Techno-Economic Evaluation of the Sizing and Operation of Battery Storage for Isolated Oil and Gas Platforms with High Wind Power Penetration

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***Abstract*—According to the plans of one of the global oil and gas (O&G) industry leaders, the integration of offshore wind power into offshore O&G platforms will become reality within the next three years. Although this implementation is going to set the standards for a cleaner platform operation, the intermittency of wind power generation does not favor the provision of scheduled constant and reliable power for the loads. To cope with this limitation, this paper proposes a configuration that integrates a Battery Energy Storage System (BESS) in the O&G platform. The manuscript focuses on how to appropriately size the BESS through a techno-economic study that considers both investment and operation costs, along with the possibility for economic benefits in terms of fuel savings and CO2 emissions reductions. The results, obtained using aggregated field data from a real platform, indicate that the sized BESS enables fuel savings and higher levels of wind power penetration. This confirms the intuition that BESSs may positively contribute towards renewable-based offshore O&G platforms.**

***Index Terms*—offshore O&G platforms, battery storage system, offshore wind power, optimization**

I. Introduction

The global oil gas (O&G) industry is deemed amongst the most emissions intensive, with the production and use of oil gas accounting for over half of global greenhouse gas emissions associated with energy consumption [1]. In Norway, which is the third larger exporter of gas in the world and covers about 2% of the global oil demand, a considerable need to maximize the O&G resources utilization, minimize environmental impact, and reduce its greenhouse gas emissions is felt and now also stated on the Norwegian OG21 strategic vision for the petroleum sector [2]. Offshore Oil and Gas (O&G) platforms are typically isolated, implying that their operations are supported by conventional power generation systems, namely diesel generators and gas turbines (GTs). These systems add a significant proportion to the total generated emissions that result from the operation of the various processing systems typically found in an O&G platform. Therefore, to control and reduce the high emission levels associated with the operation of O&G platforms, one way is to find alternatives for the power generation system. Such alternatives could include long-distance power transmission (at the cost of facing several technical and environmental challenges related to the deployment of these lines) and the integration of high amounts of renewable energy to the O&G platform [3]. Following the recent progress of the offshore wind energy sector [4], Equinor has recently announced their plan to interconnect two offshore O&G platforms with a floating wind farm to be installed at the same location, and to explore the possibility for integrating large amount of renewable power to the platforms power systems [5]. However, this introduces the problem of coupling the intermittent behavior of the wind power production with the high criticality and reliability requirements of the supplied loads. The critical point from a technical perspective is that the uncertainties associated to the energy supply and production processes can lead to system-wide power fluctuations, which can, in their turn, threaten the stability and reliability of the platform's operations [6], [7]. Facing this problem requires flexible solutions that may include advanced energy resources scheduling [8], efficient coordination of the various subsystems [9], and integrating an energy storage system in the platform's grid. However, none of the above-mentioned studies (and, to the best of our knowledge, no publicly available literature) investigated the benefits of integrating energy storage systems (ESSs) into O&G platforms, despite their proven abilities to provide ancillary services, aid improving scheduling, and help increasing renewable penetration. To this respect, battery ESSs (BESSs) provide interesting possibilities, due to their constantly decreasing installation and operation costs.

As shown in more details below, our numerical results show that optimally sized BESSs allow for a simultaneous increase in wind power penetration, a reduction of the CO2 emissions associated to the GTs, and an increase in economic benefits (also through decreasing electrical energy dumping).

II. Problem Formulation

We first describe and model the system in section II-A, and then use this information to formulate our BESS sizing

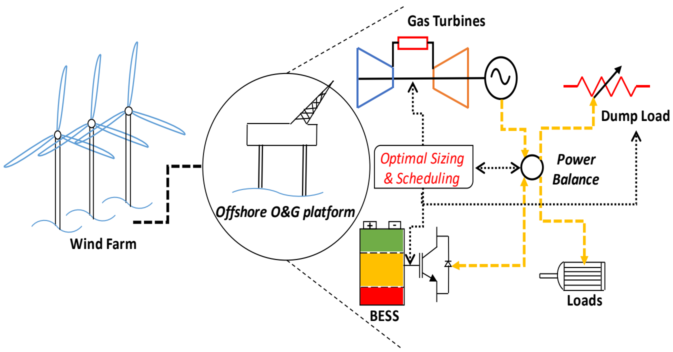

Fig. 1. The proposed system configuration.

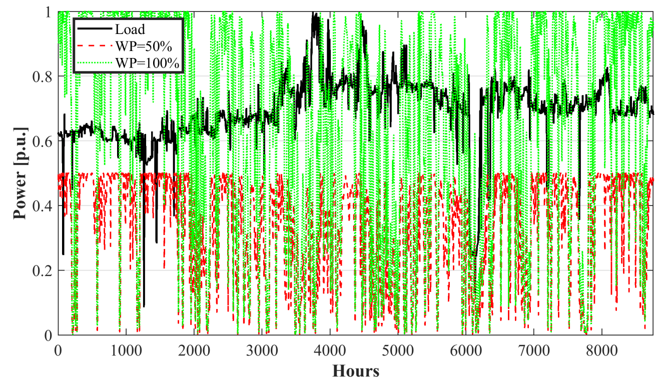

Fig. 2. Platform power consumption and wind power generation (a year).

problem.

A. System Description and Quantitative Models

The O&G platform under consideration is located in the North Sea; its power supply comes from 2 identical GTs that are operated in load sharing mode, with a capability to cover the load just by using one of them. The platform is also supplied from locally generated offshore wind power, rated at a 50% power penetration (i.e., the maximum wind power production over the peak load of the platform). For the smooth and safe operation of the system, a dump load is also included in the platform for dissipating excess energy when total generation is greater than total consumption. The proposed configuration, which is depicted in Figure 1, integrates two key components: a) a battery storage system with its corresponding balance of power components, and b) a controllable dump load. Including the controllable dump load adds essential flexibility in how to design and operate the storage system: being enforced to store surplus energy under any conditions could indeed lead to an economically unjustifiably large battery size. The wind power generation was modeled based on the tools from [10]. Thus, it was possible to simulate the hourly wind power production for a whole year, based on realistic wind conditions

Figure 2 presents the power consumption profiles of the offshore platform, along with the wind power generation on an hourly basis for a whole year. The location is characterized by extreme offshore wind conditions: more than 50% of the year the wind power generation is greater equal than 80% of its rated power, with a yearly Capacity Factor (CF) of 67%. The last, is in line with actual performance of offshore floating wind farms [11]. The wind farm operates thus at its rated capacity most of the time, but it also experiences several deep wind drops and steep ramp-ups concentrated in a few hours. At the same time, the O&G platform consumption profile is mostly constant along the different days, as it is dominated by large and scheduled loads (i.e., drilling and oil pumping equipment). However, the platform load curve presents short-term power spikes due to the startup and disconnection of individual heavy loads (i.e. compressors, cranes, thermal process equipment). The combined effects of these events lead to a constantly varying correlation between the wind power generation and the platform's consumption; to maintain reliable operations of the overall system there is thus the need for introducing appropriate power management strategies that, depending on the situation, divert or extract electrical power to / from the BESS. Designing the BESS control strategy calls then for solving the associated BESS sizing problem. Sizing the BESS shall in its turn take into account both operation costs (i.e., the operational costs of the power generation system, including fuel consumption, operation and maintenance (O&M), and additional CO2 generation taxes) and investment costs (i.e., installation, commissioning and decommissioning, potential loans). The remainder of this section will thus introduce the various models of the costs above, i.e., the atomic components of what will be our BESS sizing optimization problem. The first model relates then to the GTs operation costs, modeled based on field data about power generation and thermal efficiency of the GTs of the considered platform. More specifically, for each operation point the model estimates the fuel mass flow $\dot{m}_f(i)$ [kg/h] as

$$\dot{m}_f(i) = \frac{P_{GT}}{\eta(i) \cdot LHV} \tag{1}$$

where i indicates the operating point, (i) is the thermal efficiency of the GTs [adim.], $P_{GT}(i)$ the GT power [MW], and LHV is the lower heating value of natural gas [MJ/kg]. The dataset indicates an almost linear relationship between fuel mass flow and GTs power, so that in the following we will approximate this model with the commonly used affine map $\dot{m}_f = a \cdot P_{GT} + b$. Note moreover that in our analyses we consider dt = 1 hour, so that the average power production (in MW) is numerically equal to the hourly produced energy (in MWh). The same is valid for the fuel consumption.

The second model is relative to the produced CO2 emissions, that can be estimated from the fuel flows for each operation point by considering the ideal combustion process of natural gas through a conversion coefficient $\mu_{NG \rightarrow\ CO2}$. Thus, from the fuel sale value C_{NG}, the fuel density at standard temperature and pressure conditions ρ_N, the estimated OM cost [12] and the CO2 tax $C_{co2,tax}$ estimated from [13], it is possible to calculate the levelized cost of the power produced from the GTs, C_f as

$$C_f\left[\frac{€}{MWh}\right] = \Big(\frac{C_{NG}[\frac{€}{Nm^3}]}{\rho_N[\frac{kg}{Nm^3}]} + C_{CO_2 tax}\left[\frac{€}{kg_{CO_2}}\right]\cdot \mu_{NG\rightarrow\ CO2}\left[\frac{kg_{CO_2}}{kg_{fuel}}\right]\Big)\cdot\alpha\left[\frac{kg}{MWh}\right] + C_{O\&M}\left[\frac{€}{MWh}\right] \quad (2)$$

The third model regards the total BESS investment cost, that is divided as in [14] into two factors, i.e., its capacity $C_E[MWh]$ and its power conversion rating $C_P[MW]$,The battery type has been selected based on the lifetime duration [15], [16], power density and the possibility for deep charge/discharge cycles. Moreover, since deep-water offshore OG platforms are typically far from the shore, replacing equipment corresponds to costly and time-consuming operations. Considering the cost and maintenance trends of various battery technologies (summarized in [17]), we thus considered Li-Ion batteries as the most viable option for a BESS in a deep-water OG platform. Finally, the amortization of the initial investment cost C_BESS is split into a daily basis cost (i.e., the Capital Recovery Factor (CRF)) as in [18], and thus as

$$CRF = \frac{r\cdot(1+r)^p}{(1+r)^p - 1} \quad (3)$$

$$C_{BESS} = CRF\cdot(C_P\cdot\hat{P}_B + C_E\cdot\hat{E}_B) \quad (4)$$

where r is the daily interest rate (derived from the annual interest rate), p is the recouping periods (p=365L), where L is the investment lifetime and $\hat{P}_B$ and $\hat{E}_B$ are the BESS power rating and maximum capacity, respectively. For the sake of reproducibility of our results, we collect the values of the abovementioned parameters in Table I.

B. Formulating the BESS sizing and operation problem as a linear optimization problem

To define the BESS sizing problem we consider solving the unit commitment problem using a simplified two stage stochastic linear programming formulation based on deterministic scenarios, that emerge from expert knowledge contained in the available dataset of hourly measured load and wind power profiles for a whole year. The two-stage formulation allows for two different stages of decision variables, the first containing the sizing problem variables ($\hat{P}_B\hat{E}_B$) and the second containing the operating variables that are different based on each operational scenario, as described below. In this way, it is possible to take into account a summary of the possible future weather conditions, so that the many possible outcomes of the platform consumption and wind power generation are considered as equiprobable scenarios to be realized. Then, the scenarios are simultaneously taken into account and included in the objective function through the evaluation of the expected cost based on the sample average approximation (SAA) [19].The envisioned approach to design the maximum capacity of the storage system $\hat{E}_{bat}\geq 0$ and its power rating $\hat{P}_{bat}\geq 0$ for every possible scenario s (N=365) and examined case c (C=40), becomes thus the following: first of all, the unit commitment problem shall consider the following as controllable variables:

- The aggregated hourly power generation from the GTs, i.e., $P^s_{GT}(t)$ for t=1,…,24, s=1,…,365;
- The hourly charging/discharging power profile of the BESS, i.e., $P^s_{bat}(t)$ for t=1,…,24, s=1,…,365 (with $P^s_{bat}(t) > 0$ indicating that the BESS discharges and acts as a generation unit, and $P^s_{bat}(t) < 0$ vice versa);
- The hourly dissipated dump load, i.e., $P^s_{dump}(t)$for t=1,…,24, s=1,…,365. Moreover, the approach shall guarantee the following series of constraints:
- the system depicted in Figure 1 needs to be always in power balance, that means

$$P^s_{bat}(t) + P^s_{GT}(t) = P^s_L(t) - P^s_w(t) + P^s_{dump}(t) \quad (5)$$
$$t = 1\div 24, s = 1\div N$$

- The GTs need to always satisfy box constraints of the form

$$P^c_{GT,min}(t) \leq P_{GT}(t) \leq P_{GT,max}, c = 1\div C \quad (6)$$

- the platform power $P^s_L(t)$ demand needs to be always met;
- the dynamics of the BESS shall be respected. Relative to this, we model the energy levels for the BESS as

$$E^s_{bat}(t) = E^c_{bat,0} + \sum_{i=1}^{t} P^s_{bat}(i), \quad (7)$$
$$t = 1\div 24, s = 1\div N, c = 1\div C$$

TABLE I
TECHNICAL AND ECONOMICAL PARAMETERS

Parameter	Value
Fuel and Combustion Characteristics	
LHV [MJ/kg]	44.19 [12]
NG sale value $C_{NG}\left[\frac{€}{m^3}\right]$	0.24
$\mu_{NG\rightarrow\ CO2}\left[\frac{kg_{co2}}{kg_{fuel}}\right]$ (NG to CO2 combustion ratio)	2.53
CO2 TAX: $C_{co2,tax}\left[\frac{€}{kg_{CO_2}}\right]$	0.07 [13]
Levelized CO2 TAX $\left[\frac{€}{MWh}\right]$	30.55
Gas Turbine Characteristics	
Max GT Power $P_{GT,max}\,[MW]$	15
Min GT power $P_{GT,min}\,[MW]$ (@ Tech. Min. = 20%)	3
Min GT power $P_{GT,min}\,[MW]$ (@ Tech. Min. = 30%)	4.5
Linear Interpolation coefficient $a\left[\frac{kg}{MWh}\right]$	172.5
Linear Interpolation constant b $\left[\frac{kg}{h}\right]$	729.2
O&M cost of GT $C_{O\&M}\left[\frac{€}{MWh}\right]$	11.42
Fuel Cost $C_{NG}\left[\frac{€}{MWh}\right]$	57.74
Levelized cost of GT power $C_f\left[\frac{€}{MWh}\right]$	99.71
Battery Energy Storage System Characteristics	
Investment Lifetime L	15 [15], [16]
Annual Interest Rate	7%
BESS Capacity Cost $C_E\left[\frac{€}{MWh}\right]$	70 [17]
BESS Power Cost $C_P\left[\frac{€}{MWh}\right]$	40 [17]

T where $E_{bat}^{s}(t)$ is the remaining energy capacity of the BESS at any instant t, for every scenario s and $E_{bat,0}^{case}$ is the initial energy capacity of the BESS for every case examined, the latter calculated from a selected initial SoC_0 as

$$E_{bat,0}^{case} = SoC_0^{case} \cdot \hat{E}_{bat} \quad (8)$$

- the energy capacity and the power exchanges of the BESS need also to be box constrained, i.e.,

$$0 \leq E_{bat}^{s}(t) \leq \hat{E}_{bat}, |P_{bat}^{s}(t)| \leq \hat{P}_{bat}, \quad (9)$$
$$t = 1 \div 24, s = 1 \div N$$

- finally, a cycling behavior of the storage system shall be enforced. For this we use the common constraint such that the initial SoC shall be equal to the final one, i.e.,

$$\sum_{i=1}^{24} P_{bat}^{s}(i) = 0, \quad s = 1 \div N \quad (10)$$

Importantly, this implies that the initial state of charge SoC_0 becomes a decision variable that may affect the final results on the design variables $\hat{E}_{bat} \geq 0$ and $\hat{P}_{bat} \geq 0$. This issue will be discussed in detail in Section 3.
The cost function to be minimized for this approach is

$$J = \frac{1}{N} \sum_{s=1}^{N} \sum_{t=1}^{24} C_f P_{GT}^{s}(t) + C_p \hat{P}_B + C_E \hat{E}_B \quad (11)$$

III. Quantitive Results and Discussion

The optimization problem described in the previous section was used to study the impact of the different system parameters, in particular: 1) the technical minimum (TM) associated to the GTs, 2) the size and number of available GTs and 3) the initial state of charge of the BESS. As for the first parameter, TMs indicate the lowest operation level for the GTs: going under this minimum limit should be avoided due to increased mechanical wear [20], in addition to the inability to supply the heat demand, if any. As for the last parameter, we note that most of the studies reported in literature that consider a scenario-based approach for optimization (such as in our case) and that rely on assumption (11) do not provide deep investigations on the impact of its initial numeric value on the final results. However, our ansatz is that SoC_0 is a sensitive quantity that shall be investigated in details, because of the following intuition: the constraint (10) limits the cycling behaviors that the BESS may follow; different values of the SoC may lead to dramatically different strategies of how to charge and discharge the batteries (e.g., assume that all the scenarios start with high wind conditions and low platform power requirements; starting then fully charged is likely to be worse than starting fully discharged). For this we simulate and compare two basic scenarios, one with a lower wind power penetration (WP=50%) and one with a high one (WP=100%), a strategy that enables to examine the effects of increasing wind power integration levels. In particular, the parameter SoC_0 is varied along five equally spaced discrete values that range from initially empty ($SoC_0 = 0\%$) to initially full ($SoC_0 = 100\%$). As for the GTs, we assume that there may be either one or two GTs in operation (i.e., $N_{GT} = 1$, or $N_{GT} = 2$, respectively). Note that the second approach is common in offshore OG platforms, as having two generators increases the system reliability and the possibility of serving critical loads even during emergencies. This reliability need is however diminished when integrating BESSs, since the platform may rely on the BESS remaining capacity for emergency power provision while operating with just one GT. Finally, we specify that the proposed configuration (with the BESS) is compared against the base case where wind power is integrated in the platform, but no storage is included. Consequently, when we refer to the term "CO2 reduction", we imply that an additional CO2 reduction (compared to the case of wind integration) is achieved by introducing the BESS to the platform (when this is instructed form the optimization results) for any WP level, and when we refer to "Daily Benefit" we imply that the daily operational cost of the proposed system (including BESS) is already smaller compared to the one without the BESS. The same concept applies also to the term "Dumped energy reduction". The results can qualitatively be summarized through the following series of considerations:

1) Increasing the wind penetration rate typically implies smaller BESS, when 2 GTs are operating. This is consistent with the intuition that, given that the load of the platform to be covered is limited, with a simultaneous large base load coverage from the 2 GTs, and given that in our formulation dumping excess power is not penalized, then the more wind power is available the less there is the need to store it. Therefore, it can be preferably dumped at no cost (Figure 3). The opposite case is valid when we operate just with 1 GT and thus reduced operating costs. Then a bigger size of the BESS could be promoted despite its increasing investment cost, because the operating cost is already reduced by using 1 GT. (Figure 4)

2) Increasing the number of GTs or their TM (that, in practice corresponds to increase the minimum guaranteed load supplied by the GTs) is, from a BESS sizing point of view, equivalent to having higher wind penetration rate. This means that when the wind farm connected to the OG

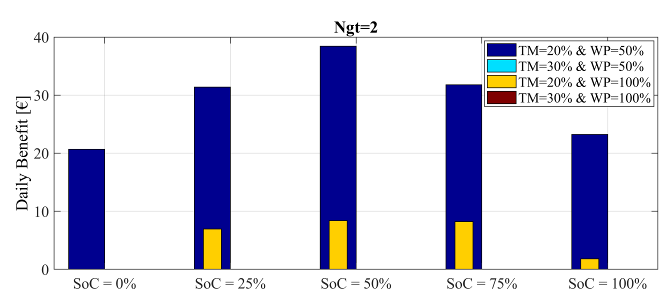

Fig. 3. The expected daily cost for the cases examined, when 2 GT are in operation.

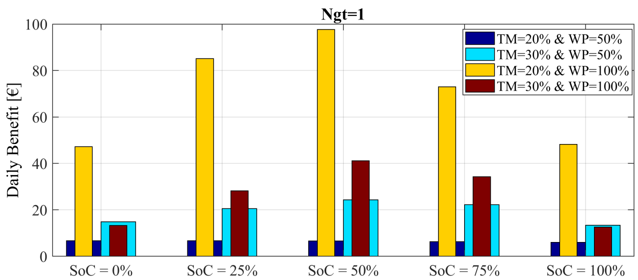

Fig. 4. The expected daily cost for the cases examined, when 2 GT are in operation.

platform and/or the GT generated power is sufficiently large, then implementing a BESS is not economically meaningful. This is depicted in Figure 5 and Figure 6 where for both cases of WP level we do not get a BESS size for the case of increased number of GTs and TM (Ngt=2 TM=30%). Especially from Figure 6 it is possible to observe that we do not get a BESS size even for the case with 2 GT and lower TM (TM=20%) when we start at zero initial state of charge, while for the remaining values we get a result. This can be interpreted as follows: based on our dataset, it is better to start with some initial energy because the system should be able to discharge power before charging, most of the times. On top of that, the higher the wind penetration, the larger the maximum possible expected daily CO2 and dump energy reduction are, with respect to the different cases considered for each WP level. As both variables are directly linked to the fuel consumption of the GT and, hence, to the operational cost, they also follow similar trends as the ones expressed in terms of the "Daily Benefit" variable, as depicted in Figure 5 and Figure 6.

3) The more balanced the initial SoC for the BESS is (i.e., more towards 50% than 0% or 100%), the larger the capacity of the sized BESS becomes and - at the same time - the better economic benefits can be obtained (Figures 3-6). Our intuitive explanation, driven by inspecting the temporal evolution of the SoC during the various daily scenarios, is that the more the BESS can follow positive and negative swings (i.e., can both charge and discharge by serving the simultaneous variations of the platform's load and wind power production) the better economic benefits one gets. The computed power rating of the BESS seems instead almost insensitive to changes in the initial SoC parameter. The reason may be that the platform load and wind power production have fixed maximum ramps amplitudes. Since the load following capabilities are provided by the BESS and the GTs simultaneously, the minimum BESS power rate parameter is more dependent on the GTs power rate rather than the BESS initial SoC.

4) The costlier the BESS is (both in terms of investment and deployment) with respect to the fuel for the GTs, the smaller the final sized BESS becomes. This is intuitive, and as expected. Moreover, the bigger the BESS, the less the overall system will dump energy and the higher the possible CO2 reduction is - again, as expected. Concluding (and summarizing the intuitions above), if one desires to dump less energy, then the best option seems to have more wind capacity, a larger battery storage, use initial SoC levels around 50%, and decrease the usage of the GTs by either reducing their size and/or (if technically possible) their TM. Considering that typically the GTs in an O&G platform are two, due to redundancy reasons, the main conclusion that can be extracted by all the intuitions above is that for the considered platform, and looking only from an electrical energy perspective, there exist combinations of wind capacity and GTs sizing for which it is economically meaningful to substitute one of the GTs with a BESS. The numeric results of the capacity and power rating sizing are summarized in Table II and Table III

TABLE II
SIZING RESULTS FOR OFFSHORE WIND POWER PENETRATION LEVELS OF 50%

	WP=50%							
	Ngt=1				Ngt=2			
	TM=20%		*TM=30%*		*TM=20%*		*TM=30%*	
SoC	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*
0	0.193	0.272	0.193	0.579	0.259	0.773	-	-
0.25	0.193	0.272	0.212	0.799	0.357	1.155	-	-
0.50	0.193	0.272	0.261	0.930	0.374	1.444	-	-
0.75	0.193	0.271	0.262	0.845	0.375	1.164	-	-
1	0.193	0.271	0.193	0.498	0.308	0.853	-	-

IV. CONCLUSIONS

This paper stems from the trend for which wind power and other renewable energy sources will eventually be integrated

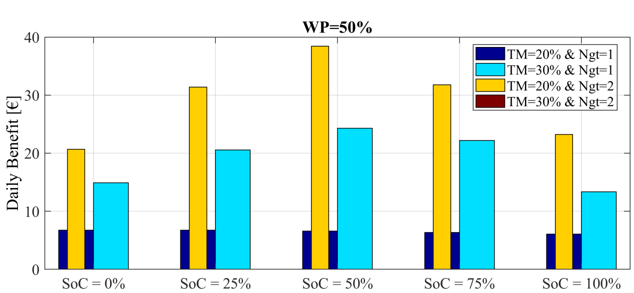

Fig. 5. The expected daily cost for the cases examined, when 2 GT are in operation.

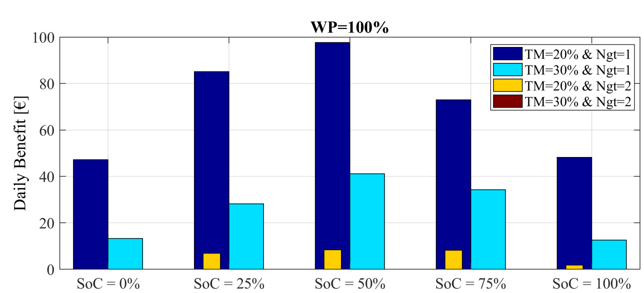

Fig. 6. The expected daily cost for the cases examined, when 2 GT are in operation.

TABLE III
SIZING RESULTS FOR OFFSHORE WIND POWER PENETRATION LEVELS OF 100%

	WP=50%							
	Ngt=1				Ngt=2			
	TM=20%		*TM=30%*		*TM=20%*		*TM=30%*	
SoC	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*
0	0.576	1.727	0.207	0.507	-	-	-	-
0.25	0.874	3.217	0.361	1.084	0.102	0.272	-	-
0.50	0.925	3.701	0.451	1.619	0.110	0.329	-	-
0.75	0.833	2.698	0.359	1.372	0.109	0.327	-	-
1	0.627	1.808	0.164	0.493	0.034	0.067	-	-

TABLE IV
CO2 AND DUMP ENERGY REDUCTION RESULTS FOR OFFSHORE WIND POWER PENETRATION LEVEL OF 50%

	WP=50%							
	Ngt=1				Ngt=2			
	TM=20%		*TM=30%*		*TM=20%*		*TM=30%*	
SoC	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*
0	29.6	0.068	65.2	0.150	90.5	0.207	-	-
0.25	29.6	0.068	89.9	0.206	137.4	0.315	-	-
0.50	28.8	0.066	106.3	0.244	168.1	0.385	-	-
0.75	27.7	0.064	97.0	0.223	139.2	0.319	-	-
1	26.6	0.061	58.4	0.134	101.6	0.233	-	-

into offshore oil and gas platforms, with the objective of reducing their environmental impact. Implementing an energy system that is based on non-dispatchable renewables, in its turn, may benefit from integrating a storage system. This study considered thus the problem of sizing and integrating Battery Energy Storage Systems (BESSs) into such renewables-oriented platforms (in our numerical case study, a wind-based one). The sizing problem was cast and solved in terms of optimizing a linear objective function that weights costs and benefits of both operations and investments. More precisely, as for the operation costs we considered that the platform-wide power system needs to provide both electrical and thermal power, and remains always in power balance (i.e., we imposed the platform's gas turbines (GTs) and BESS to serve the load following needs, and considered that the GTs shall typically respect the minimum power production levels due to efficiency, maintenance reasons and possible heat supply needs). In the formulation, moreover, dumping excess power is not penalized. The performed numerical simulations investigated the dependency of the plant's operational cost to the storage system size, and how these sizing solutions depend on the multiple variables that define the problem, i.e., the wind power penetration rate, the number of the GTs andthe technical minimum of them. Two main conclusions can be drawn from our quantitative results: first, with the used parameters (that, incidentally, are in line with current techno-economic evaluations of typical OG platform systems) it results that implementing a BESS for a platform connected with an existing wind farm is often economically meaningful in terms of reducing operational cost. Moreover, increasing the wind power penetration by 100% (i.e., from WP=50% to WP=100%) leads to 156.3% bigger BESS and a 154.2% decrease of the fuel consumption, which is in turn translated in correspondingly reduced CO2 emissions, dumped energy and increased mean daily benefits. The results moreover suggest an interesting possibility: in platforms that are connected to opportunely big wind farms, instead of using two GTs to serve the electrical loads it may be economically meaningful to consider a configuration with a single operating GT and a BESS.

TABLE V
CO2 AND DUMP ENERGY REDUCTION RESULTS FOR OFFSHORE WIND POWER PENETRATION LEVEL OF 100%

	WP=50%							
	Ngt=1				Ngt=2			
	TM=20%		*TM=30%*		*TM=20%*		*TM=30%*	
SoC	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*	**P** *MW*	**E** *MWh*
0	206.7	0.474	58.0	0.133	-	-	-	-
0.25	372.7	0.854	123.6	0.283	30.3	0.069	-	-
0.50	427.3	0.979	180.0	0.413	36.7	0.084	-	-
0.75	319.6	0.732	150.2	0.344	36.0	0.083	-	-
1	211.2	0.483	54.8	0.126	7.9	0.018	-	-

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