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Optimizing Long-Term Service Agreements for gas-fired units in the context of increasing penetration of intermittent generation

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Optimizing Long-Term Service Agreements for gas-fired units in the context of increasing penetration of intermittent generation

T. Leung, M. Sánchez-González, P. Rodilla, C. Batlle

***Abstract*— As power systems increasingly rely on gas-fired power plants (GFPP), and as thermal cycling requirements increase due to larger penetrations of intermittent generation, the long-term service agreements (LTSAs) that define the conditions and costs for GFPP maintenance are exerting more economic influence over a power system's short-term operations.**

In a previous paper, the authors proposed a unit commitment formulation that explicitly represents LTSAs and showed that these operations and maintenance (O&M) contracts substantially impact the cost of economic dispatch when GFPPs are forced to intensively cycle. The authors also showed that properly modeling these contracts can substantially alter a power system's short-term optimal scheduling.

Traditional LTSAs were designed assuming that (especially) combined cycle gas turbines would operate in a base-loaded regime. In new operating regimes characterized by heavy cycling, GFPPs with traditional LTSAs can incur excessive cycling costs. It may be possible for owners of these GFPPs to renegotiate their existing LTSAs for more flexible conditions that will allow their GFPPs to cycle at lower costs, even if this renegotiation requires the owner to pay an upfront expense.

In this paper, we propose a formulation aimed at supporting the process of optimizing LTSAs contracts for a portfolio of GFPPs.

***Index Terms*—cycling, major overhaul, O&M, operations and maintenance, gas-fired power plants, unit commitment**

NOTATION

The notation used is stated below for quick reference. Other symbols are defined as needed throughout the paper.

Indices:

$i = 1..I$	Individual power plant in the system
$t = 1..T$	Time step (hour)
$n = 1..N$	LTSA contract
$j = 1..J$	LTSA plane

Parameters:

$\underline{Q_i}, \overline{Q_i}$,	Minimum and maximum output level of plant i
ru_i, rd_i	Ramp up and ramp down limits of plant i
$Csu_{,i}$	Start-up cost of plant i
Csd_i	Shut-down cost of plant i
Cnl_i	No load cost of plant i
Cv_i	Variable generation cost of plant i
MOC_n	LTSA cost for contract n
D_t	Power demand (perfectly inelastic) for hour t
$FH_{A_{j,n}}, S_{A_{j,n}}$	Each (firing hours, starts) point that defines the boundaries of the Maintenance Interval Function (see Fig. 2)

Positive variables:

$q_{i,t}$	Total generation level for plant i
$w_{i,t}$	Generation level for plant i and hour t above its minimum
$MOCuc_i$	Maintenance cost for plant i to be allocated over the simulated unit commitment time horizon

Binary variables:

$y_{i,t}$	Start-up decision for plant i and hour t
$z_{i,t}$	Shut-down decision for plant i
$u_{i,t}$	Commitment state for plant i
$c_{i,n}$	LTSA decision for plant i and contract n; $c_{i,n}$=1 denotes that plant i is assigned to contract n

I. INTRODUCTION

Gas-fired power plants (GFPPs) play a unique economic, operational, and environmental role in power systems. Carbon prices (and other regulations aimed at limiting future emissions) in Europe and the production of shale gas in the United States has allowed GFPPs to displace coal units in the merit order of many power systems. In addition to this economic effect, as power systems continue to transition toward capacity mixes that feature more intermittent generation from variable energy resources (VERs) such as wind and solar, their need for increased operational flexibility with respect to more frequent cycling[1] operations will likely translate into greater need for GFPPs. [1][2]

As power systems increasingly rely on GFPPs, and as cycling requirements increase due to larger penetrations of intermittent generation, the long-term service agreements (LTSAs) that define and govern the conditions and costs for gas-fired power plant maintenance are playing an increasingly relevant role in a power system's dispatch decisions.

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[1] The term "cycling" refers to the cyclical operating modes of thermal plants that occur in response to dispatch requirements: on/off operation, low-load cycling operations and load following.

LTSAs originated as a method for GFPP owners and original equipment manufacturers to share risk. The generic terms of an LTSA usually involve a premium paid by the GFPP owner to the equipment manufacturer (or an alternative O&M provider) in exchange for plant O&M service over a time period defined by a maintenance interval function (MIF). By signing LTSAs, GFPP owners gain more certainty about their maintenance costs. Original equipment manufacturers, on the other hand, due to their expertise with their own equipment, can be relatively certain of the cost of maintaining a GFPP as long as the owner operates the GFPP under the conditions specified by the LTSA and its MIF. [3]

Although the MIF can take many different forms, almost all MIFs specify a number of operation hours (firing hours) after which a GFPP must be taken offline for major maintenance (at a significant cost). Additionally, most MIFs also assign a number of equivalent operating hours (EOH) to each start such that each start reduces the remaining number of allowed firing hours. For example, if the EOH of an MIF is 10 firing hours, then starting a GFPP once reduces the time until its next major maintenance by 10 operating hours (the blue line in Fig. 1).

Alternatively, an increasingly common approach for representing the MIF consists of defining both a maximum number of starts and a maximum number of firing hours. Whichever limit the GFPP reaches first triggers the major overhaul inspection of the turbine. Fig. 1 shows this alternative MIF in yellow. For this alternative MIF, if the number of starts is not relevant (i.e. if a GFPP hits its firing hours limit first) then no additional O&M-related cost per start should be considered. If the GFPP cycles frequently and reaches its starts limit first, the O&M-related cost per start can be significant. [3]

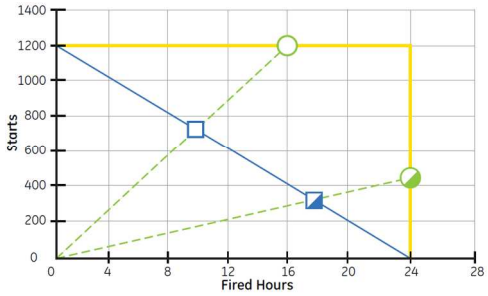

Fig. 1. Hot gas path maintenance [4]

Since the premium that GFPP owners pay represents their cost of maintenance once they exceed the firing hours/starts boundary of the MIF, the terms of an LTSA can impact a system's optimal scheduling decisions. In most cases, traditional LTSAs were designed assuming a rather stable (base-loaded) regime. The generators did not foresee that GFPPs would need to cycle frequently. Consequently, these contracts included certain conditions and constraints that imply significant costs for GFPPs that start and shut down often.

In the new context of significant renewable penetration that many power systems around the world are currently observing, two new problems arise. The first one consists of adapting the unit commitment problem (hereafter UC problem) to take into account the impact of these contracts, while the second problem entails searching for ways to redesign or renegotiate some of the conditions of these contracts to minimize the overall cost of cycling.

We take as a starting point the first of the two problems, already discussed in [5], and explore the second topic.

A. *Modeling the impact of LTSAs in the UC problem*

Generally, the vast majority of existing formulations for the UC problem consider O&M costs by means of a volumetric cost adder associated with the total energy produced (typically referred to as variable O&M cost and expressed in $/MWh) [6][7][8][9]. This is in line with the operation of GFPPs in a base-loaded regime where the number of starts is irrelevant for O&M purposes.

Recently, authors such as [10] and [5] have shown that although this simplified approach is reasonable when cycling needs are moderate, using a volumetric cost adder imprecisely models actual costs when cycling demands increase. Furthermore, this approximated allocation of costs leads to inefficient UC and scheduling results. In [10], the authors argue that the operational costs of a power system can quickly deviate from predicted costs using traditional UC models if cycling operations dynamically alter a power plant's start-up cost due to accumulated wear and tear. In [5], the authors highlight that a GFPP's LTSA may create additional and unprecedented operation costs for GFPP owners when plants are required to cycle significantly. The authors also proposed a UC formulation that explicitly represents LTSAs and demonstrated how these maintenance contracts can substantially alter a power system's optimal short-term dispatch decisions.

B. *Selecting the appropriate LTSA contract*

As noted by [11] and [12], the selection of an LTSA can realistically pose quite a difficult challenge for GFPP owners due to a variety of reasons ranging from uncertainty about a plant's future operating regime to lack of clarity about what materials and costs should be covered by the LTSA; defining the time duration of the LTSA (e.g., whether it should be defined in starts, firing hours, or absolute time); determining the warranty period for parts installed at the end of the LTSA; calculating the appropriate compensation for nonperformance if the equipment manufacturer is unable to restore a GFPP to proper operation; and defining termination clauses if the equipment manufacturer is unable to meet its obligations.

Additionally, as discussed in [13], as GFPPs roll off their existing LTSAs or as owners consider the possibility of early termination, the process of renegotiating an LTSA can be equally difficult. One example of this difficulty is the common "true-up" clause that requires each party to be made whole at the time of termination; calculating the amount of money that should change hands is not straightforward given the information asymmetry between the plant owner and the equipment manufacturer. Another problem is the market-pricing clause of LTSAs that allows owners to terminate a contract if that contract's costs are no longer competitive because of the difficulty of directly comparing multiple LTSAs. Once an owner signs or renews an LTSA, if the operating conditions in the power system unexpectedly change—for example, if the system

experiences a large and rapid deployment of VER—plant owners may find that their LTSAs restrain their ability to efficiently operate their GFPPs.

This exact problem has affected GFPPs in Spain. In the Spanish power system, 25 GWs of GFPPs were installed in the last decade with the expectation that the load factor of these plants would not fall below 50%. On average, from 2001 to 2006, electricity demand grew annually by approximately 5%; since 2009, however, demand has fallen annually by about 2%. In 2013, wind covered 21% of demand and solar covered 5% of demand. In 2013, GFPPs produced only 25 TWh, resulting in a load factor of approximately 10%. The dramatic decrease of demand coupled with the strong penetration of wind and solar has reduced the total number of hours that GFPPs operate for while increasing their number of starts over the same time period.

A first step to respond to this new and unexpected operating environment as load factors decrease and cycling needs increase is to consider the impact of LTSAs in the UC problem; the authors in [5] addressed this need. However, as the cycling needs of power systems continue to grow, power generation companies may benefit from renegotiating the existing terms of their LTSAs and modifying their number of allowed starts. By successfully renegotiating its LTSA portfolio, a generation company may be able to better adapt to its contemporary operating regime (e.g., from a system with initially few VERs to a system with a large penetration of VERs) and run its GFPPs more economically than before.

In this paper, we support the process of constructing an optimal portfolio of LTSA contracts by extending the UC formulation in [5]. First, we design an optimization problem to consider different LTSA contracts with the objective of selecting an optimal LTSA portfolio for a fleet of GFPP plants. Then, using the proposed formulation, we present a method to solve the problem of properly pricing an alternate LTSA contract relative to an LTSA with a defined MIF and known price. We also discuss how this approach can be used to determine the renegotiation price that the owner of GFPP should be willing to pay to change from one LTSA to another. For the situation where an owner may be able to renegotiate the LTSAs for a group of plants, the proposed pricing methodology yields a price-quantity "curve" that illustrates the number of plants that would switch to the alternate LTSA as a function of that alternate LTSA's price.

The paper is structured as follows: Section II contains the proposed UC formulation to optimize an LTSA portfolio. Section III describes the procedure for pricing alternate LTSA contracts. Section IV contains data about the case study presented in this paper for optimizing LTSA portfolios and pricing an unknown LTSA, and Section V describes the results of the case study. Lastly, Section VI concludes.

II. Optimal LTSA Portfolio Contracting

As noted in the introduction, a GFPP owner can commit to a variety of LTSAs with equipment providers. The suitability of an LTSA mainly depends on each GFPP's expected cycling regime. However, as discussed in [9], the characteristics of an LTSA can also significantly condition a GFPP's cycling regime. This interdependency complicates the GFPP owner's decision and requires that the owner consider both the (expected) dispatch and the selection of the optimal contract simultaneously. Additionally, if the decision involves not just one GFPP, but rather a portfolio of GFPPs, the owner may be able to plan for some units to cycle more frequently and others to cycle less frequently. Such a decision would lead the portfolio owner to sign different LTSAs for different GFPPs. In this section, we aim to solve the portfolio owner's contracting problem by proposing a novel formulation that reveals what an optimally constructed LTSA portfolio should resemble.

A. Constructing an optimal LTSA portfolio

To optimize an LTSA portfolio, we take the perspective of a cost-minimizing central planner[2]. We also assume the ability to simultaneously make initial contract decisions for all plants. Under these assumptions, we can begin to examine the optimal LTSA portfolio by minimizing the total costs required to supply the electricity demand:

$$min \sum_{t,i}[q_{i,t}Clv_i + u_{i,t}Cnl_i + y_{i,t}Csu_i + z_{i,t}Csd_i] + \sum_i MOC_i \quad (1)$$

The objective function sums hourly no-load and generation costs for all plants. To balance supply and demand and remain within the technical limits of each power plant, we add the following basic operational constraints for dispatch and UC[3].

$$\begin{aligned}
&\sum_i q_{i,t} = D_t \forall t \\
&q_{i,t} = w_{i,t} + u_{i,t}\underline{Q_i} \forall i,t \\
&q_{i,t} \le u_{i,t}\overline{Q_i} \forall i,t \\
&q_{i,t} \ge u_{i,t}\underline{Q_i} \forall i,t \\
&q_{i,t} - q_{i,t-1} \le ru_i \forall i,t \\
&(q_{i,t} - q_{i,t-1})(-1) \le rd_i \forall i,t \\
&u_{i,t} = u_{i,t-1} + y_{i,t} - z_{i,t} \forall i,t \\
&y_{i,t}, z_{i,t} \le 1 \forall i,t \\
&x_{i,t}, y_{i,t}, z_{i,t} \ge 0 \forall i,t \\
&u_{i,t} \in \{0,1\} \forall i,t
\end{aligned} \quad (2)$$

Thus far, the objective function in (1) and the constraints in (2) reflect the basic traditional UC formulation, with exception to the last term in the objective function. This last term replaces the fixed-adder representation of O&M cost with an explicit representation of the maintenance cost based on each plant's LTSA.

In [5], the maintenance cost $MOCuc_i$ (i.e., the LTSA cost for plant *i* to be allocated over the simulated UC time horizon) is determined based on the LTSA's MIF. To determine the exact cost, the authors proposed explicitly adding the following constraint for each triangular region $\measuredangle A_j O A_{j+1}$ of the MIF (see Fig. 2 below).

[2] As well known, under perfect competition, an individual firm's profit-maximizing decisions are identical to the central planner's welfare-maximizing/cost-minimizing decisions

[3] As the objective of this paper is to demonstrate the impacts of the LTSA decision, for the sake of simplicity we have omitted many well-known unit commitment constraints.

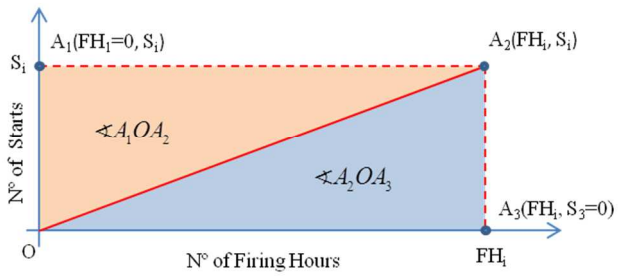

Fig. 2. MIF Region for an LTSA contract

$$\begin{aligned} &MOC(FH_{A_j} - FH_{A_{j+1}}) \sum_t u_{i,t} \\ &-MOC(S_{A_j} - S_{A_{j+1}}) \sum_t y_{i,t} \\ &+MOCuc_i(S_{A_j}FH_{A_{j+1}} - S_{A_{j+1}}FH_{A_j}) \\ &\geq 0 \forall i, \mathbb{R}(\sum_t y_{i,t}, \sum_t u_{i,t}) \in \sphericalangle A_j O A_{j+1} \forall \mathrm{j} \end{aligned} \quad (3)$$

Assuming that the MIF is convex and that each plant operates under an exogenously determined LTSA, solving the following mixed-integer linear program yields the cost-minimizing UC and dispatch decisions for each plant:

$$\begin{aligned} \min \quad & (1) \\ s.t. \quad & (2) + (3) \end{aligned}$$

In the UC formulation above, the set of planes that define the cost in each angular region ($\sphericalangle A_j O A_{j+1} \forall \mathrm{j}$) model the LTSA for each plant *i*. Here, we propose to extend the approach by removing the assumption of an exogenously determined LTSA and allow the optimization to assign each plant to one of *N* potential LTSAs. Each LTSA has its own maintenance interval function defined by $\sphericalangle A_{j,n} O A_{j+1,n} \forall \mathrm{j}$ and its own premium MOC_n. To endogenize the LTSA decision, we introduce a special ordered set type one (SOS1) binary variable, $c_{i,n}$, for each possible combination of plant *i* and LTSA *n*:

$$\begin{aligned} &c_{i,n} \in \{0,1\} \\ &\sum_n c_{i,n} = 1 \end{aligned} \quad (4)$$

and modify constraint (3) as follows with a big-M constraint:

$$\begin{aligned} &\sum_t u_{i,t} MOC_n \left(FH_{A_{j,n}} - FH_{A_{j+1,n}}\right) \\ &- \sum_t y_{i,t} MOC_n \left(S_{A_{j,n}} - S_{A_{j+1,n}}\right) \\ &+MOCuc_i MOC_i \left(S_{A_{j,n}}FH_{A_{j+1,n}} - S_{A_{j+1,n}}FH_{A_{j,n}}\right) \\ &\geq M(c_{i,n} - 1) \forall i, n, \mathbb{R}(\sum_t y_{i,t}, \sum_t u_{i,t}) \in \sphericalangle A_j O A_{j+1} \forall \mathrm{j} \end{aligned} \quad (5)$$

Reformulating the constraint in this manner requires the solver to assign one LTSA to each power plant. For all unselected LTSAs where $c_{i,n} = 0$, constraint (5) will be nonbinding because the right-hand expression evaluates to a large negative number, and MOC_i is nonnegative.

For the selected LTSA where $c_{i,n} = 1$, the right-hand side of constraint (5) evaluates to 0, and constraint (5) becomes equivalent to constraint (3). Consequently, at any given time, the cost of maintenance for plant *i* can be determined as a function of the selected LTSA. For practicality, M above can take on the value of the largest premium of the available LTSAs. Combining this modification with the traditional UC constraints results in a mixed-integer linear program that returns optimal UC, dispatch, and LTSA portfolio decisions for a power system:

$$\begin{aligned} \min \quad & (1) \\ s.t. \quad & (2) + (4) + (5) \end{aligned} \quad (6)$$

III. Pricing an Alternate LTSA with a Known Maintenance Interval Function

In the previous section, the proposed formulation in (6) optimally chooses an LTSA to assign to each power plant given that every potential LTSA *n* has a known maintenance interval function and a known premium. In reality, a firm may want to evaluate its optimal portfolio strategy given the possibility of switching (through renegotiation with the O&M provider) to a particular alternate LTSA with a known maintenance interval function, but with an unknown cost premium.

To address this contract renegotiation problem, we iteratively apply the proposed formulation from the previous section to construct a price-quantity curve that identifies how many plants in the power system should switch to the alternate LTSA at a specific premium.

For the sake of simplicity, we assume that all of the power plants have contracted the same default LTSA ($c_{i,n=0} = 1 \forall i$), that no firing hours or starts have been accumulated yet under this LTSA for any plant, and that there is only one potential alternate LTSA to switch to. The approach could be extended straightforwardly to more complex contexts.

The iteration begins by exogenously setting the LTSA's premium, $MOC_{n=1}$, at a high enough price such that all plants remain on the default contract after solving the optimization problem in (6); then, with each new iteration, decrement the price of the alternate LTSA until all plants switch ($c_{i,n=1} = 1 \forall i$). As the premium of the alternate contract, $MOC_{n=1}$, alters the number plants that should switch LTSAs, we obtain a price-quantity switching curve.

IV. Case Study: Data

In this case study, we explore the LTSA portfolio decisions for a stylized power system consisting of 1 nuclear power plant and 10 combined-cycle gas turbines operating hourly over a duration of one month. Table 1 contains the technical operating limits for each technology, while Table 2 contains cost information for each technology from the U.S. Energy Information Administration [14].

TABLE I
Thermal Plant Data

	Nuclear	CCGT
Number of Units	1	10
Maximum Output [MW]	1000	400
Minimum Output [MW]	N/A	160

TABLE II
Thermal Cost Data

	Nuclear	CCGT
Heat Rate [kBTU/MWh]	N/A	7.05
Fuel Price [$/kBTU]	N/A	4.93
Variable Operations [$/MWh]	6.62	34.73
Start-Up [$/start-mw]	1000	75
No Load Cost [$]	-	2200

Each GFPP can sign one of two potential LTSAs with a rectangular MIF as shown in Fig. 3. Each LTSA's maintenance

interval function can be defined piece-wise linearly using two planes and the values in Table 3 to construct $\prec A_{j,n} O A_{j+1,n} \forall j$. The first LTSA allows up to 250 starts and 25,000 firing hours; the second LTSA allows the same 25,000 firing hours, but increases the maximum number of starts to 750.

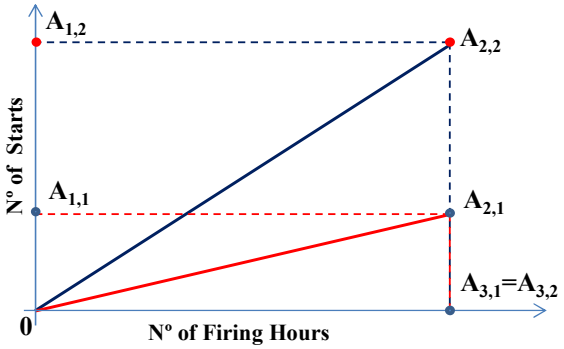

Fig. 3. Two alternate maintenance interval functions for GFPPs.

TABLE III
LTSA MAINTENANCE INTERVAL FUNCTIONS

LTSA	$A_{j,n} = (FH_{A_{j,n}}, S_{A_{j,n}})$	$B_{j,n} = (FH_{B_{j,n}}, S_{B_{j,n}})$
LTSA n=1, plane j=1	(0, 250)	(25000, 250)
LTSA n=1, plane j=2	(25000, 250)	(25000, 0)
LTSA n=2, plane j=1	(0, 750)	(25000, 750)
LTSA n=2, plane j=2	(25000, 750)	(25000, 0)

For the case study, the UC operates across several deterministic demand scenarios. The demand curve is adapted (by taking the hourly profile) from the one of the Spanish system in 2012 and peaks at 4500MW. The VER production profile is taken from the solar PV generation in Spain in 2012. In the remaining scenarios, this VER capacity is increased by 25%, 43%, and 60%. In both scenarios, to account for VERs, we subtract the total amount of energy supplied by VERs in each hour from the total demand in the same hour to obtain the net demand that thermal plants must cover. Fig. 4 below illustrates a typical week of demand and scheduling for the first scenario.

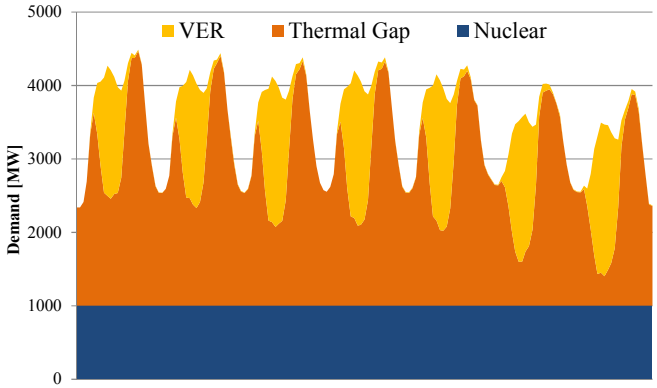

Fig. 4. Representative weekly demand, VER generation, and thermal scheduling results for the benchmark scenario

V. CASE STUDY: RESULTS

The MILP model in (6) has been formulated in GAMS and solved using CPLEX 12 on an Intel® Core™ 2 Quad CPU Q9650 @3.00 GHz with 4.00 Gb RAM. The computational time to solve the case study (33,536 variables, 8,948 integer variables, and 17,174 equations) was 6 minutes with *epgap*=1% and 5 seconds when the problem is relaxed, using 4 threads.

In the first part of this case study, we determine the optimal LTSA portfolio for a power system assuming that the first LTSA (n=1) is priced at $10 million, and that the second LTSA (n=2) is priced at $20 million. The second LTSA is more flexible (offers more starts for the same number of firing hours), but the major overhaul cost is also more expensive. In the second part of the case study, we assume that all plants have already committed to the first LTSA and then explore how the portfolio changes as the price of the second LTSA's premium changes. In the third part of the case study, we introduce VERs into the power system to illustrate how LTSA decisions may change when GFPPs must operate in an environment with fewer hours of generation and higher cycling frequencies.

A. Constructing an optimal LTSA portfolio

As a benchmark, we first solved (6) while fixing all contract decisions $c_{i,1} = 1, c_{i,2} = 0 \; \forall \; i$. This benchmark scenario assigns all plants to the first LTSA. Then, we solved (6) again after removing the fixed values for $c_{i,1}$and $c_{i,2}$ to obtain the following optimal LTSA portfolio for the power system:

TABLE IV
OPTIMAL LTSA PORTFOLIO DECISIONS

Plant i	LTSA 1 ($c_{i,1}$)	LTSA 2 ($c_{i,2}$)
1	1	0
2	0	1
3	0	1
4	1	0
5	1	0
6	1	0
7	1	0
8	1	0
9	0	1
10	0	1

Table V summarizes the cost differences for operations and maintenance and total operation between the two. Although optimizing the LTSA portfolio only reduced total operating costs by approximately 1% relative to the benchmark scenario, the portfolio optimization substantially changed operations and maintenance costs by approximately 20%.

TABLE V
O&M AND TOTAL COST COMPARISONS OF LTSA PORTFOLIOS

	Benchmark	Optimal	Δ cost
O&M [M$]	3,195	2,612	18,24%
Obj. [M$]	71,617	70,706	1,27%

In addition to reducing operating costs, the selection and representation of LTSAs in the UC formulation clearly impacts the optimal set of short-term generation and commitment decisions. Fig. 5 plots each GFPP's starts and firing hours onto the two available LTSAs after one month (744 hours) of operation. The graph shows that an optimal firing-hours-to-starts ratio exists for each contract, and that the UC tends to dispatch plants along their optimal firing-hours-to-starts ratio (more specifically, the UC formulation simultaneously decides the optimal LTSA contract and firing-hours-to-starts ratio). For the case study, the optimal operating ratio for the first contract is 25,000/50 = 100 fired hours/start, and the optimal

operating ratio for the second contract is 25,000/750 = 33.3 fired hours/start.

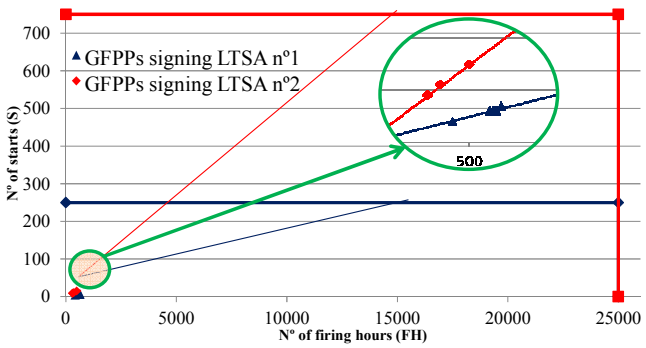

Fig. 5. Optimal starts-to-firing-hours ratio for GFPPs in the portfolio

B. Pricing an alternate contract and renegotiating an LTSA portfolio

In the previous section, the UC formulation assigned each GFPP to one of two potential LTSAs with known premiums ($10 million for the first contract, $20 million for the second). Another realistic problem to consider is that firms may need to evaluate an alternative contract where the maintenance interval function is known, but the premium is not. This is the case when there is a potential renegotiation opportunity between a firm and an equipment manufacturer. When the renegotiation affects a portfolio of plants, then firms will need to evaluate the number of plants that they would be willing to switch from the default contract to the alternate contract over a range of prices.

To evaluate the alternative contract in this case study, we iteratively constructed the price-quantity curve shown in Fig. 6 by solving (6), starting with a price of $30 million for the alternate contract and assuming that no hours and starts have been accumulated under the existing default contracts. The curve describes how many plants in the power system would switch LTSAs at each given price for the alternate contract.

At a price of $30 million, all plants remained on the default LTSA. Then, we iteratively decremented the price of the alternate contract and resolved (6) until all plants switched over to the alternate LTSA. At a price of $10 million for the alternate contract, all plants switched (this is to be expected, as the alternate contract offers more starts for the same number of firing hours, and the default contract costs $10 million).

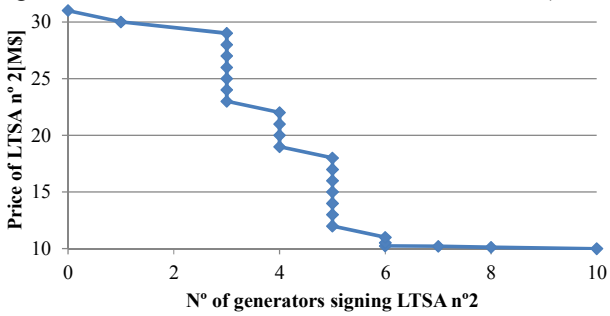

Fig. 6. Price-quantity curve for alternate LTSA contract

Although the price-quantity curve shown above illustrates the number of power plants that should switch to the alternate contract at a specific price, for the purposes of renegotiating an existing LTSA portfolio, the amount of money that a firm should be willing to pay is not the price of the alternate contract. The per-plant maximum amount that a firm should be willing to pay to switch to the alternate contract is equal to the highest price in the bid curve for each quantity of generators that would switch less the price of the default LTSA. For example, if the premium for the alternate contract is $18 million, the portfolio owner should be willing to pay ($18 - $10 million) = $8 million/GFPP to switch five GFPPs. Fig. 7 illustrates this per-plant renegotiation premium for different alternate LTSA prices.

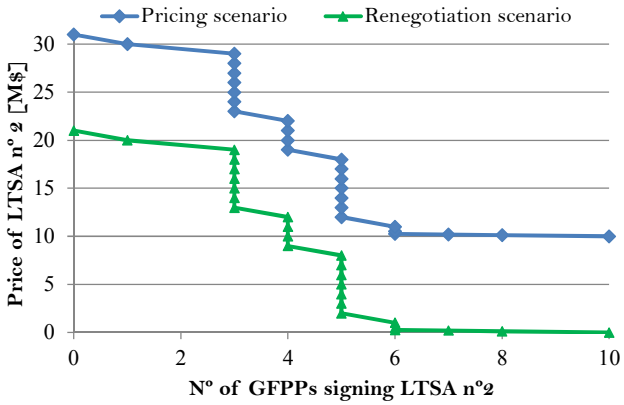

Fig. 7. Renegotiation premium to switch LTSAs

C. The impact of VERs on an optimal LTSA portfolio

To examine the impact of renewables on GFPP cycling, we examined five different VER penetration scenarios across five different alternate LTSA prices. In the default scenario, every GFPP in the portfolio operates under the default LTSA with a premium of $10 million and a rectangular MIF that allows a maximum of 25,000 firing hours and 250 starts.

To investigate the impacts of VER penetration on the optimal choices for an LTSA portfolio, we constructed price-quantity curves using the proposed iterative approach to price an alternate LTSA with an unknown price premium. Fig. 8 shows the price-quantity curves for the different penetration scenarios.

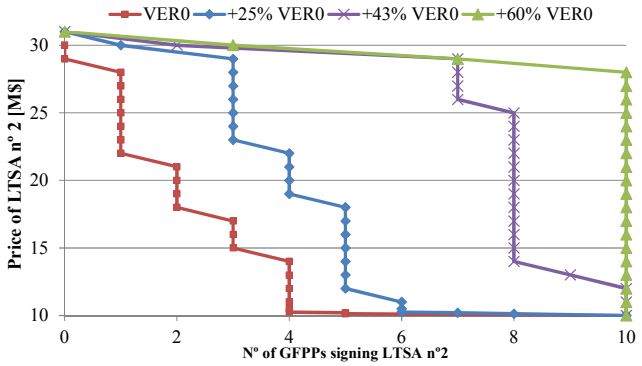

Fig. 8. Optimal LTSA portfolios under increasing penetrations of VERs

As the VER penetration level increases, the curve shifts right, and the optimal portfolio contains increasingly more switches to the alternate contract at higher price premiums. As before, we can also evaluate the price that a firm should be willing to pay to renegotiate its LTSAs by taking the difference between the highest price for each quantity and subtract-

ing the price of the default LTSA. Given the rightward shift of the price-quantity curve at higher VER penetrations, we can infer that switching to the more flexible alternate LTSA becomes increasingly beneficial to the firm as the increasing VER penetration forces its plants to cycle more frequently; additionally, as the number of starts for both contracts is the same, but the more flexible contract allows 500 more starts, we can also infer that the greater VER penetration scenarios require the firm's GFPP fleet to cycle more frequently.

VI. Conclusion

We have proposed a formulation built upon a detailed definition of the UC problem—taking into explicit consideration the different maintenance interval functions and premiums of alternative LTSAs—that optimizes a long-term service agreement portfolio for a set of gas-fired power plants. We have shown that an optimal LTSA portfolio strategy can involve signing different LTSAs for different plants where some plants may have higher firing-hours-to-starts ratios than other plants in the same portfolio. We have demonstrated an iterative method to evaluate an alternate LTSA with an unknown premium, proposed a method to calculate the lump sum for renegotiation that a firm should be willing to pay, and explored the impact of variable energy resources on optimal LTSA choices and the corresponding system costs.

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