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# MULTI-AREA REGIONAL INTERCONNECTION PLANNING UNDER UNCERTAINTY

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## ABSTRACT

This paper presents a novel methodology for multi-area interconnection planning under major uncertainties such as: demand growth and level of coordination in planning and operation among regional subsystems. The method takes these and other uncertainties into account by means of defining strategic scenarios which reflect gradual and realistic possible evolutions of the regional subsystems. A decoupled and iterative process between multi-area generation expansion, and transmission expansion is defined for each scenario. A decision analysis framework is incorporated in order to quantify and minimise risks for all scenarios. Existing software tools can be used in a new powerful way. A study of the Central-American interconnection illustrates how the method can be applied to propose a transmission plan which is robust enough in the face of uncertainties.

## 1. INTRODUCTION

Advantages associated to sharing risk, financial support, economies of scale in generation and reduction in the operating costs are key incentives to integrate energy markets. Increasing competition inside national markets is extending to neighbours. In most countries, former cost-based economic dispatch is being substituted by an energy spot market which is amenable for international transactions.

Recently, the Central American countries: Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama, have signed a flexible agreement [1] for using existing and future regional interconnections. The new rules and the restructuring of regional institutions are the foundations for creating a Regional Energy Market (MER in Spanish) and they will allow to coordinate planning and operation of their electric energy systems. Based on the MER, countries will promote and build up regional generation projects. It is expected that most of the investment will be made by the private sector. All these activities need firm interconnection transfer capacity among countries to assure efficiency and reliability of the national systems.

Under the different restructuring processes in all these countries, transmission and interconnection network assets will be owned by state or private companies but these companies will be regulated as monopolies. The SIEPAC Project consists of a new trunk interconnection along the six Central-American countries of about 1800 km to promote and facilitate the creation of the MER. The SIEPAC's facilities will belong to a private corporation. Next regional transmission projects might belong to other private investors. Property and operation of network facilities must be separated to avoid conflicts, for that reason operation of international regional transmission will be assigned to another entity called the Regional Operator (EOR in Spanish). A Regional Regulator will be the central authority in the MER. Under Regulator's supervision, the EOR will be in charge of the technical duties regarding market operation and responsible for expansion planning studies of regional generation and transmission, and other important related activities. The EOR must be provided with a suitable methodology for developing these expansion planning studies.

In cost-based regulation, the capital recovery was guaranteed by tariffs paid by ratepayers. Competition and efficiency principles recommend that the new regional transmission costs be shared among all network users [2]. Thus, cost-effectiveness of each new line is required.

Interconnection networks must be planned in order to give open access to all agents, so that economic power flows would not be restricted. Traditionally, due to shorter lead times, transmission facilities were planned and built up after generation plans were underway and in response to gradual growth of load. Planners are used to know some routing alternatives for new interconnec-tions, but they do not know which links are optimal, and also what type, voltage level, configuration, and thermal capacity is optimal for each link. Many approaches have been developed in the past dealing with the integrated generation and transmission planning problem. Those models typically consider short study periods (e.g. one year) and require committed generation plans.

In multi-area regional expansion planning, the ideal transfer capability requirements between countries can be estimated first. Afterwards, a more sophisticated study can be made for determining the electrical transmission lines which do not restrict those optimal exchanges.

Both steps can be iterated in order to refine plans. That is the general focus for the regional inter-connection planning procedure proposed in this paper. Formerly, generation and transmission planning was mandatory, now is becoming just indicative. Investors can decide to build the options recommended by the indicative plans or another projects. The uncertainty in generation plans is greater than normal because the regional transmission owner does not control which new regional plants will materialise. The new interconnec-tion lines will depend on the level of coordination in planning and operation of the regional subsystems which can vary with load growth. Therefore, a decision analysis can be incorporated for taking all uncertainties into account. Transmission plans must be robust and flexible enough for all possible generation plans.

The new methodology can be implemented using existing and generally-available software tools. A first paper has been published making emphasis in the decision analysis of the method [3]. Here, the reader can find a complete view of the problem, including the multi-area generation expansion planning process which is an essential part of the method.

Some special terms used in this paper are listed in section 2. The analytical procedure of the approach is outlined in section 3. In section 4 the study of the SIEPAC Project illustrates the method. The conclusions of the paper are in section 5.

## 2. TERMINOLOGY

Some definitions are given in this section to clarify the terminology used. The definitions are provided only to improve the readability of the text. A general discussion on terminology is beyond the scope of the paper. Similar definitions can be found in [3] and [4].

*Uncertainty*: it means the future evolution of relevant parameters which can not be derived on the basis of past observations. This kind of uncertainty should not be confused with the one related to future values of random parameters whose values follow known probability distributions.

*Flexibility*: it means the ability to adapt the planned development of the power system, quickly and at reasonable cost, to any change, foreseen or not, in the conditions which prevailed at the time it was planned.

*Scenario*: a set of outcomes or realisations of all the uncertainties. A scenario is constructed by assigning values to a set of uncertain parameters, reflecting a possible future state of the external factors affecting planning (e.g. 5%/year load growth).

*Options*: new generation or transmission facilities for expansion analysis of the system.

*Adequacy criteria*: criteria applied in the generation and transmission planning process.

*Plan*: it means a generation and/or transmission plan.

*Generation plan*: the list of investments in new plant with the related locations, ratings and commissioning dates, in conformity with the plant options, scenario and adequacy criteria for generation expansion analysis.

*Transmission plan*: the list of investments in new transmission with the related substations, configurations, ratings and commissioning dates, in conformity with the transmission options, scenario and adequacy criteria for transmission expansion analysis.

*Strategic transmission plan*: it is a transmission plan designed by the planner for the whole study period according to economic, technical and practical implementation considerations. It is also called *strategic plan*.

*Attributes*: they are measures of goodness of a strategic transmission plan for each generation plan (e.g. non-supplied energy, present value of operating costs, operating savings, and net benefits, etc.). Attributes are functions of options and uncertainties.

*Risk*: it is the hazard to which one is exposed because of uncertainties. If a strategic plan is very regrettable in most of the possible scenarios, then the *exposure risk* in that plan is high. A minimum exposure is recommended.

*Regret*: it is a measure of risk. For each scenario, regret is the difference between the value of an attribute in a given strategic plan and in the best strategic plan for that scenario.

*Robust*: if a given strategic plan has zero regret for all scenarios then that strategic plan is robust. The *degree of robustness* of a strategic plan is the number of its zero regret scenarios divided by the total number of scenarios.

*Hedges*: if there is no robust strategic plan, it might be possible to design a hedge or insurance policy to eliminate regret for a particular strategic plan, thereby creating a robust or less vulnerable strategic plan.

## 3. METHODOLOGY

In this section, a method is presented for regional interconnection planning dealing with uncertainties such as: demand growth, level of coordination between countries when planning the new investments, level of coordination in interconnected operation of their power systems, generation and transmission options, transmission costs, and operating savings. Stochastic modelling of water inflows is also included.

Since there is no any available tool to manage all uncertainties and random parameters simultaneously, a new planning method should be designed in order to take implicitly or explicitly all of them into account. Sensitivity analysis techniques can also be considered.

Figure I. General Description of the Methodology

Step 1

Step 2

Step 3

The method here presented is based on the scenario technique [4] with some particular peculiarities of the regional interconnection planning problem. The approach consists of three main steps: I) multi-area generation planning, II) transmission planning, and III) a decision analysis framework, as indicated in Figure I.

## 3.1 Multi-Area Generation Planning

The aim of the first step is to produce generation plans for several combinations of uncertainties. The main task is the formulation of scenarios.

### 3.1.1 Scenarios

The planner will in the first place list the uncertainties which could be of importance in the problem under study (e.g. demand growth, levels of coordination in planning and operation among regional subsystems).
One key aspect for the definition of scenarios is to split the study period into subperiods where flexible strategic plans can be decided. For example, in our case, the year 2000 is when the first decision about the interconnection development would be taken, and in the year 2008 the second decision about to expand the initial interconnection would be decided. The beginning of the subperiods can coincide with some relevant event (e.g. possible commissioning date of regional plants).
To limit the number of scenarios to be studied, ranges and possible combinations of uncertainties must be identified.

### 3.1.2 Coordination levels in planning

Different levels of coordination in planning between the regional subsystems can be defined by two ways:

- specifying regional generation options according to the level of coordination desired (e.g. generation capacity of the largest units within 200 and 350 MW); and
- controlling the regional interaction by specifying the maximum transfer capacity that can be expanded between subsystems (e.g. zero capacity means isolated or individual expansion).

A multi-area expansion model like [5] is needed.

### 3.1.3 Coordination levels in operation

Once a generation plan is created, different levels of coordination in economic operation between the regional subsystems can be defined using the same multi-area model [5]. Planners can specify the maximum exchange capacity that it can be expanded between subsystems without changing the generation plan (see Figure II).
Both levels of coordination may change in the course of the study in order to reflect gradual integration of the national markets in response to different integration policies and demand growth rates.

### 3.1.4 Generation options

Location and size of hydro candidates are known in advance, but may not all materialise. Location, size and type of thermal candidates are uncertain. These uncertainties can be implicitly modelled into the multi-area planning by specific options according to the coordination level in planning of the scenarios.

### 3.1.5 Transmission options

Uncertainties in transmission facilities can be implicitly modelled into the multi-area energy planning by simplified transmission options (blocks of capacities with approximated costs) according to the coordination level in planning and operation of the scenarios.

### 3.1.6 Inflows

Stochastic inflows can be modelled explicitly into an integrated planning package like [5] which includes the Stochastic Dual Dynamic Programming (SDDP) technique [6].

### 3.1.7 Generation plans

For each year of the planning period, each generation plan gives optimal selection of generation options and ideal capacity requirements for each link (pair of neigh-bouring countries). The Figure II resumes the two-phase long-term multi-area expansion process for each scenario. The phase I is subject to demand growth and coordination in planning; it selects, in the current scenario, the optimal generation options which are fixed in the next phase. The phase II is subject to the coordination in operation; it completes the ideal capacity expansion of links. The phase II is necessary only if coordination level in operation is higher than the one in planning. If both levels are the same, ideal link expansion is given by the phase I.

Figure II. Multi-Area Generation Planning

3.2 Transmission Planning

The second step is a classic transmission planning process that can be carried out with [7]. It determines the optimum transmission plan that satisfies all the ideal capacity requirements of a given scenario taking into account a more detailed representation of the national networks and interconnections.

The planner will list the transmission options for meeting the system requirements (e.g., 230-kV, 400-kV and 500-kV lines with single or double circuit and reactive compensation), and will combine them into flexible strategic transmission plans for each scenario. Since the main purpose of a planning study is to find out a first investment decision, strategic transmission plans will focus in the first years of the study period combining different flexible power lines that can be expanded later before the end of the study.

As illustrated in Figure III, the transmission planning process can be repeated for each strategic plan for each generation plan (scenario) coming from the step I. This process can be used to adjust or redefine the initial strategic plans.

Figure III. Transmission Planning

Planners can iterate between steps I and II of the global method in order to refine final generation-transmission plans as indicated in Figure I. That iterative process can be reduced or avoided if the blocks of transmission capacity options (and their costs) used during the step I coincide with the resulting transfer capabilities of the power transmission lines implemented in the step II. Final plans are characterised with common attributes.

3.3 Decision Analysis

The expected present value of the operating costs, operating savings, transmission investments, and net benefits are the main attributes of each strategic plan for implementing the decision analysis framework.

A table with the expected present value of the net benefits for each strategic transmission plan for each scenario (generation plan) must be calculated. Then, the best strategic plan(s) can be selected according to different decision criteria. It is not the aim of this paper to give a description of all the decision methods published in the literature [8]. Reference [4] discusses the most commonly used (expected-cost, min-max-regret, etc.). Each method reflects a different attitude towards risk. In most cases the use of the expected-cost method can be recommended if probabilities for scenarios are provided. For very important decisions, however, it may be wise to use the min-max-regret method. The latter may be regarded as the primary one if the decision is of capital importance for the company and emphasis is to be put on the need to survive, even under an unlikely but catastrophic scenario [4]. For that reason, the third step of our approach consists of a decision-making process to minimise the maxim. regret.

Suppose that the value of the attribute, $v_{i,j}$, for a particular strategic plan, $p_i$, and scenario, $s_j$, is:

$$v_{i,j} = f\,(p_i,s_j) \qquad (1)$$

$$v_{optimal,j} = v_{opt,j} = f\,(p_{opt},s_j) \qquad (2)$$

where $p_{opt}$ is an optimal strategic plan for scenario $j$. Then the regret is defined as:

$$r_{i,j} = v_{i,j} - v_{opt,j} \qquad (3)$$

Definition (3) is suitable for costs analysis. If benefits are considered, then $r_{i,j} = v_{opt,j} - v_{i,j}$.

In that way, another table with the regrets for each pair of "strategic plan – scenario" is computed. For each scenario, the regret is equal to zero for the optimal strategic plan. If the regret of a given strategic plan is zero for all scenarios, that is, if the same strategic plan is optimal for all scenarios, then that strategic transmission plan is robust.

If there is no robust strategic plan, then a choice has to be made among the various possible strategic plans. According to the min-max-regret method one may choose the strategic plan which minimises the maximum regret. Some hedges can also reduce unbearable risks to the selected plan trying to make it robust.

As a result, the min-max-regret method helps to define a unique flexible enough interconnection project (first decision) which can be adapted to the evolution of all generation plans.

3.3.1 Transmission costs and operating savings

Afterwards, a sensitivity analysis may be performed to study the robustness of the optimal strategic plan when uncertain parameters, such as: transmission costs, and operating savings, are inflated or deflated.

4. CASE STUDY: THE SIEPAC PROJECT

The approach has been applied to the Central-American system in order to define a robust strategic transmission plan for the SIEPAC Project. Previous studies were carried out to determine the feasibility of the SIEPAC Project based on a similar methodology [9]. The approach here presented is an improvement of that methodology.

### 4.1 Problem Formulation

A partly-existing and partly-planned single circuit 230-kV interconnection along the Central-American isthmus needs another parallel line in order to assure efficiency and reliability of the six national systems. The principal uncertainties in the planning studies were load growth, the level of coordination in planning and operation in the isthmus, and possibilities of large regional hydro and thermal plants. Additional sensitivity studies were carried out to consider uncertainties in the line construction costs, and in the line operating benefits identified in the planning studies.

### 4.2 SIEPAC Transmission Options

The transmission options to the SIEPAC Project were single and double circuit 230-kV lines, and single or double circuit lines at higher voltages (400 kV or 500 kV). Some routing alternatives for the line were also considered.

### 4.3 SIEPAC Scenarios

The study period was 20 years long, from 1996 to 2015. Three subperiods were defined for implementing different gradual levels of operation and planning coordination between countries. The beginning of the subperiods were 1996, 2000, and 2008. The 1996-1999 subperiod considered all plants and transmission networks already committed and underway in the isthmus (individual planning). The purpose of that subperiod is only for simulating realistic evolution of the unified system (e.g. state of reservoirs on January/2000) taking into account the existing and committed 230-kV interconnection.
For convenience, the first three uncertainties were spanned by six future scenarios designed as indicated in the Table I. Three had low load growth (about 4.4 %/year) and three high (about 6.8 %/year). The load growth evolution for each country is detailed in Appendix A. Four large regional hydro plants were analysed in three of the scenarios in the long term only. Different large regional thermal plants were analysed in scenarios without individual planning. The scenarios represented gradual and realistic levels of international coordination in planning and operation between countries according to load growth.

Table I: General Criteria for Construction of Future Scenarios

| Scenario Number | Scenario Title | Thermal Projects (2000-07) MT | Thermal Projects (2008-15) LT | Hydro Projects (2008-2015) LT | Coordination in Planning MT/LT | Coordination in Operation MT/LT | Demand Growth |
|---|---|---|---|---|---|---|---|
| S1 | Individual Planning | - | - | - | 0/0 | 3/3 | LOW |
| S2 | Individual (MT) & Partial (LT) Planning | - | CCD & Coal | - | 0/3 | 3/3 | LOW |
| S3 | Individual (MT) & Partial (LT) Planning | - | CCD & Coal | - | 0/3 | 3/6 | HIGH |
| S4 | Partial Planning & Operation | CCD & Coal | CCD & Coal | Tigre I 357 MW<br>Siquirres 412 MW<br>Boruca I 460 MW | 3/3 | 3/3 | LOW |
| S5 | Gradual Planning & Operation | CCNG (PA)<br>CCD & Coal | CCNG<br>(GU-PA)<br>CCD<br>Coal | Tigre I 357 MW<br>Siquirres 412 MW<br>Boruca I 460 MW<br>Patuca II 713 MW | 3/6 | 3/6 | HIGH |
| S6 | Unified Planning & Operation | CCNG<br>(GU-PA)<br>CCD & Coal | CCNG<br>(GU-PA)<br>CCD & Coal | El Tigre 704 MW<br>GranBoruca 1520 MW<br>Patuca II 713 MW | 6/6 | 6/6 | HIGH |

MT: Mid-Term from 2000 to 2007; LT: Long-Term from 2008 to 2015.
CCD: Diesel Combined Cycle; CCNG: Natural Gas Combined Cycle firing (only in Guatemala &/or Panama); Coal: Coal plant.
Coordination in Planning 0: Isolated Subsystems; 3: Groups of Three Subsystems; 6: All Subsystems.
Coordination in Operation 0: regional operation with only the existing single-circuit 230-kV line; 3: regional operation considering expansion
of links inside groups of three subsystems; 6: regional operation considering expansion of all links.

### 1.1 SIEPAC Multi-Area Planning

The multi-area planning studies were done using the Unified System for Regional Energy Planning software [5], SUPER in Spanish, a package for interconnected hydro-thermal systems developed previously under sponsorship of the Inter-american Development Bank (IDB). In SUPER, interconnection links and generation projects are decision variables (linear or discrete) in the long-term planning process; the integrated multi-area operation is solved in SUPER by the SDDP technique (references [5,6,10,11] are recommended).
The multi-area planning process was repeated for each scenario, implementing the different guidelines specified in the Table I. All national generation options (hydro and thermal plants with small economies of scale) competed with regional projects. Optimal generation plans were created for each scenario using a discount rate of 12% and satisfying adequacy criteria for regional generation planning.
For each year of the planning period, each generation plan gives optimal selection of generation projects and ideal interconnection capacity requirements for each link according to simplified transmission options.

Tables II and III resume the present value (US $M stands for US $million) of total costs and savings for each generation plan without investment for ideal transmission. The Reference Plan corresponds to individual planning of countries along the study period, and regional operation with existing and committed single circuit 230-kV line.

Table II. Present Value (US $M '96)-Low Demand

| Plans | Generation Investment | Operation Costs | Total Costs | Total Savings |
|---|---|---|---|---|
| Reference | 3925 | 2982 | 6907 | - |
| S1 | 3925 | 2920 | 6845 | 62 |
| S2 | 3758 | 2965 | 6723 | 184 |
| S4 | 3677 | 2829 | 6506 | 401 |

Table III. Present Value (US $M '96)-High Demand

| Plans | Generation Investment | Operation Costs | Total Costs | Total Savings |
|---|---|---|---|---|
| Reference | 5459 | 4663 | 10122 | - |
| S3 | 5261 | 4576 | 9837 | 285 |
| S5 | 4826 | 4268 | 9094 | 1028 |
| S6 | 4714 | 4257 | 8971 | 1151 |

The total expected savings reported for each scenario rise when the international integration reaches higher levels (coordinated planning versus individual planning) and the expected load growth increases. Those savings were derived from the expansion of the transfer capability of the interconnection. The savings in generation investment can be understand as reduction in financial support due to changing ways to invest, and taking advantage of the economies of scale of large regional competitive projects. The savings in operation costs (fuel costs) are associated to more efficient generation investments and more integrated economic operation of the regional system.

Obviously, not all the links between countries needed to increase the transfer capability at the same time. Scenarios with low regional integration imposed a partial coordination between groups of three countries, so the link between Honduras and Nicaragua was never expanded in those scenarios.

## 1.2 SIEPAC Transmission Planning

Transmission planning studies were done using the PTI's PSS/E package [7]. For each scenario, gradual strategic plans based on just 230-kV lines with single or double circuits satisfied the power exchanges necessities identified in the different generation plans. The power exchange limits used in the multi-area generation expansion studies had good approximations to the resulting transfer capabilities of the transmission options. Table IV shows the approximate construction cost and transfer capability associated with various line options for SIEPAC Project. Steady-state and dynamic contingency analyses were performed to determine actual transfer capabilities. Construction costs were estimated from similar projects for the whole distance of SIEPAC Project (about 1800 km).

Table IV. SIEPAC Transmission Options

| New Circuits | kV | Construction Cost (US $M) | Trans.Cap. (MW) |
|---|---|---|---|
| 0 (actual) | 230 | 0 | 50 |
| 1 | 230 | 190 | 300 |
| 2 | 230 | 295 | 600 |
| 0 (actual) | 230 | 0 | 50 |
| 1 | 400 | N/A | 300 |
| 2 | 400 | 723 | 1200 |
| 0 (actual) | 230 | 0 | 50 |
| 1 | 500 | N/A | 300 |
| 2 | 500 | 906 | 1500 |

The existing and committed single circuit 230-kV transfer capability is about 50 MW, even though its thermal rating is about 300 MW. This is because a single N-1 contingency would create islands, one of which would be generation deficient. The individual countries can not lose more than 50 MW of generation or imports without loss of load.

An additional line with single circuit, be it 230, 400 or 500 kV, brings the transfer capability up to about 300 MW, even though the thermal rating of the higher voltage lines is over 1000 MW. But the loss of this circuit would cause all the power it was carrying to flow on the parallel 230-kV existing link, whose thermal rating is 300 MW. Therefore, the transfer capability for both lines (existing 230-kV and the SIEPAC Project) can not be more than 300 MW, and a single-circuit 400 or 500-kV line provides no more power transfer than does a 230-kV line.

A double-circuit 400 or 500-kV line would provide a transfer capability too high for the exchange necessities identified in the generation studies.

A particular characteristic for the SIEPAC Project was required by the six countries: "the first decision must be a simultaneous and homogeneous power line in order to achieve a common regional integration of national markets and to establish a global institutional compromise among the six countries to build up and to pay the new trunk line". Then the step I was repeated in order to simulate all the generation plans for different fixed transfer capabilities along the line. Table V shows the operating costs for the six scenarios (generation plans) as a function of transfer capability between countries. The Table VI shows the operating savings.

Table V. Transfer Capability & Operating Costs

| Trans.Cap. (MW) | | Operating Costs (PV - US $M '96) | | | | | |
|---|---|---|---|---|---|---|---|
| 2000-07 | 2008-15 | S1 | S2 | S3 | S4 | S5 | S6 |
| 50 | 50 | 2982 | 3088 | 4867 | 3053 | 5121 | 5541 |
| 300 | 300 | 2886 | 2942 | 4586 | 2797 | 4311 | 4293 |
| 300 | 500 | 2886 | 2942 | 4586 | 2797 | 4256 | 4253 |
| 300 | 700 | 2886 | 2942 | 4586 | 2797 | 4240 | 4253 |

Table VI. Transfer Capability & Operating Savings

| Trans.Cap. (MW) | | Operating Savings (PV - US $M '96) | | | | | |
|---|---|---|---|---|---|---|---|
| 2000-07 | 2008-15 | S1 | S2 | S3 | S4 | S5 | S6 |
| 50 | 50 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 300 | 300 | 96 | 146 | 256 | 281 | 809 | 1248 |
| 300 | 500 | 96 | 146 | 256 | 281 | 865 | 1288 |
| 300 | 700 | 96 | 146 | 256 | 281 | 881 | 1288 |

According to the expected operating savings reported in Table VI, for four of the scenarios (S1-S4) there was no economic benefit for transfer capability over 300 MW. In scenario S6 (high load growth, three large regional hydro plants, and high international coordination in operation and planning), there was no economic benefit for transfer capability over 500 MW. In scenario S5 there was no economic benefit for transfer capability over 700 MW.

These observations eliminated definitely the 400-kV and 500-kV lines, since 700 MW of transfer capability could be achieved at lower cost using multiple 230-kV lines.

Table VII. Strategic Transmission Plans

| Strategic Plan 2000 2008 | Const.Cost (PV - US $M '96) | Trans.Cap. (MW) 2000-07 | Trans.Cap. (MW) 2008-15 |
|---|---|---|---|
| 1 x 230 | 123 | 300 | 300 |
| 2 x 230$^1$ | 153 | 300 | 300 |
| 1 x 230 +1 x 230 | 159 | 300 | 500 |
| 2 x 230$^1$+2 x 230$^2$ | 167 | 300 | 500 |
| 1 x 230 +2 x 230 | 179 | 300 | 700 |

*Note: The super-index indicates the number of installed circuit.*

Table VII lists the different strategic transmission plans that were found suitable for the different requirements of the scenarios. Normal levels of compensation were embedded in the transmission costs for each plan. Each strategic plan can be implemented according to the transfer capability evolution of the interconnection and the operating savings in each generation plan.

### 1.3 SIEPAC Decision Analysis

Table VIII shows the net benefit of the strategic transmission plans for all scenarios. Net benefit is computed as the difference in present value between the operating savings (Table VI) and the costs of strategic plans (Table VII). The net benefits for the optimal strategic plans in each scenario are in bold.

Table VIII. Net Benefits of Strategic Plans

| Strategic Plan 2000 2008 | Net Benefits (PV - US $M '96) S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|
| None None | **0** | 0 | 0 | 0 | 0 | 0 |
| 1 x 230 - | -27 | **23** | **133** | **157** | 686 | 1125 |
| 2 x 230$^1$ - | -57 | -7 | 103 | 128 | 656 | 1095 |
| 1 x 230 + 1 x 230 | -27 | **23** | **133** | **157** | **706** | **1129** |
| 2 x 230$^1$+ 2 x230$^2$ | -57 | -7 | 103 | 128 | 698 | 1121 |
| 1 x 230 + 2 x 230 | -27 | **23** | **133** | **157** | 702 | 1110 |
| ***Maxim Benefits*** | ***0*** | ***23*** | ***133*** | ***157*** | ***706*** | ***1129*** |

The 1x230 strategic plan is a single-circuit line (2000). This strategic plan can be reinforced with another same line or a double-circuit 230-kV line at the year 2008 in scenarios S5 and S6. The 2x230$^1$ strategic plan is a double-circuit line with only one circuit strung initially at the year 2000. This strategic plan can be reinforced with the second circuit at the year 2008 in scenarios S5 and S6.

In Table IX the regret is presented for each strategic plan. It is computed as the difference between the maximum benefit and the net benefit (Table VIII). The maximum regret for each strategic plan is in bold.

Table IX. Regrets

| Strategic Plan 2000 2008 | Regrets (PV - US $M '96) S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|
| None None | 0 | 23 | 133 | 157 | 706 | **1129** |
| 1 x 230 - | **27** | 0 | 0 | 0 | 20 | 4 |
| 2 x 230$^1$ - | **57** | 30 | 30 | 30 | 50 | 34 |
| 1 x 230 + 1 x 230 | **27** | 0 | 0 | 0 | 0 | 0 |
| 2 x 230$^1$+ 2 x230$^2$ | **57** | 30 | 30 | 30 | 8 | 8 |
| 1 x 230 + 2 x 230 | **27** | 0 | 0 | 0 | 4 | 20 |

According to Table IX, no interconnection expansion in Central America supposes huge regrets in all the scenarios (high exposure risk), except in the first one. One new single-circuit 230-kV line (at year 2000) along the study period has zero regrets (it is optimal) only in scenarios S2, S3 & S4. If this line is reinforced later with a double-circuit 230-kV line (at year 2008), the robustness does not change; if the reinforcement is another single-circuit, then the degree of robustness is higher, and therefore, it is the strategic plan with the lowest exposure to risk. Since all strategic plans are not optimal in all the scenarios (regrets greater than zero), then there is not a robust transmission plan.

Table X resumes the maximum regrets, exposure risk and degree of robustness for each strategic plan. There are three strategic plans with the same minimum maximum regret (US$M'96 27.0). These three plans have the same min-max-regret because they are identical in scenario S1 (the single-circuit 230-kV line at the year 2000).

Table X. Economic Indicators

| Strategic Plan 2000 2008 | Maximum Regret (US $M '96) | Exposure Risk | Robustness (%) |
|---|---|---|---|
| None None | 1129 | High | 17 |
| **1 x 230 -** | **27** | **Low** | **50** |
| 2 x 230$^1$ - | 57 | Medium | 0 |
| **1 x 230 + 1 x 230** | **27** | **Minimum** | **83** |
| 2 x 230$^1$+ 2 x230$^2$ | 57 | Medium | 0 |
| **1 x 230 + 2 x 230** | **27** | **Low** | **50** |

That regret represents economic losses to the countries if they decide to build the SIEPAC Project and continue keeping conservative levels of coordination in planning (individual planning) and operation of their power systems (scenario S1). The operating savings ($M'96 96.0) would not compensate the investment cost ($M'96 123.0). For that reason the IDB defined a hedge - creating a robust plan - by agreeing with the countries to make funds available for the construction of the line after the six power systems prove that the scenario S1 will not materialise. The countries must increase the level of coordination in operation using existing network to exchange an energy threshold limit of about 450 GWh/year.

In order to complete the analysis of robustness, a sensitivity process can be carried out including uncertainties in the line construction costs and operating savings (e.g. 20%), and repeating the same procedure described above. Other uncertain attributes such as: rights of way, environment impacts, and financial requirements can be incorporated into the same decision analysis framework.

## 2. CONCLUSIONS

The approach presented in this paper allows planners to carry out new multi-area regional planning for generation and transmission expansion analysis. The treatment of strategic and long-term uncertainties by definition of scenarios is a key factor in this new approach. An iterative process between generation planning and transmission planning existing software tools is proposed. A decision-making process using the min-max-regret method has been incorporated in order to quantify and hedge possible risks. As a result, robust regional interconnection plans are identified and evaluated. This method can be considered as an improvement of standard interconnection planning practices. These practices should be revised under the new framework of deregulation and competition in generation.

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## APPENDIX A. LOAD GROWTH EVOLUTION IN CENTRAL AMERICA

In this Appendix, the demand forecasts used in the example of the paper are detailed. Tables A.I and A.II show the yearly peak load and the energy consumption, respectively, in each Central-American country under a low demand growth hypothesis. These data are only presented for some of the years of the study period.

Table A.I. Peak Load (MW) - Low Demand

| Year | GU | ES | HO | NI | CR | PA |
|---|---|---|---|---|---|---|
| 1996 | 723 | 622 | 506 | 333 | 935 | 634 |
| 2000 | 910 | 718 | 574 | 408 | 1101 | 707 |
| 2007 | 1350 | 973 | 747 | 574 | 1495 | 893 |
| 2015 | 2124 | 1281 | 1043 | 821 | 2049 | 1216 |

Table A.II. Energy Consumption (GWh) - Low Demand

| Year | GU | ES | HO | NI | CR | PA |
|---|---|---|---|---|---|---|
| 1996 | 3781 | 3432 | 2878 | 1760 | 5126 | 3737 |
| 2000 | 4810 | 3965 | 3244 | 2180 | 6071 | 4164 |
| 2007 | 7339 | 5370 | 4173 | 3117 | 8301 | 5246 |
| 2015 | 11913 | 7070 | 5756 | 4555 | 11453 | 7105 |

Tables A.III and A.IV show the yearly peak load and the energy consumption, respectively, in each Central-American country under a high demand growth hypothesis.

Table A.III. Peak Load (MW) - High Demand

| Year | GU | ES | HO | NI | CR | PA |
|---|---|---|---|---|---|---|
| 1996 | 744 | 639 | 570 | 341 | 948 | 655 |
| 2000 | 1022 | 864 | 737 | 437 | 1193 | 832 |
| 2007 | 1777 | 1359 | 1138 | 661 | 1782 | 1311 |
| 2015 | 3307 | 2119 | 1887 | 1030 | 2711 | 2342 |

Table A.IV. Energy Consumption (GWh)-High Demand

| Year | GU | ES | HO | NI | CR | PA |
|---|---|---|---|---|---|---|
| 1996 | 3916 | 3526 | 3086 | 1800 | 5194 | 3858 |
| 2000 | 5406 | 4766 | 3965 | 2333 | 6561 | 4898 |
| 2007 | 9501 | 7498 | 6051 | 3595 | 9860 | 7685 |
| 2015 | 17980 | 11692 | 9900 | 5712 | 15089 | 13684 |