Optimal Generation and Transmission Expansion Planning Addressing Short-Term Constraints with Co-optimization of Energy and Reserves

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Abstract—The penetration of variable renewable energy (VRE) in electrical systems has changed the way the expansion planning is treated. This kind of resource has great variability in small amounts of time, which makes it important to represent hourly constraints that requires chronology. Besides that, the generation reserves should also be adjusted in order to capture the intermittent effect, and since many countries use rapid thermal plants as part of these reserves, unit commitment and ramp constraint have also become more significant. In this paper we propose a MILP expansion planning model that can represent hourly time steps while maintaining reasonable computational times, where both investment and operation problems are simultaneously solved. Because the planning horizons are long (decades), the resolution of the entire horizon in a single optimization problem would be computationally infeasible for large real systems, making it necessary, therefore, to apply a horizon decomposition heuristic in smaller sub-horizons, and use the representation of typical days and seasons to reduces the size of the problem.

Index Terms—Expansion Planning, Transmission Planning, Hourly Representation, Renewables, Optimization, Integer Programming

NOMENCLATURE

I. INTRODUCTION

T HE interest on optimal power system expansion planning has increased worldwide. In developing countries of Latin America, Asia and Africa, with high load growth and limited financial resources, the emphasis is on the most cost-effective expansion plan [1]–[3]. In developed countries, load growth is usually flat. In these cases, Renewable Energy Sources (RES) are being built as part of decarbonization policies and to displace more expensive thermal plants [4]–[7]. In both cases, selecting the "best" of a group of alternatives is what characterizes the combinatorial nature of the expansion planning problem.

The main objective of the expansion planning process is to guarantee an appropriate balance between electricity supply and demand, i.e. to determine the optimal set of generating plants and transmission routes that should be constructed to meet the demand requirements along a study horizon (mid and long term), while minimizing a cost function considering: (i) investment (capital) and operation (fuel, O&M, etc.) costs of generation plants and (ii) penalties of energy not supplied, also called deficit costs. In general terms, this decision process involves meeting economic, reliability and environmental criteria, within the framework of national policies on energy. In addition, one of the greatest challenges is how to deal with the uncertainties inherent in the planning process, such as the load growth, the hydrological inflows and the generation availability, especially in renewable based systems. Taken all the aforementioned facts into account, the expansion planning problem is modeled as a large and complex mixed integer multistage stochastic problem that must be solved by specialized optimization algorithm.

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This paper presents a description of the methodology associated with the OptGen model [8], a commercial computational tool for energy systems expansion planning, where two "Solution Strategies" are available:

- The benders decomposition strategy, proposed in [9]: A decomposition of the investment and operation problem, where the master is a MILP investment problem and the slave is a multistage stochastic optimization of the operational problem that is solved using the SDDP algorithm, first proposed in [10];
- The co-optimization strategy, which is the methodology described in this paper

The main characteristics of the model are:

- Study horizons from 1 year up to several decades;
- Many different candidate projects may be contemplated in the study, such as:
 - Production components: hydro, thermal and renewable plants (wind, solar, biomass, etc.);
 - Interconnection links and transmission circuits (lines, transformers, DC links etc.);
 - Storage devices such as Batteries, Hydro pump stations, etc.
 - Gas pipelines, production nodes, regasification stations.
- Detailed project's financial data, such as, investment costs, payment schedules, life-time, construction time;
- Detailed project specific data, such as, decision type (obligatory or optional), decision variable type (binary, integer or continuous), maximum and minimum en-trance dates, generating unit entrance schedule, etc.;
- Additional constraints, such as, firm energy/capacity constraints, exclusivity, association and precedence between projects, minimum and maximum additional capacity, generation capacity targets and so on;
- Unit commitment constraints

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- Ramping constraints
- · Co-optimization of energy and reserves

In summary, the objective of OptGen is to determine a leastcost investment schedule for the construction of new plant capacity (hydro, thermal and renewable projects), regional interconnections (or detailed transmission circuits), gas production sources and gas pipelines. This is obtained by optimizing the trade-off between investment costs to build new projects and the expected value of operating and deficit costs.

This paper is organized as follows. In the Section II, a review of the current state-of-the-art policies, methodologies and models regarding systems with a high level of renewable penetration is presented. In Section III, we discuss the assumptions used by the methodology in order to make it computational tractable. In Section IV, we analyze how the uncertainties are taken into account in the proposed model. In Section V, we provide a detailed formulation of the proposed methodology. Finally, in Section VI, the final conclusions are presented.

II. LITERATURE REVIEW

The increasing economic competitiveness of wind and solar generation sources, also called variable renewable energy sources (VRE), has widely studies in the literature. These energy resources reduces green-house gas emissions, as studied in [11]. Besides that, [12] showed that in a renewable energy economy, since renewable energy potential is available everywhere, the countries that heavily depends on fossil fuel imports will be able to use renewable energy as a manner to achieve energy independence, i.e, they will have greater energy security and more freedom to take the energy decisions that suit them, reducing its vulnerability to import fossil fuels (particularly, oil and natural gas).

However, the fast penetration of these new sources has also raised some concerns for both planners and operators that are highly studies in the literature: (i) most of these sources are non-dispatchable, i.e., their generation cannot be controlled by the system operator [13]–[15]; and (ii) their energy production presents strong variability, i.e., the production can change significantly from one hour to the next [16]–[19].

As can be seen, the VRE penetration ends up causing representative impacts on the net demand profile. In addition to the change in the profile, it is worth noting the raise of net demand ramps and their respective inclinations with the greater renewable penetration. These impacts lead to new operational challenges, which stand out:

- Over-supply situations: periods when the renewable generation is higher than the demand to be met (for example, in the middle of the night in regions with strong night winds or during the day in regions with a significant solar power capacity). [20] in hydropower-dominated regions;
- Fast upward and downward ramps: dispatchable plants must have the ability to fast respond to the increase and decrease of intermittent renewable generation to maintain supply reliability and system stability;

• **Increasing thermal cycling**: possible increase in the number of startups and shutdowns of thermal plants in the system due to renewable generation intermittency;

There are several studies in the literature that adresses these challenges. For example, [21] analyzes forms of efficiently curtail renewable generation in over-supply situations in Germany and [22] analyzes the historical operation and current practices of curtailment in the United States. Besides that, several works analyze needs for thermal flexibility due to renewable generation [23]–[25]

Because of its importance, expansion planning problems are vastly discussed in the literature. There are several decomposition approaches model in the literature. In [9] a Benders decomposition between investment problem and SDDP algorithm is proposed. Since this methodology is very scalable, stochastic and produces optimal solution, it has been used in several real-case studies, such as [26]–[28]. The work in [29] also proposes a decomposition where the master is a MILP investment problem and the slave a short-term deterministic operating model, not taking into account uncertainties.

Since those decomposition algorithm requires convexity in the operation problem, there are some constraints such as unit commitment, that requires binary variables. In order to deal with that, there are several studies proposing the co-optimization between investment and operation, so that it could be solved with a MILP. For example, [30]–[33] proposes the co-optimization with some assumptions in order to make the MILP computational tractable. Since it may be hard to solve a huge MILP, most of the co-optimization methodology proposes to aggregate the days of the year into representative days, reducing computational time. [34] showed that the clustered model (using representative days) leads to expansion planning results very similar to the unclustered model (considering all of the days of the year).

III. SOLUTION METHODOLOGY

Similar to the works in [30]–[33], the proposed model uses the co-optimization between the investment and operation. Also, some assumptions to cluster the days of the years into representative days are used in order to reduce computational effort. Besides that, a rolling horizon scheme is implemented, in order to split the horizon into windows of a year, also in order to reduce computational effort. The next section introduces the concept of the rolling horizon, seasons and typical days.

A. Horizon Decomposition Heuristic

Since the planning horizons are long, in order to solve the expansion problem when applying co-optimization of investment and operation, the horizon is decomposed into annual sub-horizons through the forward strategy in time, that is, a problem of co-optimization of the investment and operation is solved for each year in a rolling horizon scheme. An optimum expansion plan is calculated per year, this decision is fixed, and a new optimization problem is set for the following year, considering the investment decisions taken in the previous year as fixed and completing the expansion plan, when necessary, as shown in Figure 1



Fig. 1. Horizon decomposition heuristic

 TABLE I

 COMPARING BLOCKS AND HOURS RESOLUTION SIZE OF THE PROBLEMS

Constraints	Blocks	Hours
Water balance constraints	114	+80,000
Load balance constraints	30	+4,000
Maximum generation & turbining constraints	1499	+290,000
Maximum & minimum volume constraints	228	+165,000
Total	1461	+520,000

B. Typical days and seasons

Since the operation is solved with hourly representation, it may result in a large and computationally intractable problem, given the size of studies that envision long-term horizons in the planning process, and since the proposed model solves a MILP that aims to minimize investment costs and the expected value of operating costs, subject to uncertainties in hydrology and generation of intermittent renewable sources.

As a way of exemplifying this issue, taking a real energy system into account, the Table I summarizes the size of the optimization problems for 1 month and 5 blocks versus 744 hours.

As can be seen, the size of the optimization problems increases significantly. In addition to that, while evaluating real systems' expansion, it is also necessary to use multiple scenarios to incorporate the uncertainties to which the system will be exposed (hydrology, renewable generation, etc.) and, consequently, the addition of all constraints per scenario in the optimization problem. For this reason, it is necessary to create a strategy that reduces the size of the problem, but without compromising the quality of the results.

In order to reduce the computational effort required by these optimization problems, it is necessary to introduce the concepts of seasons and representative (typical) days, which in addition to enabling the solution of these problems in acceptable computational times, captures the effects of intermittent generation in the system.

The first step of this strategy is to group the months of the year into seasons, as shown in Figure 2. Once the seasons are defined, the representative days within each of them, here referred to as typical days, should be defined. This type of representation aims to reduce the number of days analyzed within each season, since the daily demand profiles are not usually so different, especially within the pre-defined seasons. The Figure 3 illustrates this grouping of real days on typical days for a set of seasons in a given year. The allocation presented in the figure was made in a generic way, with illustrative purposes.



Fig. 2. Mapping months into seasons



Fig. 3. Mapping typical days inside each season

IV. HANDLING UNCERTAINTIES

In SDDP model, the long-term production costing decision making process (generation of each plant, interconnections between regions, circuit flows, etc.) consists in a stochastic optimization problem that seeks to balance the immediate cost and the expected value of the future cost (the expected value comes from the uncertainty about future hydrology, wind, consumption, availability of equipment, etc.). This problem is intrinsically related to storage devices that create a timecoupling between stages. Therefore, today's operating decisions, such as storage levels, may impact the mid and longterm operation, affecting thus the future operating costs. For further details, please refer to the SDDP Methodology Manual.

Taking the aforementioned explanation into account and given that this expansion approach performs the investment and operation co-optimization within the same problem, the operational policy is not calculated through SDDP algorithm, the proposed model does not consider the calculation of a Future Cost Function (FCF) for the system in each stage of the operation, since its calculation would require iterations of the system operation which reflects in the simulation of the operation in each stage several times until the FCF is sufficiently well approximated. It is intuitive to see that the SDDP application to calculate the FCF is the most realistic way to simulate the operation of the system, but, as it is intended to apply co-optimization, the operation of the hydro reservoirs throughout the year should be simplified.

The formulation proposed ensures that the initial storage of the reservoir of each hydroelectric plant at the beginning of each year of the study horizon will be equal to the final storage of that year. This operating strategy prevents the model from completely depleting the reservoirs present in the system during the year, optimizing its use throughout the year. The concept behind this modeling is a multi-deterministic operation, where the operation of the reservoirs is optimized for each separate scenario, without the incorporation of hydrological uncertainty into the decision-making process of the system operation in each scenario. It is plausible to explain that this simplification of the operation of large hydropower plants with large reservoirs has an optimistic bias, however, its application indicates that it is an approximation that presents satisfactory results for investment decision making and calculation of the expansion plan.

V. PROBLEM FORMULATION

The expansion planning problem of an energy system is primarily formulated as a mathematical programming problem, expressed by the formulation below. We suppose, for the sake of simplicity, that all plants are candidate projects to the expansion problem.

A. Investment Constraints

1) Precedence between projects:

$$x_{\omega} - x_{\zeta} \ge 0 \qquad \quad \forall \omega, \zeta \in P_k^{pre}, \ \forall k \in R^{PRE}$$
(1)

2) Mutually exclusive projects:

$$\sum_{\omega \in P_{k}^{ex}} x_{\omega} \le 1 \qquad \forall k \in R^{ex}$$
(2)

3) Associated projects:

$$x_{\omega} - x_{\zeta} \ge 0$$
 $\forall \omega, \zeta \in P_k^{as}, \ \forall k \in R^{as}$ (3)

4) Minimum and maximum installed capacity / firm energy / firm capacity:

$$\sum_{\zeta \in P_k^{cap}} w_{\zeta}^k x_{\zeta} \ge \underline{w_k} \qquad \forall k \in R^{ctr}$$
(4)

$$\sum_{\zeta \in P_k^{cap}} w_{\zeta}^k x_{\zeta} \le \overline{w_k} \qquad \forall k \in R^{ctr}$$
(5)

B. Thermal plants constraints

1) Minimum and maximum energy generation:

$$\underline{g_j}\gamma_{j,t,d,h,s} \le g_{j,t,d,h,s} \le \overline{g_j}\gamma_{j,t,d,h,s} \qquad \forall j,t,d,h,s \qquad (6)$$

2) Ramp up and ramp down generation:

$$g_{j,t,d,h,s} - g_{j,t,d,h-1,s} \le \Delta_j^{UP} \qquad \forall j, t, d, h, s$$

$$g_{j,t,d,h-1,s} - g_{j,t,d,h,s} \le \Delta_j^{DN} \qquad \forall j, t, d, h, s \quad (8)$$

3) Unit commitment:

$$st_{j,t,d,h,s} \ge \gamma_{j,t,d,h,s} - \gamma_{j,t,d,h-1,s} \qquad \forall j, t, d, h, s \tag{9}$$

$$\gamma_{j,t,d,h,s} \le x_j \qquad \qquad \forall j,t,d,h,s \qquad (10)$$

$$\gamma_{j,t,d,h,s} \in \{0,1\} \qquad \qquad \forall j,t,d,h,s \qquad (11)$$

The constraint (10) model the relation between commitment and investment decisions, preventing a thermal plant to be committed without being invested before. This constraint make continuous investment decisions to be incompatible with thermal commitment constraints (because it requires binary variables).

C. Hydro plants constraints

1) Water storage balance: Since the model does not consider the Future Cost to go Function (FCF), it forces water reservoir levels of all hydro plants to finish at the same level they started (initial storage = final storage), preventing the system to deplete all water in the reservoir at the end of the horizon, in order to avoid thermal operative costs. This strategy forces the model to optimize reservoir operation in order to utilize all the water inflows that arrived in the analyzed period.

$$v_{i,t+1,s} = v_{i,t,s} + a_{i,t,s} - (u_{i,t,s} + s_{i,t,s}) + \sum_{m \in M_i} (u_{m,t,s} + s_{m,t,s}) \quad \forall i, t, s \quad (12)$$

$$v_{i,T,s} = v_{i,0,s} \qquad \qquad \forall i,s \qquad (13)$$

2) Energy production: The equation (14) guarantees that the hourly energy production of the hydro plants is equal to the total energy turbined in the season. This equation assumes that the hydro plants have total regulation within season, i.e, they may freely transfer water, from an hour to another.

$$\sum_{d,h} D_{t,d}g_{i,t,d,h,s} = \rho_i u_{i,t,s} \qquad \forall i, t, s \qquad (14)$$

$$g_{i,t,d,h,s} \le \overline{g_i} x_i \qquad \qquad \forall i, t, d, h, s \qquad (15)$$

3) Minimum and maximum storage:

$$v_{i,t,s} \le \overline{v_i} x_i$$
 $\forall i, t, s$ (16)

$$v_{i,t,s} + \delta_{i,t,s}^v = \underline{v}_i x_i \qquad \forall i, t, s \qquad (17)$$

4) Minimum and maximum turbining:

$$u_{i,t,s} \le \overline{u_i} x_i \qquad \qquad \forall i, t, s \qquad (18)$$

$$u_{i,t,s} + \delta^u_{i,t,s} = \underline{u_i} x_i \qquad \forall i, t, s \qquad (19)$$

5) Minimum total outflow:

$$u_{i,t,s} + s_{i,t,s} \le \overline{q_i} x_i \qquad \qquad \forall i, t, s \qquad (20)$$

$$u_{i,t,s} + s_{i,t,s} + \delta^q_{i,t,s} = q_i x_i \qquad \forall i, t, s \qquad (21)$$

D. Renewables contraints

(7)

Renewable plants generation decision must be lower than renewable generation scenarios.

$$g_{l,t,d,h,s} \le \psi_{l,t,d,h,s} x_l \qquad \forall l, t, d, h, s \qquad (22)$$

E. Batteries

1) Energy storage balance: Battery storage balance has hourly time steps, as in equation (23). Like the hydro plants, batteries also have regulation constraints (24), where the initial energy storage is equal the final energy storage.

$$v_{b,t,d,h+1,s} = v_{b,t,d,h,s} + \eta_b^+ q_{b,t,d,h,s}^+ - q_{b,t,d,h,s}^- \quad \forall b, t, d, h, s$$
(23)

$$v_{b,t,d,24,s} = v_{b,t,d,0,s} \qquad \forall b, t, d, s$$
(24)

2) Maximum storage, charge and discharge:

$$v_{b,t,d,h,s} \le V_b x_b \qquad \qquad \forall b,t,d,h,s \qquad (25)$$

$$q_{b,t,d,h,s}^+ \le q_b^+ x_b \qquad \forall b, t, d, h, s \qquad (26)$$

$$q_{b,t,d,h,s}^{-}s \le \overline{q_{b}^{-}}x_{b} \qquad \forall b,t,d,h,s \qquad (27)$$

F. Transmission lines constraints

1) Maximum flow: The flow variables for the network representation are $f_{k,t,d,h}^{+s}$ and $f_{k,t,d,h}^{-s}$, where these two positive variables represent the flow in both direction of each line, where + means positive oriented and – means negative oriented:

$$f_{k,t,d,h,s}^{+} \le \overline{f_{k}^{+}} x_{k} \qquad \qquad \forall k,t,d,h,s \qquad (28)$$

$$f_{k,t,d,h,s}^{-} \leq f_{k}^{-} x_{k} \qquad \forall k, t, d, h, s \qquad (29)$$

2) Second Kirchhoff law: The model considers two types of transmission lines: DC-Links and Circuits. Second Kirchhoff law will only be represented for circuits.

$$\begin{aligned}
f_{k,t,d,h,s}^{+} &- f_{k,t,d,h,s}^{-} - \gamma_{k} \left(\theta_{b_{k}^{+},t,d,h,s} - \theta_{b_{k}^{-},t,d,h,s} \right) \\
&\geq -M(1-x_{k}) \quad \forall k \\
&\in K^{p}, t, d, h, s
\end{aligned} \tag{30}$$

$$\begin{aligned} & f_{k,t,d,h,s}^{+} - f_{k,t,d,h,s}^{-} - \gamma_{k} \left(\theta_{b_{k}^{+},t,d,h,s} - \theta_{b_{k}^{-},t,d,h,s} \right) \\ & \leq M(1-x_{k}) \quad \forall k \\ & \in K^{p}, t, d, h, s \end{aligned} \tag{31}$$

3) Area import/export constraints: Area import/export constraints can limit the maximum amount of energy that enters or leave a specific electrical area.

For import constraints

$$\sum_{k \in K_a^+} f_{k,t,d,h,s}^+ + \sum_{k \in K_a^-} f_{k,t,d,h,s}^- \le \overline{Imp_a} \quad \forall a, t, d, h, s$$
(32)

$$\sum_{k \in K_a^+} f_{k,t,d,h,s} + \sum_{k \in K_a^-} f_{k,t,d,h,s} \ge \underline{Imp_a} \quad \forall a, t, d, h, s$$
(33)

For export constraints

$$\sum_{k \in K_a^-} f_{k,t,d,h,s}^+ + \sum_{k \in K_a^+} f_{k,t,d,h,s}^- \le \overline{Exp_a} \quad \forall a, t, d, h, s$$
(34)

$$\sum_{k \in K_a^-} f_{k,t,d,h,s}^+ + \sum_{k \in K_a^+} f_{k,t,d,h,s}^- \ge \underline{Exp_a} \quad \forall a, t, d, h, s$$
(35)

G. Generation constraint

Generation constraint is an operative constraint which guarantees that a certain group of generators (thermal and hydro plants) always generate energy above or below a threshold.

$$\sum_{j \in J_c^G} g_{j,t,d,h,s} + \sum_{i \in I_c^G} g_{i,t,d,h,s} + \delta_{c,t,d,h,s}^g \ge \underline{g_c} \quad \forall c, t, d, h, s$$
(36)

$$\sum_{j \in J_c^G} g_{j,t,d,h,s} + \sum_{i \in I_c^G} g_{i,t,d,h,s} + \delta_{c,t,d,h,s}^g \le \overline{g_c} \quad \forall c, t, d, h, s$$
(37)

H. Reserve balance constraints

$$g_{j,t,d,h,s} + r_{j,t,d,h,s} \leq \overline{g_j} \gamma_{j,t,d,h,s} \qquad \forall j, t, d, h, s \qquad (38)$$
$$r_{j,t,d,h,s} \leq \Delta_{j}^{UP} \qquad \forall j, t, d, h, s \qquad (39)$$

$$\begin{aligned} r_{j,t,d,h,s} &\leq \Delta_j & \forall j, \iota, u, h, s & (39) \\ q_{i+d,h,s} + r_{i+d,h,s} &\leq \overline{q_i} x_i & \forall i, t, d, h, s & (40) \end{aligned}$$

$$\eta_{\bar{\mu}}^{-} q_{\bar{\mu}_{+},d,\bar{\mu}_{-}}^{-} + r_{h+d,\bar{h},s} \leq g_{\bar{\mu}} \approx i \qquad (10)$$

$$\eta_{\bar{\mu}}^{-} q_{\bar{\mu}_{+},d,\bar{\mu}_{-}}^{-} + r_{h+d,\bar{h},s} \leq \eta_{\bar{\mu}}^{-} q_{\bar{\mu}}^{-} x_{h} \qquad \forall b, t, d, h, s \qquad (41)$$

$$\begin{array}{l} & (1) \\ & r_{b,t,d,h,s} \leq \eta_{b}^{-} v_{b,t,d,h,s} \leq \eta_{b}^{-} q_{b} q_{b} w_{b} & \forall b, t, d, h, s \\ & \forall b, t, d, h, s \leq \eta_{b}^{-} v_{b,t,d,h,s} & \forall b, t, d, h, s \end{array}$$

$$\sum_{j \in J_c^R} r_{j,t,d,h,s} + \sum_{i \in I_c^R} r_{i,t,d,h,s} + \sum_{b \in B_c^R} r_{b,t,d,h,s} + \delta_{c,t,d,h,s}^R \ge R_{c,t,d,h,s} \forall c, t, d, h, s$$

$$(43)$$

I. Load balance constraints

$$\sum_{j \in J_{n}} g_{j,t,d,h,s} + \sum_{i \in I_{n}} g_{i,t,d,h,s} + \sum_{l \in L_{n}} g_{l,t,d,h,s} + \sum_{l \in K_{n}} g_{l,t,d,h,s} + \sum_{k \in K_{n}^{+}} \left(\eta_{b}^{-} q_{b,t,d,h,s}^{-} - q_{b,t,d,h,s}^{+} \right) + \sum_{k \in K_{n}^{+}} \left(f_{k,t,d,h,s}^{+} - f_{k,t,d,h,s}^{-} \right) - DE_{n,t,d,h,s} + d_{n,t,d,h,s} = DI_{n,t,d,h,s} \ \forall n, t, d, h, s$$

$$(44)$$

2) J. Objective function

Let's define $\beta_{t,d,s}$ as:

$$\beta_{t,d,s} = \frac{p_s D_{t,d}}{(1+rt)^{t-1}} \tag{45}$$

Then the problem's objective function is the minimization of the following costs:

$$\sum_{t,d,s} \beta_{t,d,s} \left(\sum_{j,h} (co_j g_{j,t,d,h,s} + cs_j st_{j,t,d,h,s}) + \sum_{i,h} co_i g_{i,t,d,h,s} \right)$$

$$(46)$$

2) Violation Cost:

$$\sum_{i,t,s} \frac{p_s}{(1+rt)^{t-1}} (c_{\delta_i^v} \delta_{i,t,s}^v + c_{\delta_i^u} \delta_{i,t,s}^u + c_{\delta_i^q} \delta_{i,t,s}^q) + \sum_{t,d,s} \beta_{t,d,s} \left(\sum_{c,h} (c_{\delta_c^G} \delta_{c,t,d,h,s}^G + c_{\delta_c^R} \delta_{c,t,d,h,s}^R) \right)$$
(47)

3) Deficit Cost:

$$\sum_{t,d,s} \beta_{t,d,s} \sum_{n,h} c_d d_{n,t,d,h,s}$$
(48)

4) Elastic Demand Gain:

$$\sum_{t,d,s} \beta_{t,d,s} \sum_{n,h} P_n^E D E_{n,t,d,h,s}$$
(49)

5) Investment Costs:

$$\sum_{j \in J_x} ci_j x_j + \sum_{i \in I_x} ci_i x_i + \sum_{l \in L_x} ci_l x_l + \sum_{b \in B_x} ci_b x_b + \sum_{k \in K_x} ci_k x_k +$$
(50)

VI. CONCLUSIONS

The model proposed here considers explicit operative constraints in the investment model. As a result, it can represent non-convexities in the operative constraints (such as commitment decisions). On the other hand, due to the increase of the problem's complexity, some simplifications have to be made. In this approach, we consider yearly time steps opposed to full horizon steps and representative (typical) days instead of real days within a year.

Typical days are days within a season that are considered representative of the input data. Thus, instead of representing all days of a season, the user selects a certain number of typical days to represent the season and associates these typical days with actual days. For instance, it is common to differentiate weekdays from Saturdays and Sundays, but the number of typical days and their definitions are flexible and chosen by the user.

The great advantages of this model are:

- The co-optimization of investment and operating problems inside the same MILP al-lows the representation of unit commitments and other binary variables;
- The hourly chronological representation in the operation enables to capture the production variability of intermittent renewable sources and the generation ramps.

Besides the great advantages of this solution strategy, it's also important to remember its caveats. As explained in

Section IV, the operative simulation is performed in a multideterministic way, where the operation of the reservoirs is optimized for each scenario individually, without the incorporation of hydrological uncertainty into the decision-making process of the system operation (as it is done when the SDDP methodology is applied and the FCF is calculated for each time stage). It is plausible to explain that this simplification of the operation of large hydropower plants with large reservoirs has an optimistic bias, however, its application indicates that it is an approximation that presents satisfactory results for investment decision making and calculation of the expansion plan.

Furthermore, it's also worth noting that since investment and operation problems are co-optimized in this solution strategy, then the more scenarios are contemplated in the problem, the higher computational effort will be demanded to solve the MILP. As a consequence, for large scale systems, the computational time might limit the number of scenarios that can be contemplated.

Finally, the proposed model is suitable for most real-case studies of expansion planning of renewable-dominated regions, representing hourly chronology, short-term constraints such as unit commitment and ramping, co-optimizing energy and reserves and with assumptions and approximations to make it computational tractable.

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