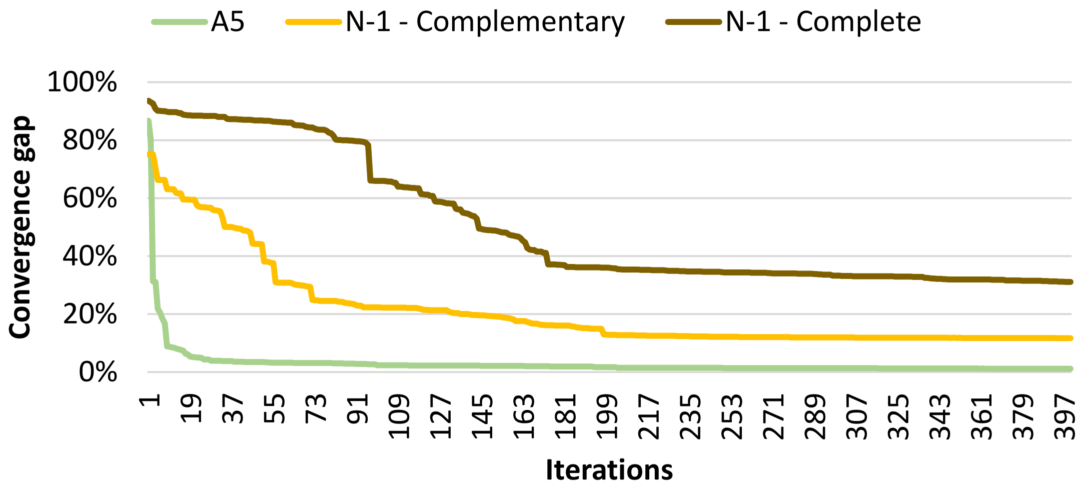

Figure 55 - Chile - Sensitivity case - N-1 convergence

The complementary approach stabilized in a gap close to 10%, while the complete approach did not pass the 30% gap in 400 iterations. The increase in the optimization problem's complexity is notable, as both approaches did not reach the convergence tolerance, defined as 3% in these executions. Perhaps by increasing the maximum number of iterations, the approaches would converge, but this requires higher computational effort.

As the complementary strategy almost reached the tolerance gap with 400 iterations and the complete approach presented a worse expansion plan due to its higher final convergence gap, only the results for complementary execution are present from now. The CPU time is described next:

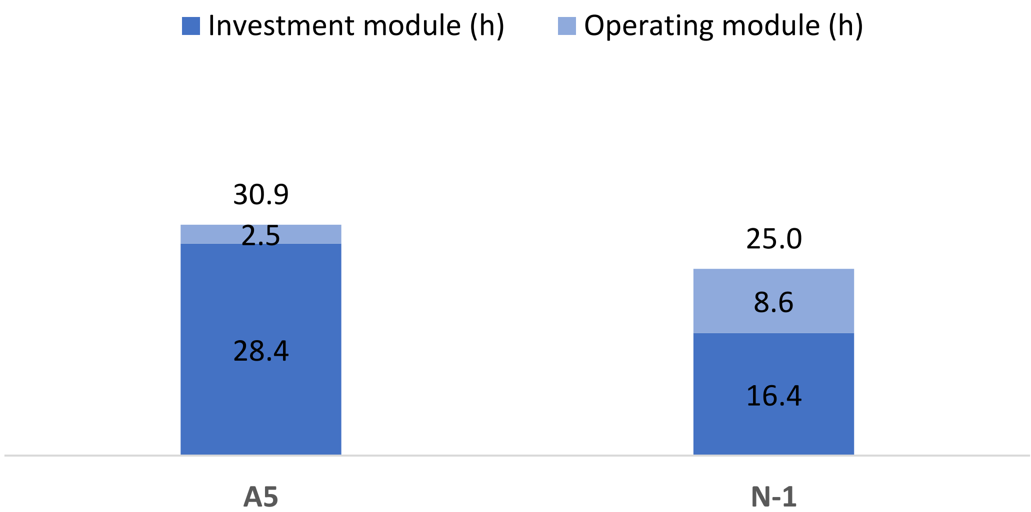

Figure 56 - Chile - Sensitivity case - N-1 CPU time

Considering a complete N-1 G&T expansion planning optimization and using the resulting plan from A5 as a starting point for the N-1 planning, the total CPU time would be the sum of both columns (30.9+25 = 55.9 hours of execution). Although the considerable total time, it seems reasonable as the expansion planning simulation does not need to be performed daily, which is different from dispatch optimization.

The resulting G&T expansion plan is illustrated in the charts below:

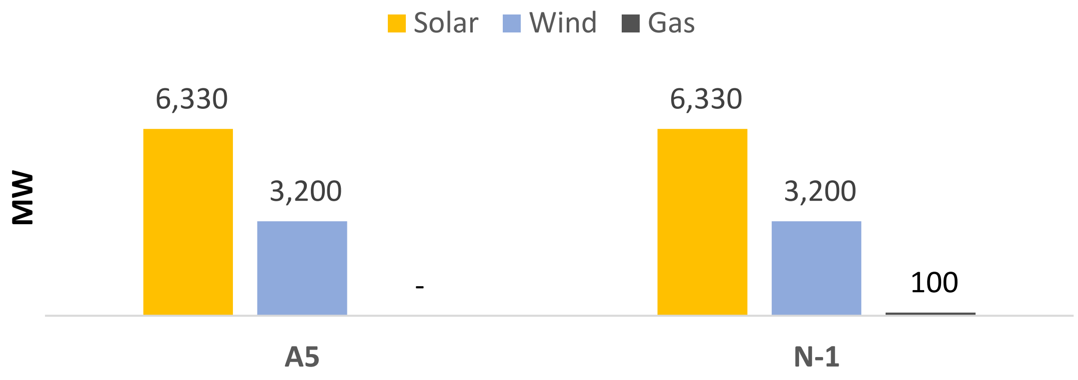

Figure 57 - Chile - Sensitivity case - N-1 G expansion plan

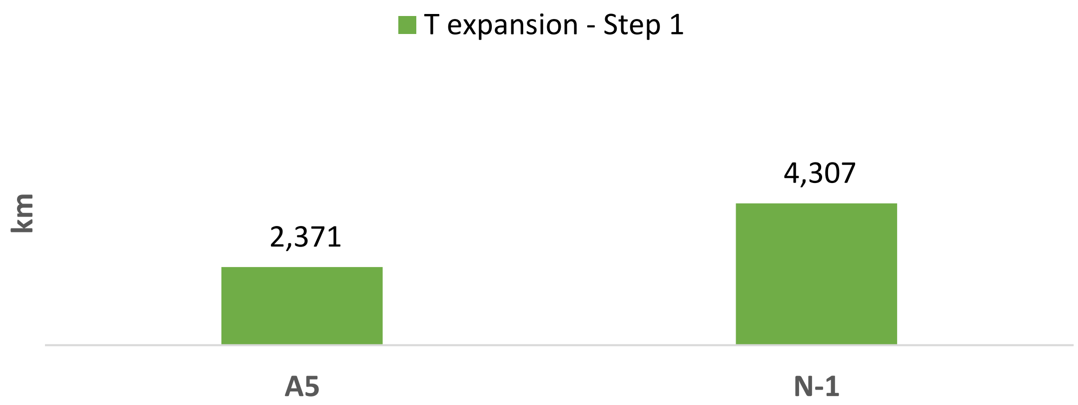

Figure 58 - Chile - Sensitivity case - N-1 T expansion plan

In addition to the A5 expansion plan, the N-1 strategy invested in one OCGT thermal plan and approximately 2,000 km of circuits (22 transmission lines and eight transformers) to meet the N-1 criterion. It is worth the investment in the gas-fired plant because, although the higher costs compared to VRE projects, they are located close to the load centers, saving transmission reinforcements when applying the N-1 criterion.

These capacity additions in the expansion plan resulted in an increase of 10.6% in the total cost, illustrated in the following chart.

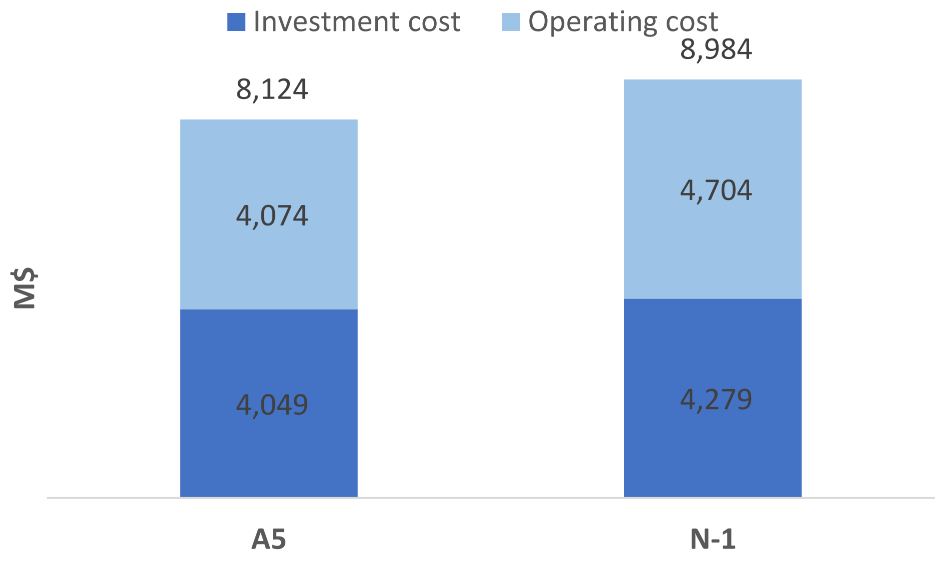

Figure 59 - Chile - Sensitivity case - N-1 total costs

The increase in the operating costs was higher than in the investment cost, showing that the dispatch decisions also changed due to the N-1 criterion and more thermal dispatch was needed to meet the requirements (the additional OCGT plant contributed to it).

6.4 Conclusion

Due to their reduced dimensions, all expansion planning alternatives applied to the Garver 6-bus system are satisfactory in terms of computational performance. Naturally, the best alternative is A6 for having a lower total cost.

Looking at a representation of a real system, the Chilean system in this case, it is evident the necessity to evaluate the trade-off between the quality of the solution and the computational time required by each alternative to choose the best of them.

The hierarchical alternatives (A1 and A2) obtained the best computational performance, but the expansion plans are about 1.2 to 2% more expensive than A6 in the base case and 8.8 to 10% above in the sensitivity case. Also, the A2 strategy does not have a guaranteed cost reduction compared to A1, as seen in the sensitivity case.

A3 has more attractive results than the previous ones because it presents better costs by a slight increase in CPU time, especially in the sensitivity case (which has 3 hours increase, not considering the reduction of time in the Transmission expansion planning). The A4, in turn, does not present good results, given the higher CPU time and more expensive total cost than the alternatives with the cheapest final costs (A5 and

A6). So, representing the KVL only for the existing circuits did not prove advantageous in representing all network constraints in the integrated expansion planning.

A5, compared to A6, which represents the minimum cost solution among the options presented, had very similar total costs for a lower computational time when looking at the base case. Despite the longer CPU burden compared to previous alternatives, it is still tolerable for an expansion planning exercise. Moreover, this strategy seems adequate when simulating with the N-1 criterion, as more iterations of the expansion planning algorithm are needed to calculate the final expansion plan. Therefore, A5 is the alternative that presents the best trade-off between solution quality and computational time.

It is noteworthy that the conclusion above is applied only to the Chilean case. Applying the same proposed alternatives to other cases with one order of magnitude larger, such as the Brazilian electrical system, A5 may not have satisfactory computational performance, making room for faster alternatives, such as A3.

7 Conclusions

This dissertation aims to propose and explore alternative methods to integrated generation and transmission expansion planning with N-1 security constraints. Some strategies are presented, which involve a chain execution of optimization methods.

The first step consists of an integrated generation and transmission expansion optimization based on Benders decomposition. Some network constraints can be neglected at this phase to accelerate the optimization process. Consequently, a second step must be performed to calculate transmission expansion additions to guarantee that the final expansion plan meets all the network constraints.

Moreover, still in the first step, simplifications in the hydrothermal dispatch optimization related to the policy operation of the reservoir can be done to speed up the convergence process without losing the quality of the solution.

In the second step, transmission expansion planning is executed for cases where some grid constraints were bypassed, considering as fixed the expansion plan and the dispatch scenarios calculated by the first step. At this stage, transmission reinforcements, in addition to the fixed plan, are decided to meet all network constraints.

Considering the N-1 constraints during the integrated planning makes the problem quite complex, so it is proposed to carry out the planning in two stages. At first, the G&T expansion plan is calculated without security constraints (using some of the alternatives presented). Then, considering the expansion plan calculated as a starting point, the additional expansion is determined so that the system meets the N-1 criterion.

Finally, having the final G&T expansion plan, hydrothermal dispatch optimization is simulated based on the Stochastic Dual Dynamic Programming method to calculate the actual operating costs of the system.

All alternatives presented were explored in two case studies: the first consists of a minor system with six buses, and the second represents the Chilean power system, with 315 buses.

Especially in Chile, the strategy to "freeze" the future cost function at the first step stood out against the remaining alternatives, presenting favorable results regarding total costs and satisfactory CPU performance. On the other hand, it does not mean that the other strategies did not present good results, as there were significant reductions in the total cost compared to the hierarchical approach. Depending on the dimensions of the system (e.g., a system with a larger size than those used in this work), the alternatives with better computational performance may stand out against those with more detailed representations of the network.

Regarding the N-1 criterion, the proposed methodology performed well, presenting consistent results with adequate computational time.

7.1 Future works

For future works, it is proposed to test the same methodology in larger systems, such as the Brazilian power system. As mentioned before, the alternatives with better CPU performance may be more suitable in the integrated expansion planning of these vast systems.

Also, considering larger systems, the N-1 criterion can be adapted to be considered in the second step (transmission expansion planning). In this case, each scenario is composed of generation/demand setpoints and single contingencies, increasing the number of scenarios considered. So, the final G&T plan will be robust to the dispatch scenarios and the N-1 criterion.

On the other hand, adding these constraints will significantly increase the computational effort in this step. So, simulating it in different case studies is essential to get the pros and cons of including it in the expansion planning process.

Finally, a similar strategy applied in the transmission expansion planning with generation deviation, described in Chapter 4, where the circuit overload is penalized by the model, can be applied in the integrated G&T expansion planning described in Chapter 3. As the case studies show, the hierarchical approach tends to overinvest in the second step, as the dispatch scenarios are calculated without any network representation. So, permitting minor overloads in the circuits in the first step can produce a more realistic dispatch scenario for step two, avoiding unnecessary transmission reinforcements.

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A Big M calculation

For each candidate right-of-way, the calculation of the smallest value of M_{k} that does not limit the angular differences between the terminal buses when the candidate circuit does not exist in the system can divide into two situations:

First, suppose that there is an existing circuit connecting the terminal buses with a susceptance γ_k^0 and capacity $\overline{f_k^0}$. Following the equation (3.15), the maximum angle difference between the terminal buses is when $f_k^0 = \overline{f_k^0}$:

$$-\frac{\overline{f_k^0}}{\gamma_k^0} \leq \Delta\theta_k \leq \frac{\overline{f_k^0}}{\gamma_k^0} \tag{A.1}$$

Also, considering that $f_k = 0$ when $x_k = 0$, the equation (4.5) becomes:

$$-M_k \leq -\gamma_k \Delta\theta_k \leq M_k \tag{A.2}$$

Comparing the inequalities (A.1) and (A.2) and considering that M_{k} must not limit the maximum angle limit between the terminal buses, results in:

$$M_{\mathrm{k}} \geq \gamma_k \frac{\overline{f_k^0}}{\gamma_k^0} \tag{A.3}$$

So, the smallest value is $\gamma_k \frac{\overline{f_k^0}}{\gamma_k^0}$.

Next, suppose that there is no existing circuit connecting the terminal buses. In this case, the set of existing circuits that connect these terminal buses and compose the smallest electrical path (greater susceptance) is considered. Therefore:

$$M_{\mathrm{k}} \geq \gamma_k W_{min} \tag{A.4}$$

Where W_{min} represents the sum of the values $\frac{\overline{f_k^0}}{\gamma_k^0}$ of the set of circuits mentioned above.

B Chile - Transmission Data

Table 12 - Candidate renewable plants

Name	Bus	Installed capacity (MW)	Technology	Name	Bus	Installed capacity (MW)	Technology
PV_Atacama	DAlmagro220	50	Solar	PV_Cernic-2	Chillan154	25	Solar
PV_LucesI/II	DAlmagro220	50	Solar	W_Alena	Charrua154	50	Wind
PV_LucI/II-2	DAlmagro220	50	Solar	W_C.Lindo	Charrua154	100	Wind
PV_InVaras2	CPinto220	50	Solar	W_La Flor	Charrua154	50	Wind
PV_Genpac1	Cardones220	25	Solar	W_Mesamavida	Charrua154	50	Wind
PV_R.Escond	Cardones220	100	Solar	W_Olmos	Charrua154	100	Wind
PV_V.Escondi	Cardones220	100	Solar	W_S.Fe	Charrua154	50	Wind
PVAtacama II	Cardones220	100	Solar	W_San Manuel	Charrua154	50	Wind
PV_AtacmII-2	Cardones220	100	Solar	W_Tolpan	Charrua154	50	Wind
PV_Genpac-2	Cardones220	25	Solar	W_Trigales	Charrua154	150	Wind
PV_Llano-2	Cardones220	100	Solar	W_Victoria	Charrua154	250	Wind
PV_R.Esc-2	Cardones220	100	Solar	PV_La Fronte	Charrua154	25	Solar
PV_SolV-2	Cardones220	250	Solar	PV_LaEsperan	Charrua154	25	Solar
PV_V.Esc-2	Cardones220	100	Solar	PV_Perquilau	Charrua154	25	Solar
W_C.Leones	Maitencil220	100	Wind	PV_S.Marta	Charrua154	75	Solar
W_Sarco2	Maitencil220	100	Wind	W_Alena-2	Charrua154	50	Wind
PV_Denersol	Maitencil220	75	Solar	W_C.Lindo-2	Charrua154	100	Wind
PV_Tamarico	Maitencil220	150	Solar	W_Cuel-2	Charrua154	50	Wind
W_Sarco-2	Maitencil220	100	Wind	W_Duqueco-2	Charrua154	50	Wind
W_Sarco2-2	Maitencil220	100	Wind	W_La Flor-2	Charrua154	50	Wind
PV_DenerS-2	Maitencil220	100	Solar	W_Mesamavi-2	Charrua154	50	Wind
PV_Tamar-2	Maitencil220	100	Solar	W_Negre-2	Charrua154	50	Wind
PV_ValleL-2	Maitencil220	50	Solar	W_Olmos-2	Charrua154	100	Wind
W_PSierra-2	PAzucar220	100	Wind	W_S.Fe-2	Charrua154	50	Wind
W_TalinayP-2	PAzucar220	50	Wind	W_Tolpan-2	Charrua154	50	Wind
PV_Luna-2	PAzucar220	25	Solar	W_Trigales-2	Charrua154	100	Wind
PV_Sol-2	PAzucar220	25	Solar	W_Victoria-2	Charrua154	100	Wind
PV_Llay Llay	Polpaico220	25	Solar	PV_LaEsper-2	Charrua154	25	Solar
PV_S.Rafael	Polpaico220	25	Solar	PV_LaFront-2	Charrua154	25	Solar
PV_LlayLly-2	Polpaico220	25	Solar	PV_Perquil-2	Charrua154	25	Solar
PV_Quilap-2	Polpaico220	100	Solar	PV_S.Marta-2	Charrua154	100	Solar
PV_SRafael-2	Polpaico220	25	Solar	PV_Quilicura	LoAguirre500	25	Solar
PV_J.Prado	Polpaico220	25	Solar	PV_Tagua	SVicente154	25	Solar
PV_J.Prado-2	Polpaico220	25	Solar	PV_Tagua-2	SVicente154	25	Solar
PV_Bunster	Polpaico220	25	Solar	PV_Carmenci1	Nogales220	25	Solar
PV_Bunster-2	Polpaico220	25	Solar	PV_Carmenci2	Nogales220	25	Solar
PV_D.Miraflo	CNavia220	25	Solar	PV_Cuz Cuz	Nogales220	25	Solar
PV_DMiflor-2	CNavia220	25	Solar	PV_LasBateas	Nogales220	25	Solar
W_Taltal-2	Paposo220	100	Wind	PV_Santa Lau	Nogales220	25	Solar
PV_Conejo-2	Paposo220	100	Solar	PV_SLaura II	Nogales220	25	Solar
PV_Loros-2	Cardones110	50	Solar	PV_Cuz Cuz-2	Nogales220	25	Solar
PV_Terraz-2	Cardones110	25	Solar	PV_DCarmen-2	Nogales220	50	Solar
W_Reina	PColorada220	50	Wind	PV_LasBat-2	Nogales220	25	Solar
PV_Abasol	PColorada220	50	Solar	PV_SJulia-2	Nogales220	25	Solar
PV_Estancia	PColorada220	100	Solar	PV_Ariztia	Nogales220	25	Solar
PV_P.Viento	PColorada220	50	Solar	PV_Ariztia-2	Nogales220	25	Solar
PV_S.Verano	PColorada220	100	Solar	W_V.Pacifico	Bocamina154	70	Wind
W_Reina-2	PColorada220	50	Wind	W_V.Pacif-2	Bocamina154	75	Wind
W_SanJuan-2	PColorada220	100	Wind	PV_LasAranas	Ventanas110	25	Solar
PV_Abasol-2	PColorada220	50	Solar	PV_San Pedro	Ventanas110	25	Solar
PV_Estanci-2	PColorada220	100	Solar	PV_LAranas-2	Ventanas110	25	Solar
PV_Pelican-2	PColorada220	100	Solar	PV_SanPed-2	Ventanas110	25	Solar
PV_PViento-2	PColorada220	50	Solar	PV_Candelari	Candela220	25	Solar
PV_S.Veran-2	PColorada220	100	Solar	PV_El Rincon	Candela220	25	Solar
W_Coih-2	Charrua220	100	Wind	PV_Candel-2	Candela220	25	Solar

W_Reinaco-2	Temuco220	100	Wind
W_Aurora2	PMontt220	100	Wind
W_Calbuco	PMontt220	50	Wind
PV_Pedernale	PMontt220	150	Solar
W_Aurora-2	PMontt220	100	Wind
W_Aurora2-2	PMontt220	100	Wind
W_Calbuco-2	PMontt220	50	Wind
W_Puel-2	PMontt220	100	Wind
PV_Pedern-2	PMontt220	100	Solar
PV_DIstCH-2	Chena220	25	Solar
PV_Constituc	LVegas110	50	Solar
PV_Libertado	LVegas110	25	Solar
PV_Rodeo	LVegas110	25	Solar
PV_Constit-2	LVegas110	50	Solar
PV_Liberta-2	LVegas110	25	Solar
PV_Panqueh-2	LVegas110	25	Solar
PV_Rodeo-2	LVegas110	25	Solar
PV_Bauza 1	PPeuco110	25	Solar
PV_Bauza 2	PPeuco110	25	Solar
PV_Sofia	PPeuco110	50	Solar
PV_Til Til	PPeuco110	100	Solar
PV_Sofia-2	PPeuco110	25	Solar
PV_Til Til-2	PPeuco110	100	Solar
PV_Tiltil-2	PPeuco110	25	Solar
PV_Cachiyuyo	Maitencil110	50	Solar
PV_Cachiyu-2	Maitencil110	50	Solar
PV_LVictori	Huasco110	25	Solar
PV_Lvictor-2	Huasco110	25	Solar
PV_Cantillan	Paine154	25	Solar
PV_Polulo	Paine154	25	Solar
PV_Cantill-2	Paine154	25	Solar
PV_Polulo-2	Paine154	25	Solar
W_P.Sierra	PAzucar110	100	Wind
PV_C.Piedra	PAzucar110	50	Solar
PV_El Olivo	PAzucar110	25	Solar
PV_Illapel	PAzucar110	100	Solar
PV_Los Loros	PAzucar110	50	Solar
PV_SpAIllape	PAzucar110	50	Solar
W_P.Sierra-2	PAzucar110	100	Wind
PV_CPiedra-2	PAzucar110	50	Solar
PV_Divis-2	PAzucar110	50	Solar
PV_ElOlivo-2	PAzucar110	25	Solar
PV_Illapel-2	PAzucar110	100	Solar
PV_LomasC-2	PAzucar110	25	Solar
PV_LosLoro-2	PAzucar110	50	Solar
PV_SpAIll-2	PAzucar110	50	Solar
PV_Tambo-2	PAzucar110	25	Solar
W_Cardonal	Rapel220	50	Wind
W_LaEstrella	Rapel220	50	Wind
W_Cardonal-2	Rapel220	50	Wind
PV_Alcones	Rapel220	50	Solar
PV_Alcones-2	Rapel220	50	Solar
PV_D.Glora 1	AMelipill220	25	Solar
PV_DGlora 2	AMelipill220	25	Solar
PV_Peumo	AMelipill220	25	Solar
PV_Peumo-2	AMelipill220	25	Solar
PV_Pilpen	AMelipill220	25	Solar
PV_Queltehue	AMelipill220	25	Solar
PV_Turcas	AMelipill220	25	Solar
PV_Pilpen-2	AMelipill220	25	Solar
PV_Quelteh-2	AMelipill220	25	Solar
PV_Turcas-2	AMelipill220	25	Solar
PV_Cabilsol	LVilos220	25	Solar
PV_Peralillo	LVilos220	25	Solar

PV_El Rinc-2	Candela220	25	Solar
W_Arrayan-2	LPalmas220	100	Wind
W_Canela-2	LPalmas220	100	Wind
W_PPalmera-2	LPalmas220	50	Wind
W_Totoral-2	LPalmas220	50	Wind
W_Malleco2	Cautin220	100	Wind
W_Malle-2	Cautin220	100	Wind
W_Malleco2-2	Cautin220	100	Wind
W_Pargua	Ancud110	50	Wind
W_Ancud	Degan110	100	Wind
W_Ancud-2	Degan110	100	Wind
W_SanPedro-2	Degan110	50	Wind
PV_A. Sol	ElPenon110	25	Solar
PV_A. Sol II	ElPenon110	25	Solar
PV_D.Anton2	ElPenon110	25	Solar
PV_D.Antoni1	ElPenon110	25	Solar
PV_D.Antonia	ElPenon110	100	Solar
PV_Lagunila1	ElPenon110	50	Solar
PV_Lagunila2	ElPenon110	50	Solar
PV_Ovalle	ElPenon110	25	Solar
PV_Q.Seca	ElPenon110	25	Solar
PV_Talquilla	ElPenon110	25	Solar
PV_A. Sol-2	ElPenon110	25	Solar
PV_AdeOval-2	ElPenon110	25	Solar
PV_BellaV-2	ElPenon110	25	Solar
PV_Divisdr-2	ElPenon110	25	Solar
PV_Ovalle-2	ElPenon110	25	Solar
PV_Q.Seca-2	ElPenon110	25	Solar
PV_Talquil-2	ElPenon110	25	Solar
PV_ElPicurio	Tinguirir154	25	Solar
PV_ElPicur-2	Tinguirir154	25	Solar
PV_Leyda 1	ASanta110	25	Solar
PV_Leyda 2	ASanta110	25	Solar
W_Espe-2	Prahue220	100	Wind
W_Cururos-2	MRedondo220	100	Wind
W_MRedondo-2	MRedondo220	50	Wind
W_P.Talca	Talinay220	100	Wind
W_P.Talca-2	Talinay220	100	Wind
W_TalinayO-2	Talinay220	100	Wind
W_Arturo	Rahue220	100	Wind
W_Arturo-2	Rahue220	100	Wind
PV_Chimbaron	Tinguirir220	25	Solar
PV_N.Aurora	Tinguirir220	25	Solar
PV_Chimbar-2	Tinguirir220	25	Solar
PV_N.Auror-2	Tinguirir220	25	Solar
W_Cabana	Mulchen220	100	Wind
W_L.Guindos	Mulchen220	350	Wind
W_Tolpan Sur	Mulchen220	100	Wind
W_Cabana-2	Mulchen220	100	Wind
W_L.Guindo-2	Mulchen220	100	Wind
W_SGabr-2	Mulchen220	100	Wind
W_Tolpan S-2	Mulchen220	100	Wind
W_CTig-2	Crucero220	100	Wind
W_Ckan-2	Crucero220	100	Wind
W_VLViento-2	Crucero220	100	Wind
PV_MElena-2	Crucero220	100	Solar
W_SGorda-2	Encuentro220	100	Wind
W_Tcha-2	Encuentro220	100	Wind
PV_Dominad-2	Encuentro220	100	Solar
PV_Fterrae-2	Encuentro220	100	Solar
PV_Granja	Lagunas220	100	Solar
PV_Granja-2	Lagunas220	100	Solar
PV_Pampa	PozoAlmon220	100	Solar
PV_Pampa-2	PozoAlmon220	100	Solar

PV_CabSol-2	LVilos220	25	Solar
PV_Peralil-2	LVilos220	25	Solar
PV_Fundacion	Tilcoco154	25	Solar
PV_Fundac-2	Tilcoco154	25	Solar
W_Pichilingu	Ciruelos220	100	Wind
W_Cama-2	Ciruelos220	100	Wind
W_Pichilin-2	Ciruelos220	100	Wind
PV_Santiag-2	CNavia110	100	Solar
PV_Gorriones	Linares154	25	Solar
PV_Gorrion-2	Linares154	25	Solar
PV_Cachanas	Chillan154	25	Solar
PV_Cernicalo	Chillan154	25	Solar
PV_Cachan-2	Chillan154	25	Solar
PV_PAS2-2	PozoAlmon220	25	Solar
PV_PAS3-2	PozoAlmon220	25	Solar
PV_Pcamaro-2	PozoAlmon220	25	Solar
PV_Lauca	Parinacot220	75	Solar
PV_Lauca-2	Parinacot220	75	Solar
PV_CTarapaca	Tarapaca220	580	Solar
PV_Quillagua	Tarapaca220	100	Solar
PV_Ctarap-2	Tarapaca220	580	Solar
PV_Quillag-2	Tarapaca220	100	Solar
PV_Capricorn	Ohiggins220	75	Solar
PV_Capric-2	Ohiggins220	75	Solar
PV_UribeS-2	Ohiggins220	50	Solar

Table 13 - Chile - Existing renewable plants

Name	Bus	Installed capacity (MW)	Technology
PV_Chanares	DAlmagro110	34.94	Solar
PV_Dalmagro	DAlmagro110	32	Solar
PV_Esperan	DAlmagro110	2.87	Solar
PV_Javiera	DAlmagro110	65	Solar
PV_Malgarida	DAlmagro110	28	Solar
PV_Pilar-Ama	DAlmagro110	3	Solar
PV_Salvador	DAlmagro110	67.8	Solar
PV_CPinto	CPinto220	93	Solar
PV_LuzNorte	CPinto220	141	Solar
PV_Cardones	Cardones220	0.4246	Solar
PV_Llano	LlanoLlam220	101.02	Solar
PV_SolV(Cox)	Cardones220	250	Solar
W_CLeo1(Ibe)	Maitencil220	115	Wind
W_CLeo2(Ibe)	Maitencil220	204	Wind
W_Sarco	Maitencil220	170	Wind
PV_Valleland	Valleland220	67	Solar
W_PSierra	PuntaSier220	82	Wind
W_TalinayP	Talinay220	60.1	Wind
PV_Luna	PAzucar110	2.96	Solar
PV_Sol	PAzucar220	2.95704	Solar
H_Tartaro	Polpaico220	0.1037	Small Hydro
PV_Quilapil	Polpaico220	103.2	Solar
W_Taltal	ETaltal220	98.1	Wind
PV_Conejo	Francisco220	104.5	Solar
PV_Lalack1	Lalackama220	54.8	Solar
PV_Lalack2	Lalackama220	16.5	Solar
PV_PampaSN	Cachiyuyal22	69.3	Solar
PV_Loros	Cardones110	46	Solar
PV_Terrazas	Cardones110	3	Solar
W_Pcolorada	PColorada220	20	Wind
W_SanJuan	PColorada220	184	Wind
PV_Pelicano	Donhector220	100	Solar
H_Llauquereo	Rucue220	1.79679	Small Hydro
W_Coih(main)	Charrua220	190	Wind
W_Huahache	Horcones66	6	Wind
W_Raki	Horcones66	9	Wind
H_Allipen	Temuco220	2.6	Small Hydro
H_Carilafque	RioTolten220	21.942	Small Hydro
H_Donguil	Temuco220	0.2494	Small Hydro
H_Malalcahue	RioTolten220	10.106	Small Hydro
H_Truful	Temuco220	0.819	Small Hydro
W_Reinaco	Temuco220	88	Wind
H_Collil	Chonchi110	6.997	Small Hydro
H_LasFlores	Rahue220	1.6	Small Hydro
H_Pichilonco	Rahue220	1.15	Small Hydro
H_Quillaileo	Mulchen220	0.816	Small Hydro

H_Trailelfu	Temuco66	2.5	Small Hydro
H_Colorado	PMontt220	2	Small Hydro
W_Aurora	Rahue220	126.4	Wind
W_Puel(Main)	PMontt220	100	Wind
H_Nido	Canutilla220	114	Small Hydro
PV_DIstCH	Chena220	2.5	Solar
H_Juncalito	LVegas110	1.47	Small Hydro
PV_Panquehue	LVegas110	6	Solar
PV_Tiltil	LVegas110	3	Solar
H_Cumpeo	Itahue154	5.76	Small Hydro
H_Montana	Teno154	3	Small Hydro
PV_LaSilla	Maitencil110	1.9	Solar
PV_Divisad	Maitencil110	65	Solar
PV_LomasCol	Punitaqui66	1.99	Solar
PV_Pama	PAzucar110	1.99	Solar
PV_SCecilia	Maitencil110	2.9452	Solar
PV_SDGx01	PAzucar110	1.25	Solar
PV_Tambo	PAzucar110	2.93	Solar
W_Ucuquer	Rapel220	7.1	Wind
W_Ucuquer2	Rapel220	10.5	Wind
W_Cama(Main)	Ciruelos220	190	Wind
PV_Santiago	Polpaico220	94	Solar
H_Hilda	Rahue220	0.4189	Small Hydro
H_ARenaico	LosAngele154	6.3	Small Hydro
W_BAires	LosAngele154	23.85	Wind
W_Cuel	LosAngele154	32.5	Wind
W_Duqueco	Charrua154	59	Wind
W_Esperanza	LosAngele154	10.5	Wind
W_Negre(WPD)	Charrua154	39	Wind
H_Rincon	Florida110	0.2846	Small Hydro
H_Vertientes	Florida110	1.629	Small Hydro
PV_DCarmen	Nogales220	33.019	Solar
PV_SJulia	LVilos220	3	Solar
PV_SPedroPeq	AMelipill220	3	Solar
W_Arrayan	DonGoyo220	115	Wind
W_Canela	LPalmas220	77.4	Wind
W_PPalmeras	LPalmas220	44.7	Wind
W_Totoral	LPalmas220	45.9954	Wind
H_Coya	Sauzal110_2	11.972	Small Hydro
W_LasPenas	Horcones66	8.4	Wind
W_Lebu	Horcones66	10	Wind
W_Lebu3	Horcones66	5.15	Wind
H_LosPadres	Rucue220	2.17	Small Hydro
H_Bureo	Mulchen220	2.2	Small Hydro
H_ElMirador	Charrua220	3	Small Hydro
H_LasNieves	Cautin220	6.5	Small Hydro
W_Malle(WPD)	Cautin220	266	Wind
W_SanPedro	Chiloe110	36	Wind
PV_AdeOvalle	ElPenon110	6	Solar
PV_Bellavist	Punitaqui66	3	Solar
PV_Divisadro	Punitaqui66	3	Solar
PV_Lagunilla	Ovalle66	2.95	Solar
W_Espe(main)	Prahue220	100	Wind
W_Cururos	LaCebada220	109.6	Wind
W_MRedondo	MRedondo220	47.5	Wind
W_TalinayO	Talinay220	89.6	Wind
H_Chanleufu	Rahue220	11.8	Small Hydro
H_MElena	Rahue220	0.285175	Small Hydro
H_Walterio	Rahue220	2.9456	Small Hydro
PV_SAndres	SanAndres220	48.2	Solar
W_SGabr(Acc)	Mulchen220	183	Wind
W_CTig(Main)	Crucero220	150	Wind
PV_Andes1	Andes220	21.42	Solar
Geo_Cpabello	ElAbra220	48	Geothermal

W_Ckan(main)	Crucero220	100	Wind
W_VLVientos	Calama110	89	Wind
PV_Cru(GPG)	Crucero220	120	Solar
PV_Jama1	Calama220	30	Solar
PV_Jama2	Calama220	21	Solar
PV_MElena	MariaElen220	67.714	Solar
W_SGorda	TapSierra220	112	Wind
W_Tcha(Main)	Encuentro220	150	Wind
PV_Dominador	Encuentro220	110	Solar
PV_Fterrae	Encuentro220	137.3	Solar
PV_Bolero	Laberinto220	146.6	Solar
PV_MElen(SP)	Lagunas220	120	Solar
H_Chapiquina	Chapiquina66	10.832	Small Hydro
PV_Aguila	ElAguila66	2.016	Solar
PV_PAS2	PozoAlmon66	7.5	Solar
PV_PAS3	PozoAlmon110	16	Solar
PV_Pcamaron	Arica110	6.15	Solar
PV_Huaica2	Tamarugal66	25	Solar
PV_UribeS	Uribe110	50	Solar
CSP_Cdominad	Encuentro220	110	CSP
PV_Chanar-2	DAlmagro220	50	Solar
PV_Dalm-2	DAlmagro220	50	Solar
PV_Esperan-2	DAlmagro220	25	Solar
PV_Javiera-2	DAlmagro220	50	Solar
PV_Malgar-2	DAlmagro220	25	Solar
PV_Salvad-2	DAlmagro220	50	Solar
PV_InVaras I	CPinto220	50	Solar
PV_L.Cobre	CPinto220	200	Solar
PV_CPinto-2	CPinto220	100	Solar
PV_L.Cobre-2	CPinto220	100	Solar
PV_LuzNor-2	CPinto220	100	Solar
PV_Lalack1-2	Paposo220	50	Solar
PV_Lalack2-2	Paposo220	25	Solar
PV_PampaSN-2	Paposo220	100	Solar
PV_LaSilla-2	Maitencil110	25	Solar
PV_Scecil-2	PAzucar110	25	Solar
PV_SAndres-2	SanAndres220	50	Solar
PV_MalgariII	Cumbres500	150	Solar
PV_Almeyda	Cumbres220	50	Solar
PV_Almeyda-2	Cumbres220	50	Solar
PV_Andes-2	Andes220	25	Solar
PV_USYA	Crucero220	25	Solar
PV_Cru-2	Crucero220	100	Solar
PV_USYA-2	Crucero220	25	Solar
PV_Bolero-2	Laberinto220	100	Solar
PV_MElenSP-2	Lagunas220	100	Solar
PV_Qanqina	PozoAlmon220	75	Solar
PV_Qanqina-2	PozoAlmon220	75	Solar
PV_Blancas 2	Ohiggins220	75	Solar

Table 14 - Chile - Candidate thermal plants

Name	Bus	Installed capacity (MW)	Fuel	Operating cost in 2025 ($/MWh)
OCGT_SIC 1	Polpaico220	100	Gas	46.426
OCGT_SIC 2	Polpaico220	100	Gas	46.426
OCGT_SIC 3	Polpaico220	100	Gas	46.426
OCGT_SIC 4	Polpaico220	100	Gas	46.426
OCGT_SIC 5	Polpaico220	100	Gas	46.426
CCGT_SIC 1	Polpaico220	250	Gas	33.99
CCGT_SIC 2	Polpaico220	250	Gas	33.99
CCGT_SIC 3	Polpaico220	250	Gas	33.99
CCGT_SIC 4	Polpaico220	250	Gas	33.99
CCGT_SIC 5	Polpaico220	250	Gas	33.99

CCGT_SING 1	Escondida220	250	Gas	33.99
CCGT_SING 2	Escondida220	250	Gas	33.99
CCGT_SING 3	Escondida220	250	Gas	33.99
CCGT_SING 4	Escondida220	250	Gas	33.99
CCGT_SING 5	Escondida220	250	Gas	33.99
OCGT_SING 1	Escondida220	100	Gas	46.426
OCGT_SING 2	Escondida220	100	Gas	46.426
OCGT_SING 3	Escondida220	100	Gas	46.426
OCGT_SING 4	Escondida220	100	Gas	46.426
OCGT_SING 5	Escondida220	100	Gas	46.426

Table 15 - Chile - Existing thermal plants

Name	Bus	Installed capacity (MW)	Fuel	Operating cost in 2025 ($/MWh)
DAlmagroTG	DAlmagro110	23.669	Diesel	290.56
EmeldaMD	DAlmagro110	66.6325	Diesel	260.52
Salvador	DAlmagro110	23.6691	Diesel	270.53
TermoChile	DAlmagro220	62	Diesel	249.33
TAmariTGD	Cardones220	152.27	Diesel	230.22
TermoPacifMD	Cardones220	86.0575	Diesel	232.88
BioCruz	Quillota220	1.8	Gas	36.211
Nehuenco1GNL	SanLuis220	327.437	Gas	76.532
Nehuenco1Die	SanLuis220	298.529	Diesel	133.54
Nehuenco2GNL	SanLuis220	365.036	Gas	67.932
Nehuenco2Die	SanLuis220	371.462	Diesel	139.63
Nehuenco31	SanLuis220	90.5	Diesel	225.84
QuinteTGD	Quintero220	255.2	Diesel	199.79
SIsidro1	SanLuis220	367.63	Gas	62.617
SIsidro2	SanLuis220	372.94	Gas	58.711
Tomaval I	Quillota220	1	Diesel	160.21
TomavalII	Quillota220	1.6	Diesel	160.21
SantaMarta	SantaMart220	13.8	Biomass	30
TaltalTG1	Paposo220	123.15	Diesel	218.92
TaltalTG2	Paposo220	121.25	Diesel	218.92
Cenizas	Cardones110	13.9	Diesel	213.1
PColoraMFO	PColorada220	16.3532	Fuel Oil	162.55
CMPC_Laja1	Charrua220	4.72857	Biomass	0
CMPC_Laja2	Charrua220	9.45714	Biomass	45.9
CMPC_Laja3	Charrua220	9.45714	Biomass	135
CMPC_Pacif1	Charrua220	11.4379	Biomass	0
CMPC_Pacif2	Charrua220	10.7477	Biomass	32.25
CMPC_Pacif3	Charrua220	10.3533	Fuel Oil	223.75
CMPC_SFe1	Charrua220	15.8266	Biomass	15.6
CMPC_SFe2	Charrua220	15.6573	Biomass	27.79
CMPC_SFe3	Charrua220	14.9802	Biomass	50.05
CMPC_SFe4	Charrua220	9.9868	Biomass	137.5
HBS	Charrua220	2.2	Biomass	2
LosGuindos	Charrua220	138.3	Diesel	232.9
LPinosTG	Charrua220	102.83	Diesel	162.3
SLidiaTG	Charrua220	137.61	Diesel	223.52
StaMaria1	SantaMari220	341.99	Coal	31.604
ChufquenMD	Temuco220	1.6	Diesel	225.2
CuracautinMD	Temuco220	2.4	Diesel	209.74
Lautaro_01	Lautaro66	23.4	Biomass	41.6
Lautaro_02	Lautaro66	20.24	Biomass	35
Lonquimay	Temuco220	1.2	Diesel	225.26
AntilhueTG	Valdivia220	101.3	Diesel	198.67
CalleCalleMD	Valdivia220	10.9	Diesel	216.83
Skretting O	Valdivia220	3	Diesel	219.56
Danisco	PMontt220	0.8	Diesel	219.56
LVegasTG	LVegas110	2.099	Diesel	227.18
LVientosTG	LVegas110	131.3	Diesel	221.15
ColigueTG	Sauzal154	21.175	Fuel Oil	163.15

EsperanMD1	Sauzal154	1.5937	Diesel	255.34
EsperanMD2	Sauzal154	1.791	Diesel	243.65
EsperanTG	Sauzal154	17.9	Diesel	338.32
Santa Irene	Rancagua154	0.37	Biomass	0
Tamm	Rancagua154	0.18145	Biomass	0
LomaColorado	PPeuco110	20	Biomass	10
CemBioBio	Teno154	12.0497	Diesel	187.1
TenoMD	Teno154	58.882	Diesel	222.55
Ara_Lican1	Rahue220	5	Biomass	0
Ara_Lican2	Rahue220	3	Biomass	63
Ara_Vinales1	Constituci66	6	Biomass	16
Ara_Vinales2	Constituci66	10	Biomass	40
Ara_Vinales3	Constituci66	6	Biomass	45
HuascoTG	Huasco110	57.681	Diesel	296.99
Tapihue	Quillota110	6.4	Gas	73.347
EPacifico	SFcoMost066	14.3052	Biomass	53.36
EspinosTG	LVilos220	124	Diesel	203.9
OlivosMD	LVilos220	112.4	Diesel	234.11
Ara_Vald1p	Ciruelos220	7.7	Biomass	0
Ara_Vald2p	Ciruelos220	12.571	Biomass	18
Ara_Vald3p	Ciruelos220	12.571	Biomass	49.78
Ara_Vald4p	Ciruelos220	12.571	Biomass	102.37
Ara_Celco1	Constituci66	3	Biomass	10
Ara_Celco2	Constituci66	2	Biomass	56.11
Ara_Celco3	Constituci66	3	Biomass	137.69
ConstElek	Constituci66	9	Diesel	286.28
MauleMD	Constituci66	6	Diesel	295.71
Linares	Linares154	0.5	Diesel	212.89
San Gregorio	Parral154	0.5	Diesel	212.89
ELeon	Chillan154	5.89016	Biomass	10
Ara_NAldea1	SantaElvir66	14	Biomass	25
Ara_NAldea2T	SantaElvir66	10	Diesel	263
Ara_NAldea3	SantaElvir66	37	Biomass	0
Ara_Cholgua1	Cholguan066	8.8	Biomass	25.84
Ara_Cholgua2	Cholguan066	3.9	Biomass	146.11
CampanaCC	Charrua154	41	Diesel	180.87
CampanaTG	Charrua154	104.5	Diesel	255.19
CampanaTG3	Charrua154	53.5	Diesel	250.21
LajaEV	Charrua066	11.466	Biomass	0
Masisa	Charrua066	7.3	Biomass	40.3
NRencaGNL	Renca110	310.215	Gas	74.821
NRencaDie	Renca110	301.729	Diesel	147.6
Renca	Renca110	92	Diesel	302.64
CMPC_Cord1	PAltoCmpc110	4	Gas	1.4
CMPC_Cord2	PAltoCmpc110	8	Gas	27.37
CMPC_Cord3	PAltoCmpc110	12	Gas	143.97
NewenTG	SVicente154	14.347	Diesel	288.1
Petropower	Hualpen154	62.977	Biomass	3.9
Campiche	Ventanas220	248.98	Coal	34.198
DonaCarmen	Nogales220	43.3	Diesel	203.21
Ventanas3	Ventanas220	248.98	Coal	33.529
Desfasador	Polpaico22A	0	Biomass	0
Fopaco	Fopaco154	12.454	Biomass	2.4
Ventanas1	Ventanas110	113.4	Coal	33.936
Ventanas2	Ventanas110	208.56	Coal	31.758
Bocamina	Bocamina154	122.2	Coal	40.353
CBlancaMD	Miraflore110	2.1	Diesel	198.35
ColmitoTG	Torquemad110	56.5797	Diesel	222.98
ConconMD	Torquemad110	2.3	Diesel	229.67
CuraumaMD	Miraflore110	2.5	Diesel	198.35
Candela1TGb	Candela220	122.1	Diesel	232.9
Candela2TGb	Candela220	125.3	Diesel	214.74
Ara_Arauco1	Horcones66	10	Biomass	40
Ara_Arauco2	Horcones66	10	Biomass	70

Ara_Arauco3	Horcones66	3.9	Biomass	100
Ara_HorcTGN	Horcones66	24.3	Gas	282.22
Ara_HorcDie	Horcones66	24.3	Diesel	312.02
CaneteMD	Coronel154	4	Diesel	224.49
CoronelTGb	Coronel66	44.5884	Diesel	282.24
LebuMD	Horcones66	2.4	Diesel	219.48
LosAlamos	Coronel154	0.8	Diesel	159.01
Tirua	Coronel154	1.9	Diesel	230.06
Trongol	Coronel154	2.8	Diesel	150.41
AncaliI	Ralco220	1.56	Biomass	0
Chiloe	Chonchi110	9	Diesel	227.31
DeganMD	Degan110	36	Diesel	257.89
Quellon2MD	Chonchi110	7	Diesel	232.46
MPatriaMD	ElPenon110	9	Diesel	248.6
PenonMD	ElPenon110	80.838	Diesel	220.64
PunitaquiMD	ElPenon110	9	Diesel	248.6
Las Pampas	Tinguirir154	0.37	Biomass	0
Guacolda1	Guacolda220	142.88	Coal	34.822
Guacolda2	Guacolda220	142.88	Coal	34.908
Guacolda3	Guacolda220	137.104	Coal	30.227
Guacolda4	Guacolda220	139.08	Coal	30.274
GuacoldaV	Guacolda220	131.7	Coal	30.274
ParguaMD	Molinos110	2.7	Diesel	204.05
TrapenMD	Molinos110	80.838	Diesel	207.1
LVerdeTG	ASanta110	17.919	Diesel	226.49
LVerdeVC	ASanta110	45.12	Diesel	354.41
PlacillaMD	ASanta110	3	Diesel	219.41
QuintayMD	ASanta110	3	Diesel	220.07
TotoralMD	ASanta110	3	Diesel	227.73
Bocamina2	Lagunilla220	322.48	Coal	34.697
ChuyacaMD	Rahue220	11.3	Diesel	370.88
Campesino	EntreRios500	580	Gas	67.7
ENE_GACC1GNL	CentralAt220	389.5	Gas	78.423
ENE_GACC1d	Tocopilla110	393.2	Diesel	164.39
ENE_GACC2GNL	CentralAt220	378.3	Gas	78.423
ENE_GACC2d	Tocopilla110	393.5	Diesel	164.39
COG_NORAC	Mejillone110	17.5	Biomass	0
ECL_CTA	Chacaya220	160.8	Coal	31.706
ECL_CTH	Chacaya220	161.34	Coal	33.556
ECL_CTM1	Chacaya220	148.63	Coal	37.409
ECL_CTM2	Chacaya220	162.84	Coal	32.718
ECL_CTM3Die	Chacaya220	243.227	Diesel	172.91
Ujina	Collahuas220	43.1	Fuel Oil	125.38
AES_NTO1	Norgener220	127.44	Coal	31.786
AES_NTO2	Norgener220	131.87	Coal	30.757
ECL_TAMFO	Tamaya110	99.2534	Fuel Oil	147.76
ECL_TG1d	Tocopilla110	20.423	Diesel	282.59
ECL_TG2d	Tocopilla110	20.423	Diesel	282.59
ECL_TG3d	Mantosdel110	35.93	Diesel	223.15
ECL_U12	Tocopilla110	81.22	Coal	36.4
ECL_U13	Tocopilla110	79.94	Coal	37.853
ECL_U14	Tocopilla220	126.87	Coal	31.311
ECL_U15	Tocopilla220	121.88	Coal	31.719
ECL_U16	Tocopilla220	354.12	Gas	54.896
ECL_U16Die	Tocopilla220	393	Diesel	144.34
DIE_INGE	Palestina220	2.4	Diesel	220.63
DIE_TECNET	Esmeralda110	3	Diesel	156.63
ECL_MIMBd	MantosBla220	27.885	Diesel	194.97
DIE_ENAEX1	Enaex110	0.6859	Diesel	263.69
DIE_ENAEX2	Enaex110	1.86105	Diesel	289.66
ECL_MAIQd	CDIquique66	5.6371	Fuel Oil	177.53
ECL_MIIQd	CDIquique66	2.7412	Diesel	221.71
ECL_MSIQd	CDIquique66	5.4398	Fuel Oil	154.92
ECL_SUIQd	CDIquique66	3.977	Diesel	238.92

ECL_TGIQd	CDIquique66	23.56	Diesel	269.15
ENOR_ESTANd	Iquique66	6.37	Diesel	246.95
ENOR_ZOFR1d	Iquique66	0.45	Diesel	242.17
ENOR_ZOFR2d	Iquique66	4.875	Diesel	239.17
ENOR_ZOFR3d	Iquique66	0.45	Diesel	208.99
ECL_GMARd	CDArica66	8.356	Diesel	219.4
ECL_M1ARd	CDArica66	2.919	Diesel	224.38
ECL_M2ARd	CDArica66	2.848	Diesel	223.46
ENE_CTTAR	Tarapaca220	148.52	Coal	32.431
ENE_TGTARd	Tarapaca220	23.655	Diesel	268.58
FO_INACAL	LaNegra110	6.623	Fuel Oil	141.94
BHP_Kelarlng	Kelar220	511.2	Gas	67.558
ECL_CTM3_LNG	LChangos220	218.357	Gas	79.668
ECL_RED1	LChangos220	375	Coal	32.598
AES_ANG1	Angamos220	248.575	Coal	29.947
AES_ANG2	Angamos220	252.97	Coal	30.247
AES_COCH1	Cochrane220	244.86	Coal	32.914
AES_COCH2	Cochrane220	244.74	Coal	32.918

Table 16 - Chile - Existing hydro plants

Name	Bus	Installed capacity (MW)	Mean production coefficient (MW/m³/s)	Maximum turbined outflow (m³/s)	Storage (hm³)
LaPaloma	MPatria66	4.416	1	4.416	0
LosMolles	MPatria66	17.951	1	17.951	0
Puclaro	PAzucar110	5.376	1	5.376	0
Rio_Huasco	Maitencil110	5.1	1	5.1	0
Blanco	Polpaico220	52.87	5.76	9.1783	0
Chacabuquito	Polpaico220	25.7	1.22	21.066	0
Hornito	Polpaico220	60.85	5	11	0
Juncal	Polpaico220	32	2.2	13.239	0
LosQuilos	Polpaico220	39.9	1.9	21	0
SauceAndes	Polpaico220	1.379	1	1.379	0
Carena	AJahuel220	10	1	10	0
Canelo	Temuco220	6.04	1	6.04	0
ElManzano	Temuco220	4.85	1	4.85	0
Maisan	Temuco220	0.5899	1	0.5899	0
TruenoPMGD	Temuco220	5.59	1	5.59	0
Pullinque	Valdivia220	51.158	1	51.158	0
Reca	Valdivia220	1.6958	1	1.6958	0
Ensenada	PMontt220	6.6	1.661	3.974	0
La_Arena	PMontt220	6.78	1	3	0
Canutillar	Canutilla220	171.57	2	85.785	975.5
Purisima	Itahue154	0.419	1	0.419	0
Rapel	Rapel220	375	0.64	588.48	290.9
Mallarauco	AMelipill220	3.3915	1	3.3915	0
Ancoa	Ancoa220	27	1	26.325	0
La_Mina	Pehuenche220	35.42	0.57	59.6	0
Laja I	Charrua220	34.3	0.137	250.365	0
LosCondores	Ancoa220	150	6	25	1453.4
Nuble	Ancoa220	136	1.36	100	0
Cipreses	Cipreses154	105.82	2.76	38.337	169.48
Curillinque	Cipreses154	91.77	1.01	86.1	0
Isla	Cipreses154	69.881	0.81	85.2	0
OjosdeAgua	Cipreses154	9	0.58	15.49	0
Lircay	Maule154	18.952	1	18.952	0
Mariposas	Maule154	6.2855	1	6.2855	0
Providencia	Maule154	14.129	0.46	30.715	0
SanIgnacio	Talca66	36.91	0.19	189.5	0
Robleria	Linares154	4	1.111	3.6	0
Itata	Chillan154	19.43	0.444	44.932	0
Abanico	Charrua154	136	1.2	113.33	0
Diuto	Charrua154	3.3	0.163	20	0
Picoiquen	LosAngele154	19.5	1	18.912	0

Eyzaguirre	Florida110	2.1	1	2.1	0
Florida	Florida110	26.072	1	28.437	0
Guayacan	Florida110	11.843	1	11.843	0
LosMorros	AJahuel110	2.6	1	2.6	0
Maitenes	Florida110	30.913	1	30.913	0
Puntilla	Florida110	21.749	1	21.749	0
Vol+Quel	Florida110	62	1	62	0
Aux_maipo	Buin110	5.0745	1	5.0745	0
El_Llano	Florida110	1.9079	1	1.9079	0
Losbajos	Buin110	5.4725	1	5.4725	0
Las Lajas	Florida110	267	4.2	63.57	0
Alfalfal	Alfalfal220	178	5.94	29.966	0
Alfalfal2	Almendros220	264	9.8	26.94	0
Sauzal	Sauzal110_2	37.6	1	37.6	0
Chacayes	Sauzal110_1	111.72	1.54	72.545	0
SauzalAJ	Sauzal110_2	51.2	1	51.2	0
Chiburgo	Colbun220	19.157	0.97	19.749	0
Colbun	Colbun220	472.82	1.47	298.7	1171.63
Machicura	Colbun220	94.76	0.31	272.7	0
SanClemente	Colbun220	5.8853	0.324	18.164	0
LomaAlta	Pehuenche220	39.932	0.45	86.7	0
Los_Hierros	Pehuenche220	25.1	0.96	26.1	0
Los_Hierros2	Pehuenche220	6	0.237	25.3	0
Pehuenche	Pehuenche220	568.29	1.771	309	27.06
R_Colorado	Pehuenche220	16.48	1	14.965	0
Mampil	Rucue220	54.906	1	54.906	0
Peuchen	Rucue220	84.872	1	84.872	0
Quilleco	Rucue220	70.65	0.55	127.27	0
Rucue	Rucue220	178.4	1.28	139.16	0
SanMiguel	Rucue220	48	1.067	44.985	0
Antuco	Antuco220	320	1.6	199.47	0
ElToro	Antuco220	450	4.8	93.75	5154.9
Pangue	Pangue220	465.83	0.9	500	41.15
Palmucho	Ralco220	32	1.143	28	0
Ralco	Ralco220	690	1.482	463.4	764.1
Dongo	Chonchi110	5.9976	1	5.9976	0
Confluencia	LaConflue154	163.2	3.11	52.476	0
El Paso	LaConflue154	60	5	12	0
San Andres	LaConflue154	40.058	3.88	10.324	0
LaHiguera	LaHiguera154	155	3.18	49.68	0
Callao	Rahue220	3.2918	1	3.2918	0
Capullo	Rahue220	11.843	1	11.843	0
H_Bonito1	Rahue220	8.9546	1	8.9546	0
H_Bonito2	Rahue220	3.15	1	3.15	0
L_Corrales1	Rahue220	0.8	1	0.8	0
L_Corrales2	Rahue220	1.025	1	1.025	0
Lican	Rahue220	17.955	1	17	0
Muchi	Rahue220	0.9975	1	0.9975	0
Nalcas	Rahue220	6.783	1	6.783	0
Pehui	Rahue220	1.1	1	1.1	0
Pilmaiquen	Rahue220	40.6776	0.27	144.444	0
Pulelfu	Rahue220	8.955	1	8.955	0
Rucatayo	Prahue220	59.3	0.315	174.6	0
LosLagos	Rahue220	46	0.2738	168	0
Osorno	Rahue220	42	0.2854	147.16	0
Angostura	Angostura220	321	0.43	753	14.2
Rucalhue	Mulchen220	90	0.13	692.3	0

Table 17 - Chile - Demand

Month	Block	2025 (GWh)	2026 (GWh)	2027 (GWh)	2028 (GWh)	2029 (GWh)	2030 (GWh)
1	1	86.998	90.451	94.011	97.71	101.62	105.69
2	1	78.978	82.11	85.339	88.691	92.237	95.937
3	1	91.245	94.855	98.575	102.44	106.52	110.79

4	1	91.569	95.205	98.959	102.86	106.97	111.27
5	1	85.291	88.678	92.171	95.799	99.63	103.63
6	1	90.246	93.814	97.492	101.31	105.35	109.57
7	1	88.759	92.259	95.864	99.6	103.57	107.71
8	1	88.155	91.635	95.221	98.941	102.88	107
9	1	88.641	92.147	95.757	99.506	103.47	107.62
10	1	89.727	93.308	97.015	100.86	104.91	109.14
11	1	91.075	94.726	98.508	102.44	106.56	110.86
12	1	90.815	94.431	98.169	102.05	106.14	110.41
1	2	622.94	647.6	673.02	699.4	727.32	756.48
2	2	382.78	397.98	413.68	429.98	447.18	465.14
3	2	598.79	622.56	647.08	672.52	699.41	727.48
4	2	571.27	593.99	617.47	641.84	667.54	694.37
5	2	407.54	423.81	440.63	458.1	476.49	495.68
6	2	491.47	510.95	531.04	551.88	573.93	596.95
7	2	409.33	425.57	442.32	459.71	478.08	497.27
8	2	393.72	409.35	425.5	442.26	459.95	478.42
9	2	653.96	680.1	707.14	735.23	764.77	795.58
10	2	400.55	416.51	433	450.12	468.16	486.98
11	2	591.56	615.29	639.87	665.41	692.21	720.15
12	2	623.79	648.63	674.29	700.94	729.03	758.35
1	3	1103.2	1146.8	1191.7	1238.2	1287.6	1339.2
2	3	647.77	673.53	700.12	727.73	756.86	787.27
3	3	632.05	657.21	683.22	710.22	738.69	768.39
4	3	328.2	341.31	354.87	368.96	383.78	399.23
5	3	810.28	842.76	876.41	911.37	948.06	986.32
6	3	616.08	640.57	665.87	692.13	719.84	748.77
7	3	678.23	705.3	733.3	762.38	792.98	824.9
8	3	865.05	899.61	935.36	972.5	1011.6	1052.3
9	3	724.89	753.91	783.94	815.14	847.93	882.11
10	3	876.44	911.58	947.99	985.82	1025.5	1066.9
11	3	788.04	819.63	852.35	886.34	922.03	959.23
12	3	1029.2	1070.1	1112.5	1156.4	1202.7	1251.1
1	4	871.7	906.21	941.8	978.71	1017.8	1058.6
2	4	998.52	1038.3	1079.3	1121.9	1166.9	1213.8
3	4	1118	1162.6	1208.7	1256.6	1307	1359.6
4	4	779.66	810.96	843.4	877.12	912.46	949.31
5	4	1005.4	1045.8	1087.6	1131.1	1176.7	1224.3
6	4	1038.4	1080	1123	1167.8	1214.8	1263.8
7	4	1345.4	1399.2	1454.9	1512.7	1573.4	1636.8
8	4	1027.6	1068.7	1111.2	1155.4	1201.8	1250.2
9	4	911.9	948.41	986.21	1025.5	1066.7	1109.8
10	4	998.72	1038.8	1080.3	1123.4	1168.7	1215.8
11	4	664.17	690.88	718.57	747.36	777.51	808.93
12	4	933.34	970.67	1009.3	1049.4	1091.6	1135.6
1	5	726.4	755.31	785.18	816.2	848.89	883.02
2	5	835.42	868.75	903.21	938.99	976.67	1016
3	5	945.44	983.21	1022.3	1062.9	1105.5	1150.1
4	5	1040.2	1081.9	1125.1	1170.1	1217.2	1266.3
5	5	626.34	651.58	677.76	704.98	733.47	763.13
6	5	1045.1	1087.1	1130.6	1175.8	1223.2	1272.6
7	5	899.27	935.3	972.62	1011.4	1052.1	1094.5
8	5	811.79	844.35	878.06	913.09	949.87	988.2
9	5	675.24	702.38	730.51	759.76	790.4	822.33
10	5	942.99	980.84	1020	1060.8	1103.5	1148.1
11	5	828.51	861.89	896.53	932.54	970.22	1009.5
12	5	918.68	955.56	993.76	1033.5	1075.1	1118.5
1	6	852.25	886.32	921.59	958.22	996.72	1036.9
2	6	605.4	629.67	654.81	680.92	708.33	736.91
3	6	592.96	616.73	641.35	666.94	693.79	721.78
4	6	835.54	869.11	903.92	940.1	978.01	1017.5
5	6	683.59	711.13	739.7	769.4	800.48	832.85
6	6	672.14	699.24	727.35	756.6	787.18	819.03
7	6	730.2	759.66	790.24	822.04	855.28	889.91

8	6	680.21	707.62	736.04	765.6	796.52	828.75
9	6	658.32	685	712.76	741.63	771.72	803.04
10	6	598.23	622.35	647.39	673.43	700.65	729.01
11	6	623.98	649.13	675.23	702.37	730.74	760.32
12	6	516.85	537.67	559.26	581.72	605.21	629.69
1	7	524.26	545.34	567.19	589.9	613.69	638.49
2	7	592.53	616.36	641.07	666.75	693.64	721.68
3	7	586.84	610.51	635.08	660.63	687.34	715.16
4	7	549.78	572.08	595.27	619.41	644.55	670.71
5	7	758.69	789.42	821.37	854.61	889.26	925.33
6	7	608.95	633.58	659.18	685.79	713.57	742.49
7	7	611.5	636.25	661.99	688.77	716.69	745.76
8	7	729	758.51	789.18	821.09	854.37	889.01
9	7	576.79	600.24	624.64	650.04	676.46	703.95
10	7	493.81	513.84	534.67	556.35	578.93	602.44
11	7	630.22	655.72	682.22	709.79	738.54	768.49
12	7	590.7	614.65	639.55	665.47	692.47	720.57
1	8	527.81	549.12	571.25	594.27	618.32	643.36
2	8	539.04	560.9	583.65	607.31	631.95	657.61
3	8	408.86	425.43	442.65	460.56	479.24	498.68
4	8	530.58	552.24	574.81	598.31	622.7	648.06
5	8	663.11	690.11	718.25	747.53	777.95	809.6
6	8	462.4	481.18	500.73	521.07	542.24	564.27
7	8	581.46	605.15	629.83	655.52	682.2	709.96
8	8	586.86	610.78	635.7	661.64	688.59	716.61
9	8	505.03	525.72	547.31	569.8	593.09	617.29
10	8	529.93	551.56	574.12	597.61	621.97	647.3
11	8	693.81	722.17	751.75	782.55	814.48	847.68
12	8	452.4	470.9	490.19	510.28	531.1	552.75
1	9	356.85	371.35	386.43	402.12	418.45	435.45
2	9	478.13	497.63	517.94	539.08	561.04	583.87
3	9	571.89	595.2	619.5	644.78	671.04	698.35
4	9	498.86	519.38	540.84	563.19	586.28	610.25
5	9	362.34	377.21	392.74	408.92	425.65	443.04
6	9	461.95	480.91	500.7	521.32	542.65	564.81
7	9	414.26	431.24	448.95	467.41	486.52	506.36
8	9	515.43	536.53	558.55	581.47	605.22	629.91
9	9	505.5	526.35	548.15	570.88	594.32	618.64
10	9	558.69	581.67	605.7	630.74	656.59	683.43
11	9	518.82	540.2	562.57	585.87	609.91	634.87
12	9	636.74	662.88	690.17	718.61	748.01	778.56
1	10	880.66	916.7	954.3	993.46	1034	1076.2
2	10	565.33	588.52	612.74	637.96	664.04	691.15
3	10	687.75	716.03	745.59	776.38	808.19	841.22
4	10	710.65	740.1	770.97	803.17	836.25	870.57
5	10	743.72	774.42	806.54	840.03	874.54	910.35
6	10	632.19	658.28	685.58	714.03	743.35	773.79
7	10	665.73	693.19	721.92	751.86	782.72	814.77
8	10	427.54	445.17	463.61	482.83	502.64	523.21
9	10	809.39	842.92	878.06	914.7	952.36	991.44
10	10	626.68	652.6	679.75	708.05	737.18	767.4
11	10	768.37	800.28	833.75	868.65	904.48	941.64
12	10	575.8	599.59	624.48	650.44	677.17	704.91
1	11	977.52	1017.7	1059.6	1103.3	1148.5	1195.4
2	11	887.4	923.97	962.21	1002.1	1043.2	1085.9
3	11	1016	1058	1102	1147.9	1195.1	1244.2
4	11	961.08	1001.2	1043.2	1087.1	1132.1	1178.7
5	11	698.48	727.49	757.92	789.65	822.21	856
6	11	800.05	833.26	868.08	904.4	941.7	980.38
7	11	821.31	855.41	891.16	928.45	966.73	1006.5
8	11	905.76	943.32	982.68	1023.7	1065.9	1109.7
9	11	775.62	807.9	841.79	877.15	913.39	950.95
10	11	965.26	1005.5	1047.7	1091.7	1136.9	1183.7
11	11	1024.7	1067.5	1112.4	1159.3	1207.2	1256.9

12	11	785.2	817.74	851.84	887.4	923.96	961.88
1	12	362.68	377.76	393.56	410.05	426.97	444.52
2	12	559.66	582.84	607.12	632.45	658.48	685.49
3	12	515.53	536.96	559.44	582.89	606.94	631.89
4	12	520.33	542.22	565.27	589.36	613.89	639.27
5	12	748.86	780.08	812.85	847.05	882.07	918.37
6	12	561.03	584.33	608.76	634.24	660.39	687.52
7	12	498.22	519.04	540.9	563.72	587.06	611.25
8	12	567.84	591.46	616.23	642.07	668.57	696.06
9	12	487.42	507.94	529.55	552.13	575.12	598.91
10	12	619.51	645.43	672.68	701.12	730.18	760.29
11	12	467.77	487.42	508.1	529.7	551.72	574.51
12	12	753.68	785.15	818.22	852.72	888.03	924.61
1	13	126.84	132.16	137.76	143.61	149.57	155.75
2	13	290.55	302.72	315.54	328.91	342.56	356.7
3	13	297.54	310.03	323.17	336.89	350.88	365.37
4	13	247.47	257.98	269.09	280.71	292.46	304.62
5	13	316.16	329.52	343.62	358.35	373.31	388.78
6	13	404.51	421.51	439.39	458.07	477.11	496.83
7	13	330.79	344.76	359.5	374.9	390.54	406.73
8	13	417.72	435.25	453.7	472.95	492.6	512.95
9	13	272.81	284.41	296.66	309.47	322.44	335.85
10	13	240.12	250.33	261.11	272.39	283.8	295.6
11	13	162.95	169.86	177.16	184.79	192.53	200.52
12	13	282.19	294.09	306.62	319.71	333.03	346.81

Table 18 - Chile - Transmission buses

Name	Voltage (kV)	Demand (%)	Name	Voltage (kV)	Demand (%)
Paposo220	220		Lalackama220	220	
DAlmagro220	220		Francisco220	220	
CPinto220	220	0.01%	Cachiyuyal22	220	
Cardones220	220	1.52%	Rahue220_aux	220	
Cardones110	110	1.69%	DAlmagro22A	220	
Maitencil220	220	1.16%	CPinto220_Au	220	
Maitencil110	110	0.26%	Cardones22A1	220	
Huasco110	110	0.50%	Cardones22A2	220	
PAzucar220	220	0.66%	Secc_Car_220	220	
PAzucar110	110	1.25%	PuntaSier220	220	
LVilos220	220	0.40%	LChangos220	220	
Quillota220	220	1.65%	LChangos500	500	
ASanta220	220		Cumbres500	500	
Miraflore110	110	0.93%	PAzucar500	500	
Quillota110	110	1.11%	Maitencil500	500	
Ventanas110	110	0.72%	Cardones500	500	
Pachacama110	110	0.90%	LaHiguera154	154	
LVegas110	110	0.47%	LaConflue154	154	
PPeuco110	110	0.29%	PNegro220	220	
Batuco110	110	0.83%	AJahuel500_A	500	
Polpaico220	220	4.41%	Charrua500	500	
Lampa220	220	0.37%	Ancoa500AuxS	500	
Rapel220	220	1.05%	Propulli220	220	
AMelipill220	220	1.07%	Propulli22A	220	
CNavia220	220		NvaValdiv220	220	
CNavia110	110	1.52%	NvaValdiv22A	220	
Chena220	220		EntreRios220	220	
AJahuel220	220	0.05%	EntreRios500	500	
PAltoCmpc110	110	0.13%	Cumbres220	220	
Colbun220	220	0.58%	DonaCarmen22	220	
AJahuel110	110	0.62%	Nogales220au	220	
Paine154	154	0.37%	RioTolten220	220	
Rancagua154	154	0.79%	Cautin220aux	220	
Sauzal110_1	110	0.01%	PAzucar220au	220	
PCortes154	154	0.83%	A110	110	0.69%

Tilcoco154	154	
SFernando154	154	0.57%
Teno154	154	0.60%
Itahue154	154	1.18%
Cipreses154	154	
Maule154	154	0.03%
Linares154	154	0.47%
Parral154	154	0.60%
Chillan154	154	0.49%
Ancoa220	220	0.01%
Charrua220	220	0.52%
Charrua154	154	0.01%
LosAngele154	154	0.94%
Concepcio154	154	0.60%
SVicente154	154	1.38%
Petroquim154	154	0.73%
Hualpen154	154	0.58%
Mapal154	154	0.05%
Fopaco154	154	0.11%
Bocamina154	154	
Duqueco220	220	0.09%
Temuco220	220	
Valdivia220	220	0.76%
Rahue220	220	1.09%
PMontt220	220	0.98%
Canutilla220	220	
Horcones66	66	0.35%
Constituci66	66	0.13%
Coronel154	154	0.12%
EIndio110	110	
SJavier66	66	0.04%
SMiguel66	66	0.10%
Talca66	66	0.77%
Rancagua066	66	0.29%
Dole066	66	
Indura066	66	
Graneros066	66	0.24%
SFcoMost066	66	0.20%
Charrua066	66	0.60%
Cholguan066	66	0.21%
Pehuenche220	220	
Rucue220	220	0.03%
Antuco220	220	
Pangue220	220	
Trupan220	220	
Cholguan220	220	
Alfalfal220	220	
Candela220	220	2.38%
Ralco220	220	
Ciruelos220	220	0.12%
Ancoa500	500	
Sauzal110_2	110	
Tuniche_1	13.8	
Tuniche_2	13.8	
Cautin220	220	
Polpaico500	500	
AJahuel500	500	
Ancoa500Aux	500	
Ancud110	110	0.08%
Degan110	110	0.03%
Pid-Pid110	110	0.46%
Chonchi110	110	
ElPenon110	110	0.23%
Ovalle66	66	0.43%

AltoHospi110	110	0.15%
Andes220	220	
Andes345	345	
Angamos220	220	0.25%
Antofag110	110	
Antofag13	13.8	0.29%
Antucoya220	220	0.48%
Arica110	110	
Arica66	66	
Barriles110	110	
Barriles220	220	
Calama110	110	0.39%
Calama220	220	
Capricorn110	110	
Capricorn220	220	
CDArica66	66	
CDIquique66	66	
CentralAt220	220	
Centro110	110	0.43%
CerroDrag110	110	0.19%
CerroPabe220	220	
Chacaya220	220	
Chapiquina66	66	
Chinchorro66	66	0.18%
Chuquicam110	110	0.03%
Chuquicam220	220	0.66%
Cochrane220	220	
Collahuas220	220	1.93%
Coloso220	220	0.04%
Concentra220	220	
Conchi220	220	
Condores110	110	
Condores220	220	
Crucero220	220	
Desalant110	110	
Dolores110	110	0.04%
Domeyko220	220	0.91%
ElAbra220	220	1.03%
ElAguila66	66	0.04%
ElCobre220	220	
ElLoa220	220	0.26%
ElNegro110	110	0.04%
ElTesoro220	220	0.44%
Enaex110	110	
Encuentro220	220	1.96%
Escondida220	220	1.34%
Esmeralda110	110	
EsperanNG220	220	1.32%
Gaby220	220	0.56%
Iquique66	66	
Kelar220	220	
Kimal220	220	
Kimal500	500	
KM6110	110	
Laberinto220	220	
LaCruz220	220	0.04%
Lagunas220	220	
Lagunas23	220	0.07%
LagunaSec220	220	1.24%
LaNegra110	110	0.20%
LaPortada110	110	0.16%
Lince110	110	
LomasBaya220	220	0.52%
MantosBla220	220	0.25%

Punitaqui66	66	0.07%
MPatria66	66	0.09%
Tinguirir154	154	
Guacolda220	220	
Nogales220	220	
CNavia220_Au	220	
SantaElvir66	66	0.30%
Hualpen220	220	
Lagunilla220	220	
Molinos110	110	0.43%
Polpaico22A	220	
ElSalto110	110	0.14%
Almendros220	220	
Almendros110	110	1.06%
Chena110	110	2.46%
LoEspejo110	110	0.91%
Ochagavia110	110	2.68%
Florida110	110	1.19%
PColorada220	220	
LPalmas220	220	
Buin110	110	1.52%
Renca110	110	1.85%
Malloa154	154	0.74%
ASanta110	110	1.12%
Sauzal154	154	
Sauzal110_3	110	
SantaMari220	220	
Temuco66	66	1.44%
Pillanlelb66	66	0.07%
Lautaro66	66	0.33%
LVegas110_ex	110	
Ventanas220	220	
SanLuis220	220	
Quintero220	220	
Coronel66	66	0.51%
Concepcio66	66	0.93%
Torquemad110	110	0.66%
LlanoLlam220	220	
Talinay220	220	
MRedondo220	220	
Chiloe110	110	
Prahue220	220	
ETaltal220	220	
Donhector220	220	
LoAguirre220	220	
LoAguirre500	500	
Tinguirir220	220	
LaCebada220	220	
DonGoyo220	220	
SanAndres220	220	
SantaMart220	220	
Mulchen220	220	0.08%
Angostura220	220	
DAlmagro110	110	1.29%
Valleland220	220	
Maitencil22A	220	
SCristoba110	110	4.00%
StaRosa110	110	1.61%
Apoquindo110	110	3.42%
Mantosdel110	110	0.04%
MariaElen220	220	
Mejillone110	110	0.38%
MinistroH220	220	
Minsal110	110	0.33%
Miraje220	220	
Norgener220	220	
NvaVictor220	220	0.09%
NvaZaldiv220	220	
Oeste110	110	
Oeste220	220	
OGP1220	220	1.45%
Ohiggins220	220	1.30%
Pacifico110	110	0.18%
Palafitos110	110	0.15%
Palestina220	220	0.18%
Pampa110	110	
Parinacot220	220	
Parinacota66	66	
PozoAlmon110	110	0.32%
PozoAlmon13	13.8	0.08%
PozoAlmon220	220	
PozoAlmon66	66	0.06%
Pukara66	66	0.24%
Quiani66	66	0.09%
Quillagua220	220	
RadomiroT220	220	0.86%
Salar110	110	
Salar220	220	0.89%
Salta345	345	
TapSierra220	220	
Spence220	220	0.96%
Sulfuros220	220	0.76%
Sur110	110	0.12%
Tamarugal66	66	0.09%
Tamaya110	110	
Tarapaca220	220	0.08%
Tchitack220	220	0.33%
Tocopilla110	110	
Tocopilla220	220	
Tocopilla005	5	0.05%
Uribe110	110	0.03%
Zaldivar220	220	0.68%
AJahuel154	154	
AltoNorte110	110	0.48%
Concepcio220	220	
Esmeralda220	220	
Kapatur220	220	
Lagunilla154	154	
LaHiguera220	220	
Mejillone220	220	
Cautin500	500	
PMontt500	500	
Almendros500	500	
Ciruelos500	500	
NTaltal500	500	
Propulli500	500	
Mulchen500	500	

Table 19 - Chile - Existing circuits

FROM bus	TO bus	Reactance (%)	Capacity (MW)	FROM bus	TO bus	Reactance (%)	Capacity (MW)

Paposo220	ETaltal220	1.5654	285
ETaltal220	Cachiyuyal22	4.0309	285
Cachiyuyal22	DAlmagro220	8.8837	285
Paposo220	Lalackama220	1.5654	285
Lalackama220	DAlmagro220	12.922	285
Lalackama220	Francisco220	4.0412	285
Francisco220	DAlmagro220	8.8812	285
CPinto220	DAlmagro22A	6.11	214
Cardones220	CPinto220	5.85	220
Cardones22A1	SanAndres220	2.3307	214
Cardones220	Cardones110	2.8664	270
Maitencil110	Cardones110	52.3	46.679
Maitencil220	Maitencil110	17.44	180
Guacolda220	Maitencil220	0.752	971.68
PAzucar110	Maitencil110	62.31	78
Maitencil110	Huasco110	5.5021	150
PAzucar220	PAzucar110	5.5542	246
SanLuis220	ASanta220	0.97	400
ASanta220	ASanta110	14.412	300
Quillota110	Miraflore110	4.55	98
Quillota220	Quillota110	6.2191	312
Ventanas110	Quillota110	4.85	280
Quillota110	Pachacama110	2.445	270
Pachacama110	LVegas110	2.015	270
PPeuco110	LVegas110	5.635	210
Batuco110	PPeuco110	2.855	210
CNavia110	Batuco110	3.13	210
Quillota220	Polpaico220	2.4278	1500
Rapel220	AMelipill220	4.62	320
CNavia220	CNavia110	1.5936	771
CNavia220	CNavia110	1.0624	1171
CNavia220	Chena220	0.4904	553.85
AJahuel220	Chena220	2.7337	525
AJahuel220	SantaMart220	0.97	525
SantaMart220	Chena220	1.7637	525
AJahuel220	PAltoCmpc110	96.19	48
Candela220	AJahuel220	1.5337	900
AJahuel220	AJahuel154	3.2167	300
AJahuel220	AJahuel110	2.941	429
AJahuel154	Paine154	2.83	179
Paine154	Tuniche_1	5.3545	179
AJahuel110	Sauzal110_1	10.62	153.2
AJahuel154	Tuniche_2	8.18	179
Rancagua154	Tuniche_1	1.66	179
Rancagua154	Tuniche_2	1.66	179
Tuniche_1	PCortes154	1.58	128
Tuniche_2	PCortes154	1.58	128
Tilcoco154	PCortes154	3.2687	198
Cipreses154	Itahue154	9.4239	253.4
Itahue154	Maule154	7.47	141.6
Maule154	Linares154	7.42	106.69
Parral154	Linares154	6.4	106.69
Chillan154	Parral154	11.32	106.69
Charrua220	Charrua154	2.8	390
Charrua220	Concepcio220	5.74	265.21
Concepcio220	Concepcio154	2.3363	261
Charrua154	LosAngele154	7.36	114.7
Charrua154	Concepcio154	12.49	176
Concepcio154	SVicente154	0.985	316.35
SVicente154	Petroquim154	0.4	209
Charrua220	Hualpen220	4.8549	227
Hualpen220	Hualpen154	3.2166	300
SVicente154	Hualpen154	0.87	209
Petroquim154	Hualpen154	0.46	209

LoAguirre500	LoAguirre220	0.98	1542.5
LoAguirre500	Polpaico500	0.186	2800
Ancoa500Aux	AJahuel500	0.3325	4200
Tinguirir220	Tinguirir154	3.2	300
Chena220	Chena110	1.305	800
DAlmagro220	DAlmagro110	5.8316	240
Maitencil22A	Valleland220	4.0345	260
Valleland220	Cardones220	6.8694	260
Maitencil220	Maitencil22A	0.0207	660
Ancoa500	Ancoa220	1.084	1500
DAlmagro220	DAlmagro22A	0.0207	731.6
CPinto220	CPinto220_Au	0.0207	731.6
Cardones22A2	DAlmagro22A	12.128	365.8
CPinto220	DAlmagro22A	6.1959	365.8
Cardones22A2	CPinto220_Au	5.9323	365.8
CPinto220	DAlmagro22A	6.1959	365.8
Cardones22A2	CPinto220_Au	5.9323	365.8
CPinto220	DAlmagro22A	5.9323	400
Cardones22A1	SanAndres220	2.3635	400
SanAndres220	CPinto220_Au	3.5688	400
Cardones22A2	Cardones22A1	0.0207	731.6
Cardones220	Cardones22A1	0.0207	731.6
Cardones22A2	SanAndres220	2.3635	342.7
Cardones22A2	SanAndres220	2.3635	342.7
SanAndres220	CPinto220_Au	3.5688	342.7
SanAndres220	CPinto220_Au	3.5688	342.7
LChangos500	LChangos220	1.336	750
LChangos500	LChangos220	1.336	750
LChangos500	LChangos220	1.336	750
DAlmagro220	Cumbres220	0.7851	1200
Cumbres500	Cumbres220	1.336	750
LChangos500	Cumbres500	4.5081	1500
Cumbres500	Cardones500	2.2379	1500
Cardones500	Cardones220	0.975	750
Maitencil500	Cardones500	0.368	1700
Maitencil500	Maitencil220	1.95	750
PAzucar500	Maitencil500	0.544	1700
PAzucar500	PAzucar220	1.95	750
PAzucar500	Polpaico500	1.121	1700
Cardones500	Cardones220	0.975	750
Maitencil500	Maitencil220	1.95	750
PAzucar500	PAzucar220	1.95	750
LaConflue154	LaHiguera154	2.4591	300
LaHiguera154	Tinguirir154	4.7941	440
LaHiguera154	LaHiguera220	3.2167	450
LaHiguera220	PNegro220	1.6444	440
Colbun220	PNegro220	1.9475	680
PNegro220	Tinguirir220	0.7047	440
PNegro220	Candela220	1.3085	680
Propulli220	Prahue220	3.9103	145
Propulli220	Rahue220_aux	4.9656	182.9
Propulli22A	Propulli220	0.0207	435
Valdivia220	Propulli22A	2.2382	182.9
Ciruelos220	Propulli220	2.7527	290
NvaValdiv220	Propulli22A	0.2111	290
NvaValdiv22A	NvaValdiv220	0.0207	145
Valdivia220	NvaValdiv22A	2.027	290
Propulli220	PMontt220	11.207	660
Charrua500	Charrua220	0.65	2250
Charrua500	Ancoa500	0.6381	1600
Charrua500	Ancoa500AuxS	1.2762	1600
Ancoa500AuxS	Ancoa500	0.004	2600
EntreRios500	EntreRios220	1.95	750
EntreRios500	Ancoa500AuxS	0.588	1600

Hualpen154	Mapal154	1.85	188
Mapal154	Fopaco154	1.05	188
Charrua220	Duqueco220	4.0098	264.07
Duqueco220	Temuco220	12.625	264.07
Cautin220	Cautin220aux	0.0207	232
Cautin220aux	Ciruelos220	8.2072	174
Cautin220aux	RioTolten220	2.6277	174
RioTolten220	Ciruelos220	6.9899	174
Charrua220	Mulchen220	1.7975	500
Mulchen220	Cautin220	4.314	500
Angostura220	Mulchen220	1.2198	500
Ciruelos220	Valdivia220	1.7339	174
Valdivia220	Rahue220_aux	8.7	174
Temuco220	Cautin220	0.2143	385.62
Rahue220	PMontt220	9.42	172
Canutilla220	PMontt220	2.53	194.34
Bocamina154	Coronel154	0.15	213
Coronel154	Horcones66	163.28	84.6
Maule154	SMiguel66	4.53	84.6
SMiguel66	Talca66	1.285	84.6
Linares154	SJavier66	72.94	28.6
SJavier66	Constituci66	77.16	27.9
PAzucar110	EIndio110	71.56	30
Rancagua154	Rancagua066	13.1	110
Rancagua066	Dole066	6.05	43.67
Dole066	Indura066	2.75	41.454
Indura066	Graneros066	1.5	41.454
Graneros066	SFcoMost066	6	43.3
Charrua154	Charrua066	18.88	73.5
Charrua066	Cholguan066	21.81	17.64
Pehuenche220	Ancoa220	0.98	675
Rucue220	Charrua220	2.54	362
Antuco220	Charrua220	2.665	1023.1
Antuco220	Trupan220	1.84	512
Pangue220	Trupan220	6.98	336.14
Pangue220	Cholguan220	4.8	336.14
Trupan220	Charrua220	3.5	512
Cholguan220	Charrua220	5.86	336.14
Colbun220	Candela220	2.77	900
Talca66	SJavier66	18.165	34.295
Ancoa220	Itahue154	5.7987	300
Charrua220	Ralco220	4.0814	722
Charrua154	Chillan154	10.338	157
Charrua154	Parral154	21.37	106.69
Itahue154	Teno154	6.06	198
Valdivia220	Prahue220	9.4437	174
Prahue220	PMontt220	8.405	182.9
Prahue220	Rahue220_aux	0.2648	182.9
Rahue220_aux	Rahue220	0.0207	182.9
Rahue220	PMontt220	4.5857	182.9
Polpaico500	Polpaico220	0.975	1500
AJahuel500_A	AJahuel220	0.98	1500
AJahuel500_A	AJahuel220	0.6533	2250
AJahuel500	AJahuel500_A	0.004	1920
Ancoa500	Ancoa500Aux	0.004	4200
Cautin220aux	Valdivia220	12.552	182.9
PMontt220	Molinos110	23.994	60
Pid-Pid110	Chonchi110	8.4772	55.252
Chiloe110	Ancud110	11.124	61.3
Chiloe110	Degan110	0.0512	39.5
Chiloe110	Pid-Pid110	10.452	159.6
PMontt220	Chiloe110	20.398	90
PAzucar110	ElPenon110	6.4947	93.358
ElPenon110	Ovalle66	28.583	68.4

EntreRios500	Charrua500	0.0501	1600
Charrua220	EntreRios220	0.0207	1000
Charrua500	Ancoa500AuxS	1.2762	1500
Salta345	Andes345	12.03	777
Andes345	Andes220	1.52	750
Lagunas220	PozoAlmon220	6.0252	328
Lagunas220	Lagunas23	79.556	93
PozoAlmon220	PozoAlmon110	13.275	200
PozoAlmon110	PozoAlmon66	19.75	30
PozoAlmon220	PozoAlmon13	36.875	20
Iquique66	PozoAlmon66	18.385	87
CDIquique66	Iquique66	1.4968	48
Tarapaca220	Lagunas220	2.2541	366
Tarapaca220	Condores220	5.7851	183
Condores220	Parinacot220	18.735	91
Condores220	PozoAlmon220	2.97	250
PozoAlmon220	Parinacot220	14.1	250
Lagunas220	Collahuas220	4.9053	202
Encuentro220	Collahuas220	16.965	109
Encuentro220	Collahuas220	16.83	159
Crucero220	NvaVictor220	13.609	183
NvaVictor220	Lagunas220	1.3971	183
LaCruz220	Crucero220	0.7066	474
Norgener220	LaCruz220	5.12	474
Norgener220	Barriles220	1.4	474
Crucero220	Barriles220	4.36	474
Barriles220	Barriles110	40	30
Barriles110	Mantosdel110	8.792	71
Tocopilla220	ElLoa220	5.11	225
ElLoa220	Crucero220	0.82	330
Tocopilla220	Crucero220	6.1743	330
Tocopilla220	Tocopilla110	4.425	200
Tocopilla220	Tocopilla005	2.167	20
Crucero220	RadomiroT220	6.8121	450
Crucero220	Conchi220	7.8445	170.1
Conchi220	ElAbra220	0.2674	170.1
Conchi220	CerroPabe220	6.3958	92.6
Crucero220	Chuquicam220	5.9463	330
Chuquicam220	Chuquicam110	6.21	240
Salar220	Chuquicam220	1.0745	330
Crucero220	Salar220	6.359	330
Salar220	Salar110	14.25	120
Salar220	Calama220	18.795	307.24
Calama220	Calama110	5.03	307.24
Crucero220	Encuentro220	0.0426	1000
Crucero220	Laberinto220	11.003	290
Crucero220	Laberinto220	11.294	278
Laberinto220	NvaZaldiv220	6.0391	350
Chacaya220	Crucero220	13.144	305
Chacaya220	ElCobre220	5.6484	700
TapSierra220	ElTesoro220	6.6326	125
ElTesoro220	EsperanNG220	1.0718	125
ElCobre220	EsperanNG220	3.5352	548
ElCobre220	Gaby220	4.649	328
Encuentro220	Lagunas220	7.089	580
Encuentro220	MinistroH220	6.07	273
Encuentro220	Tchitack220	6.611	273
MinistroH220	Tchitack220	0.58	273
Chacaya220	Capricorn220	4.2304	351
Chacaya220	Mejillone220	0.11	332
Capricorn220	MantosBla220	1.3537	305
Laberinto220	ElCobre220	0.2141	500
Laberinto220	LomasBaya220	0.86	290
Laberinto220	MantosBla220	6.0227	300

Ovalle66	MPatria66	13.31	68.4
Ovalle66	Punitaqui66	32.735	18.7
Polpaico220	ElSalto110	3.1181	800
ElSalto110	SCristoba110	1.0209	425.25
SCristoba110	CNavia110	2.5392	425.25
CNavia110	Chena110	1.5116	409.25
Chena110	LoEspejo110	0.1526	450
LoEspejo110	Ochagavia110	0.7599	409.25
Ochagavia110	Florida110	2.1468	409.25
Florida110	Almendros110	3.0323	400
Almendros110	Apoquindo110	0.6683	425.25
Apoquindo110	ElSalto110	1.1723	425.25
Renca110	CNavia110	0.4541	460
Florida110	StaRosa110	0.8143	301.8
StaRosa110	AJahuel110	2.0375	301.8
Almendros220	AJahuel220	1.7449	409.25
Almendros220	Almendros110	2.61	400
AJahuel220	Buin110	2.941	400
Buin110	LoEspejo110	2.3661	409.25
Alfalfal220	Almendros220	1.785	373.4
Tuniche_1	Tinguirir154	4.8313	198
Tinguirir154	SFernando154	0.71	198
Tinguirir154	Itahue154	10.51	198
Tinguirir154	Teno154	5.1593	198
Tilcoco154	Malloa154	1.3845	198
Malloa154	Tinguirir154	1.3425	198
AJahuel220	Chena220	1.1042	622.36
Maitencil22A	Cardones220	5.5673	580
Maitencil22A	Secc_Car_220	2.0666	580
Secc_Car_220	Cardones220	3.5007	580
LVilos220	Nogales220au	7.72	328
LVilos220	DonaCarmen22	5.2553	328
DonaCarmen22	Nogales220au	2.4647	328
PAzucar220	PAzucar220au	0.01	9999
Nogales220au	Nogales220	0.0207	656
Nogales220	Quillota220	2.1968	328
Nogales220	Polpaico220	2.9307	1422
AJahuel500	Polpaico500	0.7893	1400
Chillan154	SantaElvir66	10.672	75
Charrua220	Lagunilla220	4.3347	450
Lagunilla220	Hualpen220	0.9431	450
PAzucar220au	LaCebada220	10.541	224
LaCebada220	MRedondo220	0.2526	328
LPalmas220	LVilos220	2.82	656
Maitencil220	PColorada220	4.5505	359.1
Maitencil220	Donhector220	2.3927	359.1
Donhector220	PColorada220	2.1579	359.1
PColorada220	PAzucar220	3.3947	359.1
Maitencil220	PColorada220	3.4971	1000
PColorada220	PAzucar220	2.8199	1000
ASanta110	Miraflore110	0.9305	300
Lampa220	Polpaico22A	1.33	540
CNavia220_Au	Polpaico22A	2.38	540
Polpaico220	Polpaico22A	0.0021	540
CNavia220	CNavia220_Au	2.0661	540
CNavia220_Au	Lampa220	1.05	540
Lagunilla154	Coronel154	0.6461	188
Lagunilla220	Lagunilla154	1.5451	390
Fopaco154	Lagunilla154	1.2413	188
Sauzal110_3	Sauzal110_1	0.0083	500
Sauzal110_3	Sauzal110_2	0.0083	500
Sauzal110_2	Sauzal154	12.372	60
Sauzal110_2	Sauzal154	6.1882	100
Sauzal154	Rancagua154	0.8584	108

Laberinto220	NvaZaldiv220	8.0247	270
Oeste220	Laberinto220	7.312	290
Andes220	Oeste220	3.265	290
Oeste220	Oeste110	26.67	55
Oeste110	Minsal110	11.536	50
Antofag110	Antofag13	39.5	30
Condores110	Condores220	7.21	195
Condores110	AltoHospi110	0.8611	98
Condores110	Pacifico110	3.1273	98
Condores110	Palafitos110	2.7666	98
Parinacota66	Chinchorro66	2.9003	70
Parinacota66	Parinacot220	10.98	120
Quiani66	Parinacota66	6.3971	59
Parinacota66	Pukara66	3.709	46
AltoHospi110	CerroDrag110	0.7165	98
Angamos220	Kapatur220	0.344	1401
Cochrane220	Encuentro220	4.5085	1208
Encuentro220	TapSierra220	1.1104	125
Ohiggins220	Coloso220	2.8975	467
Quillagua220	Lagunas220	8.4384	183
MariaElen220	Quillagua220	5.7676	183
Crucero220	MariaElen220	0.5982	183
Domeyko220	OGP1220	1.356	246
Domeyko220	LagunaSec220	1.117	246
NvaZaldiv220	OGP1220	2.3981	246
KM6110	Salar110	0.3314	194.34
Chuquicam110	KM6110	2.39	100
Tamaya110	A110	42.35	65
Tamaya110	Salar110	40.168	65
Tocopilla110	Tamaya110	4.6685	65
Tocopilla110	Tamaya110	5.3594	65
Miraje220	Encuentro220	0.5058	733.4
CentralAt220	Miraje220	8.5511	366.7
Antucoya220	Miraje220	2.12	366.7
CentralAt220	Antucoya220	6.33	366.7
Encuentro220	Spence220	5.62	318
Quiani66	Arica66	3.5124	28
CDArica66	Quiani66	3.114	17
Esmeralda110	Uribe110	5.2054	98
Andes220	NvaZaldiv220	2.5795	740
NvaZaldiv220	Zaldivar220	0.0165	270
Zaldivar220	Escondida220	1.1408	366
NvaZaldiv220	Sulfuros220	1.0994	362
Domeyko220	Sulfuros220	0.0846	293
Domeyko220	Escondida220	0.6009	300
CentralAt220	Ohiggins220	3.1165	467
Ohiggins220	Domeyko220	5.6271	467
Ohiggins220	Palestina220	4.8422	229
Palestina220	Domeyko220	4.314	225
Mejillone220	Ohiggins220	4.3317	242
Esmeralda220	CentralAt220	5.8285	197
Esmeralda220	Esmeralda110	7.2211	195
Esmeralda110	Centro110	0.179	98
Esmeralda110	LaPortada110	5.4336	98
Esmeralda110	Sur110	2.1368	98
Mejillone220	Mejillone110	13.238	100
Mejillone110	Enaex110	0.399	183
Arica110	Arica66	19.7	30
Arica110	Dolores110	47.18	29
Dolores110	PozoAlmon110	27.206	29
PozoAlmon66	Tamarugal66	21.3	10
Tocopilla110	A110	23.509	130
Chuquicam110	A110	0.01	200
Mejillone110	Lince110	24.597	48

Colbun220	Ancoa220	0.0052	600
SantaMari220	Charrua220	2.1942	517
Temuco220	Temuco66	4.5701	310
Temuco66	Pillanlelb66	10.081	50
Pillanlelb66	Lautaro66	6.3548	50
PPeuco110	LVegas110	11.27	210
Batuco110	PPeuco110	5.71	210
CNavia110	Batuco110	6.26	210
CNavia110	LVegas110_ex	23.24	210
Nogales220	Ventanas220	0.9465	680
Ventanas220	Ventanas110	4.9998	300
SanLuis220	Quillota220	0.2324	1973.8
Quintero220	SanLuis220	2.2211	550
Ciruelos220	Valdivia220	1.7339	182.9
Cautin220aux	Ciruelos220	4.4261	182.9
Coronel154	Coronel66	7.6013	120
Coronel66	Concepcio66	120.98	30
Concepcio154	Concepcio66	10.491	142
Ventanas110	Torquemad110	3.3607	300
Torquemad110	Miraflore110	2.2143	300
Cardones220	LlanoLlam220	3.7258	327
MRedondo220	LPalmas220	2.1281	224
PAzucar220au	DonGoyo220	6.119	328
DonGoyo220	Talinay220	2.8332	328
Talinay220	LPalmas220	3.9752	224
MRedondo220	PuntaSier220	1.3391	328
PuntaSier220	LPalmas220	0.3967	656
Talinay220	PuntaSier220	3.1716	224
Talinay220	LaCebada220	1.5838	328
LaCebada220	PuntaSier220	1.5878	328
PAzucar220au	DonGoyo220	6.119	328
DonGoyo220	LaCebada220	4.4417	328
LaCebada220	LPalmas220	2.3817	224
Valdivia220	Cautin220	0.0207	182.9
Rapel220	LoAguirre220	8.015	386
AMelipill220	LoAguirre220	3.435	386
Rapel220	AMelipill220	4.62	386
AMelipill220	LoAguirre220	3.435	386
LoAguirre220	CNavia220	0.5725	600
LoAguirre220	CNavia220	0.3917	1500
LoAguirre500	LoAguirre220	1.95	771.26
LoAguirre500	AJahuel500	0.4159	1400
LoAguirre500	Polpaico500	0.3721	1400
LoAguirre500	AJahuel500	0.2079	2800

Pampa110	Mejillone110	10.166	57
Desalant110	Pampa110	6.6583	57
Antofag110	Desalant110	3.7351	57
Antofag110	LaNegra110	6.2202	122
LaNegra110	AltoNorte110	1.555	122
ElNegro110	AltoNorte110	2.4167	137
Capricorn220	Capricorn110	12.9	100
Capricorn110	ElNegro110	12.594	137
Antofag110	Capricorn110	9.8579	76
Chapiquina66	ElAguila66	35.378	48
ElAguila66	Arica66	44.939	48
Concentra220	Chuquicam220	2.4	457
RadomiroT220	Concentra220	6.883	457
LChangos220	Kapatur220	0.0996	1500
Kapatur220	Laberinto220	4.0389	1301.8
Kapatur220	Ohiggins220	4.0389	1301.8
Kelar220	Kapatur220	0.4516	1448
Quillagua220	NvaVictor220	7.1846	183
MariaElen220	Quillagua220	2.834	366
MariaElen220	NvaVictor220	13.01	183
Crucero220	MariaElen220	0.2935	366
Encuentro220	Kimal220	0.0106	1000
Kimal220	Crucero220	0.0106	1000
Kimal500	Kimal220	0.9	1500
LChangos500	Kimal500	0.368	1500
ElLoa220	Kimal220	0.82	330
Tocopilla220	Kimal220	6.1743	330
Kimal220	Chuquicam220	5.9463	330
Kimal220	Salar220	6.359	330
Kimal220	Laberinto220	11.003	290
Kimal220	Laberinto220	11.294	278
Kimal220	MariaElen220	0.2935	366
AltoHospi110	CerroDrag110	0.7165	98
Condores110	AltoHospi110	0.8611	98
NTaltal500	ETaltal220	1.336	750
Cumbres500	NTaltal500	1.0362	1500
LChangos500	NTaltal500	3.4719	1500
Lagunas220	PozoAlmon220	6.0252	328
EntreRios220	Mulchen220	6.6076	660
Mulchen220	Cautin220aux	11.716	660
Cautin220aux	Ciruelos220	9.4045	660
Ciruelos220	Propulli220	9.5612	660
EntreRios500	EntreRios220	1.95	750

Table 20 - Chile - Transmission candidates

FROM bus	TO bus	Reactance (%)	Capacity (MW)	Investment cost (M$)
PAzucar500	Polpaico500	1.121	1700	113.68
PAzucar500	Maitencil500	0.544	1700	61.95
PuntaSier220	LPalmas220	0.3967	656	3.19
Maitencil500	Cardones500	0.368	1700	41.08
Lagunas220	Collahuas220	4.9053	202	8.49
Cardones220	Cardones22A1	0.0207	731.6	2.72
Charrua220	Charrua154	2.8	390	6.16
Cautin220	Cautin220aux	0.0207	232	2.72
CPinto220	CPinto220_Au	0.0207	731.6	2.72
Tarapaca220	Lagunas220	2.2541	366	7.52
LPalmas220	LVilos220	2.82	656	10.39
Cardones500	Cardones220	0.975	750	11.35
PColorada220	PAzucar220	3.3947	359.1	10.42
LVilos220	Nogales220au	7.72	328	12.66
Rahue220_aux	Rahue220	0.0207	182.9	2.72
Batuco110	PPeuco110	2.855	210	3.61

NvaVictor220	Lagunas220	1.3971	183	4.2
Itahue154	Maule154	7.47	141.6	6.84
Cardones22A2	SanAndres220	2.3635	342.7	6.84
Capricorn220	Capricorn110	12.9	100	4.74
Quillagua220	Lagunas220	8.4384	183	12.71
MariaElen220	Quillagua220	2.834	366	9.13
EntreRios500	Ancoa500AuxS	0.588	1600	57.74
Quillagua220	NvaVictor220	7.1846	183	10.81
Cumbres500	Cardones500	2.2379	1500	55.89
SanAndres220	CPinto220_Au	3.5688	342.7	8.94
SanAndres220	CPinto220_Au	3.5688	342.7	8.94
LoAguirre500	Polpaico500	0.186	2800	11.92
Cardones22A2	Cardones22A1	0.0207	731.6	2.72
Propulli220	Prahue220	3.9103	145	6.51
Ancoa220	Itahue154	5.7987	300	5.78
Cardones22A1	SanAndres220	2.3635	400	9.43
Ancoa500AuxS	Ancoa500	0.004	2600	5.74
Almendros220	Almendros110	2.61	400	6.2
Quillota110	Miraflore110	4.55	98	5.21
Ciruelos220	Valdivia220	1.7339	174	4.27
Cautin220aux	Ciruelos220	8.2072	174	12.47
PAzucar110	ElPenon110	6.4947	93.358	4.12
Charrua220	Mulchen220	1.7975	500	7.65
Charrua220	EntreRios220	0.0207	1000	3.07
Prahue220	Rahue220_aux	0.2648	182.9	3.03
Charrua154	LosAngele154	7.36	114.7	5.1
Tinguirir220	Tinguirir154	3.2	300	5.78
DonGoyo220	LaCebada220	4.4417	328	7.99
LoEspejo110	Ochagavia110	0.7599	409.25	2.7
PAzucar220	PAzucar110	5.5542	246	5.52
Nogales220	Quillota220	2.1968	328	5.88
Chena110	LoEspejo110	0.1526	450	2.22
Cautin220aux	RioTolten220	2.6277	174	5.07
Paposo220	ETaltal220	1.5654	285	4.73
CNavia110	Batuco110	3.13	210	3.76
PAzucar220au	DonGoyo220	6.119	328	9.96
Cardones220	Cardones110	2.8664	270	5.64
PNegro220	Candela220	1.3085	680	7.52
Cumbres500	NTaltal500	1.0362	1500	28.96
PMontt220	Molinos110	23.994	60	4.5
Polpaico500	Polpaico220	0.975	1500	13.01
Colbun220	Ancoa220	0.0052	600	2.74
Ventanas220	Ventanas110	4.9998	300	5.78
Almendros110	Apoquindo110	0.6683	425.25	2.59
Antofag110	Capricorn110	9.8579	76	3.95
Colbun220	PNegro220	1.9475	680	7.52
RioTolten220	Ciruelos220	6.9899	174	9.04
Oeste110	Minsal110	11.536	50	4.14
Charrua220	Hualpen220	4.8549	227	9.08
Malloa154	Tinguirir154	1.3425	198	3
LoAguirre500	AJahuel500	0.2079	2800	12.65
Rahue220	PMontt220	4.5857	182.9	7.76
Kimal220	MariaElen220	0.2935	366	3.39
Ohiggins220	Palestina220	4.8422	229	8.45
Almendros220	AJahuel220	1.7449	409.25	6.46
Chena220	Chena110	1.305	800	7.2
Cipreses154	Itahue154	9.4239	253.4	6.59
AJahuel220	AJahuel154	3.2167	300	5.78
Oeste220	Oeste110	26.67	55	4.47
AJahuel500	AJahuel500_A	0.004	1920	5.74
Petroquim154	Hualpen154	0.46	209	2.38
Charrua220	Ralco220	4.0814	722	18.48
Quillota220	Quillota110	6.2191	312	5.83
Polpaico220	ElSalto110	3.1181	800	7.2

ElSalto110	SCristoba110	1.0209	425.25	2.96
Concepcio220	Concepcio154	2.3363	261	5.6
Cardones500	Cardones220	0.975	750	11.35
Cardones500	Cardones220	0.975	750	11.35
PAzucar500	Polpaico500	1.121	1700	113.68
PAzucar500	Maitencil500	0.544	1700	61.95
PuntaSier220	LPalmas220	0.3967	656	3.19
Maitencil500	Cardones500	0.368	1700	41.08
Lagunas220	Collahuas220	4.9053	202	8.49
Cardones220	Cardones22A1	0.0207	731.6	2.72
Cautin220	Cautin220aux	0.0207	232	2.72
CPinto220	CPinto220_Au	0.0207	731.6	2.72
PAzucar500	Polpaico500	1.121	1700	113.68
PAzucar500	Maitencil500	0.544	1700	61.95
Tarapaca220	Lagunas220	2.2541	366	7.52
Propulli220	Prahue220	3.9103	145	6.51
Quillota110	Pachacama110	2.445	270	3
AJahuel154	Paine154	2.83	179	5
Pehuenche220	Ancoa220	0.98	675	8.45
Cautin220aux	Ciruelos220	8.2072	174	12.47
PAzucar500	Polpaico500	1.121	1700	113.68
Propulli220	Rahue220_aux	4.9656	182.9	8.45
LaHiguera220	PNegro220	1.6444	440	8.45
Encuentro220	Collahuas220	16.83	159	8.45
NvaVictor220	Lagunas220	1.3971	183	4.2
Quillagua220	Lagunas220	8.4384	183	12.71
MariaElen220	Quillagua220	2.834	366	9.13
Quillagua220	NvaVictor220	7.1846	183	10.81
Apoquindo110	ElSalto110	1.1723	425.25	10
Maitencil500	Cardones500	0.368	1700	41.08
Rahue220_aux	Rahue220	0.0207	182.9	2.72
Palestina220	Domeyko220	4.314	225	8.45
NvaZaldiv220	Zaldivar220	0.0165	270	3.39
Sauzal110_2	Sauzal154	6.1882	100	4.47
PAzucar110	ElPenon110	6.4947	93.358	4.12
Mulchen220	Cautin220	4.314	500	7.52
NvaValdiv22A	NvaValdiv220	0.0207	145	2.72
Tarapaca220	Lagunas220	2.2541	366	7.52
Charrua220	Mulchen220	1.7975	500	7.65
Cautin220	Cautin220aux	0.0207	232	2.72
NvaVictor220	Lagunas220	1.3971	183	4.2
PAzucar220	PAzucar110	5.5542	246	5.52
PAzucar110	ElPenon110	6.4947	93.358	4.12
Quillagua220	NvaVictor220	7.1846	183	10.81