A Risk-Constrained Project Portfolio in Centralized Transmission Expansion Planning

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***Abstract*—The implementation of a centralized transmission expansion plan is a complex task when several investors compete and bid to build a new transmission asset, as is the case now in Chile. The assessment of a transmission project depends on the number of competitors, where the project is subject to risks, such as delays, penalties, and cost overruns. The risk faced by an investor is measured using the Conditional Value at Risk (CVaR), which can be interpreted as the risk of not reaching an expected return on investment, depending on the tolerance to risk and the real income obtained with the investor's portfolio. This risk comes from the difference between the regulated income (investor's bid) and the real cost during the implementation and operation of the transmission project. The difference is the "surplus" profit that the investor obtains by participating in the tender, considering their risk tolerance. The goal is to determine the optimal value of a risky investor's portfolio made up of several transmission projects. The optimal portfolio may allow the central planner to improve the efficiency of the project allocation process. To test the methodology, two case studies are analyzed: the IEEE 24-bus Reliability Test System and a predefined expansion plan of Chile's Central Interconnected System (SIC).**

***Index Terms*—Bidding contract, Conditional Value at Risk (CVaR), investment, risk, transmission expansion.**

NOMENCLATURE

A. Indexes

j	Index of projects.
s	Index of scenarios.
Z	Expansion plan done by a centralized planner with project j.
P	Investment portfolio of an investor.

B. Decision Variables

RoW_j	Expected right of way cost of project j [\$m].
C_j	Expect optimal cost for an investor in project j [\$m].
$\mathrm{aC}_{j,s}$	Annuity of the expected cost of the winning bid V_j in scenario s [\$m].
V_j	Expected value of the winning bid for project j [\$m].
aV_j	Annuity of the expected value of the winning bid for project j [\$m].
$\mathrm{aV}_{j,s}$	Annuity of V_j in scenario s [\$m].
VaR_P	Value at Risk of portfolio P.
CVaR_P	Conditional Value at Risk of portfolio P [\$m].
η_s	Auxiliary variable to calculate CVaR_P for each scenario s [\$m].
x_j	Binary variable related to the selection of project j.
q_P	Investor's risk tolerance factor of portfolio P [%].
q_{Max}	Maximum tolerable risk level [%].

C. Random Variables

$\lambda_{j,s}$	Annual cost of operation, maintenance and administration (OPEX) of project j in scenario s as a percentage of the reference cost of project j, c_j [%].
$\delta_{j,s}$	Number of days of delay with respect to the operation start-up of project j in scenario s [days].
φ_j	Unpredictable cost of project j [\$m].

D. Constants

c_j	Reference cost of project j [\$m].
e_j	Investor's effort value to reduce the cost of project j [\$m].
ω	Confidence level in per unit.
π_s	Probability of occurrence of scenario s.
B_P	Annual maximum investor budget for portfolio P [\$m].
G_P	Maximum investor's guarantee for portfolio P [\$m].
S	Number of scenarios.
n_j	Number of investors that participate in the tender of project j.
α_j	Cost recognition factor of project j.
g_j	Requested guarantee for project j as a percentage of the reference cost c_j [%].
r	Regulated discount factor [%].
l_j	Lifetime of project j [years].
af	Annuity factor, $\mathrm{af} = r \cdot \left[1-(1+r)^{-l_j}\right]^{-1}$
m_j	Daily cost of the penalty for delays in project j as a percentage of the reference cost of project j, c_j [%].
$\lambda_{j,R}$	Annual regulated cost of operation, maintenance and administration of project j as a percentage of the reference cost of project j, c_j, [%].
μ_j	Historical mean percentage of the variation of the annual OPEX.
t_j	Construction time of project j [years].

I. INTRODUCTION

THE process of defining the optimum transmission plan and the most suitable methodology to deploy it in an

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electricity market context leads to consideration of multiple alternatives. The combinatorial nature of the problem [1], [2] and market and environmental constraints increase its complexity [3]. Investment in transmission networks is characterized by the following: high capital requirements, long periods of construction, long service life of the assets, and long payback periods. In [2] and [4]–[6], the most relevant aspects in transmission expansion are described (planning and investment). Financial valuations depend on who are the owners and who are the ones that control transmission assets. These types of problems can be framed as principal–agent problems [7] requiring the use of different techniques to evaluate the alternatives as a function of the interests of the principal, the increase in social welfare after investment, reliability, nonsupplied energy, and congestion cost reduction.

A. Motivation

In planning a transmission system, two approaches can be considered: centralized and decentralized. In the centralized model, the planner, typically a government, defines the expansion plan. In contrast, in a decentralized model, private agents independently perform the expansions that will be profitable for them. Another major change that has taken place with the restructuring and separation of the electricity sector is the arrival of new approaches for the construction, operation, and ownership of transmission assets.

In this context, transmission expansion planning occurs under a centralized approach, i.e., a centralized planner evaluates and defines the necessary investment projects in an expansion plan. In turn, the centralized market planner bids transmission projects to private investors. The energy market model in Chile considers that investors in generation and transmission are independent and the government does not participate as an investor, just as a regulator, where the transmission business is a regulated activity with open access.

Mechanisms such as tenders or other types of auctions are used to encourage investments in transmission expansion. Typically, the lowest net present value of cost or its annuity is used to determine the winner of the tender.

However, an efficient allocation is influenced by various risks, including financial, technical, and regulatory ones. One important aspect that is missing in the assessment is the feasibility of executing an optimal transmission expansion plan while avoiding cost overruns, NIMBY dilemma, etc. In the last decades, regulatory and political adversity to construct new transmission assets and land cost overruns have increased. This has resulted in inevitable delays. Therefore, it becomes a challenge for transmission investors to quantify the investment risk associated with a transmission asset.

B. Literature Review

Financial evaluation depends on the type of business model applied in transmission [8]. The most popular methods to evaluate transmission from a theoretical standpoint are net present value and cost/benefit analysis, and mechanisms for anticipated investment have been proposed [9]. The most common techniques are binomial trees [10], real option valuation [11], [12], and Markowitz's portfolio theory and risk analysis [13].

There are several methods to quantify the degree and the impact of risk, including the "Expected Shortfall," "Tail Conditional Expectation," "Value at Risk (VaR)," and "Conditional Value at Risk (CVaR)" [14]. The VaR method is widely used in risk management. However, this method has the disadvantage of not meeting the conditions of subadditivity and convexity of nonNormal probability distributions [15], [16]. In addition, VaR usually ignores or is indifferent to the potential risk of a severe loss, i.e., VaR only determines the loss associated with a predetermined profit with a certain level of probability. Hence, the CVaR method is often used since it provides more information than VaR and is a commonly used risk measure in portfolio optimization models [15], [16].

Note that the methods described are mainly used in models where income or profits do not have a ceiling value, meaning that, at greater risk, the expected profit would be higher. However, regulated businesses, such as the transmission of electricity, have a limited income, and a greater risk does not imply a higher benefit. In fact, an increased risk may decrease the income of investors because their investments are irreversible, at least during their remunerated lifetime. In this sense, one important aspect missing in the assessment is the feasibility or the stability of executing a transmission asset investment plan. Therefore, it becomes a challenge for transmission investors to quantify the investment risk associated with a transmission asset.

C. Contributions

Investment in a transmission expansion project is a regulated activity and as such only receives a fixed revenue over a period of time (indexed to economic variables or commodities) subject to a single assessment of a first-price or a sealed envelope auction. Thus, the contribution of the proposed work focuses on identifying the offers that a private investor would make under a centralized model subject to construction risk, variability of operating costs, maintenance and administration costs, and rules of participation in the transmission projects auction by the central planner. The auction mechanism presented is currently applied in Chile.

The main contributions of this paper are given here.

1) An approach for investors to improve their optimal investment portfolios, subject to strategic bids and project execution risks.
2) A model that establishes the impact of competition on the selection of the project portfolio.
3) The model allows a centralized planner to identify projects of an expansion plan, as investors only choose those ones that maximize their profits.
4) A practical solution of the problem is obtained applying mixed-integer linear programming, including risk using CVaR. It is emphasized that the mixed-integer programming technique proposed is an optimization technique that guarantees a robust solution and a global optimum.

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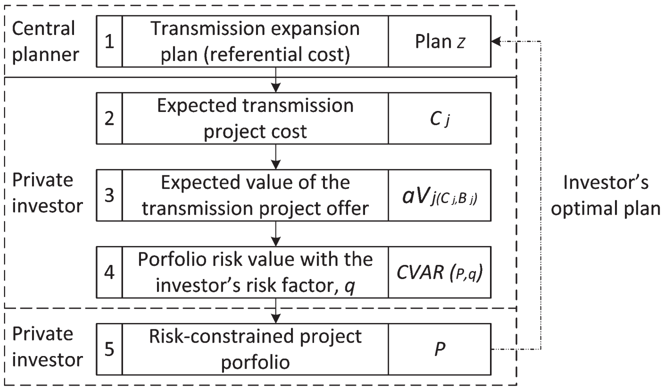

Fig. 1. Methodology framework.

D. Paper Organization

This paper is organized as follows: Section II presents the overall methodology to define feasible expansion plans and the expected value of the transmission expansion plan, subject to the type of investor. The methodology determines the optimal cost of a project with negotiating rights of way and the optimal bid, considering competition and risk, using CVaR. Section III presents two case studies where sensitivity analysis is performed with respect to financial, construction, and bidding risks. Conclusions are provided in Section IV.

II. Optimal Risk-Constrained Project Portfolio

The mathematical model to construct a project portfolio of an investor is presented. The types of risks and a method based on CVaR to quantify them are described.

A. Methodology and Regulatory Framework

The Chilean energy market considers a centralized planning model, where the planner defines the optimal expansion plan via expansion planning scenarios. The planner expects the expansion plan to be allocated to the investors with efficient bids. However, an efficient investor is faced with various risks that influence their bids or the selection of projects to bid for. Fig. 1 shows the proposed methodology.

The methodology starts with the reference cost that the centralized planner defines for the transmission projects belonging to each transmission expansion plan. Then, according to the rules of participation in the tender and the constraints of the investor, the values of the transmission projects are a function of the expected investment and operational costs and the bidding strategy. Finally, the centralized planner awards the tender to the bidder with the lowest annuity offer.

Basically, the steps are as follows: 1) a transmission expansion plan Z with a reference project cost c_j is defined by the centralized planner; 2) an assessment of the transmission project cost C_j is done; 3) the private investor defines the expected transmission project offer aV_j bidding for project j subject to specific policies of profitability; 4) risk assessment based on CVaR defines the risk value of the investment portfolio based on the investor's tolerance risk; and 5) definition of the private portfolio P consisting of several projects for which the investor will make an offer aV_j with an annuity cost aC_j.

Note that the implemented methodology focuses on assessing the valuation reference defined by the centralized planner and the feasibility of the proposed expansion plan from the point of view of the private investor. The objective of the methodology is to assess the expected risk of the proposed expansion plan. The risk of transmission project j is due to the difference between the value offered by the investor and the real value of the project. The proposed methodology also shows the investment risk an investor perceives with respect to a transmission project. This way, the portfolio of projects that provides the highest profit to the investor subject to their CVaR is obtained.

Given the discrete nature of the problem, there is no curve that represents the efficient frontier. However, the methodology identifies the initial annuity portfolio without risk and the one associated with a particular risk tolerance q_P. This defines a limit of the portfolio, measured in terms of q_P and CVaR, which define an area of risk tolerance. For the centralized transmission expansion plan Z, the risk tolerance level q_p shows the investor's participation. For example, if the private investor is the most efficient and desirable to execute the optimal expansion plan proposed, it is possible that the private investor would not make a bid for some projects. This shows that if there were no other bids for these projects, the tender would be declared void, implying project delays and overruns, which would also affect the optimal implementation of the expansion plan proposed by the central planner.

B. Risk Evaluation

It is important to note that investors in transmission asset projects with regulated revenues must evaluate how risk can impact their profits and best bids. Competition risks, financial risks (underestimation of costs or overestimation of benefits), and technical risks (project implementation) are elements to consider not only by investors but also by the central planner.

The risk evaluation method considers that VaR in a portfolio is the profit during a certain time horizon with a probability value $1-\omega$, i.e.,

$$\mathrm{prob}(f \leq \mathrm{VaR}_\omega) = 1 - \omega \tag{1}$$

where f denotes the profits of a portfolio during a certain time horizon. VaR represents a single point, whereas CVaR is the conditional mean value of profits lower than VaR, i.e.,

$$\mathrm{CVaR} = \boldsymbol{E}[f | f < \mathrm{VaR}_\omega]. \tag{2}$$

The analysis and optimization of the selection of a portfolio with CVaR as a risk measure should consider that the density function of the risk factor is feasible. Approximation methods and/or scenario analysis are used to estimate these risk factors. A CVaR linear approximation is used [15], [16], i.e.,

$$\mathrm{CVaR} = \mathrm{VaR} - \frac{1}{1-\omega}\sum_{s=1}^{S} \pi_s \cdot \eta_s \tag{3}$$

where η_s is an auxiliary variable in scenario s, and π_s is the associated probability with a confidence level ω.

C. Transmission Project Cost C_j

Initially, the proposed model considers that the expected cost of project j for an investor is a function of the reference transmission asset cost c_j, the right of way cost RoW_j, and the investor's effort e_j, i.e.,

$$C_j = c_j + \varphi_j + \mathrm{RoW}_j - e_j \tag{4}$$

where φ_j is a random variable that represents unpredictable costs. Note that C_j is only known to the investor as a distribution function $G(C_j)$. Variable e_j is a measure of the effectiveness of the productive effort. Therefore, e_j is the cost reduction due to the effort of the investor. In the proposed model, the project's profits are affected by e_j. To define the effort of each investor, a principal–agent model is used to identify their type [7]. The investor maximizes its profits based on their type, individual rationality, and incentive compatibility.

The constraint to acquire the RoW_j for the construction of transmission projects has generated conflicts between land owners and transmission investors. Defining the true cost of land is a bargaining process that depends on each partner and the rules that define each market. On one side, investors want to pay as little as possible, but, on the other side, landowners want to receive as much as possible, even delaying or rejecting the construction of a project in order to make it highly profitable. To determine the right of way cost RoW_j, a bargaining game between landowner o and investor i is assumed. In this regard, the proposed model considers a Nash bargaining solution [17]. The Nash bargaining solution RoW^N is the outcome for which the product $(\mathrm{RoW}_i - d_i)(\mathrm{RoW}_o - d_o)$ is maximum; hence, the following equation holds:

$$\mathrm{RoW}^N(S,d) \epsilon \arg\max_{\mathrm{RoW} \in S} (\mathrm{RoW}_i - d_i) \cdot (\mathrm{RoW}_o - d_o) \tag{5}$$

where S is compact and convex and has finite alternatives with a payment RoW^N such that $\mathrm{RoW}^N \geq d$ for all $\mathrm{RoW}^N \in S$ and $\mathrm{RoW}^N > d$ for some $\mathrm{RoW}^N \in S$, and d is the disagreement point or threat point.

The cost of project j, i.e., C_j, is determined by (4) and the annuity cost with an annuity factor af is

$$\mathrm{aC}_{j,s} = \mathrm{af} \cdot C_j \cdot [1 + \lambda_{j,s}] \tag{6}$$

where $\lambda_{j,s}$ represents the annual operation, maintenance, and administration cost as a percentage of C_j. It is important to note that the centralized planner sets a reference project cost and the value of the bid is a regulated revenue for investors. Cost overruns and the risk in the design, construction, and operation of the projects are paid by the investor. The investor has an incentive to optimize its OPEX, but it must also consider that these costs may increase and the central planner will not recognize them. Therefore, in this paper, it is assumed that the variation of $\lambda_{j,s}$ has an average value that is equivalent to the value recognized by the central planner.

D. Expected Value of a Transmission Project aV_j

At this stage, the proposed method defines the expected value of a transmission project. A linear convex combination of the bid and the cost is considered (incentive contract) [18]. The transmission project value V_j is the expected payment by the centralized planner, subject to the bid, i.e., b_j, and the expected optimal cost of project j, i.e., C_j, that entails the lowest expected value of project j, i.e.,

$$V_j = \boldsymbol{E}\left[(1-\alpha_j) \cdot b_j + \alpha_j \cdot C_j\right] \tag{7}$$

where α_j is the cost–share factor with $0 < \alpha_j < 1$.

The bid b_j may be expressed in a single-valued auction or in a first-price sealed envelope auction. A uniform distribution of the project's valuation, i.e., C_j, is assumed. The optimal bid of project j with n_j bidders, i.e., $b_j(C_j)$, with a minimum valuation, i.e., $C_{j,min} = 0$, is determined by [19]

$$b_j(C_j) = \frac{n_j - 1}{n_j} \cdot C_j \tag{8}$$

where C_j is the expected optimal cost for an investor. According to (7), V_j represents the expected transmission project value. Moreover, considering (8), b_j is dependent on the number of bidders n_j and the cost recognition factor α_j of the tender, i.e.,

$$V_j = C_j \cdot (n_j + \alpha_j - 1)/n_j. \tag{9}$$

An investor should know the expected value because this value determines the fixed expected regulated revenue of a project during their lifetime, i.e., aV_j. In this case, it is assumed that the real annual regulated revenue, i.e., $\mathrm{aV}_{j,S}$, depends on two risks: cost overrun of $\lambda_{j,s}$ and penalties m_j for delays $\delta_{j,s}$ in the execution and operation of the project. Based on the previous items, the annual regulated revenue function is given by

$$\mathrm{aV}_{j,s} = \mathrm{af} \cdot V_j \cdot \left[1 + (\lambda_{j,R} - \lambda_{j,s}) - m_j \cdot \delta_{j,s}\right]. \tag{10}$$

Note that $(\lambda_{j,R} - \lambda_{j,s})$ is applied when $\lambda_{j,s} > \lambda_{j,R}$, given that $\lambda_{j,s} < \lambda_{j,R}$ does not imply a reduction of profit but a greater profitability. Note that aV_j is the annuity of the expected value of the winning bid for project j without risk ($\lambda_{j,s} = 0$, $\delta_{j,s} = 0$).

E. Risk-Constrained Portfolio Model

Finally, the proposed methodology provides an algorithm for a combinatorial auction (bids expressed in terms of annuities) to identify a project j in which a private investor participates with their expected offer aV_j to recover their investment costs. The proposed model focuses on a centralized expansion plan Z to establish the maximum expected value of the expansion plan P from the point of view of a private investor subject to competition in the award of project j. There is a risk due to the difference between the income proposed in the offer, i.e., aV_j, and the real income during the implementation and operation of the project, i.e., $\mathrm{aV}_{j,s}$. The difference between these incomes is the "surplus" profit that the investor receives by participating in the tender, considering their risk tolerance q_p.

The regulated revenue function of an investor in project j and scenario s is given by (10). Thus, the optimization problem to maximize the investment portfolio of a single investor subject to a CVaR profit constraint can be formulated as

$$\max_{\mathrm{aV}_{j,s}} \sum_{s=1}^{S}\sum_{j=1}^{J} \pi_s \cdot \mathrm{aV}_{j,s} \cdot x_j \tag{11}$$

subject to :

$$\mathrm{CVaR}_p = \mathrm{VaR}_p - \frac{1}{1-\omega}\sum_{s=1}^{S} \pi_s \cdot \eta_s \tag{12}$$

$$\eta_s \geq \mathrm{VaR}_p - \sum_{j=1}^{J} [\mathrm{aV}_j \cdot x_j - \mathrm{aV}_{j,s} \cdot x_j] \quad \forall_s \in S \tag{13}$$

$$\sum_{j=1}^{J} \mathrm{aC}_{j,s} \cdot x_j \leq B_p \quad \forall_s \in S \tag{14}$$

$$\sum_{j=1}^{J} g_j \cdot C_j \cdot x_j \leq G_p \quad \forall_p \in EP \tag{15}$$

$$\eta_s \geq 0 \tag{16}$$

$$x_j \epsilon [0,1] \tag{17}$$

$$\mathrm{CVaR}_p \geq q_p \cdot \sum_{j=1}^{J} \mathrm{aV}_j \cdot x_j \quad \forall_p \in EP; \quad q_p > 0. \tag{18}$$

The optimization selects the portfolio of projects in which the investor makes a bid that maximizes the overall profit assuming a risk preference. Constraint (12) represents the definition of CVaR. The model uses the CVaR linearity constraint in (13) to measure the difference between VaR and the value of the profit for each one of those scenarios with a profit lower than VaR [16]. The second term on the right-hand side of constraint (13) represents the expected profit surplus. In addition, budget constraints are considered in the annual costs (14) and the amount of guarantees to participate in the tender (15). Constraint (16) defines the auxiliary variable to be a nonnegative variable. Constraint (17) is a binary variable x_j to determine the projects in which the investor participates in the tender. Constraint (18) defines a tolerance level q_p [16]. In this case, q_p is the percentage of the value of the portfolio without risk, that is, without cost overruns or delays in the project implementation. The probability of each scenario is equally likely.

The spread between the maximum value set in the combinatorial algorithm and the reference value set by the planner reveals asymmetric or hidden information known only to the private investor. Thus, the efficiency of the tender and the feasibility of the values defined by the private investor can be evaluated. For example, higher values or abstention from participating in certain projects produce undervaluing by the central planner, and very low values identify suboptimal offers that imply inefficiencies in the implementation and operation of the project.

Additionally, the difference between the expected value of the solution and the solution of the stochastic problem, considering all possible scenarios, is performed. This difference represents the expected value of the stochastic solution (VSS). VSS is the cost of ignoring uncertainty when a decision is made [20]. Basically, it calculates the cost of knowing the distributions of the stochastic variables and indicates the loss of profit due to the presence of uncertainty in the optimization problem [21]. The value of VSS is

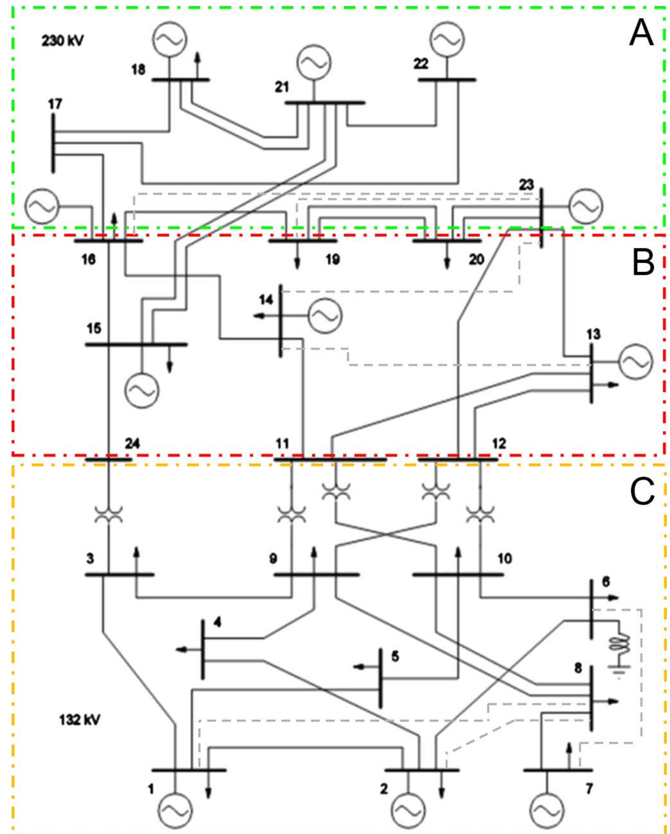

Fig. 2. IEEE 24-bus RTS.

$$\mathrm{VSS} = \mathrm{ES} - \mathrm{SS} \tag{19}$$

where ES is the expected average profit when replacing the random variables with their expected values in the optimization problem, and SS is the stochastic average profit of the objective function of the stochastic problem taking into account all possible risk scenarios.

It is noteworthy that the problem modeled in (11)–(18) defines the value of the bid of project j, and the annuity of this value will be the maximum annual income that the investor would receive. In that sense, risk quantification would establish how much the investor's real income could decrease when there are risks related to the variation of OPEX, delays in commissioning of the project, and risk tolerance q_p.

III. Case Studies

To test the methodology, two case studies are analyzed: the IEEE 24-bus Reliability Test System (RTS) and a predefined expansion plan of Chile's Central Interconnected System (SIC).

A. IEEE 24-Bus RTS Expansion Plan

The case study described in this section is based on the IEEE 24-bus RTS [22]. The transmission network comprises 24 buses, 34 existing corridors, and seven possible expansion corridors (gray dashed lines) (see Fig. 2) [23], [24].

TABLE I
EXPANSION PLANS

Expansion	Corridor	C_j ($m)
Plan 1	7-8, 14-16, 16-17	10.49
Plan 2	3-9, 14-16, 16-17, 20-23	15.08
Plan 3	1-8, 2-8, 12-13, 14-16, 16-17	19.82
Plan 4	14-16, 15-24, 16-17, 19-20	20.95
Plan 5	10-11, 14-16, 14-23, 15-16, 16-17	25.82

TABLE II
OPTIMAL VALUATION COST C_J WITHOUT RoW ($m)

j	1	2	3	4	5
Plan 1	1.80	5.21	3.48	-	-
Plan 2	3.49	5.21	3.48	2.90	-
Plan 3	2.45	2.31	6.37	5.21	3.48
Plan 4	5.21	6.95	3.48	5.31	-
Plan 5	9.65	5.21	5.16	2.32	3.48

TABLE III
OPTIMAL VALUATION COST C_J WITH RoW ($m)

j	1	2	3	4	5
Plan 1	2.21	6.44	4.29	-	-
Plan 2	4.32	6.43	4.29	3.58	-
Plan 3	3.01	2.83	7.87	6.44	4.29
Plan 4	6.45	8.58	4.30	6.54	-
Plan 5	11.9	6.44	6.36	2.85	4.30

It is assumed that all transmission lines are identical and the number of transmission lines per corridor is 3. Investment costs per corridor are obtained from [23]. There are three geographic areas that reflect the degree of difficulty to carry out a transmission project (line). (A = minimum risk, B = high risk, and C = medium risk.)

The proposed methodology identifies a possible expansion plan according to the algorithm described in [23]. This algorithm consists of three phases: 1) reduction of the search space of possible transmission expansion plans by an ordinal optimization method; 2) multiobjective optimization using the concept of Pareto dominance and an intelligent search for solutions through Tabu search and path relinking techniques; and 3) an $N-1$ reliability criterion with maximum load shedding subject to the cost of failure. Finally, the multiobjective optimization under Pareto dominance defines a set of feasible solutions that establishes expansion plan scenarios [23].

In this case study, the proposed methodology identifies five transmission expansion plans (by the centralized planner). The five expansion plans are described in Table I.

The winner is determined by the cost of the transmission asset, the effort factor, and the negotiation cost of the right of way [see (4)].

Now, if the optimal cost does not include the right of way cost, the valuation cost is shown in Table II. If the right of way cost is used, the valuation cost is shown in Table III.

Scenario analysis is used to determine the impact of risk. The proposed methodology considers a number of days of delay after the scheduled date of delivery of the project (gamma distribution) and the variation of the annual operating, maintenance, and administration costs (OPEX) for project j and scenario s, i.e., $\lambda_{j,s}$ (Normal distribution).

There are 5000 scenarios, and the number of projects of the portfolio depends on the expansion plans Z (see Table I).

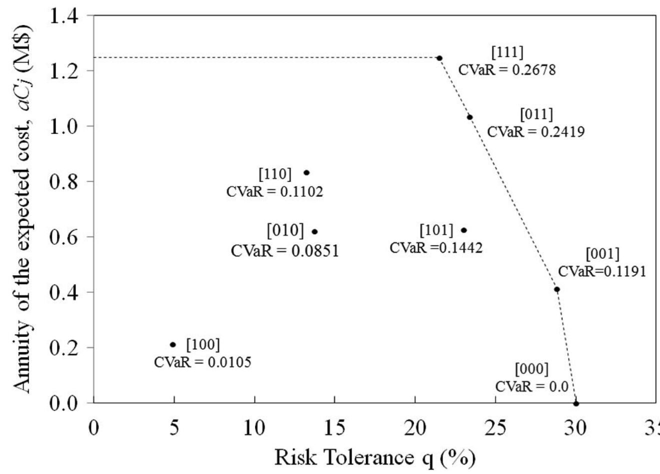

Fig. 3. Annuity of the expected cost in the optimal expansion plan (Plan1—Table III) with risk tolerance q_P.

The confidence level ω is 0.95, the discount rate r is 10%, and the lifetime l is 20 years. The number of investors n_j is 5 for all the projects (transmission assets) and without any incentive, i.e., $\alpha_j, = 0$. The delay probability distribution has an average value of 6, 12, and 24 months for areas A, B, and C, respectively (see Fig. 2). The Normal distribution of $\lambda_{j,s}$ has an average value of $\lambda_{j,R}$. The standard deviation of the delay, i.e., μ_j, depends on the area, i.e., $\mu_{jA} = 5\%$, $\mu_{jB} = 15\%$, and $\mu_{jC} = 10\%$ (see Fig. 2). The execution time of each project (line) j is 42 months, and the penalty factor for delay m_j is 0.068% of c_j. The percentage of the regulated cost $\lambda_{j,R}$ is 2.5% of c_j, and the guarantee asked for the project g_j to participate in the tender is 15% of c_j. The budget B_P is $5.0m, and the maximum guarantee of the portfolio G_P is $5.0m.

For Plan 1, the risk tolerance level q ranges between 20% and 28%. Fig. 3 shows that for $q_P = 22.5\%$, the investor participates in the complete plan, projects [111] of Plan 1, and its participation decreases as q_P increases. From $q_P = 30\%$ onward, the investor does not participate in any project, even if there is enough budget. Given the discrete nature of the problem, there is no curve that represents the efficient frontier. This defines a limit set of the portfolio, measured in terms of q_P and CVaR, which define an area of risk tolerance.

For example, Plan 1 uses a dotted line to determine this area with the annuity of the expected cost aC_j (see Fig. 3).

Fig. 4 shows the area for the five plans with the annuity of the expected value aV_j.

In assessing Plans 1, 2, 3, 4, and 5, the investor has a maximum annual cost constraint per portfolio B_P of $2.0m and a maximum portfolio guarantee G_P of $3.0m. Fig. 4(a) shows the influence of risk tolerance. As q increases, the number of projects to bid for decreases. Fig. 4(b) describes the behavior of CVaR, where the maximum CVaR is obtained for each portfolio. Risk tolerances are 21.49%, 20.17%, 27.52%, 24.42%, and 27.14% for Plans 1, 2, 3, 4, and 5, respectively [see Fig. 4(a)]. The associated maximum CVaR*s* are $0.268m, $0.359m, $0.648m, $0.608m, and $0.833m, respectively [see Fig. 4(b)]. If risk is considered, the expected value of the portfolio decreases, and CVaR increases until it reaches a maximum CVaR with a tolerance level q_{Max}. From q_{Max} onward,

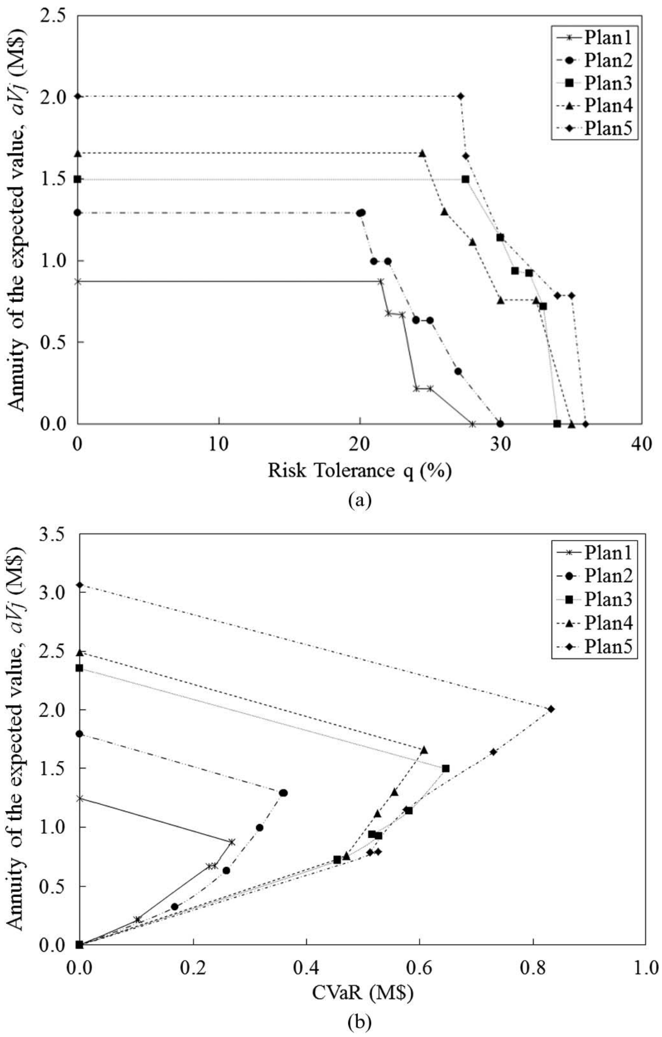

Fig. 4. Annuity of the expected value of the investor's expansion plan (see Table IV). (a) Tradeoff between risk tolerance q_P and annuity portfolio. (b) Tradeoff between CVaR and annuity portfolio.

TABLE IV
OPTIMAL VALUE V_j AND PORTFOLIO ANNUITY WITH RoW ($m)

j	1	2	3	4	5	Total_p	$\Sigma_P aV_j$	$CVaR_P$
Plan 1	1.77	5.15	3.43	-	-	10.35	1.25	0.19
Plan 2	3.46	5.14	3.43	0.0	-	12.03	1.45	0.22
Plan 3	2.41	2.26	6.30	0.0	0.0	10.97	1.32	0.20
Plan 4	0.0	6.86	0.0	5.23	-	12.10	1.46	0.22
Plan 5	0.0	5.15	0.0	0.0	3.44	8.59	1.03	0.16

the number of profitable projects decreases until reaching a portfolio without any project [see Fig. 4(b)].

Table IV shows the results for all plans where investors fully participate in Plan 1 only. The other plans have at least one project (transmission asset) where there is no investment.

The implemented methodology focuses on assessing the reference cost defined by the centralized planner and the feasibility of the proposed expansion plan from the point of view of the private investor. For example, the central planner defines Plan 3 (see Table IV) as the optimal plan, and the private investor is the most efficient and desirable to execute the expansion plan proposed. Note that the private investor would not make bids for projects 4 and 5. This shows that if there were no other

TABLE V
VSS OF PORTFOLIO ANNUITY ($m)

Expansion Plan	EAP	SAP	VSS
Plan 1	1.2630	1.2463	0.0166
Plan 2	1.4664	1.4486	0.0178
Plan 3	1.3400	1.3205	0.0195
Plan 4	1.4761	1.4563	0.0197
Plan 5	1.0462	1.0344	0.0118

TABLE VI
PREDEFINED EXPANSION PLAN

j	1	2	3	4	5	6	7	8
C_j	29.8	36.6	63.8	104.7	112.9	225.2	55.5	16.66
$\lambda_{j,R}$	2.1	2.07	1.44	1.57	1.44	1.5	1.44	2.1
t_j	4	4	4	4	4	4	3	1.5
μ_j	0.15	0.05	0.10	0.10	0.15	0.10	0.05	0.05

TABLE VII
PROJECT VALUE ($n_j = 10$)

j	1	2	3	4	5	6	7	8
V_j	26.82	32.94	57.42	94.23	101.61	202.68	49.96	14.99

bids for these projects, the tender of projects 4 and 5 would be declared void, implying project delays and overruns, which would also affect the implementation of the centralized optimal expansion plan.

The value of the stochastic solution VSS is shown in Table V. VSS results describe the tradeoff between the expected competitive bid with OPEX and risks due to uncertainty of project j in expansion plan Z.

The results of Table V show the impact of risk over the expected income of each expansion plan.

B. Chile's SIC Expansion Plan

The case study described in this section is based on the predefined plan for the Chile's SIC, where the investment plan is coordinated by the central grid operator CDEC-SIC. The optimal cost C_j, the annual cost regulated rate $\lambda_{j,R}$, and the construction time t_j in years are shown in Table VI. Additional features are described in [25]. The number of investors participating in the tender, i.e., n_j, is 10. The parameters that are not listed here are assumed equal to those in Section III-A.

The value of $\lambda_{j,S}$ is determined by a Normal distribution with mean $\lambda_{j,R}$ and variance $\mu_j \cdot \lambda_{j,R}$, where μ_j represents the historical mean percentage of variation of the OPEX (see Table VI). The bid is for each project and the allocation process and the beginning of the execution of the projects are in the same period of time (2011–2012 auction rules of trunk-transmission expansion plan) [25].

The optimal values V_j for each project given the number of participants n_j and the optimal cost of the project C_j are shown in Table VII.

This paper considers the selection of projects taking into account the financial, construction, and competition risks. In the first case, a budget of $100m and guarantees amounting to $150m are considered. Note that, even with this budget,

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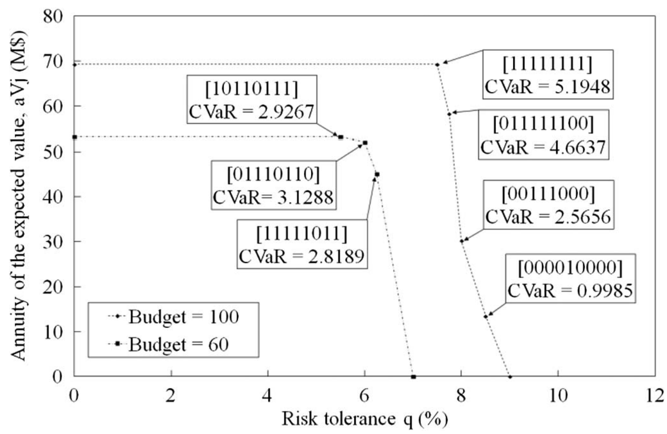

Fig. 5. Annuity of the expected value in the SIC expansion plan with risk tolerance q_P.

TABLE VIII
FINANCIAL RISK: BUDGET CONSTRAINT ($m)

j	40	45	50	55	60	65	70	75	80	85	90	95
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	0	1	1	1	1	1	1	1
3	1	0	0	0	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1
5	0	1	0	0	0	0	0	0	0	0	0	1
6	0	0	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	0	0	1	0	0	0	0	0	0	1

TABLE IX
OPEX RISK: MAX $\lambda_{j,s}$ SCENARIOS (%)

j	1	2	3	4	5	6	7	8
$C1$	2.1	2.07	1.44	1.57	1.44	1.5	1.44	2.1
$C2$	2.6	2.57	1.94	2.07	1.94	2.0	1.94	2.6
$C3$	3.1	3.07	2.44	2.57	2.44	2.5	2.44	3.1

TABLE X
OPEX RISK: PROJECT SELECTION

j	1	2	3	4	5	6	7	8	*CVaR*($m)
$C1$	1	0	1	1	0	1	1	1	2.661
$C2$	1	1	0	1	0	1	1	1	2.516
$C3$	1	1	1	1	0	1	0	1	2.561

with a risk tolerance level higher than 7.5%, fewer projects are selected. Now, with a budget of $60m and an amount for guarantees of $100m, the tolerance level decreases to 5.5% (see Fig. 5), but the selection of projects is adjusted to the new budget. This shows a tradeoff between risk and budget.

Table VIII shows the variation of the portfolio when the annual budget sensitivity ranges from $40m to $95m. It can be seen that from $95m onward, the guarantee constraint is active, this being relevant to companies with substantial financial backing (a constant value of $q_P = 5\%$ is assumed).

Another issue to consider is the effect of a higher value of $\lambda_{j,S}$. To do that, three scenarios are considered: $C1$, the base case with $\lambda_{j,S} = \lambda_{j,R}$ (see Table VI); $C2$, with a value of $\lambda_{j,S} + 0.5\%$; and $C3$, with a value of $\lambda_{j,S} + 1\%$ (a constant budget of $B_P =$ $60m is assumed; see Table IX).

Table X shows that the variation of $\lambda_{j,s}$ does not modify CVaR, but influences project selection.

An important aspect to consider is the impact of delays and their associated penalties. For example, doubling the days of delay with the same percentage of penalty, the optimal portfolio remains the same (base case budget = $60m) with an expected value of $36.39m. The results show that the optimal portfolio does not change with a percentage variation, just their expected value.

TABLE XI
OPTIMAL VALUE V_j AND PROJECT SELECTION ($m)

J	α	1	2	3	4	5	6	7	8	Total_P	*CVaR*
n_j=2	0.75	3.1	0.0	6.6	10.9	0.0	23.5	5.8	1.7	51.7	2.59
	0	1.8	0.0	3.8	6.2	0.0	13.4	3.3	1.0	29.6	1.48
n_j=4	0.75	3.4	0.0	7.1	11.7	0.0	25.2	6.2	1.9	55.4	2.77
	0	2.7	0.0	5.7	9.4	0.0	20.1	5.0	1.5	44.3	2.22
n_j=6	0.5	3.3	0.0	7.0	11.5	0.0	24.6	6.1	1.8	54.2	2.71
	0	3.0	0.0	6.3	10.4	0.0	22.4	5.5	1.7	49.3	2.46
n_j=8	0.25	3.2	0.0	6.9	11.3	0.0	24.3	6.0	1.8	53.6	2.68
	0	3.1	0.0	6.6	10.9	0.0	23.5	5.8	1.7	51.7	2.59
n_j=10	0	3.2	0.0	6.8	11.2	0.0	24.2	6.0	1.8	53.2	2.66
x_j		1	0	1	1	0	1	1	1	6	

TABLE XII
RESTRICTED PROJECT SELECTION ($m)

Budget ($m)	j	1	2	3	4	5	6	7	8	*CVaR*
50	B	1	1	0	1	0	1	1	0	2.426
	$X3$	0	0	1	1	0	1	0	1	2.202
55	B	1	1	0	1	0	1	1	0	2.426
	$X3$	0	1	1	1	0	1	0	1	2.400
60	B	1	0	1	1	0	1	1	1	2.661
	$X3$	1	0	1	1	0	1	1	1	2.661
65	B	1	1	1	1	0	1	1	0	2.768
	$X3$	1	1	1	1	0	1	1	0	2.769
70	B	1	1	1	1	0	1	1	0	2.768
	$X3$	1	1	1	1	0	1	1	0	2.771

In turn, it is also possible to study the investment decision with respect to the number of investors participating in the tender. Table XI shows the impact when considering the variation of the number of investors and their respective cost recognition factors, i.e., α_j. It is shown that this variation does not affect the selection of projects, but changes the perception of risk. The $\alpha_j = 0$ factor states that the value V_j depends on the bid b_j. In addition, the CVaR decreases when $\alpha_j = 0$ due to the decrease in the expected value of the annuity [see (9)]. In this case, a competitive tender occurs when $n_j = 10$; thus, there is no cost recognition factor in that case, and $\alpha_j = 0$. In turn, the maximum recognition factor α for two, four, six, or eight participants is 0.75, 0.75, 0.5, and 0.25, respectively. In this way, using these factors, similar results are obtained compared to the case $n_j = 10$.

Finally, a case in which the central planner restricts their participation in a range of projects is considered. For example, if an investor wants to participate and make a bid for project $x = 3$, it is bound to bid for projects 4 and 6. This type of restrictions is applied on projects that are technologically similar and are part of an expansion corridor. Under this scenario, Table XII shows how the selection of projects is done according to the budget constraint and the base portfolio, as well as the impact on CVaR. Case B represents the unconstrained or base case, and case $X3$ represents the minimum number of projects, i.e., 3, that a portfolio must contain if the investor wants to participate in at least one of them. A budget constraint between $60m and $70m does not change the portfolio, but a budget $55m does.

The methodology described is implemented in MATLAB 7.3 with an interface to GAMS [26], [27]. An Intel Core i5 760 processor at 2.80 Hz with 6 GB of RAM is used. Note that the projects of each transmission expansion plan are identified and validated by an optimal power flow (OPF), and then, the optimization problem described by (11)–(18) is solved. To calculate the OPF tool, MATPOWER 4.0b3 is used [28]. The optimization model is solved in GAMS with the ILOG CPLEX Optimizer [26]. The CPU time was 22.63 min.

IV. Conclusion

A market-based transmission investment portfolio may be different from the one established by a central planner. The proposed methodology shows the impact of the initial valuation and risk of a project aiming at establishing a portfolio that provides the highest profit to a transmission investor. The case studies show how the portfolio varies subject to risk tolerance and CVaR. The proposed method allows a private investor to determine its investment portfolio. It is also useful for a central planner, in order to infer which projects will present a greater risk, in terms of the optimal project values and execution times. All this allows for a better criterion for the design of an efficient tender among transmission investors.

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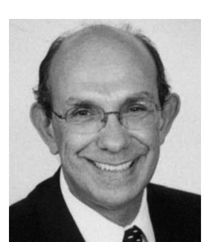

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