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OPERATIONAL PLANNING AND POWER MANAGEMENT SYSTEM FOR OFFSHORE PLATFORM WITH WIND ENERGY SUPPLY – IMPACTS ON CO_2 REDUCTION AND POWER QUALITY

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ABSTRACT

This paper considers the operation of offshore oil and gas platform energy systems with energy supply from wind turbines to reduce CO_2 emissions. The study is conducted through simulations of a case that reflects a "typical" oil and gas platform on the Norwegian Continental Shelf, with energy demand for gas lift and gas export compressors, separator train, oil export pump, water injection pumps, accommodation and utilities.

The study case with wind energy is compared to a base case with only gas turbines, and both cases have been implemented and analysed in multiple simulation tools. Results have been compared and used to assess the impact of wind integration on CO_2 emissions, gas turbine fuel usage and wear and tear, power system frequency stability and other key indicators.

The results are consistent between the modelling tools, and indicate a potential for CO_2 emission reduction of 20–25 % for this case with a wind energy share of 26 %. There is some variation depending on the amount of reserve power required and the rules for when to start up and shut down gas turbine generators.

1 Introduction

Greenhouse gas emission reductions from offshore oil and gas installations require new solutions for the energy supply. In this paper we consider emission reductions through the integration of offshore wind turbines, working in combination with gas turbines in isolated offshore energy systems. The inclusion of wind energy adds variability and reduces inertia, which affects operational planning, power quality and system stability, and therefore needs to be carefully assessed to ensure efficient and safe operation.

Existing offshore oil and gas installations typically have an energy system isolated from the outside world and supplied by gas turbines running on natural gas fuel extracted locally or provided via pipeline from a neighbour platform. In addition to supplying both electricity and heat demand, the fast response and high ability for control of these gas turbines have ensured safe and stable power supply satisfying power quality requirements. With abundant natural gas supply and low taxes, this has been a very convenient and low cost option.

Presently, this is changing. With increased emphasis on CO_2 emission reductions, increasing CO_2 taxes and targets for emission reduction, alternatives are needed. In Norway, CO_2 emissions from gas turbines installed offshore constitute about 20 % of the country's total greenhouse gas emissions [1]. Reducing these emissions are clearly important to reach national targets and international commitments.

Some emissions reductions are possible through reduced energy demand due to improved efficiency [2, 3], but by itself this can never give the big reductions needed. What is clearly needed,

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is a shift to energy supply that does not give CO_2 emissions. Gas turbines with carbon capture and associated infrastructure for transport and storage is theoretically possible [4,5], but feasibility and costs for individual platform installations are rather uncertain. Hydrogen-based fuels may be mixed in with natural gas to reduce emissions, or may replace natural gas completely with modified gas turbines [6] or a shift to fuel cells. This may become feasible options in the future although there are no such installations at present. Energy supply via power cables from shore can completely eliminate the need for offshore gas turbines, and this is an option installed already for many Norwegian oil and gas fields. [7, 8] However, cables are expensive, and although this option eliminates *offshore* emissions, it increases power demand and therefore emissions *onshore*. However, since onshore power plants are more efficient than offshore gas turbines, and the onshore European energy mix is gradually becoming greener, the net effect is in most cases significant emission reductions.

Finally, one alternative for local emission-free energy supply to oil and gas platforms that is well advanced is the integration of wind turbines. The Hywind Tampen development [9], to become operational in 2022, has such a solution where 11×8 MW floating wind turbines will supply power to the Snorre and Gullfaks oil and gas fields.

Wind energy is of course variable, and cannot be controlled at will. The variability needs to be balanced by gas turbines in a hybrid system, or by sufficiently large energy storage, perhaps in combination with flexible operation of injection pumps and other loads [10]. Therefore, new strategies for operating the energy system are needed to ensure a balanced energy system with minimal costs and emissions. Both new operating strategies [11, 12] and new solutions for maintaining power stability and power quality are needed [13, 14, 15, 16].

In this paper we analyse an isolated offshore oil and gas platform with energy supply from wind turbines in combination with gas turbines, as illustrated in Figure 1. The paper extends previous work by considering a new case and by combining multiple analysis tools to gain insight in various aspects of energy and power system operation.

Firstly, an operational optimisation model (Oogeso) is used to simulate and assess the impact of different system configuration and operational planning strategies. It applies a rolling horizon mixed-integer linear programming approach, using forecasts for energy demand and supply to find the optimal generator power setpoints and start/stop signals. *Secondly*, we use ABB's process power simulator (PPSim), which simulates dynamic electrical responses including control functions representing a power management system (PMS). It is used to investigate the impact of different control algorithms on emissions, gas turbine generator wear and tear, short-term stability and longer-term energy efficiency. The PMS has a range of potential strategies to obtain both the wanted reduction of emissions, but also keeping a stable operation in this complex system. *Thirdly*, an electrical

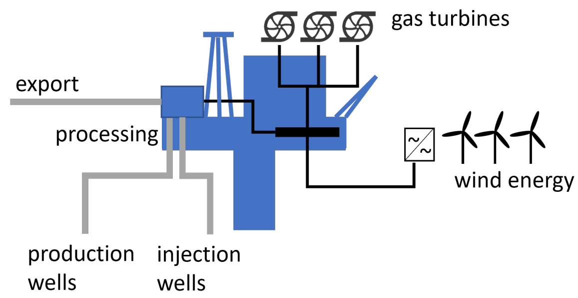

FIGURE 1. Offshore oil and gas platform with isolated energy system supplied partly by wind energy

model implemented in Digsilent PowerFactory is used to assess electrical stability under events such as load steps and component failures.

2 Analysis models

This section describes the different models used in this study.

2.1 Oogeso

For analyses of operational performance and how different system configurations and operating strategies influence emissions and other key indicators, the *Offshore Oil and Gas Energy System Optimisation* (Oogeso) tool [17] has been applied. This is a tool (still in development) that provides a flexible and relatively easy way to model different offshore energy systems with the connections between different energy carriers such as electricity, gas and heat included. At its core it has a rolling-horizon optimisation problem that is solved at regular time intervals. Conceptually it performs operational optimisation. However, the main intended use of the tool is as a simulation tool to address what-if questions, such as here: What if we add wind turbines to the power supply, how does this affect emissions and gas turbine wear and tear? The optimisation part may be thought of as a computational technique for obtaining realistic system behaviour in operation.

The tool can be used to model a multi-energy system or the electric system only, for a single platform or multiple platforms connected together. A multi-energy representation is relevant if we want to consider e.g. heat supply both from gas turbine waste heat recovery and electric boiler or heat pump, or the links between energy consumption and oil and gas flow rates, which is particularly important if we include the possibility to allow variable production rates to alleviate some of the challenges with variable wind energy supply. In the present study we consider fixed energy demand, but include the modelling of the oil and gas flows for completeness.

2.2 PPSim

To gain further insight regarding how electrical system dynamics and power management controls affect the results obtained above, the same simulation case has been studied in a simulator including realistic behaviour of the power management system (PMS).

The simulator used for these dynamic simulations with PMS is the ABB Process Power Simulator (PPSim) [18], which simulates steady state and system dynamic responses for voltages, currents, frequencies, and power flows. The simulator provides equipment dynamics for typical electrical components and represent typical component interfaces. This includes single phase positive sequence solution and accurate voltages, power flows and frequencies at all buses. Dynamics influenced by generator, automatic voltage regulation, governor, engine and loads are included.

With the use of Initial Conditions (IC) to save and reload operations points and the ability to run and rerun scenarios with variations of power network and control, the simulator can illustrate the trade-offs between network design and operational philosophy.

The simulator is intended for use throughout the lifecycle of a plant:

1. Early-stage testing of control concepts by implementing control logic in simulation.
2. Connecting ABB 800xA simulator with control system for detailed engineering and FAT.
3. Operator training and test of modifications while the plant is in operation.

In the present study, only some of the PPSim capabilities have been used.

2.3 PowerFactory

To assess electrical system behaviour in more detail, the widely-used PowerFactory software by DIgSILENT has been applied. The study case (see below) was implemented in RMS domain, allowing to study power flow, electro-mechanical transients, outer-level controls, stability indices, short circuit levels, etc.

3 Study case

The analysis in this paper is based on a study case that is described in the following.

3.1 Case description

The oil and gas platform studied here is the *Low Emission Oil and Gas Open* (LEOGO) reference platform [19], which is a hypothetical but realistic case representative of a typical oil and gas platform on the Norwegian Continental Shelf. It is suitable as a study case since the specification is well defined and the data is publicly available.

TABLE 1. Simulation cases

Base case	Wind case
3×21.8 MW gas turbines	3×21.8 MW gas turbines 3×8 MW wind turbines

The LEOGO platform is meant to represent an oil and gas platform that relies on gas lift to assist well-stream flow from the reservoir through the wells up to the platform, and water injection to maintain reservoir pressure. The gas-over-oil (GOR) ratio is 500 and the water cut (WC) is 0.6. Daily oil and gas export rates are about $8600\,\text{Sm}^3/\text{day}$ and $4.3\times10^6\,\text{Sm}^3/\text{day}$ respectively. Electric power demand is about 40 MW, with the main loads being gas lift and export compressors, oil export pumps, water injection pumps, and accommodation and utility loads. Heat demand is about 8 MW. Power supply, in the base case, is provided by three 28 MVA gas turbines.

The LEOGO platform as represented in the Oogeso tool is illustrated in Figure 2.

The electrical model includes major components in main busbars (11 kV), utility busbars (0.69 kV), living quarters (0.4 kV) and drilling busbars ($1.3\,\text{kV}_{\text{DC}}$) including component dynamics (gas turbines, induction motors). The dymanics of the variable speed drive motors are not represented, as it is assumed that they are sufficiently decoupled from the 50 Hz system by their back-to-back converter interfaces. Details on the electrical model can be found in [19].

The three 8 MW wind turbines are modelled as direct drive type-4 wind turbines. Their model attempts to resemble the Siemens Gamesa SG 8.0-167 DD wind turbine, as these are used for the Hywind Tampen project [9]. However, as no model of the SG 8.0-167 DD is openly available, the similarity is limited to the general parameters like power rating, turbine type, voltage level, e.t.c. The details of the implemented wind turbine model just resemble a generic wind turbine.

As this model contains no proprietary information, it has been made public and can be freely downloaded [19], used and modified.

In the present study, two variations based on the LEOGO specification are considered: The *base case* representing a traditional system with power supply only from gas turbines, and a *wind case* with the addition of 3×8 MW wind power, see Table 1.

3.2 Simulation of normal operation

Normal operation was simulated with Oogeso and PPSim for a one-week period using time-series profiles for wind speed variation and variations in oil and gas production as indicated in Figure 3.

An important system parameter is the required online power

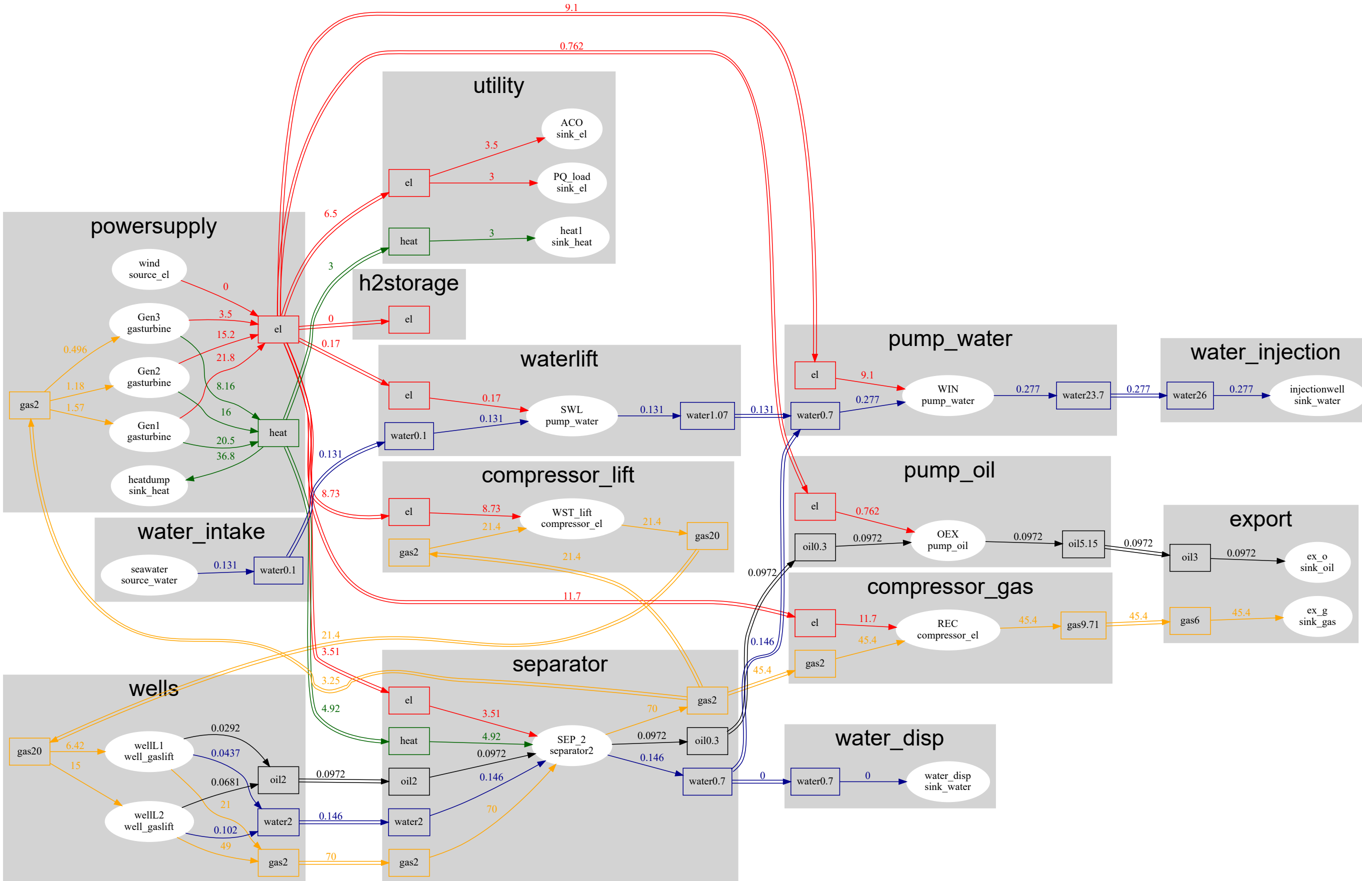

FIGURE 2. Overview of the LEOGO model implemented with Oogeso. Edge colours represent different energy carriers. Numbers on edges indicate flow rates in MW or Sm^3/s) in the base case.

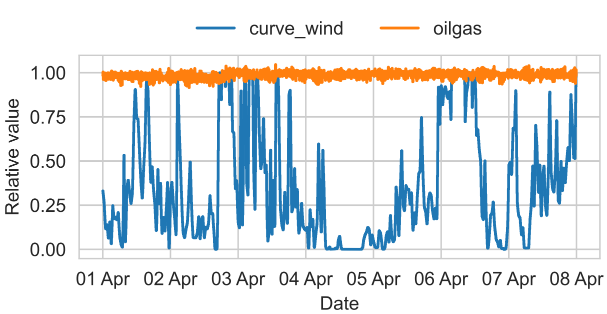

FIGURE 3. Time series profiles for wind forecasts and oil and gas production (wellstream flow rate)

reserve (spinning reserve), that is available to balance unforeseen variations in demand and supply due for example to a motor startup or wind forecast error. In traditional systems, only gas turbine generators provide reserve, but in general both unused generator capacity, load reduction potential and energy storage may contribute to the reserve. The reserve in an isolated offshore energy system is typically not sufficient to cover all demand in case of generator failure or other similar rare events. In those cases, frequency-based load shedding will be activated.

The Oogeso model considers operational planning close to real-time, but not the real-time control actions. The PPSim model is capable to simulate this, although it has not been done in the present study.

3.3 Simulation of loss of generation events

The event simulated with the electro-mechanical PowerFactory model is the loss (disconnection) of a gas turbine. Both the base case and the wind case are simulated, with the wind case further split in three variations, with different wind speeds: One variation with strong winds and full wind turbine power output,

TABLE 2. Main simulation parameters

Parameter	Value
Power demand	40 MW
Heat demand	8 MW
Gas turbine generator max power	21.8 MW
Gas turbine generator min power	3.5 MW
Gas turbine generator startup time	30 min

TABLE 3. Oogeso simulation parameters

Parameter	Value
Time resolution	5 min
Time between each optimisation	30 min
Planning horizon	120 min
Reserve required	5 MW

one with 80 % wind power output and a third with 60 % wind power output.

In the base case, all three gas turbines operate of which one is lost (disconnected). In the wind case, only two gas turbines operate, of which one is lost, and the other having to handle the incident alone. The wind turbines, equipped with more-or-less standard wind turbine control, operate with maximum power tracking without upward headroom, and do not have special control features like virtual inertia which could assist the remaining gas turbine in handling the disturbance. Load shedding is not implemented yet.

4 Simulation results

This section presents results from simulations of the offshore oil and gas platform described above. The first part shows results using the quasi-static *Oogeso* operational optimisation tool described above. The second part shows results from dynamic simulations using the *PPSim* power management system simulation tool. Results from these are then compared. The third part shows results of simulation of special events using the *PowerFactory* tool.

4.1 Operational optimisation with Oogeso

For the operational optimisation simulations, time-steps of 5 minutes were used. This resolution is high enough to account for wind power variability and gas turbine generator start-up delays. Further key input parameters are given in Table 2. The full data and simulation settings are provided with the LEOGO dataset [19]. The main observations from the simulations are elaborated in the following.

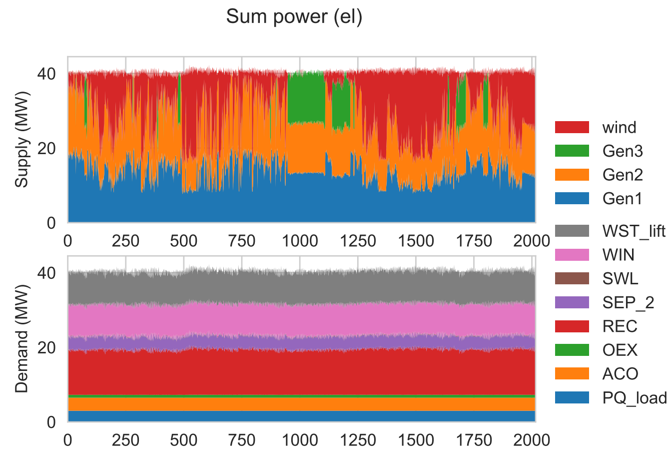

FIGURE 4. Power supply and demand (wind case)

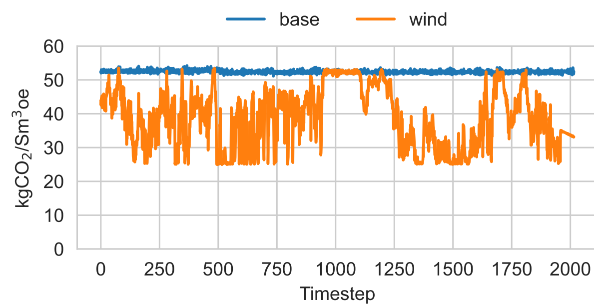

FIGURE 5. CO_2 emission intensity

In the base case, a more or less constant power demand is supplied by three gas turbine generators. For the wind case, shown in Figure 4 the demand is the same, but variations in the supply reflect the wind power variations (Figure 3). We see that the third gas turbine generator (Gen3) is turned on only when there is too little wind power available.

CO_2 emission intensity (Figure 5), i.e. kilograms of CO_2 emissions per exported standard cubic metre of oil equivalents, is around 52 $kgCO_2/Sm^3oe$ with small fluctuations due to the fluctuating demand, and hence gas turbine power supply. Wind power reduces gas turbine fuel usage and therefore emissions. The emission reduction obtained in these simulations are on average 25 %,

Figure 6 shows the scheduled wind power output compared to the wind power predictions. The "forecast" curve represents predictions obtained more than an hour ahead, and is used for planning ahead, while the "nowcast" curve represents updated predictions closer to the operating time. We see that the wind power output follows the nowcast prediction. In some circum-

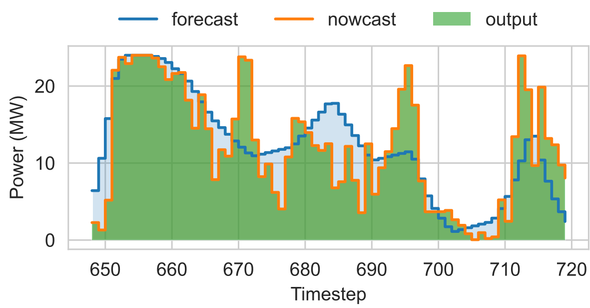

FIGURE 6. Wind power output vs forecast

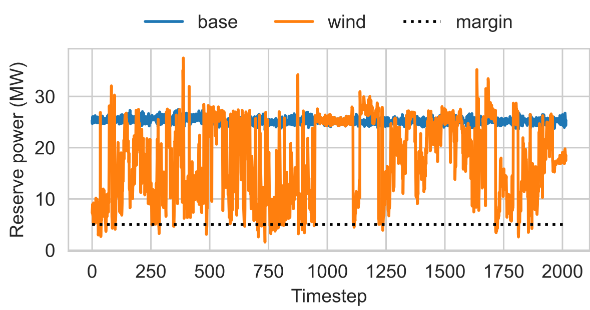

FIGURE 7. Available reserve compared to the reserve margin required

stances, ramping rate limitations or other constraints may limit the wind power output such that it is less than the available power.

The curves presented above are *scheduled* power updated at 5 minute intervals. However, electricity demand and wind power varies on shorter time-scales in ways that can not be fully predicted. That is why there is a power reserve requirement. In our simulations, this requirement is that there should always be at least 5 MW non-scheduled online free capacity to accommodate for these fluctuations. This is shown in Figure 7, for both the base case and wind case. In the base case, three gas turbines are always online, and with a combined capacity of 65 MW supplying a load of about 40 MW they provide 25 MW reserve power. In the wind case, there is more variation since the number and loading of the gas turbines varies a lot. However, we see that the reserve is generally above the margin required. The reason the reserve is sometimes below the margin is the fact that the optimisation problem does not enforce the reserve requirement for the first few time-steps in each rolling optimisation. This is done to allow the reserve to help balance out the deviation between forecast and nowcast wind power. In other words, the free reserve can drop below the specified margin when some reserve capacity is actually in use.

4.2 Power management and power quality analysis with PPSim

The LEOGO reference platform has also been configured in PPSim with both electrical system and relevant plant control. The lower part of Figure **??** shows an overview of the electrical configuration. Relevant actuators are included such as circuit breakers. All components are represented with appropriate dynamic models, e.g. gas turbine generator model also including temporary over-load capability. The upper part of Figure **??** shows the plant control included in the simulation, consisting of both a Power Management System (PMS) and a wind power plant controller. The purpose of the wind power plant controller is to make the wind power plant act more like one unit.

Power balance is an essential task of the PMS, meaning that it must secure sufficient generation capability available for the given load and wind situation. This is done through automatic start and stop of generators and through load reduction, to ensure that enough reserve capacity is available. If enabled, the control starts a generator when the total non-scheduled online free capacity (spinning reserve) is below 4 MVA, with a startup delay of 900 s, and stops when reserve is above 7 MVA. Note that this differs slighly from the fixed 5 MW threshold used with Oogeso. The load reduction control can reduce load on the 3 variable speed water injection pumps. It reduces load with a rate of 0.1 p.u. per second with a minimum load of 0.05 p.u. to reduce the need of start and stop of generators.

The functions use a wind power production forecast as input. The forecast model is currently simple with only one forecast value updated every 10 minutes. It has also been assumed that a perfect forecast is given.

The base case with only gas turbine generators (GTGs) and the wind case have been analysed. The wind case is subdivided into three variations:

Wind 0: 3GTGs, 3WTGs – without starting or stopping GTGs
Wind 1: 3GTGs, 3WTGs – including starts and stops of GTGs
Wind 2: 3GTGs, 3WTGs – including starts and stops of GTGs and load reduction

For the wind case, and with the perspective of reducing emissions, the goals of the PMS on the platform can be summarised in four points: 1) Minimise fuel usage of gas turbine generators. 2) Maximise use of power from wind. 3) Keep a stable operation. 4) Ensure sufficient availability of energy.

Reaching these goals is dependent on proper control of power generation. The PMS has a range of potential strategies to obtain both the wanted reduction of emissions whilst maintaining a stable operation in this complex system. The challenge is to tune the control algorithms, so they operate well together for both the short-term stability and longer-term energy efficiency.

The results from the simulations is presented in Figure 9. Without further control, the three wind turbines reduce the CO_2 emissions by 17.2 %. Adding control of gas turbine starts and

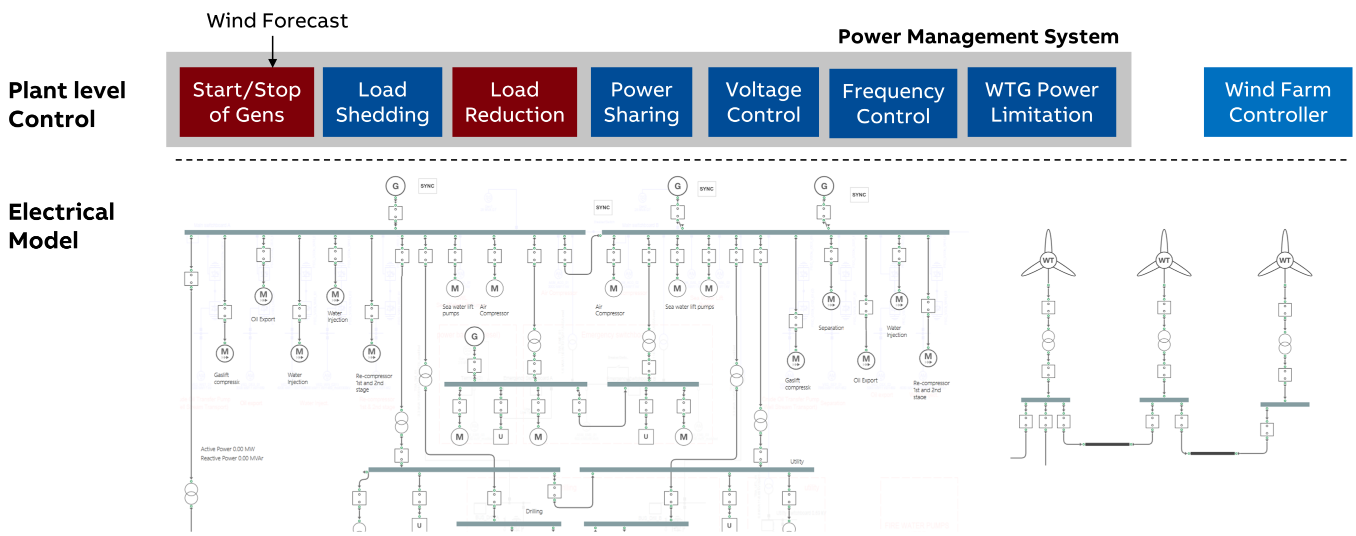

FIGURE 8. Overview of implementation of LEOGO Platform in PPSim. Lower part shows screen shot of part of the electrical configuration in PPSim, while upper part (plant level control) illustrates the control included.

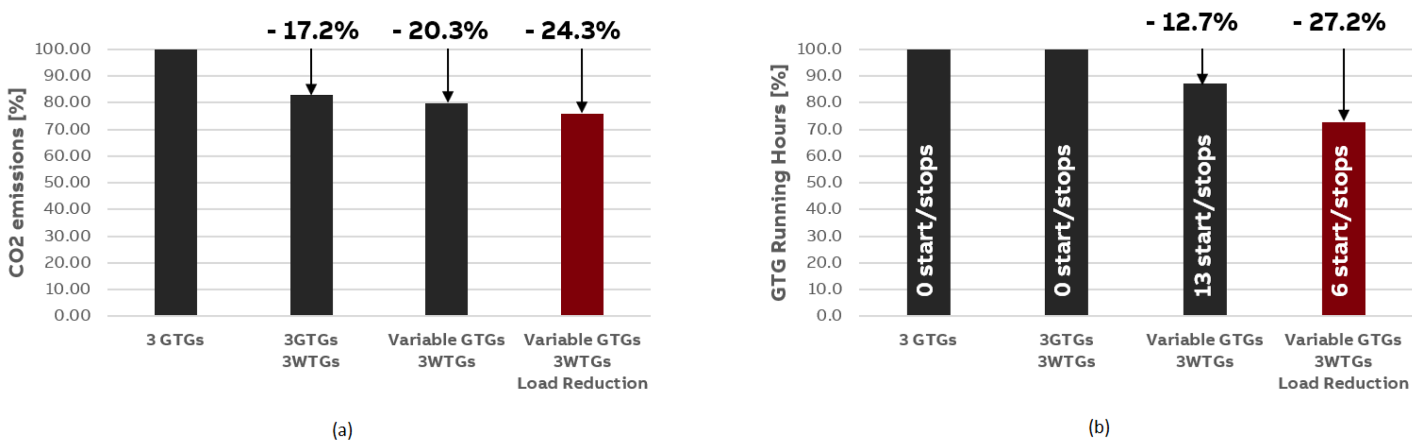

FIGURE 9. Overview of main KPIs for the different PPSim scenarios. (a) CO_2 emission comparison, (b) GTG running hour comparison

stops reduces this further to 20.3 % and adding load reduction contributes to a further reduction to 24.3 % of the original base case. For the base case and the wind case variation 0 (without starting and stopping GTGs), the generator running hours are 100 % of the time. When the flexibility of starting and stopping GTGs is included (variation 1), the running hours is reduced by 12.7 % which results in 13 starts and stops during the week of simulation. When the added flexibility of load reduction is included (variation 2), the running hours are reduced by 27.2 % resulting in 6 starts and stops.

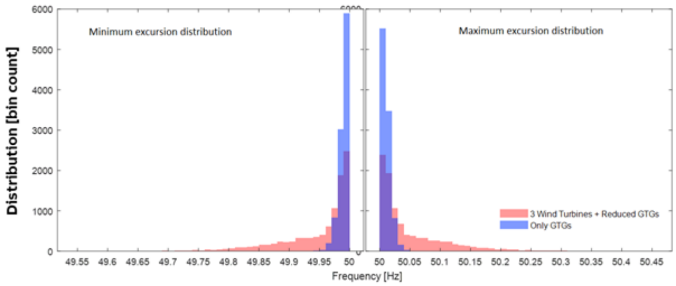

FIGURE 10. Distribution of maximum and minimum excursion of frequency variations for PPSim simulations in the base case (blue) and the wind case 1 (red).

	Oogeso	PPSim
Base case:		
Power demand per week (MWh)	6865	7073
CO_2 emissions per week (tonnes)	4627	4698
CO_2 specific emissions (kg/MWh)	674	664
Wind case:		
Reduction in CO_2 emissions	25%	20%
Number of GTG start-ups per week	19	13
Reduction in running hours of GTGs	27%	13%

TABLE 4. Comparison of results obtained with Oogeso and PPSim

An important power quality measure is the distribution of minimum and maximum frequency excursions, which is shown in Figure 10 for the base case and for the wind case variation 1. For the conventional system with only gas turbine generators (GTGs) as power source, the frequency keeps within narrow boundaries. Adding wind turbines and GTG flexibility to start and stop increases the frequency variations in the system.

4.3 Comparison of Oogeso and PPSim results

The results obtained with the operational optimisation tool (Oogeso) and the power system stability tool (PPSim) have been presented above. Both models have been used to simulate the base case without any wind power, and with 24 MW wind power capacity. A comparison of key results are given in Table 4.

The simulations have some differences in the power demand due to differences in the setup, mainly the fact that the Oogeso model *computes* power demand on pumps and compressors based on flow rates and pressure whereas this is given as input in PPSim. The specific CO_2 emissions, i.e. emissions per electric power consumed, matches well between the two simulations in the base case.

Results where wind power is present and gas turbines can start and stop are also shown. In this case there are significant differences. One reason for the observed differences is the difference in reserve requirement affecting when to turn on and off gas turbines. In PPSim, gas turbines are started if the reserve drops below 4 MW and shut down if the reserve increases above 7 MW, whilst in Oogeso a flat 5 MW threshold is assumed. The hysteresis in PPSim is a way to avoid frequent starts and stops when the reserve is close to the threshold. In Oogeso, higher generator start-up costs and the implementation of minimum uptime once started would reduce the number of start/stops, in turn giving less reduction in the gas turbine generator running time.

The number of of starts and stops (13 or 19) for one week is high in both models, so the criteria for when to start or stop should be evaluated. The selected week of wind variations also includes large wind variations, based on coastal recordings. Offshore wind variations are likely lower, also giving lower number of starts and stops. At the same time, the results show that significant CO_2 emission reductions can be achieved by more aggressive operation of the GTGs.

As Oogeso is a steady-state optimisation model whereas PPSim is a dynamic electrical model, the results showing more optimistic result in terms of emission reductions from Oogeso is as expected.

4.4 Electric power system stability after a loss of generation event

The frequency course during the simulated events is displayed in figure 11, and the active power output of the remaining gas turbine (one of the two remaining gas turbines in the base case) is displayed in figure 12.

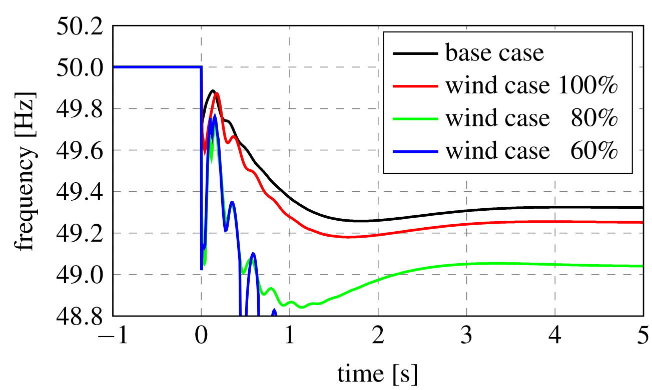

FIGURE 11. Electrical frequency measured at the main busbar

The smoothest and *best* results appear at the base case, where the power shortage can be handled by two remaining gas

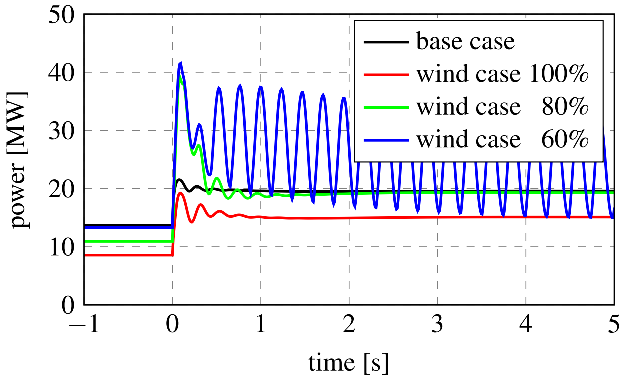

FIGURE 12. Active power output of the remaining gas turbine

turbines that share the burden (black curves). The wind case with 100 % wind power output (red curves) shows a similar course even though only one remaining gas turbine has to handle the situation alone. This is caused by the fact that more than half of the power comes from the wind turbines, with the gas turbines operating at low power: As the failing gas turbine was at low power, the total amount of lost generation is lower than the other cases, and as the remaining gas turbine also was at low power, it has large headroom for handling the incident. When it comes to the wind case with 80 % wind power output (green curves), the behaviour changes significantly. The remaining gas turbine is pushed to its limits, as it starts at a higher output and has to compensate for more lost generation. The frequency deviation is much larger and the power output reaches almost 200 % of rated power (for a very short time though). It is unclear if the simulated result is realistic, if the remaining gas turbine would be automatically disconnected to prevent damage in such an overload situation, or if load shedding would activate. The overload protection of the gas turbines and the load shedding scheme are not modelled yet, leaving this question open. The wind case with 60 % wind power output (blue curves) does not give feasible results. The electric power system becomes unstable, leading to unacceptable frequency deviations within only one second, and it leads to extreme power output oscillations of the remaining gas turbine. The curves as displayed here would not happen in reality, as the situation would result in load shedding or a black out. The remaining gas turbine simply does not have sufficient headroom to handle the incident, and it would disconnect to protect itself from damage instead of sustaining the massive oscillations.

It should be noted that all of the simulations were performed with a *standard* wind turbine controller. Such control approach is based on maximum power tracking, and does not *react* to the incident with supportive control actions like fast frequency support or virtual inertia. It is possible that the 80 % wind case could be improved when wind turbine control is adapted for that purpose. However, the 60 % wind case could not be handled sufficiently even with adapted wind turbine control. Only load shedding or another additional power source could prevent system collapse in that case.

The electro-mechanical simulations show that operational regimes that might be optimal from the perspective of fuel consumption reduction, might come at the cost of reduced stability and resilience. The decision when to turn off the third gas turbine must therefore take into account the risk of unexpected high-impact low-probability events like the simulated gas turbine failure.

5 Conclusion

Simulation results of the LEOGO reference platform using the Oogeso and PPsim tools show a good mach in the base case, giving confidence that case and model parameters have been specified in a consistent way. With the inclusion of wind power, the details determining when to start and stop gas turbine generators is, as expected, seen to have a significant impact on emission reduction and number of gas turbine starts and stops. This highlights the importance of tuning operational strategies.

Results quantify the potential for CO_2 emission reduction to 20–25 % for this case with a wind energy share of 26 %. There is some variation depending on the amount of reserve power required and the rules for when to start up and shut down gas turbine generators, with consistent results across the three different tools.

More aggressive operation of the gas turbine generators, where they are switched on and off more frequently to minimise fuel usage, increases the emission reductions, but at the same time increases the wear and tear of the units themselves. The inclusion of wind turbines increases power variability and reduces the inertia when gas turbines are switched off, both of which lead to less stable frequency and potential power quality issues. The work presented in this paper has demonstrated that the Oogeso and PPSim simulation tools give valuable insight into energy and power system operations of offshore oil and gas platforms.

Dynamic electro-mechanical simulations in PowerFactory have shown how electric power system stability and resilience is affected by the displacement of gas turbines by wind turbines, highlighting that also other operational aspects than emission reductions must be taken into account.

Acknowledgements

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REFERENCES

[1] Norwegian Petroleum, "Emissions to air," https://www.norskpetroleum.no/en/environment-and-technology/emissions-to-air, Accessed 2021-09-29.

[2] Nguyen, T.-V., Voldsund, M., Breuhaus, P., and Elmegaard, B., 2016, "Energy efficiency measures for offshore oil and gas platforms," Energy, **117**, pp. 325–340.

[3] Voldsund, M., Nguyen, T.-V., Elmegaard, B., Ertesvåg, I. S., Røsjorde, A., Jøssang, K., and Kjelstrup, S., 2014, "Exergy destruction and losses on four North Sea offshore platforms: A comparative study of the oil and gas processing plants," Energy, **74**, pp. 45–58.

[4] Roussanaly, S., Aasen, A., Anantharaman, R., Danielsen, B., Jakobsen, J., Heme-De-Lacotte, L., Neji, G., Sødal, A., Wahl, P., Vrana, T., and Dreux, R., 2019, "Offshore power generation with carbon capture and storage to decarbonise mainland electricity and offshore oil and gas installations: A techno-economic analysis," Applied Energy, **233-234**, pp. 478–494.

[5] Nord, L. O., Anantharaman, R., Chikukwa, A., and Mejdell, T., 2017, "CCS on Offshore Oil and Gas Installation - Design of Post-Combustion Capture System and Steam Cycle," Energy Procedia, **114**, pp. 6650–6659, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland.

[6] Æsøy, E., Aguilar, J. G., Wiseman, S., Bothien, M. R., Worth, N. A., and Dawson, J. R., 2020, "Scaling and prediction of transfer functions in lean premixed H2/CH4-flames," Combustion and Flame, **215**, pp. 269–282.

[7] Marvik, J. I., Øyslebø, E. V., and Korpås, M., 2013, "Electrification of offshore petroleum installations with offshore wind integration," Renewable Energy, **50**, pp. 558–564.

[8] Kolstad, M. L., Sharifabadi, K., Årdal, A. R., and Undeland, T. M., 2013, "Grid integration of offshore wind power and multiple oil and gas platforms," *2013 MTS/IEEE OCEANS - Bergen*, pp. 1–7, doi:10.1109/OCEANS-Bergen.2013.6608004.

[9] Equinor, 2021, "Hywind Tampen," https://www.equinor.com/en/what-we-do/hywind-tampen.html, Accessed 2021-07-02.

[10] Sanchez, S., Tedeschi, E., Silva, J., Jafar, M., and Marichalar, A., 2017, "Smart load management of water injection systems in offshore oil and gas platforms integrating wind power," IET Renewable Power Generation, **11**(9), pp. 1153–1162.

[11] Korpås, M., Warland, L., He, W., and Tande, J. O. G., 2012, "A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs," Energy Procedia, **24**, pp. 18–26.

[12] He, W., Jacobsen, G., Anderson, T., Olsen, F., Hanson, T. D., Korpås, M., Toftevaag, T., Eek, J., Uhlen, K., and Johansson, E., 2010, "The Potential of Integrating Wind Power with Offshore Oil and Gas Platforms," Wind Engineering, **34**(2), pp. 125–137.

[13] Svendsen, H. G., Hadiya, M., Øyslebø, E. V., and Uhlen, K., 2011, "Integration of offshore wind farm with multiple oil and gas platforms," *2011 IEEE Trondheim PowerTech*, pp. 1–3, doi:10.1109/PTC.2011.6019309.

[14] Årdal, A. R., Undeland, T., and Sharifabadi, K., 2012, "Voltage and Frequency Control in Offshore Wind Turbines Connected to Isolated Oil Platform Power Systems," Energy Procedia, **24**, pp. 229–236, Selected papers from Deep Sea Offshore Wind R&D Conference, Trondheim, Norway, 19-20 January 2012.

[15] Hu, D., Zhao, X., Cai, X., and Wang, J., 2008, "Impact of wind power on stability of offshore platform power systems," *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 1688–1692, doi:10.1109/DRPT.2008.4523677.

[16] Xie, X., Zhong, J., Sun, Y., Wang, J., and Wei, C., 2018, "Online Optimal Power Control of an Offshore Oil-Platform Power System," Technology and Economics of Smart Grids and Sustainable Energy, **3**.

[17] Svendsen, H. G. and Aslesen, M. D., "Offshore Oil and Gas Energy System Operational Optimisation (Oogeso) software code v1.0.0," doi:10.5281/zenodo.5971182.

[18] ABB, "Process Power Simulator," https://new.abb.com/oil-and-gas/products/automation/process-power-simulator, Accessed 2021-07-07.

[19] Svendsen, H. G., Holdyk, A., and Vrana, T. K., 2022, "LEOGO reference platform dataset," Zenodo, doi:10.5281/zenodo.5827900.

