Transient Stability Analysis of Offshore Wind With O&G Platforms and an Energy Storage System

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***Abstract*—The electrification of offshore O&G platforms with offshore wind farms in the off-grid configuration is a business model that is in the process of developing in the North Sea. As such, an integrated system consisting of an offshore floating WTG and O&G production platforms with on-board battery energy storage system (BESS) is proposed in this paper. With this proposed system, four different test scenarios are simulated in ETAP with varying capacity in a modular Battery Energy Storage System (BESS). Results have shown that the transient stability characteristics in a conventional system and a proposed system 1 with only 1MW of BESS, do not meet the IEC standards for O&G platforms. By doubling the capacity of the BESS, ETAP simulation results have shown that a proposed system 2, has a reduction in transient deviation that meets the IEC standard, IEC 61892-1. In addition, the capital expenditure (CapEx) and operational expenditure (OpEx) of proposed system 2 is presented in this paper.**

***Index Terms*—Energy Storage, Microgrids, Oil Platforms, Power Quality, Renewable Energy**

I. Introduction

Throughout the 20th century and today in the marine and offshore industry, offshore wind turbine generation (WTG) has been a prominent and enabling technology to slow down climate change by reducing carbon emissions [1]. Worldwide effort has targeted to reduce annual greenhouse gas (GHG) emissions from the shipping industry by at least 50 percent in 2050, as committed by International Maritime Organisation (IMO) [2]. Furthermore, the Norwegian Ministry of Climate and Environment introduced the Norwegian CO2-tax in 1991, in addition to the EU Emission Trading System regulation, resulting in the oil and gas (O&G) industry paying both CO2-tax and EU ETS pricing for GHG emissions [3]. Norway has also committed to the UN Framework on Climate Change to reduce GHG emissions by at least 40 percent by the year 2030 [4].

These targets to reduce carbon emissions have led to the growing interest in feasibility studies in the research and development of integrating offshore WTG with oil and gas (O&G) platforms to reduce the carbon footprint [5]–[8]. Hence, in the latest development in the marine and offshore industry sector, offshore WTG has been considered as an alternative source of energy for electrification of O&G platforms in the North Sea for the world's first industrial project [9].

In our recent research study, a battery energy storage system (BESS) has been proposed to integrate with an offshore floating wind farm and O&G production platforms for load flow analysis [10]. Hence, this paper seeks to include maximum and continuous transient stability studies on voltage and frequency deviations in the proposed system configuration. Subsequently, the results are compared against the international IEC standards 61892-1 for oil and gas industry [11] as shown in Table I.

TABLE I
TOLERANCES VOLTAGE AND FREQUENCY FOR O&G PLATFORMS

Operation	Voltage Deviation	Frequency Deviation
Maximum Continuous Deviation	+/-6 / -10%	+/-5%
Maximum Cyclic Deviation	+/-2%	+/-0.5%
Maximum Transient Deviation	+/-20%	+/-10%
Maximum Transient Recovery Time	+/-1.5sec	+/-10sec

The outline of this paper is as follows. Section 2 presents the detailed system configurations for the proposed System 1 and System 2 where System 2 has an increased BESS capacity. Four different test scenarios are presented in Section 3. Simulations results for the transient condition where there is a drop in wind speed is presented in Section 4. Section 5 will present the simulation results where the one of the gas turbines is tripped. The summary of simulation results for all test cases, will be shown in Section 6. Section 7 presents the capital expenditure (CapEx) and operation expenditure (OpEx) of the proposed System 2. Conclusions and future work are discussed in Section 8.

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II. PROPOSED SYSTEM CONFIGURATION

In this section, the detailed system configuration for the proposed System 1, consisting of $1MW$ of BESS 1, and proposed System 2, consisting of two modular units that are $1MW$ each in BESS1 and 2, is presented in Figure 1.

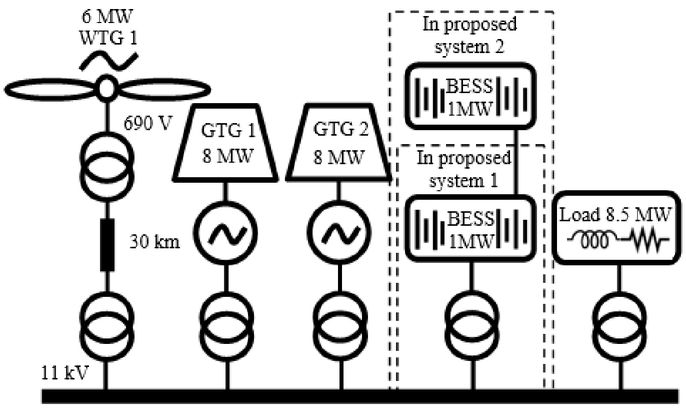

Fig. 1. Proposed offshore integrated system.

Typical O&G platforms are equipped with three platforms consist of a utility and living quarter (ULQ) platform, a processing and heating (CPF) platform and a wellhead (WHP) platform. These platforms are powered by three sets of SCGTs to meet the load requirement of the platforms. In the conventional O&G platforms, two GTs will always be running and one GT will on standby mode. In sufficiently large oil fields, the GTs burn extracted natural gas from the field under normal operating conditions, which powers the three platforms via three main switchboards that are rated at $11kV$. The output voltage is stepped down via integral transformers in distribution panels to $3.3kV$ and $400V$, to power the water injection pumps, gas compressors, drilling unit, utility loads and etc.. [12].

In the conventional system, the O&G platforms are equipped with 2 x SCGTs (20 MW) which has a power factor of 0.8 lagging, where one SCGT acts as an essential GTG 1 and the other serves as GTG 2. The standby GTG has been removed, which allows integration of the BESS 1 (1 MW) and 2 ($1MW$) on-board the O&G platform. The conventional O&G platforms will have a fixed load of around 8.5 MW. The conventional system consists of 1 x 6 MW Siemens (SWT-6.0-154) Permanent Magnet Synchronous Generator (PMSG) floating WTGs connected in parallel, which mirrors the Hywind Park configuration in the North Sea [13]. In the proposed System 1, BESS 1with an output of $1MW$ is installed whereas, System 2 is installed with BESS 1 and 2 with an output of 2 MW. In these two systems, BESS 1 and 2 are installed on-board the platforms and connected to the $11kV$ main switchboard on O&G platforms.

III. TEST SCENARIOS

In this section, four test scenarios are described, as shown in Table II.

TABLE II
FOUR SCENARIOS FOR SIMULATION

Scenario	Event
1	Continuous wind
2	WTG 1 is tripped and GTG 2 is turned on
3	No wind
4	GTG 2 is tripped and WTG 1 is turned on

These four scenarios are simulated in ETAP 19.0 in Sections 4 and 5. In these test scenarios, there is adequate wind speed in Scenario 1 and no wind speed is assumed in Scenario 3. This simulation study is based on the ability of the power system, to maintain electrical power to load when subjected to transient fault such as the loss of a large energy generation source. Usually, the duration of the trip event to study transient stability is around 3 to 5 seconds [14], [15].

For these four test scenarios, the simulation results for the conventional and proposed System 1 and 2 are presented. The simulation results are compared against the international IEC standards, IEC 61892-1 for maximum continuous deviation and maximum transient recovery time, as shown in Table I. For a fair comparison, the conventional system is assumed to have two SCGTs running on-board, which are GTG 1 and GTG 2.

IV. SIMULATION RESULTS:SCENARIOS 1 TO 2

In this section, both the conventional and proposed offshore integrated system discussed in Section II is started in Scenario 1 and switched to Scenario 2. In Scenario 1 where there is continuous wind, the WTG 1 and GTG 1 are supplying electrical power to O&G platforms. In this simulation, GTG 2 is turned on when the WTG 1 is tripped and GTG 1 is running in operation mode.

A. *Case 1: Power Deviation*

In this case study, it can be seen from Fig. 2 that Load (Conventional system) has a significant surge to 1.23 $p.u.$, followed by drop of output power to the load of 1.12 $p.u.$ and the recovery time takes up to about $6s$. In this case, there is transient deviation of 23% from its initial load of 1.02 $p.u.$. In comparison, the Load with BESS 1 (System 1) and Load with BESS 1 and 2 (System 2) have shown a significantly lower surge in the transient period by 18% and 14% respectively.

B. *Case 2: Voltage Deviation*

In voltage deviation, it can be seen from Fig. 3 that there is a significant surge of output voltage of the Conventional system which has a maximum transient deviation of 11% from its initial voltage of 1.03 $p.u.$ and the maximum continuous deviation is +9.4%. This is significantly higher than that in System 1, which has a transient deviation of 9%

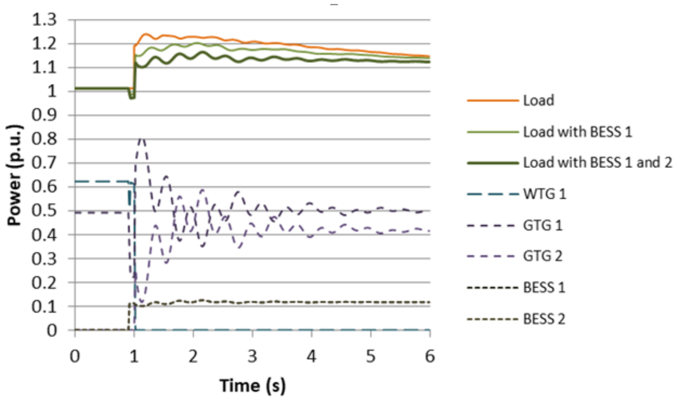

Fig. 2. Power flow in $p.u.$ when WTG 1 is disconnected and GTG 2 is turned on (Pbase =8.5 MW).

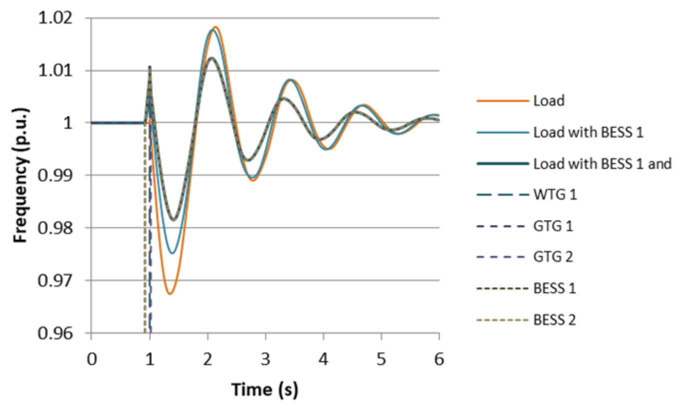

Fig. 4. Frequency in $p.u.$ when WTG 1 is disconnected and GTG 2 is turned on (Fbase =50 Hz).

with continuous deviation of 8.1%. It is also observed that System 2 has the lowest surge in transient deviation of 8% with continuous deviation of 5.7%.

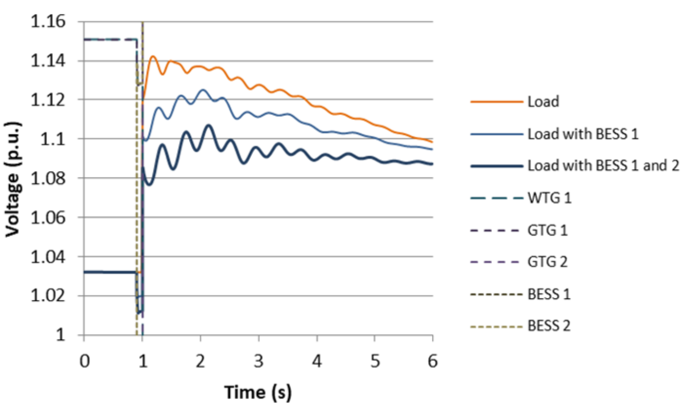

Fig. 3. Voltage in $p.u.$ when WTG 1 is disconnected and GTG 2 is turned on (Vbase =11 kW).

C. Case 3: Frequency Deviation

In Fig. 4, it is shown that the Conventional system has a surge of output frequency which has a maximum transient deviation of 1.8/-3.3% from its initial frequency of 1 $p.u.$ and the maximum continuous deviation is 0.1%. In comparison, System 1 has shown a lower surge in transient period of 1.7/-2.5% with continuous deviation of 0.1%. It is also observed that System 2 has the lowest surge in transient period of 1.2/-1.9% with continuous deviation of 0.05%.

V. SIMULATION RESULTS: SCENARIOS 3 TO 4

In this section, a similar study is conducted when the conventional and proposed offshore integrated system is started in Scenario 3 and switched to Scenario 4. Scenario 3 simulates the no wind condition and both GTG 1 and GTG 2 are turned on to electrify the O&G platforms. In Scenario 4, when the wind speed picks up till rated speed, WTG 1 is turned on, GTG 2 is tripped and GTG 1 is running in operation mode to supply power to the O&G platforms.

A. Case 4: Power Deviation

In this case study, it is observed in Fig. 2 that maximum transient deviation of the Conventional system in load power is 21% as the initial load is 1.23 $p.u.$. The load power is maintained around 1 $p.u.$ after the transient period with maximum continuous deviation is 1%. A similar surge is observed in System 1 with 22% in maximum transient deviation. On the other hand, only 1% in maximum transient deviation is observed in System 2 as BESS 1 and 2 are switched on throughout Scenarios 3 and 4 and this maintains quality power to the load during the transient period.

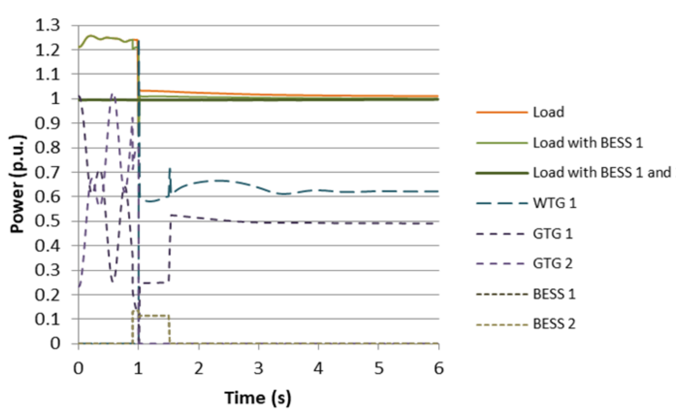

Fig. 5. Power flow in $p.u.$ when GTG 2 is disconnected and WTG 1 is turned on (Pbase =8.5 MW).

B. Case 5: Voltage Deviation

In voltage deviation, it can be seen from Fig. 3 that there is a significant dip of output voltage to 0.94 $p.u.$ and surge back of 1.04 $p.u.$ to the load in the Conventional system. In this case, it is shown that the output load power profile has a maximum transient deviation of -20% from its initial voltage of 1.14 $p.u.$ and the maximum continuous deviation is -10%. System 1 has shown that there is a significant lower surge in transient deviation of 19% with continuous deviation of -11%. However, it is observed that System 2 provides the lowest surge in transient period of 18% with continuous deviation of -9.5%.

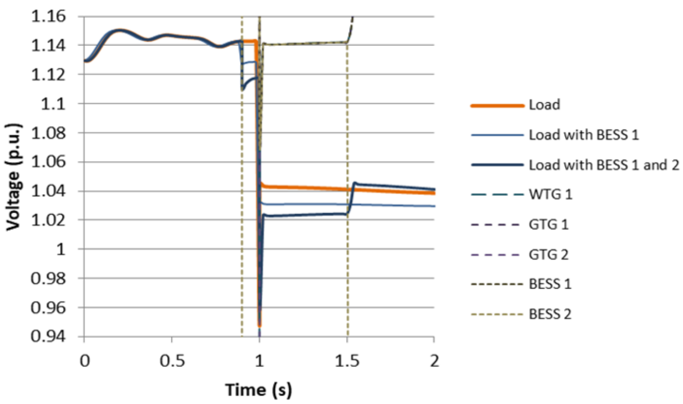

Fig. 6. Voltage in $p.u.$ when GTG 2 is disconnected and WTG 1 is turned on (Vbase =11 kW).

C. Case 6: Frequency Deviation

In frequency deviation of the Conventional system, it can be seen from Fig. 4 that there is a surge in maximum output frequency of 1.01 $p.u.$ with dip in maximum output frequency of 0.99 $p.u.$ to the load and the recovery time takes up to about 4s. In this case, it is shown that the output load power profile has a maximum transient deviation of 1/-1% from its initial frequency of 1 p.u. and the maximum continuous deviation is 0.01%. System 1 has shown a significant surge in transient period of 1.9% with continuous deviation of 0.01%. In comparison, System 2 has showed the significant highest surge and dip in transient period of 2.9/-3.4% with continuous deviation of 0.01%.

VI. Summary of Results

The summary of simulation results from Sections IV and V of power, voltage and frequency deviations are presented in Fig. 8. In the simulation for frequency deviation, the Conventional system and proposed System 1 and 2 are within the maximum frequency deviation. In the simulation for voltage deviation, Section IV-B has shown that all systems are within the maximum transient voltage deviation but the Conventional system and proposed System 1 did not meet the maximum continuous voltage deviation of 6% after 1.5s. In addition, Section V-B has shown that the Conventional system has a maximum voltage deviation of -20% which is barely meeting the IEC standard, as compared to proposed System 2 which can be lowered to -18%.

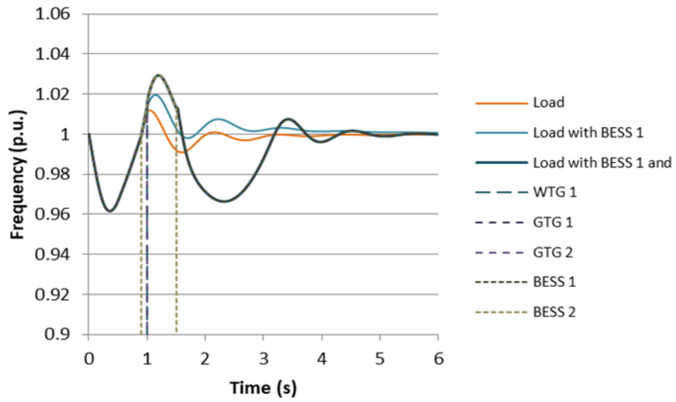

Fig. 7. Frequency in $p.u.$ when GTG 2 is disconnected and WTG 1 is turned on (Fbase =50 Hz).

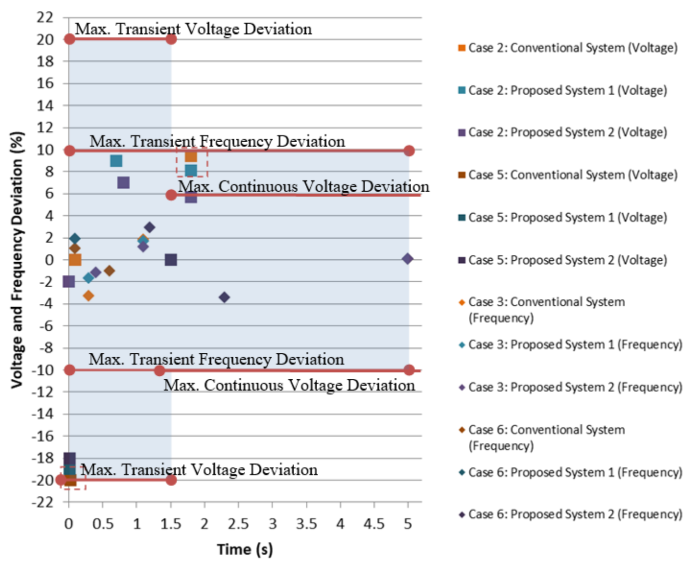

Fig. 8. Frequency in $p.u.$ when GTG 2 is disconnected and WTG 1 is turned on (Fbase =50 Hz).

VII. Cost Analysis of Proposed System 2

The cost of proposed System 2 is based on the CapEx and OpEx from the cost analysis in United States (US) [16]–[19]. The mathematical function of CapEx cost of GTG, GTG_C on-board the O&G platform is written as follows:

$$GTG_C = [GT_{10MW}(2)(1415)], \quad (1)$$

where GT_{10MW} represents 10,000kW and GT is approximately $1415 per kW.

Capital cost of $WTG, WTGC$ on-board the platform can be calculated in the following equation:

$$WTG_C = [WTG_{10MW}(2870)], \quad (2)$$

where offshore WT_{6MW} represents 6000kW and GT is approximately $2870 per kW.

BESS has the lifespan of 10 years and would require double times of the capital cost for lifespan of 20 years. Thus, Capital cost of $BESS, BESS_C$ on-board the platform can be calculated in the following equation:

$$BESSC = [BESS_{1MW}(1930)(2)(2)], \quad (3)$$

where $BESS_{1MW}$ represents $1000kW$ and GT is approximately 1937 \$ per kW.

$OPEXofGTG_{1,2}$ on-board the platform can be calculated as follows:

$$GTG_{O\&M} = [GT_{10MW}(1930)(2)(89.4)], \quad (4)$$

where GT_{10MW} represents 10 $000kW$ and OPEX of GT is approximately 89.4 \$ per kW.

$OPEXofWTG, WTG1$ on-board the platform can be calculated as follows:

$$WTG_{O\&M} = [WTG_{6MW}(80)], \quad (5)$$

where $WT6MW$ represents $6000kW$ and O&M cost of WT is approximately 137 \$ per kW.

BESS has the lifespan of 10 years and would require double times of the capital cost for lifespan of 20 years. Thus, Operational and Maintenance (O&M) cost of $BESS$ on-board the platform can be calculated as follows:

$$BESS_{O\&M} = [BESS_{1MW}(10)(2)(2)], \quad (6)$$

where $BESS_{O\&M}$ represents $6000kW$ and O&M cost of WT is approximately 10 \$ per kW.

The CapEx and OpEx are shown in Fig. VII, which comprise of GTG, WTG and BESS for proposed System 2. Both of the pie charts have revealed that GTG has the highest cost of 53% in CapEx and 78% in OpEx. As such, BESS has the lowest cost 15% in CapEx and 1% in OpEx.

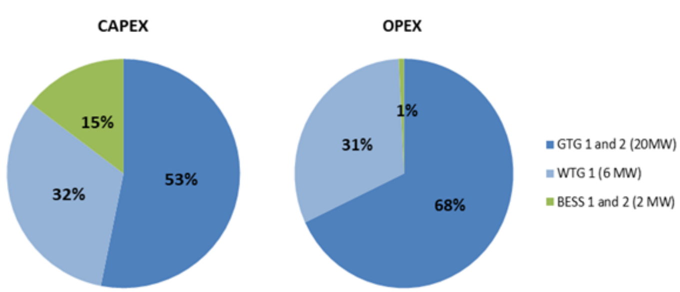

Fig. 9. Cost analysis of CapEx and OpEx of proposed system 2.

VIII. CONCLUSION

In this paper, an integrated system consisting of an offshore floating WTG and O&G production platforms with on-board battery energy storage system (BESS) was studied, Using four test scenarios, ETAP simulations were conducted for the Conventional O&G platform with 2 GTGs, the proposed System 1 with BESS that is integrated with offshore WTG and O&G platforms and a proposed System 2 with a both BESS 1 and 2 integrated with offshore WTG and O&G platforms. Simulation results on transient stability between the Conventional system, proposed System 1 and 2 are presented. Simulation results have shown that proposed System 2 demonstrated significant improvement in power quality, as compared to the conventional system. From Scenario 1 to 2, it is shown that the proposed System 2 has lowered the maximum voltage transient from 11% to 5.7% and maximum transient frequency deviation of 1.8/-3.3% . Moreover, only the proposed System 2 fulfilled the continuous voltage deviation where Conventional system and proposed System 1 have failed to meet. In addition, switching from Scenario 3 to 4 has shown that the Conventional system barely meets the IEC standards with a maximum voltage deviation of -20%, which can be lowered to -18% by proposed System 2. As such, the proposed System 2 with a larger BESS capacity is capable of meeting the transient stability requirements in the IEC standards 61892-1 and provide quality energy enhancement for the oil and gas industry. In the cost analysis section with propsed System 2, pie charts have revealed that BESS has the lowest CapEx and OpEx, as compared with GTG and WTG.

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REFERENCES

[1] D. Zhang, Z. Xu, C. Li, R. Yang, M. Shahidehpour, Q. Wu, and M. Yan, "Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions," *The Electricity Journal*, vol. 32, no. 6, pp. 7–12, 2019.
[2] B. Comer, C. Chen, and D. Rutherford, "Relating short-term measures to imo's minimum 2050 emissions reduction target," in *international council on clean transportation*, 2018.
[3] E. Gavenas, K. E. Rosendahl, and T. Skjerpen, "Co2-emissions from norwegian oil and gas extraction," *Energy*, vol. 90, pp. 1956–1966, 2015.
[4] C. Bücker, U. Jenisch, S. Lutter, N. Matz-Lück, J. Messner, S. Petersen, L. H. Rüpke, U. Schwarz-Schampera, K. Wallmann, C. Berndt *et al.*, "World ocean review 2015: living with the oceans 3. marine resources-opportunities and risks," 2014.
[5] S. Sanchez, E. Tedeschi, J. Silva, M. Jafar, and A. Marichalar, "Smart load management of water injection systems in offshore oil and gas platforms integrating wind power," *IET Renewable Power Generation*, vol. 11, no. 9, pp. 1153–1162, 2017.
[6] M. Korpås, L. Warland, W. He, and J. O. G. Tande, "A case-study on offshore wind power supply to oil and gas rigs," *Energy Procedia*, vol. 24, pp. 18–26, 2012.
[7] M. L. Kolstad, K. Sharifabadi, A. R. Årdal, and T. M. Undeland, "Grid integration of offshore wind power and multiple oil and gas platforms," in *2013 MTS/IEEE OCEANS-Bergen*. IEEE, 2013, pp. 1–7.
[8] A. R. Årdal, T. Undeland, and K. Sharifabadi, "Voltage and frequency control in offshore wind turbines connected to isolated oil platform power systems," *Energy Procedia*, vol. 24, pp. 229–236, 2012.
[9] Å. S. Tveiten and B.-T. Tangerås, "Hywind tampen, project npv calculation with and without subsidies," Master's thesis, University of Stavanger, Norway, 2018.
[10] J. Z. Tee, K. H. Tan, I. L. H. Lim, K. Zhou, and O. Anaya-Lara, "Integration of offshore wind with o&g platforms with an energy storage system," in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*. IEEE, pp. 1–5.

[11] *IEC Std. for Mobile and fixed offshore units, Electrical installations, General requirements and conditions*. BS IEC 61892-1:2019, 2019.
[12] M. Bothamley *et al.*, "Offshore processing options for oil platforms," in *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers, 2004.
[13] D. Nilsson and A. Westin, "Floating wind power in norway-analysis of opportunities and challenges," *CODEN: LUTEDX/TEIE*, 2014.
[14] J. I. Marvik, E. V. Øyslebø, and M. Korpås, "Electrification of offshore petroleum installations with offshore wind integration," *Renewable energy*, vol. 50, pp. 558–564, 2013.
[15] J. Z. Tee, K. H. Tan, I. L. H. Lim, K. Zhou, and O. Anaya-Lara, "Techno-economic analysis and battery storage placement in grid-connected photovoltaic (pv) system," in *2019 EUPVSEC Conf.* EUPVSEC, pp. 1–5.
[16] . U. E. I. Adminstration, "Distributed generation and combined heat & power system characteristics and costs in buildings sector," Indepenent Statistics & Analysis, Tech. Rep., 2017.
[17] W. D. Musial, P. C. Beiter, P. Spitsen, J. Nunemaker, and V. Gevorgian, "2018 offshore wind technologies market report," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2019.
[18] T. J. Stehly and P. C. Beiter, "2018 cost of wind energy review," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2020.
[19] K. Mongird, V. V. Viswanathan, P. J. Balducci, M. J. E. Alam, V. Fotedar, V. S. Koritarov, and B. Hadjerioua, "Energy storage technology and cost characterization report," Pacific Northwest National Lab.(PNNL), Richland, WA (United States), Tech. Rep., 2019.