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Generation Capacity Expansion Problem Considering Different Operation Modes of Combined-Cycle Gas Turbines

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ABSTRACT The design of future decarbonized power systems is one of the most relevant and challenging problems that power system planners are facing nowadays. It is expected that Combined-Cycle Gas Turbines (CCGTs) play a relevant role in these systems to provide peak power and reserve capacity when intermittent power units be unavailable. However, the large computational size of planning problems has prevented so far from modeling the actual operation of CCGTs accurately. This paper intends to quantify the effect of the modeling of CCGTs in the generation capacity expansion problem. For doing that, the operation of CCGTs is modeled using a mixed-integer linear formulation that considers different operation modes. Afterwards, generation expansion decisions in a realistic case study are analyzed using different accuracy degrees for modeling the operation of CCGTs. The numerical results suggest that the simplification of the modeling of the operation of CCGTs overestimates the flexibility provided by these units, which increases the capacity installed from renewable units between 15 and 25%.

INDEX TERMS Combined-cycle gas turbines, generation capacity expansion, reserve provision, stochastic programming, storages.

I. NOTATION

The notation used throughout the rest of this section is included below for quick reference.

SETS AND INDICES

B	Set of buses, indexed by b
D	Set of characteristic days, indexed by d
G/S	Set of generating/storage units, indexed by g/s
G_b/S_b	Set of generating/storage units located in bus b
$G^{\mathrm{CC/OC}}$	Set of CCGT/ Open-Cycle Gas Turbines (OCGT) units
$G^{\mathrm{D}}/G^{\mathrm{I}}$	Set of dispatchable/intermittent generating units
$G^{\mathrm{D}}_b/G^{\mathrm{I}}_b$	Set of dispatchable/intermittent generating units located in bus b
L	Set of transmission lines, indexed by ℓ
M	Set of operation modes of CCGTs, indexed by m
T	Set of time periods, indexed by t
Ω	Set of scenarios, indexed by ω

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PARAMETERS

A^{D}_{gdt}	Availability of intermittent unit g in characteristic day d and period t
$C^{\mathrm{TC,M}}_{gmm'\omega}$	Transition cost between modes m and m' of CCGT unit g in scenario ω
$C^{\mathrm{G},0}_{g\omega}$	Fixed operation cost of OCGT unit g in scenario ω
$C^{\mathrm{G},1}_{g\omega}$	Linear operation cost of OCGT unit g in scenario ω
$C^{\mathrm{G,RD/RU}}_{g\omega}$	Offering cost of down/up-reserve capacity of generating unit g in scenario ω
$C^{\mathrm{I,G}}_{g}$	Annualized capital cost of generating unit g

$C_s^{\mathrm{I,SE}}$ Annualized capital cost of storage unit s

$C_{gm\omega}^{\mathrm{M,0}}$ Fixed operation cost of CCGT unit g in mode m in scenario ω

$C_{gm\omega}^{\mathrm{M,1}}$ Linear operation cost of CCGT unit g in mode m in scenario ω

$C_s^{\mathrm{S,C/D}}$ Consumption bid/offering cost of storage unit s in the day-ahead energy market

$C_s^{\mathrm{S,RD/RU}}$ Offering cost of down/up-reserve capacity of storage unit s

C^{UD} Cost of unserved demand

$E_{\max,s}^{\mathrm{I,SE}}$ Maximum energy capacity that can be installed from storage unit s

$P_{bdt\omega}^{\mathrm{D}}$ Demand in bus b, characteristic day d, period t and scenario ω

$P_{\max,g}^{\mathrm{I,G}}$ Maximum power output of generating unit g

$P_{\max,gm}^{\mathrm{I,G}}$ Maximum power output of CCGT unit g in mode m

$P_{\min,gm}^{\mathrm{I,G}}$ Minimum power output of CCGT unit g in mode m

$P_{\max,s}^{\mathrm{I,SP}}$ Maximum power capacity that can be installed from storage unit s

$P_{\max,\ell}^{\mathrm{L}}$ Capacity of transmission line ℓ

W_d Weight of characteristic day d

X_ℓ Reactance of line ℓ

$\gamma^{\mathrm{D/U,D}}$ Up/down reserve capacity margin that must be scheduled according to the demand value

$\gamma^{\mathrm{D/U,I}}$ Up/down reserve capacity margin that must be scheduled according to the intermittent production

$\gamma_s^{\mathrm{S,0/F}}$ Factor used to model the initial/final status of the storage unit s

$\gamma_s^{\mathrm{S,EP}}$ Relationship between energy and power capacities in storage unit s

$\gamma_s^{\mathrm{S,min}}$ Factor used to model the minimum energy that must contain storage unit s

η^{S} Efficiency of charging/discharging storage units

π_ω Probability of scenario ω

VARIABLES

$c_{gmm'dt\omega}^{\mathrm{TC}}$ Transition cost between modes m and m' of CCGT unit g in characteristic day d, period t and scenario ω

$e_{sdt\omega}^{\mathrm{S,max/min}}$ Maximum/minimum energy level in the battery of storage unit s, characteristic day d, period t and scenario ω

$c_{gdt\omega}^{\mathrm{SU}}$ Startup cost of OCGT unit g in characteristic day d, period t and scenario ω

$p_{gdt\omega}^{\mathrm{G,D}}$ Generation power scheduled by generating unit g in the day-ahead market, in characteristic day d, period t and scenario ω

$p_{gdt\omega}^{\mathrm{G,DS}}$ Power spillage of intermittent generating unit g in characteristic day d, period t and scenario ω

$p_g^{\mathrm{I,G}}$ Capacity built of generating unit g

$p_s^{\mathrm{I,SE/SP}}$ Energy/peak power capacity built of storage unit s

$p_{\ell dt\omega}^{\mathrm{L}}$ Power flow through line ℓ in characteristic day d, period t and scenario ω

$p_{sdt\omega}^{\mathrm{S,C/D}}$ Consumption/discharged power scheduled by storage unit s in characteristic day d, period t and scenario ω

$p_{bdt\omega}^{\mathrm{UD}}$ Unserved demand in bus b, characteristic day d, period t and scenario ω

$r_{gdt\omega}^{\mathrm{G,D/U}}$ Down/up-reserve capacity scheduled by generating unit g, characteristic day d, period t and scenario ω

$r_{gmdt\omega}^{\mathrm{G,D/U,M}}$ Down/up-reserve capacity scheduled by CCGT unit g in operation mode m in characteristic day d, period t and scenario ω

$r_{sdt\omega}^{\mathrm{S,D/U}}$ Down/up-reserve capacity scheduled by storage unit s, characteristic day d, period t and scenario ω

$r_{sdt\omega}^{\mathrm{S,DC/DD}}$ Down-reserve capacity scheduled by storage unit s in charging/discharging mode, characteristic day d, period t and scenario ω

$r_{sdt\omega}^{\mathrm{S,UC/UD}}$ Up-reserve capacity scheduled by storage unit s in charging/discharging mode, characteristic day d, period t and scenario ω

$v_g^{\mathrm{I,G}}$ Binary variable that is equal to 1 if candidate and dispatchable unit g is installed, being equal to 0 otherwise

$v_{gmdt\omega}^{\mathrm{M}}$ Binary variable that is equal to 1 if CCGT unit g is working at operating mode m in characteristic day d, period t and scenario ω, being equal to 0 otherwise

$v_{gdt\omega}^{\mathrm{M,1/2/3}}$ Auxiliary binary variable used to model the selection of operating mode for CCGT unit g in characteristic day d, period $t$and scenario ω.

$\theta_{bdt\omega}$ Voltage angle of bus b in characteristic day d, period t and scenario ω

II. INTRODUCTION

The European Commission has defined a long-term strategy aiming to achieve net-zero greenhouse gas emissions by 2050 [1]. In this transformation process, the electricity production coming from open-cycle (OCGTs) and combined-cycles gas turbines (CCGTs) is intended to play a principal role in providing a dispatchable and reliable supply of electricity as the participation of renewable technologies increases [2]. OCGTs burn natural gas or an alternative fuel to rotate one or several gas turbines using the combustion gases. A compressor is used to force the injection of air in the chamber for increasing the efficiency of the generating unit. OCGTs are scalable for different electric power capacities and they are suitable to be used for base or peak load electricity production. On the other hand, CCGTs are equipped with one or several steam turbines that are used to exploit the remaining heat of exhaust gases of the gas turbines. CCGTs have been installed widely in power systems around the world because these units present high energy efficiency, low installation costs, and short construction times. Additionally, CCGTs, as well as OCGTs, allow fast startups and shutdowns and they can change their production very quickly.

Unfortunately, the modeling of the operation of CCGTs is more complex than that of OCGTs because of the simultaneous presence of gas and steam turbines result in different operation modes depending if gas and steam turbines are either at operation or not. The modelling of the operation characteristics of CCGTs is key in the formulation of short-term operation problems where generating units must be characterized as detailed as possible. This detail level is difficult to reach in the long-term planning problems, where the computational complexity is much higher. However, the adequate modeling of decision-making problems intended to design future power systems also requires a high enough degree of accuracy in the modelling of generating units if the resulting generation capacity expansion decisions are desired to be implemented in practice.

The modeling of the operational behaviour of CCGT units is currently an active research topic. Reference [3] proposes a unit commitment problem formulation that takes into account the transition processes among the different operation modes of CCGTs and their efficiencies. In [4], the formulation derived in [3] is improved by increasing the computational efficiency and including tighter constraints. The authors of [5] propose a novel tight mixed-integer linear formulation for the modeling of CCGTs. This formulation can be used in either unit commitment problems or in the bidding problems faced by those CCGTs participating in energy markets. Reference [6] proposes an enhanced stochastic-constrained unit commitment model especially tailored for the presence of CCGTs that is tested in the Midcontinent Independent System. In [7], the Surrogate Lagrangian Relaxation technique is applied to solve large unit commitment problems with high presence of CCGTs. Reference [8] develops a node-based formulation for the operation of CCGTs considering different levels of accuracy in the representation of the physical constraints of these units. The authors of [9] analyze different existing CCGT models and propose a hybrid model considering the best features of configuration-base and component-base models. Reference [10] considers the medium-term operation under uncertainty of a CCGT unit that has a gas storage available. Reference [11] proposes a mixed-integer linear formulation that considers the transitions between different operation modes spanning more than one time interval. In [12], the startups and shutdowns of individual turbines of CCGTs are precisely modelled and they are included in the formulation of a unit commitment problem that also considers the provision of spinning reserves. Reference [13] formulates a unit commitment problem that considers simultaneously gas and power network constraints.

Observe that all works mentioned here are focused in the short-term operation of CCGTs and none of them is designed to be implemented in large-scale long-term expansion problems.

Many modeling approaches have been proposed to formulate the generation capacity expansion problem in the last years, [14]- [22]. Table 1 lists the most relevant features of these works regarding the modeling of CCGTs. Observe that none of the analyzed works takes into account the operation modes of CCGTs. Additionally, most of these works do not take into account the binary variable that models the commitment of generating units.

TABLE 1. Previous works analyzing the generation capacity expansion problem.

Work	Trans. network	Unit comm. variables	Op. modes of CCGTs	Uncer.	Reserve capacity	Stor.
[14]	✓	✗	✗	✗	✗	✓
[15], [18]	✓	✓	✗	✓	✗	✗
[16]	✓	✗	✗	✓	✗	✗
[17]	✗	✗	✗	✓	✓	✓
[19]	✓	✓	✗	✓	✓	✓
[20]	✗	✗	✗	✗	✗	✗
[21]	✗	✓	✗	✗	✓	✗
[22]	✓	✗	✗	✓	✗	✗

This paper seeks to overcome these limitations proposing for the first time a generation capacity expansion formulation considering explicitly the different operation modes of CCGTs. Therefore, the objective of this paper is to analyze the influence of the modeling of CCGT units in the generation expansion decisions. Traditionally, the large computational size of expansion problems has prevented decision-makers of an accurate modeling of the operation of CCGTs. As a consequence of this, minimum power outputs, startup costs and the establishment of specific operation costs for each operation mode of CCGTs are usually neglected. This fact may cause an overestimation of the flexibility of this type of generating units, which may render in the implementation of generation capacity portfolios that are not able to supply the demand in situations with high penetration of intermittent capacity.

III. MODELING OF CCGTs

A. DESCRIPTION OF CCGTs

A CCGT is a type of power plant specifically fed with natural gas. The operation of these units is based on the combination of two thermodynamic cycles that seeks to improve the efficiency of the plant. The first thermodynamic cycle occurs in the gas turbines, which is composed of a compressor and a combustion chamber. In this Brayton cycle, the energy, which is present in the chemical bonds of fuel, is transformed into work and thermal energy. In the Rankine cycle, the thermal energy of exhaust gases outgoing from the gas turbine is transformed into work through a Heat Recovery Steam Generator (HRSG) and the steam turbine. In both cases, the mechanical work is transformed into electricity by a generator. The configuration of a CCGT could be by single-shaft or multi-shaft. In the first case, gas turbine and steam turbine share shaft and generator. In the second case, each turbine has its own generator.

Considering that the determination of the generation capacity expansion of a power system is a long-term decision-making problem, the following assumptions are considered:

- The generation capacity expansion is determined for a target year that is represented using a set of characteristic days. Each day is divided into 24 hourly periods.
- Different operation modes are defined for each CCGT depending on the number of gas and steam turbines that are at operation.
- Each operation mode is characterized by maximum and minimum power limits, as well as by different operation costs.
- The uncertainty related to demand growth and fuel costs of thermal units is characterized using a set of scenarios, indexed by $\omega \in \Omega$.
- The operation cost of the resulting power system is modelled considering the day-ahead energy and reserve capacity markets.

B. MATHEMATICAL FORMULATION OF THE OPERATION MODES OF CCGTs

The mathematical formulation of the different operation modes of CCGTs is presented in this section. For the sake of clarity, the proposed formulation is derived for a typical multi-shaft CCGT with a configuration comprising two gas turbines (2GT), a steam turbine (1ST) and three generators. Fig. 1 represents the schema of this type of unit. In this approach it is assumed that the exhaust gases of the steam turbines are not used for other purposes.

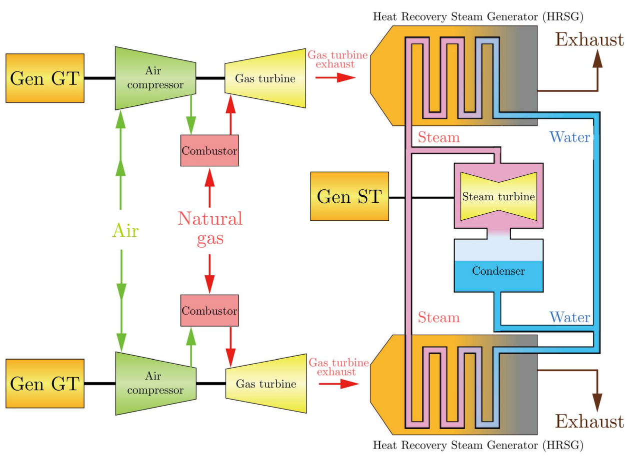


FIGURE 1. Schema of a CCGT unit with 2GT+1ST configuration. Based on [23] and modified.

Considering a 2GT+1ST configuration, the following five operation modes can be distinguished:

- Mode 0: The unit is offline.
- Mode 1: One gas turbine is at operation.
- Mode 2: One gas turbine and the steam turbine are at operation.
- Mode 3: Two gas turbines are at operation.
- Mode 4: Two gas turbines and the steam turbine are at operation.

The different operation modes are denoted by index $m \in M$. In this manner, variable $v^{\mathrm{M}}_{gmdt\omega}$ is equal to 1 if CCGT unit g is at operation in mode m in day d, period t and scenario ω, being equal to 0 otherwise. Considering this, the power output of the CCGT is denoted by $p^{\mathrm{G,D}}_{gdt\omega}$ and it is equal to the sum of the power output in each operation mode, $p^{\mathrm{G,D,M}}_{gmdt\omega}$. Considering this, the mathematical formulation of the power output of a CCGT unis can be expressed as follows:

$$p^{\mathrm{G,D}}_{gdt\omega} = \sum_{m\in M} p^{\mathrm{G,D,M}}_{gmdt\omega}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{1}$$

$$P^{\mathrm{I,G}}_{\min,gm} v^{\mathrm{M}}_{gmdt\omega} \leq p^{\mathrm{G,D,M}}_{gmdt\omega} \leq P^{\mathrm{I,G}}_{\max,gm} v^{\mathrm{M}}_{gmdt\omega}, \quad \forall g, \forall m, \forall d, \forall t, \forall \omega \tag{2}$$

$$\sum_{m\in M} v^{\mathrm{M}}_{gmdt\omega} = 1, \quad \forall g, \forall d, \forall t, \forall \omega \tag{3}$$

$$0 \leq v^{\mathrm{M}}_{gmdt\omega} \leq 1, \quad \forall g, \forall m, \forall d, \forall t, \forall \omega \tag{4}$$

Expression (1) computes the power output of the CCGT as the sum of the power generated in each operation mode. The power limits in each operation mode are defined by (2). Then, if $v^{\mathrm{M}}_{gmdt\omega} = 1$, the power output in mode m is constrained by $P^{\mathrm{I,G}}_{\min,gm} \leq p^{\mathrm{G,D,M}}_{gmdt\omega} \leq P^{\mathrm{I,G}}_{\max,gm}$, being equal to zero otherwise. Constraints (3) establish that only one operation mode can be selected at the same time. Expressions (4) indicate the upper and lower limits of variable $v^{\mathrm{M}}_{gmdt\omega}$.

To formulate mathematically the five operation modes of a CCGT with 2GT+1ST configuration, at least three binary variables are required. Note that three binary variables are able to model up to eight different states, $2^3 = 8 > 5$. Therefore, auxiliary binary variables $v^{\mathrm{M},1}_{gdt\omega}$, $v^{\mathrm{M},2}_{gdt\omega}$ and $v^{\mathrm{M},3}_{gdt\omega}$ are defined to model each specific operation mode. Considering these auxiliary variables, the selection of the operation modes denoted by $v^{\mathrm{M}}_{gmdt\omega}$, $\forall m = 0, \cdots, 4$, is computed as follows:

$$v^{\mathrm{M}}_{g1dt\omega} \geq 1 - v^{\mathrm{M},1}_{gdt\omega} - v^{\mathrm{M},2}_{gdt\omega} - v^{\mathrm{M},3}_{gdt\omega}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{5}$$

$$v^{\mathrm{M}}_{g2dt\omega} \geq v^{\mathrm{M},3}_{gdt\omega} - v^{\mathrm{M},1}_{gdt\omega} - v^{\mathrm{M},2}_{gdt\omega}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{6}$$

$$v^{\mathrm{M}}_{g3dt\omega} \geq v^{\mathrm{M},2}_{gdt\omega} - v^{\mathrm{M},1}_{gdt\omega} - v^{\mathrm{M},3}_{gdt\omega}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{7}$$

$$v^{\mathrm{M}}_{g4dt\omega} \geq -v^{\mathrm{M},1}_{gdt\omega} + v^{\mathrm{M},2}_{gdt\omega} + v^{\mathrm{M},3}_{gdt\omega} - 1, \quad \forall g, \forall d, \forall t, \forall \omega \tag{8}$$

$$v^{\mathrm{M}}_{g5dt\omega} \geq v^{\mathrm{M},1}_{gdt\omega} - v^{\mathrm{M},2}_{gdt\omega} - v^{\mathrm{M},3}_{gdt\omega}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{9}$$

$$v^{\mathrm{M},1}_{gdt\omega} + v^{\mathrm{M},2}_{gdt\omega} \leq 1, \quad \forall g, \forall d, \forall t, \forall \omega \tag{10}$$

$$v^{\mathrm{M},1}_{gdt\omega} + v^{\mathrm{M},3}_{gdt\omega} \leq 1, \quad \forall g, \forall d, \forall t, \forall \omega \tag{11}$$

$$v^{\mathrm{M},1}_{gdt\omega}, v^{\mathrm{M},2}_{gdt\omega}, v^{\mathrm{M},3}_{gdt\omega} \in \{0, 1\}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{12}$$

Constraints (5)-(9) compute the minimum value of variable $v^{\mathrm{M}}_{gmdt\omega}$ for each operation mode $m = 0, \cdots, 4$. Observe that if this minimum value is equal to 1, then constraints (4)

TABLE 2. Mathematical formulation of the operation modes of a 2GT+1ST CCGT.

Mode	$v_{gdt\omega}^{M,1}$	$v_{gdt\omega}^{M,2}$	$v_{gdt\omega}^{M,3}$	$v_{g0dt\omega}^{M}$	$v_{g1dt\omega}^{M}$	$v_{g2dt\omega}^{M}$	$v_{g3dt\omega}^{M}$	$v_{g4dt\omega}^{M}$
0	0	0	0	1	0	0	0	0
1	0	0	1	0	1	0	0	0
2	0	1	0	0	0	1	0	0
3	0	1	1	0	0	0	1	0
4	1	0	0	0	0	0	0	1

enforce that $v_{gmdt\omega}^{M} = 1$, and operation mode m is selected. If operation mode m is not selected, then the value of $v_{gmdt\omega}^{M}$ should not be further constrained by (5)-(9). Since only five operation modes are considered, constraints (10)-(11) are used to avoid combinations of auxiliary variables not desired. Constraints (12) define the binary nature of auxiliary binary variables.

It is also worth to note that, because of the binary nature of these auxiliary variables and the enforcement of constraints (3), (4) and (5)-(12), the value of variable $v_{gmdt\omega}^{M}$ is always either 0 or 1. Then, it is not necessary to define $v_{gmdt\omega}^{M}$ as a binary variable.

As an example, if $v_{gdt\omega}^{M,1} = v_{gdt\omega}^{M,2} = v_{gdt\omega}^{M,3} = 0$, constraints (5)-(9) take the following values:

$$v_{g0dt\omega}^{M} \geq 1 \tag{13}$$
$$v_{g1dt\omega}^{M} \geq 0 \tag{14}$$
$$v_{g2dt\omega}^{M} \geq 0 \tag{15}$$
$$v_{g3dt\omega}^{M} \geq -1 \tag{16}$$
$$v_{g4dt\omega}^{M} \geq 0. \tag{17}$$

Considering that variables $v_{gmdt\omega}^{M}$ are bounded by 0 and 1 by constraints (4), it is observed that constraints (14)-(17) do not further constrain the value of $v_{gmdt\omega}^{M}$ for $m = 1, \cdots, 4$. However, constraint (13), together with (14)-(17), enforces that $v_{g0dt\omega}^{M} = 1$. Therefore, it can be concluded that if $v_{gdt\omega}^{M,1} = v_{gdt\omega}^{M,2} = v_{gdt\omega}^{M,3} = 0$ then $v_{g1dt\omega}^{M} = 1$ and the operation mode $m = 0$ is selected. Additionally, constraints (3) impose that $v_{gmdt\omega}^{M} = 0, \forall m = 1, \cdots, 4$.

Table 2 shows the value of variable $v_{gmdt\omega}^{M}$ for each operation mode and for all possible combinations of auxiliary variables $v_{gdt\omega}^{M,1}$, $v_{gdt\omega}^{M,2}$ and $v_{gdt\omega}^{M,3}$.

C. PARTICIPATION OF CCGTs IN THE RESERVE CAPACITY MARKET

The formulation (1)-(4) can be expanded to consider that CCGTs can participate in the reserve capacity market. If the participation of CCGT unit g in the up- and down-reserve capacity services is modeled by $r_{gdt\omega}^{G,U}$ and $r_{gdt\omega}^{G,D}$, the following constraints must be also considered:

$$P_{\min,gm}^{I,G} v_{gmdt\omega}^{M} \leq p_{gmdt\omega}^{G,D,M} + r_{gmdt\omega}^{G,U,M} \leq P_{\max,gm}^{I,G} v_{gmdt\omega}^{M}, \quad \forall g, \forall m, \forall d, \forall t, \forall \omega \tag{18}$$

$$P_{\min,gm}^{I,G} v_{gmdt\omega}^{M} \leq p_{gmdt\omega}^{G,D,M} - r_{gmdt\omega}^{G,D,M} \leq P_{\max,gm}^{I,G} v_{gmdt\omega}^{M}, \quad \forall g, \forall m, \forall d, \forall t, \forall \omega \tag{19}$$

$$0 \leq r_{gmdt\omega}^{G,U,M} \leq P_{\max,gm}^{I,G} v_{gmdt\omega}^{M}, \quad \forall g, \forall m, \forall d, \forall t, \forall \omega \tag{20}$$

$$0 \leq r_{gmdt\omega}^{G,D,M} \leq p_{gmdt\omega}^{G,D,M}, \quad \forall g, \forall m, \forall d, \forall t, \forall \omega \tag{21}$$

$$r_{gdt\omega}^{G,U} = \sum_{m \in M} r_{gmdt\omega}^{G,U,M}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{22}$$

$$r_{gdt\omega}^{G,D} = \sum_{m \in M} r_{gmdt\omega}^{G,D,M}, \quad \forall g, \forall d, \forall t, \forall \omega \tag{23}$$

Constraints (18) and (19) define the power limits of the operation of CCGTs when they provide up- and down-reserve capacity, respectively. Constraints (20) and (21) establish that the scheduled reserve capacity associated with operating mode m has to be equal to zero if the CCGT is not working in that operating mode. Constraints (22) and (23) enforce that the total scheduled reserve capacity of a CCGT unit has to be equal to the sum of the reserve capacities associated with each operating mode.

D. MODELING OF THE TRANSITION COST BETWEEN OPERATION MODES OF CCGTs

The transition between different operation modes of CCGTs has associated a cost that depends on the number of gas and steam turbines that are started in the transition process. If $C_{gmm'\omega}^{TC,M}$ is the cost related to the transition of unit g from operation mode m to m' in scenario ω, the resulting transition cost between these operation modes in day d, period t and scenario ω, $c_{gmm'dt\omega}^{TC}$, is formulated as follows:

$$c_{gmm'dt\omega}^{TC} \geq C_{gmm'\omega}^{TC,M} \left(v_{gm'dt\omega}^{M} - (1 - v_{gmdt-1\omega}^{M}) \right), \quad \forall m <> m', \forall g, \forall d, \forall t, \forall \omega \tag{24}$$

$$c_{gmm'dt\omega}^{TC} \geq 0, \quad \forall m, \forall m', \forall g, \forall d, \forall t, \forall \omega \tag{25}$$

In some CCGT units, the transition between two operation modes in a single time period is not physically possible. For instance, the transition between modes 0 (0GT + 0ST) and 4 (2GT+1ST) may not be performed in a single time period. For modeling this situation, we define parameter $FT_{mm'}$ that is equal to 1 if the transition from mode m to m' is forbidden, being equal to 0 otherwise. Therefore, the prohibition of the transition between two operation modes is formulated as follows:

$$v_{gm'dt\omega}^{M} - v_{gmdt-1\omega}^{M} \leq 1 \quad \forall m, m' \text{ if } FT_{mm'} = 1, \forall g, \forall d, \forall t, \forall \omega \tag{26}$$

IV. GENERATION EXPANSION PROBLEM

A. DECISION-MAKING FRAMEWORK

The generation expansion problem consists in determining the power capacity to install in a power system for a given target year from a set of candidate generation technologies minimizing the total cost including investment and operation costs. For the sake of tractability, the target is represented by a set of characteristic days.

In this paper, a static generation expansion model has been considered. In this manner, it is assumed that all investment decisions are made simultaneously at the beginning of the planning horizon. Note that static expansion models are used because they provide an appropriate trade-off between modeling accuracy and computational tractability. Since the objective of this paper is to quantify the effect of modelling the different operation modes of CCGTs, transmission expansion decisions are not considered in the proposed model. Consequently, all transmission expansion plans decided beforehand by the transmission system planner must be incorporated in the proposed model as input data. The power flow in the transmission lines is computed using the DC model. Investments in storage units based on electrochemical batteries are also considered to favor the installation of intermittent generation units. Finally, the operation of the resulting system is considered by modeling the day-ahead and reserve capacity markets.

B. OPTIMIZATION PROBLEM

The mathematical formulation of the problem described above is included below. The proposed generation expansion problem is formulated as a risk-neutral two-stage stochastic programming problem [24], in which investment decisions in generating and storage units are made at the first stage, whereas the operation of the system is determined at the second stage. The objective function of this problem is the total cost, including annualized investment and operation costs.

$$\begin{aligned}
&\text{Minimize}_{\Theta} \\
&\sum_{\omega\in\Omega}\pi_{\omega}\Bigg[\sum_{g\in G}C_g^{\mathrm{I,G}}p_g^{\mathrm{I,G}}+\sum_{s\in S}\left(C_s^{\mathrm{I,SE}}e_s^{\mathrm{I,SE}}\right) \\
&+\sum_{d\in D}\sum_{t\in T}W_d\Bigg(\sum_{g\in G^{\mathrm{OC}}}\left(C_{g\omega}^{\mathrm{G},0}v_{gdt\omega}^{\mathrm{G}}+C_{g\omega}^{\mathrm{G},1}p_{gdt\omega}^{\mathrm{G,D}}\right) \\
&+\sum_{g\in G^{\mathrm{CC}}}\left(\sum_{m\in M}\left(C_{gm\omega}^{\mathrm{M},0}v_{gmdt\omega}^{\mathrm{M}}+C_{gm\omega}^{\mathrm{M},1}p_{gdt\omega}^{\mathrm{G,D}}\right)\right) \\
&+\sum_{g\in G^{\mathrm{D}}}\left(C_{g\omega}^{\mathrm{G,RU}}r_{gdt\omega}^{\mathrm{G,U}}+C_{g\omega}^{\mathrm{G,RD}}r_{gdt\omega}^{\mathrm{G,D}}\right)+\sum_{g\in G^{\mathrm{OC}}}c_{gdt\omega}^{\mathrm{SU}} \\
&+\sum_{g\in G^{\mathrm{CC}}}\sum_{\{m,m'\}\in M}c_{gmm'dt\omega}^{\mathrm{TC}}+\sum_{s\in S}\left(C_s^{\mathrm{S,D}}p_{sdt\omega}^{\mathrm{S,D}}-C_s^{\mathrm{S,C}}p_{sdt\omega}^{\mathrm{S,C}}\right. \\
&\left.+C_s^{\mathrm{S,RU}}r_{sdt\omega}^{\mathrm{S,U}}+C_s^{\mathrm{S,RD}}r_{sdt\omega}^{\mathrm{S,D}}\right)+\sum_{b\in B}C^{\mathrm{UD}}p_{bdt\omega}^{\mathrm{UD}}\Bigg)\Bigg] \qquad (27)
\end{aligned}$$

Subject to:

- Investment constraints:

$$p_g^{\mathrm{I,G}}=P_{max,g}^{\mathrm{I,G}}v_g^{\mathrm{I,G}},\quad \forall g\in G^{\mathrm{D}} \qquad (28)$$

$$0\le p_g^{\mathrm{I,G}}\le P_{\max,g}^{\mathrm{I,G}},\quad \forall g\in G^{\mathrm{I}} \qquad (29)$$

$$0\le e_s^{\mathrm{I,SE}}\le E_{\max,s}^{\mathrm{I,SE}},\quad \forall s\in S \qquad (30)$$

$$0\le p_s^{\mathrm{I,SP}}\le P_{\max,s}^{\mathrm{I,SP}},\quad \forall s\in S \qquad (31)$$

$$e_s^{\mathrm{I,SE}}=\gamma_s^{\mathrm{S,EP}}p_s^{\mathrm{I,SP}},\quad \forall s\in S \qquad (32)$$

$$v_g^{\mathrm{I,G}}\in\{0,1\},\quad \forall g\in G^{\mathrm{D}} \qquad (33)$$

- Operation of generating units:

$$p_{gdt\omega}^{\mathrm{G,D}}+r_{gdt\omega}^{\mathrm{G,U}}\le P_{\max,g}^{\mathrm{I,G}}v_{gdt\omega}^{\mathrm{G}},\quad \forall g\in G^{\mathrm{OC}},\forall t,\forall d,\forall\omega \qquad (34)$$

$$P_{\min,g}^{\mathrm{I,G}}v_{gdt\omega}^{\mathrm{G}}\le p_{gdt\omega}^{\mathrm{G,D}}-r_{gdt\omega}^{\mathrm{G,D}},\quad \forall g\in G^{\mathrm{OC}},\forall t,\forall d,\forall\omega \qquad (35)$$

$$p_{gdt\omega}^{\mathrm{G,D}}+p_{gdt\omega}^{\mathrm{G,DS}}=A_{gdt}^{\mathrm{D}}p_g^{\mathrm{I,G}},\quad \forall g\in G^{\mathrm{I}},\forall t,\forall d,\forall\omega \qquad (36)$$

$$\{p_{gdt\omega}^{\mathrm{G,D}},r_{gdt\omega}^{\mathrm{G,U}},r_{gdt\omega}^{\mathrm{G,D}},p_{gdt\omega}^{\mathrm{G,DS}}\}\ge 0,\quad \forall g\in G,\forall t,\forall d,\forall\omega \qquad (37)$$

$$\{r_{gdt\omega}^{\mathrm{G,U}},r_{gdt\omega}^{\mathrm{G,D}}\}=0,\quad \forall g\in G^{\mathrm{I}},\forall t,\forall d,\forall\omega \qquad (38)$$

$$c_{gdt\omega}^{\mathrm{SU}}\ge C_{g\omega}^{\mathrm{SU}}\left(v_{gdt\omega}^{\mathrm{G}}-v_{gdt-1\omega}^{\mathrm{G}}\right),\quad \forall g\in G^{\mathrm{OC}},\forall t,\forall d,\forall\omega \qquad (39)$$

$$c_{gdt\omega}^{\mathrm{SU}}\ge 0,\quad \forall g\in G^{\mathrm{OC}},\forall t\in T,\forall d\in D,\forall\omega\in\Omega \qquad (40)$$

$$\sum_{t=1}^{G_{gm}^{\mathrm{UT}}}\left(1-v_{gmdt\omega}^{\mathrm{M}}\right)=0,\quad \forall g\in G^{\mathrm{CC}},\forall m,\forall t,\forall d,\forall\omega \qquad (41)$$

$$\begin{aligned}&\sum_{t'=t}^{t+UT_{gm}-1}v_{gmdt'\omega}^{\mathrm{M}}\ge UT_{gm}\left(v_{gmdt\omega}^{\mathrm{M}}-v_{gmdt-1,\omega}^{\mathrm{M}}\right),\\ &\forall g\in G^{\mathrm{CC}},\forall m,\forall t=G_{mg}^{\mathrm{UT}}+1,\cdots,N_{\mathrm{T}}-UT_{mg}+1,\\ &\forall CC,\forall\omega\end{aligned} \qquad (42)$$

$$\begin{aligned}&\sum_{t'=t}^{N_{\mathrm{T}}}\left(v_{gmdt'\omega}^{\mathrm{M}}-\left(v_{gmdt\omega}^{\mathrm{M}}-v_{gmdt-1,\omega}^{\mathrm{M}}\right)\right)\ge 0,\\ &\forall g\in G^{\mathrm{CC}},\forall m,\forall t=N_{\mathrm{T}}-UT_{gm}+2,\cdots,N_{\mathrm{T}},\forall d,\forall\omega\end{aligned} \qquad (43)$$

$$\sum_{t=1}^{L_{gm}^{\mathrm{DT}}}v_{gmdt\omega}^{\mathrm{M}}=0,\quad \forall g\in G^{\mathrm{CC}},\forall m,\forall t,\forall d,\forall\omega \qquad (44)$$

$$\begin{aligned}&\sum_{t'=t}^{t+DT_{gm}-1}\left(1-v_{gmdt'\omega}^{\mathrm{M}}\right)\ge DT_{gm}\left(v_{gmdt-1,\omega}^{\mathrm{M}}-v_{gmdt\omega}^{\mathrm{M}}\right),\\ &\forall g\in G^{\mathrm{CC}},\forall m,\forall t=L_{gm}^{\mathrm{DT}}+1,\cdots,N_{\mathrm{T}}-DT_{gm}+1,\\ &\forall d,\forall\omega\end{aligned} \qquad (45)$$

$$\begin{aligned}&\sum_{t'=t}^{N_{\mathrm{T}}}\left(1-v_{gmdt'\omega}^{\mathrm{M}}-\left(v_{gmdt\omega}^{\mathrm{M}}-v_{gmdt-1,\omega}^{\mathrm{M}}\right)\right)\ge 0,\\ &\forall g\in G^{\mathrm{CC}},\forall m,\forall t=N_{\mathrm{T}}-DT_{gm}+2,\cdots,N_{\mathrm{T}},\forall d,\forall\omega\end{aligned} \qquad (46)$$

- Operation of CCGT units: Constraints (1)-(26)
- Operation of storage units:

$$r_{sdt\omega}^{\mathrm{S,U}}=r_{sdt\omega}^{\mathrm{S,UC}}+r_{sdt\omega}^{\mathrm{S,UD}},\quad \forall s,\forall t,\forall d,\forall\omega \qquad (47)$$

$$r_{sdt\omega}^{\mathrm{S,D}}=r_{sdt\omega}^{\mathrm{S,DC}}+r_{sdt\omega}^{\mathrm{S,DD}},\quad \forall s,\forall t,\forall d,\forall\omega \qquad (48)$$

$$p_{sdt\omega}^{\mathrm{S,D}}+r_{sdt\omega}^{\mathrm{S,UD}}\le p_s^{\mathrm{I,SP}},\quad \forall s,\forall t,\forall d,\forall\omega \qquad (49)$$

$$0\le p_{sdt\omega}^{\mathrm{S,D}}-r_{sdt\omega}^{\mathrm{S,DD}},\quad \forall s,\forall t,\forall d,\forall\omega \qquad (50)$$

$$p_{sdt\omega}^{\mathrm{S,C}}+r_{sdt\omega}^{\mathrm{S,DC}}\le p_s^{\mathrm{I,SP}},\quad \forall s,\forall t,\forall d,\forall\omega \qquad (51)$$

$$0\le p_{sdt\omega}^{\mathrm{S,C}}-r_{sdt\omega}^{\mathrm{S,UC}},\quad \forall s,\forall t,\forall d,\forall\omega \qquad (52)$$

$$p_{sdt\omega}^{\mathrm{S,C}},p_{sdt\omega}^{\mathrm{S,D}},r_{sdt\omega}^{\mathrm{S,U}},r_{sdt\omega}^{\mathrm{S,D}}\ge 0,\quad \forall s,\forall t,\forall d,\forall\omega \qquad (53)$$

$$r^{\mathrm{S,UD}}_{sdt\omega}, r^{\mathrm{S,UC}}_{sdt\omega}, r^{\mathrm{S,DD}}_{sdt\omega}, r^{\mathrm{S,DC}}_{sdt\omega} \geq 0, \quad \forall s, \forall t, \forall d, \forall \omega \tag{54}$$

$$e^{\mathrm{S,min}}_{sdt\omega} = e^{\mathrm{S,min}}_{sdt-1,\omega} + \eta^{\mathrm{S}}\left(p^{\mathrm{S,C}}_{sdt\omega} - r^{\mathrm{S,UC}}_{sdt\omega}\right) - \frac{1}{\eta^{\mathrm{S}}}\left(p^{\mathrm{S,D}}_{sdt\omega} + r^{\mathrm{S,UD}}_{sdt\omega}\right), \quad \forall s, \forall t, \forall d, \forall \omega \tag{55}$$

$$e^{\mathrm{S,max}}_{sdt\omega} = e^{\mathrm{S,max}}_{sdt-1,\omega} + \eta^{\mathrm{S}}\left(p^{\mathrm{S,C}}_{sdt\omega} + r^{\mathrm{S,DC}}_{sdt\omega}\right) - \frac{1}{\eta^{\mathrm{S}}}\left(p^{\mathrm{S,D}}_{sdt\omega} - r^{\mathrm{S,DD}}_{sdt\omega}\right), \quad \forall s, \forall t, \forall d, \forall \omega \tag{56}$$

$$\gamma^{\mathrm{S,min}}_{s} e^{\mathrm{I,SE}}_{s} \leq e^{\mathrm{S,max}}_{sdt\omega} \leq e^{\mathrm{I,SE}}_{s}, \quad \forall s, \forall t, \forall d, \forall \omega \tag{57}$$

$$\gamma^{\mathrm{S,min}}_{s} e^{\mathrm{I,SE}}_{s} \leq e^{\mathrm{S,min}}_{sdt\omega} \leq e^{\mathrm{I,SE}}_{s}, \quad \forall s, \forall t, \forall d, \forall \omega \tag{58}$$

$$e^{\mathrm{S,min}}_{sdt\omega} = \gamma^{\mathrm{S,0}}_{sd} e^{\mathrm{I,SE}}_{s}, \quad \forall s, t = 0, \forall d, \forall \omega \tag{59}$$

$$e^{\mathrm{S,max}}_{sdt\omega} = \gamma^{\mathrm{S,0}}_{sd} e^{\mathrm{I,SE}}_{s}, \quad \forall s, t = 0, \forall d, \forall \omega \tag{60}$$

$$e^{\mathrm{S,min}}_{sdt\omega} \geq \gamma^{\mathrm{S,F}}_{sd} e^{\mathrm{I,SE}}_{s}, \quad \forall s, t = 24, \forall d, \forall \omega \tag{61}$$

$$e^{\mathrm{S,max}}_{sdt\omega} \geq \gamma^{\mathrm{S,F}}_{sd} e^{\mathrm{I,SE}}_{s}, \quad \forall s, t = 24, \forall d, \forall \omega \tag{62}$$

- Energy balance

$$\sum_{g \in G_b} p^{\mathrm{G,D}}_{gdt\omega} + \sum_{s \in S_b}\left(p^{\mathrm{S,D}}_{sdt\omega} - p^{\mathrm{S,C}}_{sdt\omega}\right) - \sum_{\ell \in L^{\mathrm{O}}_b} p^{\mathrm{L}}_{\ell dt\omega} + \sum_{\ell \in L^{\mathrm{F}}_b} p^{\mathrm{L}}_{\ell dt\omega} = P^{\mathrm{D}}_{bdt\omega} - p^{\mathrm{UD}}_{bdt\omega}, \ \forall b, \forall t, \forall d, \forall \omega \tag{63}$$

$$0 \leq p^{\mathrm{UD}}_{bdt\omega} \leq P^{\mathrm{D}}_{bdt\omega}, \ \forall b, \forall t, \forall d, \forall \omega \tag{64}$$

- Reserve-capacity provision

$$\sum_{g \in G^{\mathrm{D}}} r^{\mathrm{G,U}}_{gdt\omega} + \sum_{s \in S} r^{\mathrm{S,U}}_{sdt\omega} \geq \gamma^{\mathrm{U,D}} \sum_{b \in B} P^{\mathrm{D}}_{bdt\omega} + \gamma^{\mathrm{U,I}} \sum_{g \in G^{\mathrm{I}}} p^{\mathrm{G,D}}_{gdt\omega}, \quad \forall t, \forall d, \forall \omega \tag{65}$$

$$\sum_{g \in G^{\mathrm{D}}} r^{\mathrm{G,D}}_{gdt\omega} + \sum_{s \in S} r^{\mathrm{S,D}}_{sdt\omega} \geq \gamma^{\mathrm{D,D}} \sum_{b \in B} P^{\mathrm{D}}_{bdt\omega} + \gamma^{\mathrm{D,I}} \sum_{g \in G^{\mathrm{I}}} p^{\mathrm{G,D}}_{gdt\omega}, \quad \forall t, \forall d, \forall \omega \tag{66}$$

- Transmission power flow

$$p^{\mathrm{L}}_{\ell dt\omega} = \frac{1}{X_\ell}\left(\theta_{O(\ell)dt\omega} - \theta_{F(\ell)dt\omega}\right), \quad \forall \ell, \forall t, \forall d, \forall \omega \tag{67}$$

$$-P^{\mathrm{L}}_{\max,\ell} \leq p^{\mathrm{L}}_{\ell dt\omega} \leq P^{\mathrm{L}}_{\max,\ell}, \quad \forall \ell, \forall t, \forall d, \forall \omega \tag{68}$$

$$-\pi/2 \leq \theta_{bdt\omega} \leq \pi/2, \quad \forall b, \forall t \tag{69}$$

where Θ is the set of all optimization variables in this problem. The objective function (27) formulates the total costs, which are equal to the summation of the annualized investment costs of generating and storage units, the yearly operation and reserve capacity costs of generating and storage units, startup costs of OCGTs, the transition mode costs of CCGTs and the unserved demand cost. Observe that the operation costs of CCGTs depend on the operation mode m. The investment decisions on new generating and storage units are formulated through constraints (28)-(33). Observe that the power to install from intermittent units, $p^{\mathrm{I,G}}_{g}$, and storage facilities, $p^{\mathrm{I,SP}}_{s}$, are continuous variables because of the modularity and scalability of these technologies. On the other hand, the power to install from OCGTs and CCGTs depends on binary variable $v^{\mathrm{I,G}}_{g}$, which is used to force that the whole capacity of the unit be installed if the unit is built. The investment decisions related to storages comprise two different decisions: 1) maximum power to charge and discharge and 2) the energy capacity of the storage. In practice, both variables are related. This relationship has been modeled through parameter $\gamma^{\mathrm{S,EP}}_{s}$ in constraint (32). The technical constraints of generating units are imposed by (34)-(46). The operation of CCGTs is formulated by constraints (1)-(25). The technical constraints of generating units include the power limits considering the participation of the units in the reserve capacity market and the modeling of the startup costs. The availability of intermittent power units is modeled by parameter A^{D}_{gdt} which value ranges between 0 and 1. The minimum up and down times of CCGT units are formulated by constraints (44)-(46). The operation of storages is modeled by constraints (47)-(62). These constraints model: i) the provision of up- and down-reserve capacity of storages considering charging and discharging modes, ii) the maximum power to be charged and discharged, iii) the state-of-charge of storages in cases where up- and down-reserve capacities are deployed, and iv) maximum and minimum bound to the energy stored in each period and scenario. The energy balance is formulated by constraints (63). The limits of the unserved demand are established in constraints (64). The requirement of the up- and down-reserve capacities is formulated through constraints (65) and (66). The reserve needs are computed according to the values of demand and intermittent production in each period and scenario. Finally, constraints (67)-(69) formulate the power flows in transmission lines using the DC model.

V. NUMERICAL RESULTS

A realistic case study based on the power system of Gran Canaria (Spain) has been solved to test the performance of the proposed formulation. Gran Canaria is an island that has a total population over 866 thousand inhabitants and an annual electricity consumption equal to 3469 GWh in 2019. The objective of this case study is to determine the optimal generation capacity expansion decisions that should be implemented by year 2050. It is assumed that all generating units that are currently at work will be decommissioned prior to this year.

A. INPUT DATA

The main input data describing the Gran Canaria system is provided in reference [25]. This power system comprises 43 candidate generating units that can be installed in 30 buses that are connected by 58 lines. The transmission system considers the future transmission expansion plans announced by the Spanish transmission planner, [25]. Fig. 2 represents the single-line diagram of Gran Canaria transmission network. The technologies of the generating candidate units are CCGT, OCGT and wind and solar PV. Two different types of OCGT units are considered, and they are denoted as OCGT-1 and OCGT-2. The characteristics of these units are provided in Table 3 and they are based on actual OCGT plants installed

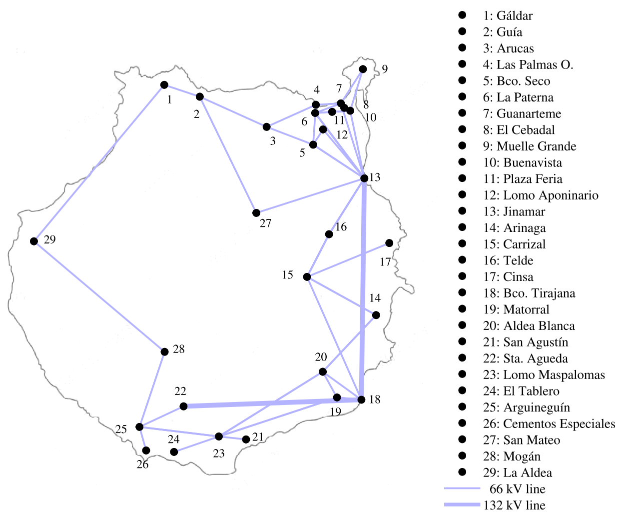


FIGURE 2. Single-Line diagram of Gran Canaria power system.

TABLE 3. Description of candidate OCGTs.

Technology	Capacity (MW)	Min. Power Out. (MW)	Capital cost (M€)
OCGT-1	17.4	9.35	13.6
OCGT-2	24.0	9.52	18.7

TABLE 4. Description of candidate CCGTs.

Technology	Mode	Configuration	Capacity (MW)	Min. Power Out. (MW)	Capital cost (M€)
CCGT	0	0GT+0ST	0.00	0.00	225.0
	1	1GT+0ST	71.00	6.39	
	2	1GT+1ST	117.25	30.00	
	3	2GT+0ST	142.00	12.78	
	4	2GT+1ST	214.50	68.00	

in the Spanish power system which are named as Ibiza16 and Ibiza25, respectively, [26].

A single type of candidate CCGTs is considered, which is based on an actual CCGT plant installed in the Spanish power system, which is named as CA's, [26]. This is a CCGT plant with two gas turbines and a single steam turbine. This plant has 5 operation modes. The technical characteristics of this candidate power plant are listed in Table 4.

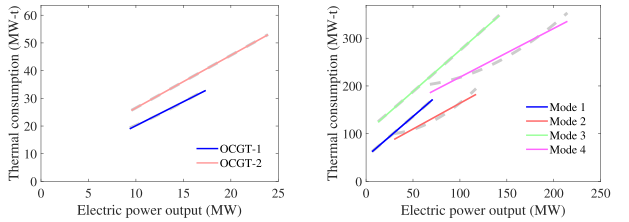
Fig. 3 depicts the thermal consumption of the considered candidate OCGTs and CCGTs units. Slashed lines represent the actual quadratic thermal consumption obtained from [26], whereas continuous lines represent the linearization of these values.

Table 5 provides the parameters of the linear approximation of heat consumption (MWh-t) of the different thermal generating units and operation modes represented in Fig. 3.

The thermal consumption in transitions between two operation modes entailing the startup of either a steam or a gas turbine is not negligible. In this manner, the thermal consumption in MWh-t and, in brackets, the fixed cost in k€ of the transitions between different operation modes is included in Table 6. In the same manner, Table 7 lists the thermal consumption and the fixed cost of startups of OCGT units. These values have been obtained from [26]. Transitions between modes 0 and 4 in a single period are not allowed. The minimum up and down times of CCGT units in modes 2 and 4, in which the steam turbine is on, are 2 hours.

Natural gas prices are considered as an uncertain parameter, which is modeled using the data provided by [27]. Two scenarios with maximum and minimum prices equal to 62.63 and 20.14 €/MWh-t are considered for Spain in 2050 assuming current energy policies.

The capital costs of wind and solar PV power units are equal to 1452 and 660 €/kW which are based on the estimations provided by IEA [28]. Capital costs are annualized using a capital recovery factor equal to 10.95%.



(a) OCGTs (b) CCGTs

FIGURE 3. Actual thermal consumption of OCGTs and CCGTs.

TABLE 5. Heat rate and O&M cost of thermal units.

Technology	Fixed term (MWh-t)	Linear term (MWh-t/MWh)	O&M cost (€/MWh)
OCGT-1	1.731	2.811	32.96
OCGT-2	1.899	22.52	11.29
CCGT (0GT+0ST, $m=0$)	0.000	0.000	0.00
CCGT (1GT+0ST, $m=1$)	1.692	51.487	18.16
CCGT (1GT+1ST, $m=2$)	1.801	55.725	18.16
CCGT (2GT+0ST, $m=3$)	3.384	51.487	18.16
CCGT (2GT+1ST, $m=4$)	1.021	116.247	18.16

TABLE 6. Thermal consumptions (MWh-t) and fixed costs (k€) of operation mode transitions in CCGT units.

Initial mode	Final mode 0	1	2	3	4
0	0.0 (0.0)	42.2 (11.1)	241.6 (13.9)	84.4 (22.2)	351.1 (27.8)
1	0.0 (0.0)	0.0 (0.0)	199.4 (2.9)	42.2 (11.2)	308.9 (16.7)
2	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	42.2 (0.3)	109.5 (13.9)
3	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	266.7 (5.6)
4	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

TABLE 7. Thermal consumptions (MWh-t) and fixed costs (k€) of startups in OCGT units.

Technology	Thermal consumption (MWh-t)	Fixed cost (€)
OCGT-1	24.071	177.393
OCGT-2	9.442	751.045

TABLE 8. Technical characteristics of candidate generating units.

Techn.	Unit	Node	Potential capacity (MW)	Techn.	Unit	Node	Potential capacity (MW)
OCGT-1	1-3	13	17.4	Solar PV	27	4	46.6
	4-6	18	17.4		28	5	46.6
OCGT-2	7-9	13	24.0		29	6	23.2
	10-12	13	24.0		30	7	23.2
CCGT	13-14	13	214.5		31	8	46.6
	15-16	18	214.5		32	9	46.6
Wind	17	1	45.6		33	10	46.6
	18	14	331.6		34	11	46.6
	19	15	4.7		35	12	46.6
	20	16	3.5		36	14	472.4
	21	18	222.1		37	15	381.3
	22	23	287.3		38	16	607.2
	23	29	1.2		39	18	24.1
Solar PV	24	1	44.6		40	23	101.8
	25	2	11.9		41	27	17.4
	26	3	77.0		42	28	37.0
					43	29	10.8

The technology, location and capacity of each candidate generating unit are included in Table 8.

Additionally, four utility-scale storage units based on Li-on batteries can be installed in buses 13 and 18. The maximum energy capacity that can be installed per bus is 2000 MWh, and a typical relationship energy/power (γ_i^{SP}) equal to 6 has been considered [29]. The investment costs of storage units is equal to 300 €/kWh.

The target year is represented by a set of characteristic days. The hourly values of the system demand, and wind and solar PV availabilities in each day are assigned using real data pertaining to 2019. A set of 6 characteristic days has been selected by using the scenario reduction algorithm described in [30]. The weights of each day, W_d, are assigned minimizing the daily square error between the reduced set of days and the original set containing 365 days. Fig. 4 plots the daily square error of wind and solar availabilities and demand for different number of selected days. As Fig. 4 shows, a number of days greater than or equal to 6 is adequate to represent the planning horizon. Fig. 5 represents the expected system demand, and wind and solar PV availabilities for the considered days.

The system demand in 2050 is characterized as a random variable characterized by a set of scenarios. According to [31], two electricity demand scenarios are computed considering demand increases of 1.9 and 2.1% per year between 2018 and 2050.

The values of parameters $\gamma^{\mathrm{U,D}}$ and $\gamma^{\mathrm{U,I}}$ used to establish the minimum requirements of up and down reserve capacities are equal to 0.03 and 0.05, respectively. It is considered that up-reserve requirements are equal to the down-reserve requirements, i.e., $\gamma^{\mathrm{D,D}} = \gamma^{\mathrm{U,D}}$ and $\gamma^{\mathrm{D,I}} = \gamma^{\mathrm{U,I}}$. Reserve capacity costs are equal to 0.25 times the operating cost for each unit. It is assumed that wind and solar PV units are not qualified to supply reserve capacity. The unserved demand cost is equal to 1000€/MWh.

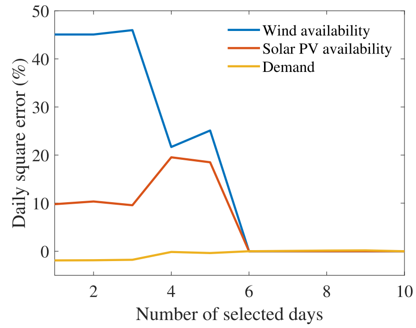
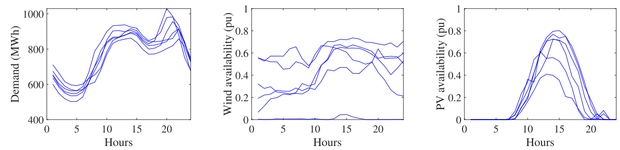


FIGURE 4. Daily square error of wind and solar availabilities and demand for different number of selected days.



(a) Demand (b) Wind availability (c) PV availability

FIGURE 5. Demand and wind and solar PV availabilities.

B. RESULTS

In this section, we analyze the influence of the modelling of the operation of CCGTs in the generation expansion decisions. For the sake of comparison, two different models are tested considering if minimum power outputs and the different operation modes of CCGTs are formulated or not:

- *Simplified (S)*: This model does no consider minimum power outputs and different operation modes of CCGTs. Therefore, this model does not use the binary variables modelling i) the unit commitment, $v^{\mathrm{G}}_{gdt\omega}$, and ii) the operation modes of CCGTs, $v^{\mathrm{M},1}_{gdt\omega}$, $v^{\mathrm{M},2}_{gdt\omega}$ and $v^{\mathrm{M},3}_{gdt\omega}$.
- *Full (F)*: This model considers the complete formulation derived in Section IV, including minimum power outputs, minimum up and down times, and different operation modes of CCGTs.

In order to test the performance of both models, five different cases have been solved for each model:

- *Th*: Only thermal units can be installed
- *0Sto*: Thermal and renewable units can be installed, but storages are not considered.
- *0.25Sto*: Thermal and renewable units can be installed, and only 25% of the potentials of storages.
- *BAU*: Business-as-usual case where thermal and renewable units can be installed, as well as the full potential of storages.
- *75R*: This case is similar to *BAU*, but it is enforced that 75% of the demand must be provided by CO_2-free sources. Note that higher limits of non pollutant production lead to large amounts unserved demand in the analyzed system.

All simulations are performed with CPLEX 12.6.1 using a server with four 3.0 GHz processors and 250 GB of RAM.

TABLE 9. Computational size and solution time.

Case	Constraints (millions #)	Number of continuous variables (millions #)	Number of binary variables (#)	Solution times (hours)
S-BAU	0.290	0.241	16	0.03
F-BAU	0.510	0.415	40336	116.9

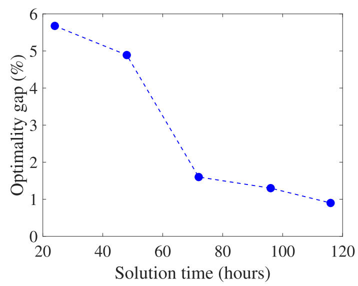


FIGURE 6. Optimality gap with respect to solution time in *F-BAU* case.

TABLE 10. Annualized expected costs (million €).

Case	Gen. inv.	Sto. inv.	Day-ahead energy	Reserve capacity	Start up	Unserved demand	Total
S-Th	110.3	0.0	825.3	12.7	0.00	0.00	948.30
S-0Sto	310.4	0.0	414.6	18.0	0.00	0.00	743.04
S-0.25Sto	309.8	7.6	404.6	16.7	0.00	0.00	738.91
S-BAU	302.1	49.1	355.4	15.2	0.00	0.00	723.64
S-75R	349.3	122.2	249.2	14.4	0.00	172.48	911.64
F-Th	113.8	0.0	705.1	11.2	11.97	0.00	842.15
F-0Sto	300.0	0.0	390.1	16.1	28.72	0.00	734.90
F-0.25Sto	287.2	7.6	386.0	14.8	18.93	0.00	714.95
F-BAU	280.4	50.4	340.3	14.6	11.16	0.00	699.20
F-75R	349.3	122.2	237.1	13.1	11.83	184.70	922.47

The numbers of constraints and binary and continuous variables are reported in Table 9. As expected, the problem that considers all constraints and variables, *F-BAU* case, achieves the largest numbers of variables and constraints, as well as the highest solution times. However, note that the obtained times are reasonable for solving a long-term problem. Fig. 6 represents the optimallity gap of *F-BAU* case with respect to the solution time. It is observed that the time needed to reduce the gap increases as the gap becomes smaller.

Table 10 provides the resulting expected cost obtained in each case. Startup costs include startup costs of OCGTs and transition mode costs of CCGTs. Note that these costs are not considered in the modelling of S-cases. It is worth noting that S-cases overestimate the total expected cost with respect to those in F-cases. Observe that F-cases obtain significant lower day-ahead energy costs due to a more accurate modelling of the operation costs of CCGT units. It is also interesting to note the high relevance that the amount of available capacity to install from storages has in the total costs. As expected the *BAU* case attains the lowest cost for S- and F-cases.

Tables 11 lists the generation and storage capacities installed in each case. In all cases, it is observed that solar PV is the generation technology most installed, which value increases as the potential storage capacity grows. However, it is worth emphasizing that the investment decisions on renewable units in S- and F-cases are appreciably different. For instance, it is remarkable that the capacity installed from wind and solar PV units ranges between 15 and 25% higher in S-cases with respect F-cases. Then, it is observed that the simplification of the modeling of thermal units in S-cases overestimates the flexibility of these units which favors the installation of wind and solar PV units.

TABLE 11. Capacity installed (MW).

Case	OCGT-1	OCGT-2	CCGT	Wind	Solar PV	Storage
S-Th	69.6	144.0	858.0	0.0	0.0	0.0
S-0Sto	69.6	144.0	858.0	848.8	1110.7	0.0
S-0.25Sto	34.8	144.0	858.0	843.0	1167.7	41.7
S-BAU	0.0	144.0	643.5	829.8	1478.4	268.0
S-75R	0.0	0.0	643.5	896.0	2205.0	666.7
F-Th	121.8	120.0	858.0	0.0	0.0	0.0
F-0Sto	104.4	144.0	858.0	804.2	1000.1	0.0
F-0.25Sto	17.4	144.0	858.0	784.9	986.4	41.5
F-BAU	17.4	120.0	643.5	756.6	1317.7	274.8
F-75R	0.0	0.0	643.5	896.0	2205.0	666.7

TABLE 12. Energy produced (GWh).

Case	OCGT-1	OCGT-2	CCGT	Wind	Solar PV	Storage
S-Th	85.0	19.9	6403.2	0.0	0.0	0.0
S-0Sto	26.1	14.3	2954.7	1680.6	1832.4	0.0
S-0.25Sto	12.0	12.3	2889.3	1672.1	1926.4	36.9
S-BAU	0.0	100.2	2379.0	1632.6	2435.2	360.2
S-75R	0.0	0.0	1627.0	1704.4	3095.3	816.4
F-Th	111.9	36.4	6359.8	0.0	0.0	0.0
F-0Sto	59.3	38.7	3043.4	1700.6	1666.1	0.0
F-0.25Sto	10.1	53.1	3067.5	1744.7	1642.9	81.6
F-BAU	18.1	81.1	2599.9	1676.0	2195.2	465.2
F-75R	0.0	0.0	1627.0	1715.4	3092.3	838.7

Tables 12 provides the energy produced by technology in each case. The energy produced by storages refers to the energy discharged. In most cases, the technologies that produce the maximum quantity of energy are solar PV and CCGT. Note that the energy produced by thermal units in F-cases is higher than in S-cases. This result is consequence of the reduced power capacity installed from renewable energies in F-cases. Then, the estimation of the total renewable production using S-cases is also overestimated. Despite of the simultaneous charge and discharge of storage units is not explicitly forbidden in the presented formulation, we have verified that storage units do not simultaneously charge and discharge in the analyzed case studies.

Table 13 shows the annual scheduled up and down reserve capacities per technology and case. It is noticed that CCGT units provide most of the up reserves, storages schedule down-reserve capacity if storage units are available to be installed. However, the contribution of storages to the up-reserve capacity in F-cases is much more higher than in S-cases. The reason of this result is that the simplification of

TABLE 13. Up/Down reserve capacity (GW).

Case	OCGT-1	OCGT-2	CCGT	Wind	Solar PV	Storage
S-Th	44.2/0.0	24.7/0.0	126.3/195.3	0.0/0.0	0.0/0.0	0.0/0.0
S-0Sto	3.5/0.0	9.7/0.0	357.8/195.3	0.0/0.0	0.0/0.0	0.0/0.0
S-0.25Sto	2.2/0.0	11.0/0.0	362.0/147.3	0.0/0.0	0.0/0.0	0.0/48.0
S-BAU	0.0/0.0	28.1/0.0	370.7/69.1	0.0/0.0	0.0/0.0	0.0/126.2
S-75R	0.0/0.0	0.0/0.0	432.4/14.6	0.0/0.0	0.0/0.0	2.9/180.8
F-Th	42.0/0.0	17.0/0.0	136.4/195.3	0.0/0.0	0.0/0.0	0.0/0.0
F-0Sto	18.0/ 21.5	16.9/ 22.6	328.7/ 151.2	0.0/ 0.0	0.0/ 0.0	0.0/ 0.0
F-0.25Sto	4.2/18.8	34.5/24.5	324.6/106.5	0.0/0.0	0.0/0.0	1.3/45.5
F-BAU	6.7/ 19.3	44.8/ 21.1	325.6/ 85.9	0.0/ 0.0	0.0/ 0.0	11.8/ 69.0
F-75R	0.0/ 11.6	0.0/ 11.6	415.3/ 15.3	0.0/ 0.0	0.0/ 0.0	20.4/ 156.8

TABLE 14. Performance of thermal units.

Case	Nonsynchronized up-reserve of thermal units (%)	Number of operation mode changes of CCGTs (%)
S-Th	29.15	3.94
S-0Sto	12.00	28.08
S-0.25Sto	20.44	30.49
S-BAU	34.01	27.05
S-75R	59.81	26.58
F-Th	0.0	4.78
F-0Sto	0.0	23.54
F-0.25Sto	0.0	18.02
F-BAU	0.0	13.08
F-75R	0.0	16.37

the operation of CCGTs in S-cases does not allow to estimate adequately the reserve capacity available from thermal units.

Table 14 includes some relevant data pertaining to the performance of thermal units in the different analyzed cases. In particular, two items are considered. First, it is provided the percentage of hours in which thermal units are providing up-reserve capacity when they are not participating in the day-ahead energy market. This undesired situation indicates that the provided reserve cannot be considered as spinning reserve, and it may occur in S-cases where the minimum power output of the units is not considered. The second item is the number of operation mode changes of CCGTs with respect to the number of working hours of these units. Note that high values of these parameters are negative since they indicate high cycling costs of thermal units.

In this table we observe that the percentage of hours in which thermal units provide irregular up-reserve in S-cases is very high. It should be highlighted that in *S-75R* case, more than half of the hours in which thermal units are assumed to provide up-reserve they are offline. This table also reveals that the cycling of CCGT units measured as the number of operation mode changes modes is higher in most S-cases. This result is explained by the fact that S-cases do not take into account transition mode costs in their formulations.

Fig. 7 represents the energy production for each considered day and the scenario with lowest demand and gas prices. This figure shows that the solar PV supplies most of the demand in the middle of the day. This fact forces to reduce

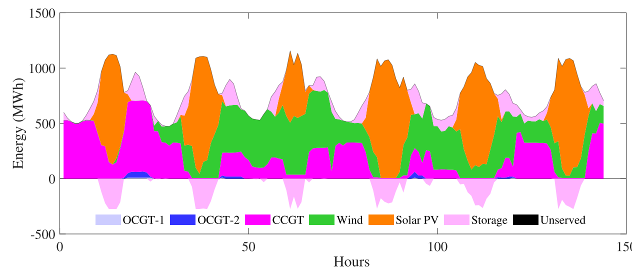


FIGURE 7. Demand provision in scenario with low demand and low gas prices.

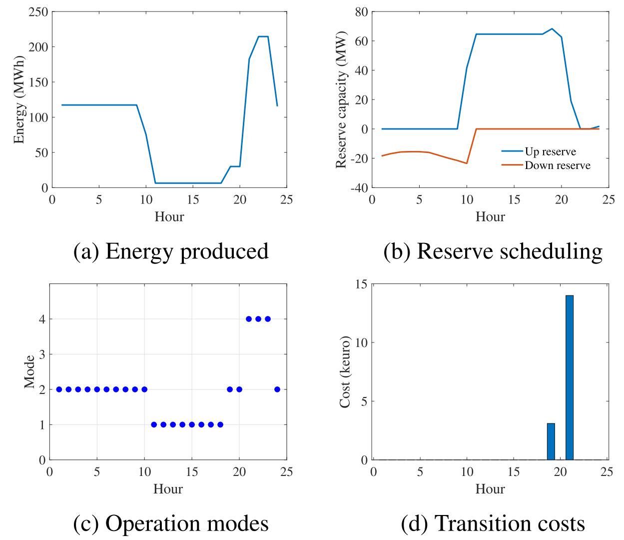


FIGURE 8. Operation of CCGT unit 13 a in scenario with low demand and low gas prices.

the power output of OCGT and CCGT units between 10:00 and 20:00 hours. Storages are charged during these hours, and discharged when the production of solar PV is low.

As an example, the operation of the CCGT unit number 13 during the first day of the planning horizon is represented in Fig. 8 in terms of the energy production, reserve capacity scheduling, operation mode and transition cost between operation modes. In this figure, it is observed how the production of the CCGT unit is equal to the maximum capacity (214.5 MW) at hours 22 and 23, in which the system demand is high and there is not renewable production. However, the output of the CCGT unit is equal to the minimum power output (6.39 MW) during the middle part of the day, where the solar PV production is high. During these hours, the CCGT unit is providing up-reserve capacity. The unit is operating at modes 1 and 2 during most part of the day, except in hours 21-23, in which it is operating at mode 4 to provide a higher quantity of power. Observe that the minimum up time constraint forces that the CCGT unit remain in operating mode 2 at least two hours, 19 and 20. Finally, observe that at hours 19 and 21, the CCGT unit changes from mode 1 to mode 2 and from mode 2 to mode 4, which has transition costs equal to 3.6 and 14.4 k€, respectively.

VI. CONCLUSION

This paper presents a generation capacity expansion problem formulation that explicitly accounts different operation modes of CCGTs. The proposed model considers the long-term uncertainty pertaining to the demand growth and natural gas costs. The model is tested on a realistic case study based on the Gran Canaria power system. Based on the numerical results presented in the case study, the following main conclusions can be drawn:

- The proposed formulation is able to characterize properly the operation modes and the transitions between different modes of CCGT units in generation capacity expansion problems.
- The computational size of the problem that considers different operation modes of CCGTs is significantly higher than that of the problem in which operation modes are ignored. Specifically, the number of binary variables grows linearly with the number of time periods, scenarios and CCGT units. This fact has a strong impact in solution times.
- The obtained generation capacity expansion depends on the degree of precision of the modeling of CCGT units. The capacity installed of the different candidate generation technologies varies if the technical characteristics of CCGT and OCGT units are relaxed.
- The up-reserve capacity provided by CCGT units is significantly overestimated if the technical characteristics of CCGT units are neglected. The reserve capacity in the simplified model is 10% higher than that obtained with the proposed model.

Future research is underway to determine the optimal upgrade of existing CCGT units to improve their performance in renewable dominated power systems.

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