ISSN 2004-2965 Energy Proceedings, Vol. 20, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 853

Optimal Operation of Virtual Power Plants Bidding in the Day-Ahead and Ancillary Services Markets

Andrea Fusco[1], Domenico Gioffrè[1], Alessandro Francesco Castelli[1], Cristian Bovo[2], Emanuele Martelli[1,*]

[1] Politecnico di Milano, Department of Energy, Via Lambruschini 4, 20156, Milano

[2] Università di Pavia, Dipartimento di Ingegneria Industriale e dell'Informazione, Via Adolfo Ferrata 5, 27100 Pavia

[*] corresponding author email: emanuele.martelli@polimi.it

ABSTRACT

This work presents a multi-stage stochastic Mixed Integer Linear Program with binary recourse for optimizing the day-ahead unit commitment of power plants and virtual power plants operating in the day ahead and balancing markets. Scenarios are characterized by profiles representing the expected maximum quantities of energy/bids accepted by the balancing market, and photovoltaic panels generation for each hour of the day. Since the deterministic equivalent MILP model cannot be solved in a practical computation time (> 24 hours), a novel decomposition is developed. Results show how the proposed decomposition approach provides close-to-optimal solutions in much shorter computational time (<20 minutes).

Keywords: Multi-stage stochastic programming, unit commitment, Virtual Power Plant, balancing markets.

NONMENCLATURE

Abbreviations	
ASM	Ancillary-services market
BM	Balancing Market
DAM	Day-ahead market
IDM	Intraday market
MILP	Mixed Integer Linear Programming
PV	Photovoltaic
RES	Renewable Energy Source
VPP	Virtual Power Plant
Sets	
$\mathcal{M}$	Set of conventional generation units
$\mathcal{Sc}$	Set of scenarios
$\mathcal{T}$	Set of timestep
Binary variables	
$z_{sc,t}^{DAM}, z_{sc,t}^{ASM}$	One if plant is selling in DAM/ASM
$z_{sc,t}^{cc}$	One if at least one conventional generation unit is on
$z_{m,sc,t}$	One if conventional unit *m* is on
$\delta_{sc,t}^{SU}$	One if start-up revenue is awarded
$\delta_{sc,t}^{Pen}$	One if start-up penalty is given
$\delta_{m,sc,t}^{on}$	One if unit *m* starts up at *t*

1. INTRODUCTION

In the recent year, many countries experienced an increase of renewable energy generation. To achieve an even higher penetration of renewable sources, integration between conventional and renewable generation units can be considered. To achieve this goal, VPPs can be a solution. These aggregated energy systems can comprise both energy storages, renewable energy sources, and conventional units. Given the mix of technologies, such a power plant could operate not only in the DAM but also in the ASM, which is now forbidden to RESs.

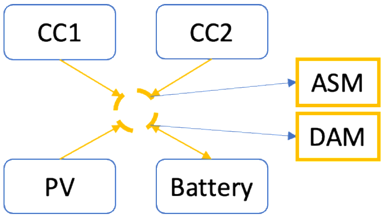

Fig. 1 VPP scheme with CC being the combined cycle units

Bidding in the Italian DAM and ASM require to consider the uncertainty related to the actual quantities that will be awarded by the TSO in the ASM. Therefore, a time series analysis on the past ASM awarded quantities profiles must be made to evaluate the probability distributions needed for creating the ASM scenarios. These scenarios can then be used for the evaluation of the power plant scheduling. For the VPP case then, scenarios must consider both the expected ASM awarded quantities profile and the RES production ones.

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

In this study, a multistage stochastic programming model and a solution algorithm are proposed to optimize the day-ahead unit commitment considering the two markets. The approach is tested on two different plant layouts: the first one featuring two NGCCs units, the second one comprising two NGCCs, a PV field, and a battery.

2. PROBLEM STATEMENT

The problem can be formulated as follows.

Given:

- The conventional generation and storage units performance curves and operational limits,
- The probability distributions for the ASM and the hourly irradiance in order to generate scenarios,
- Time/scenario-dependent prices for selling electricity on the ASM and DAM,

determine for each time period t:

- The on/off statuses of the units and their loads,
- Battery charge/discharge profile,
- The 24-hour bidding profile for both DAM and ASM,

which maximize the expected power-plant/VPP profit, defined as the sum of:

- Conventional units' and storage operational costs (fuel, O&M and start-up costs),
- Expected revenue from the DAM, ASM and start-up revenues,

subject to the following constraints:

- Units (generation and storage) operating and ramping limits, and minimum on/off time
- All the generated energy and battery discharge can be sold to only the DAM and ASM,
- The DAM session take place only in the day-ahead (here-and-now decision),
- ASM has 6 sessions throughout the day (one every 4 hours). In each session the TSO decides how much energy to purchase for the following hours,
- Start-up revenues rules (more on this in Section 3.3).

3. MODELLING FEATURES AND ASSUMTPIONS

3.1 Main assumption

Here are listed the main assumption of the problem:

- Uncertainty is exogenous: the stochastic processes are independent from the decisions made (valid if the power plant is not able to change the dynamics of the electricity markets),
- IDM sessions are neglected (only day-ahead decision are considered),
- BM is not considered (much lower awarded quantities than ASM and almost random process).

Given the multiple market sessions and the uncertainty related to both the RES generation and the quantities awarded in the TSO, the problem is modelled as a multi-stage stochastic MILP. The problem is modelled by using a scenario-based formulation with non-anticipativity constraints added so to consider decisions for the different ASM and DAM sessions (DAM bidding profile is the same for each scenario)

3.2 Power plant modelling

Constraints modelling the generation units behavior were taken from [1] (minimum on/off time and logical relationship between on/off binary and start-up/shut-down ones). The other constraints related to ramping limits are those found in [2]. A linear model of the generating units is achieved by linearizing the non-linear performance curves of the combined cycles (absolute error lower than 1%).

Storage charge/discharge efficiency and self-discharge parameters are considered constant. Hence, the stored energy evolution in time the can be defined as done in [3].

The whole power plant is then characterized by the following characteristics:

- It can only export electricity to the grid, either by selling in the DAM or ASM, or both,
- Quantities sold to the ASM cannot exceed the maximum one that the TSO is expected to buy (expected maximum ASM in each scenario),
- the TSO imposes the operator to keep a 6% power reserve on the sum of the controllable units nominal power.

3.3 Start-up revenues

In the Italian electricity market start up revenues can be awarded if certain requirements are met. These are:

1. the plant is not serving on the DAM at start-up,
2. at least one controllable unit is turned on,
3. at the previous timestep *t-1* all controllable units were switched off.

These statements can then be modelled as:

$$z_{sc,t}^{DAM} + z_{sc,t-1}^{cc} - \delta_{m,sc,t}^{on} + \delta_{sc,t}^{SU} \geq 0 \qquad \forall m \in \mathcal{M}, \tag{1}$$

$$\delta_{sc,t}^{SU} + z_{sc,t-1}^{cc} \leq 1 \qquad \forall sc \in \mathcal{S}c, \ \forall t \in \mathcal{T} \tag{2}$$

$$\sum_{m \in \mathcal{M}_{El}} \delta_{m,sc,t}^{on} \geq \delta_{sc,t}^{SU} \qquad \forall sc \in \mathcal{S}c, \tag{3}$$

$$\delta_{sc,t}^{SU} + z_{sc,t}^{DAM} \leq 1 \qquad \forall t \in \mathcal{T} \tag{4}$$

Then, the $z_{sc,t}^{cc}$ flagger is 1 if and only if at least one conventional unit is on.

$$z^{cc}_{sc,t} \geq z_{m,sc,t} \qquad \forall sc \in \mathcal{S}c, \qquad (5)$$

$$z^{cc}_{sc,t} \leq \sum_{m \in \mathcal{M}} z_{m,sc,t} \qquad \forall t \in \mathcal{T} \qquad (6)$$

Finally, the binary penalty variable $\delta^{Pen}_{sc,t}$ is 1 if the plant is selling into the DAM at time *t* or it was selling in the ASD at *t-1.*

$$\delta^{Pen}_{sc,t} \geq z^{ASM}_{sc,t-1} + z^{DAM}_{sc,t} - 1 \quad \forall sc \in \mathcal{S}c, \forall t \in \mathcal{T} \quad (7)$$

This auxiliary variable is used in the objective function to define the start-up revenue as follows at any time *t* and scenario *sc*:

$$c^{SU} \cdot \left(\delta^{Pen}_{sc,t} - \delta^{SU}_{sc,t}\right) \qquad (8)$$

4. SCENARIO GENERATION

Data analysis has been performed on historical data related to awarded ASM quantities of the Marghera-Azotati plant (Venice, Italy). From this, the conditional probability distributions were found on the actual ASM values. For the PV, conditional probability distributions on the forecasting error were considered by evaluating the error between real and forecast profiles [4].

Scenarios are generated by extracting sequentially values of the ASM and PV generation using the conditional probability distribution within a random roulette wheel process.

To improve tractability, scenario reduction was considered by using k-medoids clustering on the different level of the scenario tree. In this way, given *m* the number of clusters (that also defines the number of branches per node and level of the tree), the tree will have m^6 scenarios.

5. DECOMPOSITION METHOD

Since the equivalent deterministic model is computationally intractable for a number of scenarios higher than 81 , a decomposition method was developed to shorten computational times. It consists in a sequence of two stage stochastic programs where values of the first-stage variables are taken as solution and fixed.

As shown in Fig. *2*, at first a two-stage problem is solved by considering 30 independent scenarios so to get the DAM profile. This is then fixed for all the following subproblems with an equality constraint (comprising a penalty variable used to update the profile to guarantee feasibility). For each iteration *n*, the solution is obtained by solving 3^n two-stage stochastic problems. Each problem has then 3 scenarios evaluated by applying k-medoids on the scenarios belonging to each children node (for a total of 3^{n+1}).

6. CASE STUDY

The VPP considered in this study is composed by two combined cycle units with a nominal power of 120 MW a 100 MW PV field and a 100 MWh. The combined cycle units' size was chosen since the closest to the ones of the Marghera Azotati's units. All the other parameters are listed in Table 1.

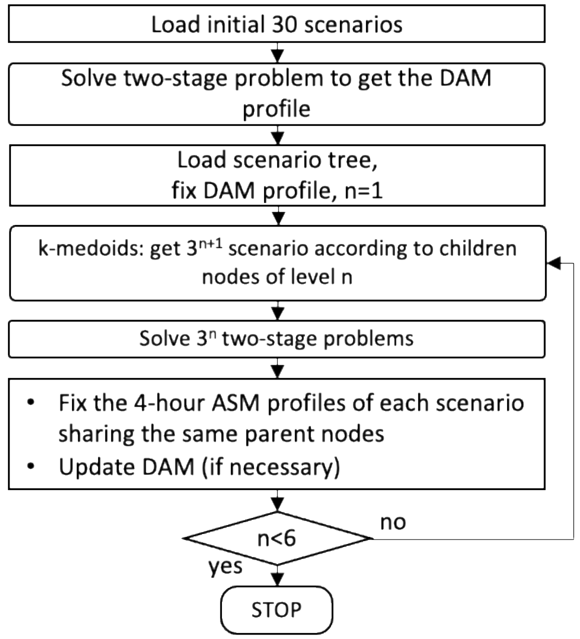

Fig. 2 Decomposition method flowchart

Table 1 Techno-economic parameters considered.

Market Parameter	
Natural gas cost	22 €/MWh
DAM price range	44-75 €/MWh
ASM price range	85-95 €/MWh
Start-up revenue	65160 €
Combined Cycle	
Min/max nominal power	60-120 MW
Performance curve	Out = 0.629*In - 17.058
Nominal efficiency	55%
Ramp up/down limit	117 MW/h
Ramp-up limit at start-up	62 MW/h
O&M cost	2 €/MWh
Start-up cost	19000 €
Battery	
Nominal capacity	100 MWh
Nominal charge/ discharge power	50 MW
Charge/discharge efficiency	97%
Self-discharge	0.05%/h
PV	
Nominal installed power	100 MW
Efficiency (NOCT)	15.8%

7. RESULTS

Fig. *3* show the DAM and expected ASM bidding profile when the decomposition is not used and just 81 scenarios are considered (otherwise intractable). The VPP bids only in the DAM, with no quantities on the ASM. If the decomposition is used, then all the 729 scenarios can be considered. However, even if the DAM profiles changes (due to the higher number of scenarios considered), the ASM profile keeps being null. DAM profiles obtained in the different iteration of the decomposition and without it can be seen in Figure 4.

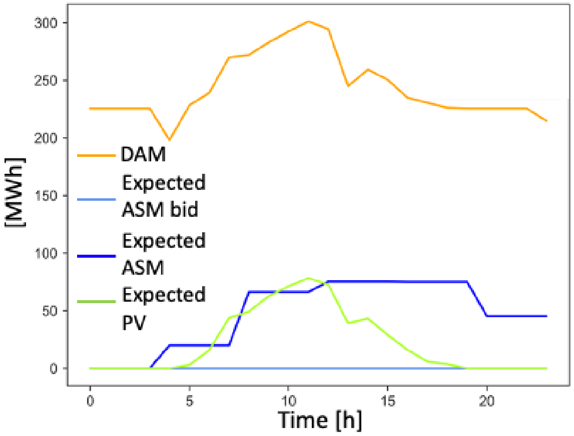

Fig. 3 DAM, expected ASM bidding profile, average of non-null ASM scenarios (they are 60% of the total ones) and expected PV operation of the VPP.

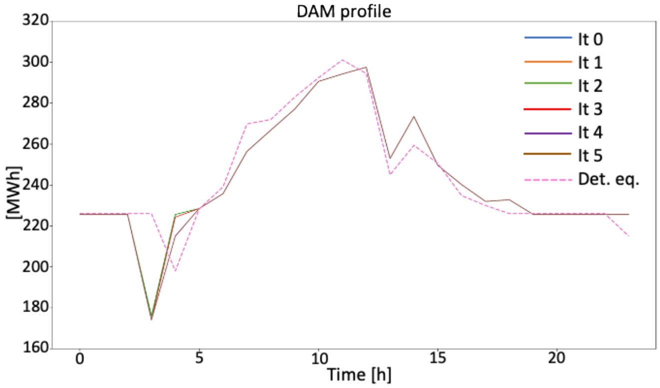

Figure 4 DAM profiles obtained at the different iteration of the decomposition and the one obtained with the monolithic deterministic model with 81 scenarios.

Table 2 shows the run time, objective function, EVPI and VSS when solution was obtained by means of the deterministic equivalent model or the decomposition. As it can be seen, the run time is much lower if the decomposition is considered. Difference in the objective function can be due to both the different number of scenarios considered, and optimality gap introduced by the decomposition. Then, VSS cannot be evaluated since the solution with average profiles is infeasible. This means that the problem can only be solved by means of a stochastic model.

Table 2 Solution details.

	Without decomposition	**With decomposition**
Scenarios	81	729
Run Time	4days	< 20 min
Objective	-1.26E+05	-1.23E+05
EVPI	3.24E+04	3.53E+04
VSS	/	/

8. CONCLUSION

The results show how a solution close to optimal can be obtained in a short time thanks to a decomposition method. However, it can't be proved how far to optimality the solution is. It is important to highlight that the computational time of the deterministic model, despite being reduced in the number of scenarios, is still too long (solution must be obtained in less than a day so to be able to submit the bidding profiles to the TSO on the day-ahead). A more detailed analysis must then be done on the scenario generation in order to consider shorter timesteps (e.g. 15 min) and different power plants. However, the proposed work shows a possible path for getting the optimal operation of power plants and VPP while considering uncertainty.

REFERENCE

[1] G. Morales-España, C. Gentile, and A. Ramos, "Tight MIP formulations of the power-based unit commitment problem," *OR Spectr.*, vol. 37, no. 4, pp. 929–950, Oct. 2015, doi: 10.1007/s00291-015-0400-4.

[2] G. E. Constante-Flores, A. J. Conejo, and F. Qiu, "AC network-constrained unit commitment via conic relaxation and convex programming," *Int. J. Electr. Power Energy Syst.*, vol. 134, 2022.

[3] L. Moretti, E. Martelli, and G. Manzolini, "An efficient robust optimization model for the unit commitment and dispatch of multi-energy systems and microgrids," *Appl. Energy*, vol. 261, Mar. 2020.

[4] E. Ogliari, A. Dolara, G. Manzolini, and S. Leva, "Physical and hybrid methods comparison for the day ahead PV output power forecast," *Renew. Energy*, vol. 113, pp. 11–21, 2017.