Open Access Journal

Journal of Power Technologies 95 (1) (2015) 40–47

journal homepage:papers.itc.pw.edu.pl

Process Simulation and Plant Layout of a Combined Cycle Gas Turbine for Offshore Oil and Gas Installations

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Abstract

Since the development of the first oil fields on the Norwegian Continental Shelf, the petroleum industry in Norway has been making continuous progress in oil production engineering. With greater environmental awareness and increasing taxation of NO_x and CO_2 emissions, the economic pressure has been rising in recent decades. The energy demand for offshore oil and gas production is high. With a view to improving power generation on offshore oil and gas installations, four models of different power cycles were investigated: a simple cycle gas turbine (currently the default option), a compact combined cycle with enhanced fuel utilization, a steam injection gas turbine cycle as an innovative solution, and a state of the art combined cycle for onshore applications as a reference cycle. Special requirements for offshore installations are discussed and sizing was identified as the major criterion. The power demand of an oil platform and its change during different states in field life were analyzed. To complete the simulations, the models were set to off-design conditions and the part-load behavior was investigated. The plant layouts were laid out and visualized with 3D CAD models.

Keywords: steam cycle, once-through steam generator, process modeling, heat recovery, efficiency

1. Introduction

Environmental pollution taxation in Norway is based on the amount of CO_2 and NO_x emitted. It is based partly on a quota obligation system, where licenses must be purchased for all emissions. For practical reasons, the tax is related to the usage of fuel and not to the gas actually emitted. This so-called 'carbon tax' differ from the 'energy taxation' system. An 'energy tax' covers all consumed energy, although nuclear and renewable energy do not generate any CO_2emissions [1]. The carbon tax started in 1991 and by 2013 had increased to 0.96 NOK (=0.11 EURO) per standard cubic meter of natural gas [2]. This leads, with a conversation factor of 2.34 kg CO_2 per standard cubic meter, to a charge of 410 NOK (= 49.29 EURO) per metric ton of CO_2 emitted. Furthermore, according to the Gothenburg Protocol, Norway is obligated to reduce its NO_x emissions. This led to the introduction of a NO_x tax in 2007, which is now 17.01 NOK (= 2.05 EURO) per kg NO_x [3, 4].

In addition, under the European Union's emission trading system, Norwegian companies have to pay allowances of about NOK 50 per metric ton of CO_2. In sum, there is a tax of 450 NOK (=54.10 EURO) per metric ton of CO_2 emitted. This economic pressure has already led to much effort being devoted to energy saving measures [5].

Nguyen identified the highest potential for an efficiency increase on an average Norwegian offshore platform with an exergy analysis in the power generation part in [6]. The three parts with the most promising potential for improvement are:

- Combustion chambers of the gas turbine
- Flared and vented gases from the processing plant
- Exhaust gases from the waste heat recovery system

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The combustion itself and the dimensions and layout of the combustion chamber are determined by the vendors of the gas turbines. In particular, the thermal stress limits of the material act as the limiting factor for the first point. Flaring on the Norwegian Continental Shelf is already at a minimum, but improvements in gas recovery systems are still under development. The third main source is associated with the exhaust gases that are emitted to the atmosphere at high temperature.
By utilizing this wasted energy from the gas turbine total efficiency could be increased and CO_2 emissions reduced [7].

Economic pressure led to two main approaches: waste gas treatment and conservation of energy consumption, as confirmed by Vanner [4] in an investigation into offshore energy use in the UK. The only practical arrangements on the NCS for CO_2 extraction are at the Sleipner field in the North Sea and at the Snřhvit field in the Barents Sea. More efforts were put into practice by reducing the energy consumption during the oil production process. However, the concept of the combined power cycle has been put into operation only at the following three fields: Oseberg, Snorre and Eldfisk [8].

One detailed investigation for improving power generation at offshore installations has been done by Kloster [9]. He assessed the options for energy conservation and discussed the existing combined cycle solutions on the NCS. A special focus was placed on CO_2 reduction; Kloster calculated the greenhouse gas reduction between a single gas turbine and a combined cycle at 25%. Nord and Bolland [8] considered the use of once-through technology for heat recovery steam generators on offshore installations.

2. Methodology

This section includes description of the four fpower plant models as well as the modelling and simulation routine.

The analyses of the NCS done by Kloster [9] confirmed that the most widely used gas turbine is the LM2500 aeroderivative gas turbine package of General Electrics. Therefore, to keep the models close to reality, this turbine was chosen for all topping cycles. The four layouts were given as:

1. Simple cycle; based on a GE LM2500+(G4); as a base case which represents the present status on offshore installations
2. Combined cycle offshore; which utilizes waste heat in flue gas
3. Steam injection gas turbine cycle; with high efficiency but certain unknowns
4. Onshore combined cycle, as a reference plant with up to date technology

Table 1: Arrangement of the modelled skid equipment

Gas turbine skid	Gas turbine; compressor, combustor, turbine
	Fuel system
	Starter equipment
	Bearing lube oil system including tank
	Seal gas system
	Driven equipment
	GT generator
Steam turbine skid	Steam turbine with bypass system
	ST generator
	Speed reduction gear
	Condenser with condenser pumps
	Lubrication oil
	Hydraulic system incl. pumps
	ST governor and controller
	Piping with extraction valves
HRSG skid	OTSG with economizer boiler and superheater
	Inlet and outlet transitions and main stack
	High pressure pumps
	Instruments and instruments valves incl. water monitoring
	Instrument junction boxes on skid edge
	Single lift skid structure
	Feedwater/ blowdown-tank

According to [10] the conditions regarding offshore requirements are as: Reliability and availability; ruggedness; high power to weight ratio, minimum footprint; easy maintenance and repair; decent off design performance; flexible in process parameters; robust against harsh environment offshore. To fulfil these requirements a modular skid build-up, as suggested by Wall, Lee and Frost in [11] was used and listed in Table 1. As a heat recovery steam generator a once-through type was chosen, as suggested by Nord and Bolland for offshore installations [12].

For comparison and evaluation of modelled and simulated plant layouts, the Thermoflow software package was utilized. The software includes single packages for the design, simulation and cost estimation of power, process, heating and co-generation plants. Beside the combined cycle applications, which were used for the simulation, the program offers a wide range of modelling tools. The main modelling module GT PRO provides a sample environment for designing a combined cycle or gas turbine co-generation plant. GT Master is a linked module that allows a given plant to be run in different operating conditions, such as different ambient conditions and loads. It is particularly suitable for off-design simulations.

The PEACE module (Plant Engineering and Construction Estimator) provides additional inputs to automate the preliminary engineering and cost estimation of the plant. The output of PEACE is based on charts of the selected parameters. Finally, the THERMOFLEX module provides the operator with a fully flexible design environment for modelling a plant.

The layout of the power plant models was built up using a computer-aided design (CAD) software program, Autodesk Inventor. Since the CAD models should give a realistic impression, the power generation units are placed on a fictitious offshore platform. For a realistic ambience, a few typical offshore facilities are placed on the platform: a helicopter base on the left side, a red crane in the front, offices and an accommodation container at the back, and a yellow drilling unit in the middle of each platform. Each cycle is placed on the same platform setting in the lower right corner.

2.1. Modelling assumptions

The assumptions for the process models are listed in Table 2 and Table 3.

Table 2: Vendor data for GE LM2500+ (G4)

Model	GE LM2500+(G4)	(-)
Shafts	2	(-)
Speed	3 600	(rpm)
Pressure ratio	23	(-)
Exhaust gas temp	524	(°C)
Exhaust mass flow	90	(kg/s)
Generator power	33 300	(kWe)
Efficiency (LHV)	39	(%)

The definition of the offshore installation was broad. In terms of the water supply system, two major impacts are water quality and the existing water treatment and storage system on the platform. We chose a constant medium seawater quality with medium turbidity. As we were investigating improvement of an existing platform, where we could fall back on some existing equipment, we assumed there was an existing fire protection system on offshore installations. The whole water storage system was declared redundant and the water treatment system was designed to an adequate point. However, according to Flatebř [13] there must already be some sort of treatment system on platforms, and even more adaptions can be made if specific platforms are investigated.

Table 3: Process model assumptions

Fuel @ 25°C	methane	(-)
LHV @ 25°C	50 047	(kJ/kg)
Ambient pressure	1.013	(bar)
Ambient temperature	15	(°C)
Sea water temperature	10	(°C)
GT inlet pressure loss	10	(mbar)
GT exhaust loss	5	(mbar)

3. Results and Discussion

3.1. Process simulation at design point

As key parameters, the footprint and the weight were minimized while keeping the efficiency and the power output as high as possible. The footprint of the simple cycle gas turbine was very low, calculated to be 136 m^2. That is about one-third of the reference plant size. This very low specific size for power output is the reason why it is often installed on offshore platforms. The footprints of the combined cycle and the STIG cycle are about twice the size of the simple cycle. The small difference between them is due to the very similar HRSG with about 11 kg/s steam mass flow; just the steam turbine is left but the treatment system is increased in the STIG cycle. The large onshore HRSG and the large tanks extend the size of the reference plant.

A similar ranking can be found with the total operating weight output. No water is necessary in the gas turbine cycle with dry low NO_x burners, resulting in a weight of 284 metric tons. The combined cycle weighs 595 metric tons and the STIG cycle 500 metric tons, about twice the weight of the simple cycle. The water in the steam bottoming cycle weighs 6 metric tons and 5 metric tons respectively. These water amounts are at the lower limit; a further decrease in the water amount is not possible. The reference plant has 980 metric tons at the top, because of the heavy pressure drums, large heat transfer areas, water tanks, and a water containment of 25 tons.

The total net power output and the electrical net efficiency were very similar between the offshore combined cycle and the STIG cycle. The data of the STIG cycle are based on scaling and estimations and were more uncertain. The highest efficiency (53.6%) was achieved by the onshore plant. Here, the high steam parameters and the most efficient HRSG were implemented. The lowest stack gas temperature of 99 °C indicates that most energy was utilized in the HRSG. The combined cycle and the STIG cycle exhaust gas were at 170 °C and 182 °C respectively, and achieved 50.9% and 49% efficiency respectively. These are still high values for offshore plant installations. The power output of the simple cycle was 32 MW with 38.1% efficiency. The exhaust gases of the simple cycle GT were emitted to the atmosphere at 527 °C. Since the same gas turbine was used in each model, the CO_2 content in the exhaust gases hardly differed from 4.63 kg/s in the onshore plant to 4.79 kg/s in the STIG cycle and the other plants between these values. When the value is normalized to the power output, however, the contrast between the simple cycle and the other ones becomes obvious.

Consequently, reasonable values were achieved for the improvement of sizing from the reference plant to an offshore installation. The footprint was reduced by 30% and the weight by about 48%, whereas the power output and efficiency were reduced by just 4%. The values of the STIG cycle were even more promising, but were based on uncertain scaling of the steam injection mass flow. The simulations showed that there was room for improvement with regard to the energy supply on the NCS. With the same fuel input, one could obtain 30% higher power output by using the heat of the exhaust gases in a steam bottoming cycle. The technology is well known and available on the market. With rising economic pressure owing to fuel prices and increasing environmental taxes the number of offshore combined cycle installations could increase. There are still a few drawbacks, however, which were confirmed by this work. The dimensions and weight of an optimized combined cycle were twice those of a simple gas turbine. Because of the long life of a platform, most of them are retrofitted, with few being built completely new, so the size and weight are a problem for the structure of the platform. The STIG cycle has shown that there are alternative ways of reducing the dimensions even more than a combined cycle does, as well as increasing efficiency, but none of the vendors offer an up-to-date gas turbine for the steam injection cycle suitable for offshore installations. It is unlikely that the STIG cycle will be established on the NCS in the near future.

On the other hand, it must be mentioned that modern simple cycles on their own achieve acceptable values in terms of efficiency. They have advantages over the combined cycle, which have not been subject to study until now: for example, structure, ease of maintenance, high availability and flexibility. Gas turbines are very flexible and easy to control for power demand peaks. With the installation of several gas turbines, as is common practice, and driving each of them at 80% one can react very flexibly to peak loads. Alternatively, it is possible to shut one turbine down without influencing the others, in contrast to the combined cycle. Furthermore, the dynamic behavior of a gas turbine is very good.

3.2. Process simulation in off-design conditions

For off-design simulations, the optimized plants were converted into the GT Master module without any change to the hardware layout. The part-load cases were set to 70% and 50% gas turbine load respectively. The values for the STIG cycle were based on the steam process to satisfy the steam demand of the injection at part load; realistic estimations were based on scaling values from [14] and [15]. A comparison in efficiency for all cycles and the three load cases is plotted in Fig. 2. The simple cycle in red showed a large decrease of 15% in efficiency from full to half load. The offshore (green) and onshore (black) combined cycles lose about 10% in efficiency. This is due in particular to the previously described effect of keeping the temperature of the exhausted gases high for high live steam parameters, which guarantees a high steam turbine power output when the gas turbine is operating at part load. The STIG cycle seems to be very good at part-load conditions, and the loss in optimistic estimations was less than 10% of the design point efficiency. This is owing to the relatively low influence of the steam temperature in the gas turbine. In sum, at part load a bottoming cycle dampens the decrease in efficiency. Thus, combined cycles benefit from off-design more than simple cycles do. Gas turbines, however, are very often installed in modules: for instance, three identical skids are next to each other, and if there is a lower power demand one gas turbine is turned off and the others still run at design point. This turns a drawback into an advantage and is linked to the excellent dynamic behavior of aeroderivative gas turbines. The STIG cycle seems to have even more benefits in off-design conditions. Also other working medium bottoming cycles are conceivable and have some advantages compared with steam, but this needs to be confirmed by more detailed research [16].

3.3. Plant layout

As the simulation with Thermoflow has shown, the combined cycle included a lot more equipment. Fig. 3 shows that many more components are located in the lower right corner of the platform. The HRSG and the steam turbine in particular had large dimensions. What is not shown is that these both units were estimated to weigh about 160 metric tons, which is one third of the whole plant. The gas turbine skid was exactly the same as for the simple cycle. The HRSG is placed on top of the gas turbine skid. This arrangement is a well-proven method to save footprint and the losses are minimized in the transition piece from the gas turbine to the HRSG. However, the skids must be configured for that weight and resist the stress. The vertical gas flow leads to a high stack and must be protected against storm conditions. Due to the increased power output, the transformer (pink) capacity was increased. The water cycle requires a condenser (golden colored), which is located below the steam turbine skid, to ensure a short piping. For several reasons, the condenser is one of the lowest points of the steam cycle. Normally the water is collected at ground level in the hotwell; the connected condensate pumping has a good Net Positive Suction Head (NPSH) value and can be secured against cavitation; furthermore, easy access for seawater coolant must be provided. The small blue container between the steam turbine and the HRSG houses the water treatment system. Due to the small makeup water flow, the dimensions were kept to a minimum. Both cylindrical tanks are for additive chemicals, acid and caustic. Other tanks are neglected, because of the assumption – factored into the simulation – that there must already be some kind of water storage on the platform. All the supply equipment is housed in the orange containers. Since there was much more pumping and controlling equipment to be stored, there were two of these containers. The piping between the different skids was not implemented in the CAD model. To construct a more detailed level that includes the piping, much more data regarding the platform's dimensions and facilities is required.

Lastly, a model for the onshore cycle was designed and shown in Fig. 4. To show an equal setup with a similar environment, the plant was also placed on the platform. Although this configuration would never be installed offshore, it delivers an impression as to how many square meters could be saved by the optimization. The equipment was the most voluminous and heaviest of all the models. The HRSG technology changed from once-through to drum type, with large pressure drums on top of the HRSG. Due to the material change of the heat exchanger areas, the HRSG was unable to run dry, thus a bypass stack was installed. The water treatment system (blue container) consists of: pressure filter, softener, reverse osmoses and two-bed demineralizer, and guarantees high quality even at inland waters. However, it is not as large as that of the STIG cycle, due to the minor makeup water flow. The steam turbine, the transformers and the condenser were enlarged in comparison to the offshore combined cycle ones, and adapted to the higher power output. All the supplementary equipment was scaled up and required more space in the orange containers. In addition, three tanks, for demineralized water, raw water and neutralized water respectively, are placed on the platform. The raw water tank also served as a fire protection source and can store up to 250,000 liters.

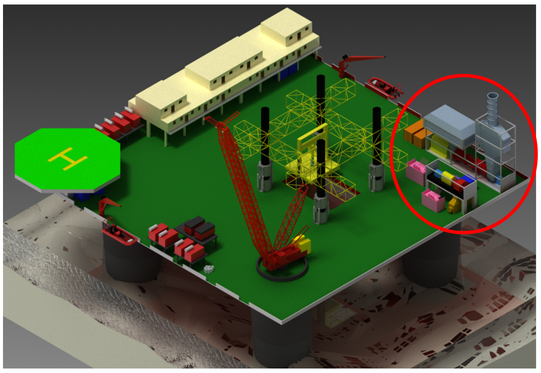

Figure 3: Offshore combined cycle (circled) on a fictitious platform.

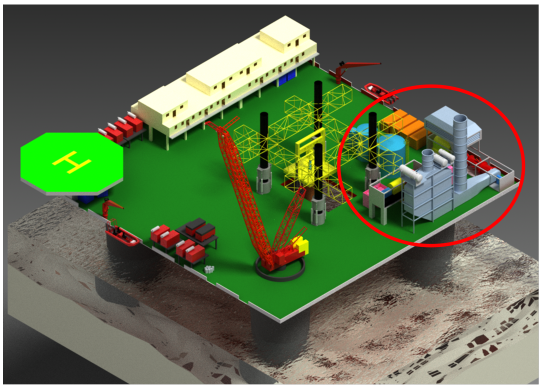

Figure 4: Reference plant (circled) designed for an onshore installation, but laid out on a fictitious platform for size comparison.

4. Conclusions

The simple cycle with a weight of 280 metric tons has an advantage in terms of sizing, with a very compact build, and a disadvantage due to its efficiency of 38%. The offshore combined cycle could be sized down to 600 metric tons or about half of the reference plant. The efficiency of 51% was much higher than the simple cycle GT plant. The steam injection cycle, with 49% efficiency, almost reached the power values of the combined cycle, but had a smaller layout. However, the data for the STIG cycle was based on estimations, and the technology is not ready for the offshore market. Combined cycles can handle off-design situations better than simple cycles, but single gas turbines could balance that with their dynamic behavior and modular design. Bjerve and Bolland [17] also attest to the STIG's good performance, but the cycle has a big disadvantage in that it needs a great deal of treated water. We simulated an efficiency increase from 38% with the simple cycle, to 51% with the combined cycle, making a further CO_2 emissions saving of 25%. Comparable simulations of Nord and Bolland confirm these values of optimization potential in [12]. That reduces the operating costs, both through lower fuel consumption and lower CO_2 taxation. However, taxation in the field of power generation is politically influenced and therefore subject to change. In general, environment taxation looks set to increase in the future, but it is hard to give an exact prediction as to how it will look long-term. As mentioned at the beginning, power generation is subordinate to gas and oil production. The focus will always be on maximising the production margin and therefore, modifications with trade-offs must be made to the power generation unit. This also means that no general advice can be made either for or against a combined cycle, as the special requirements of each platform are paramount.

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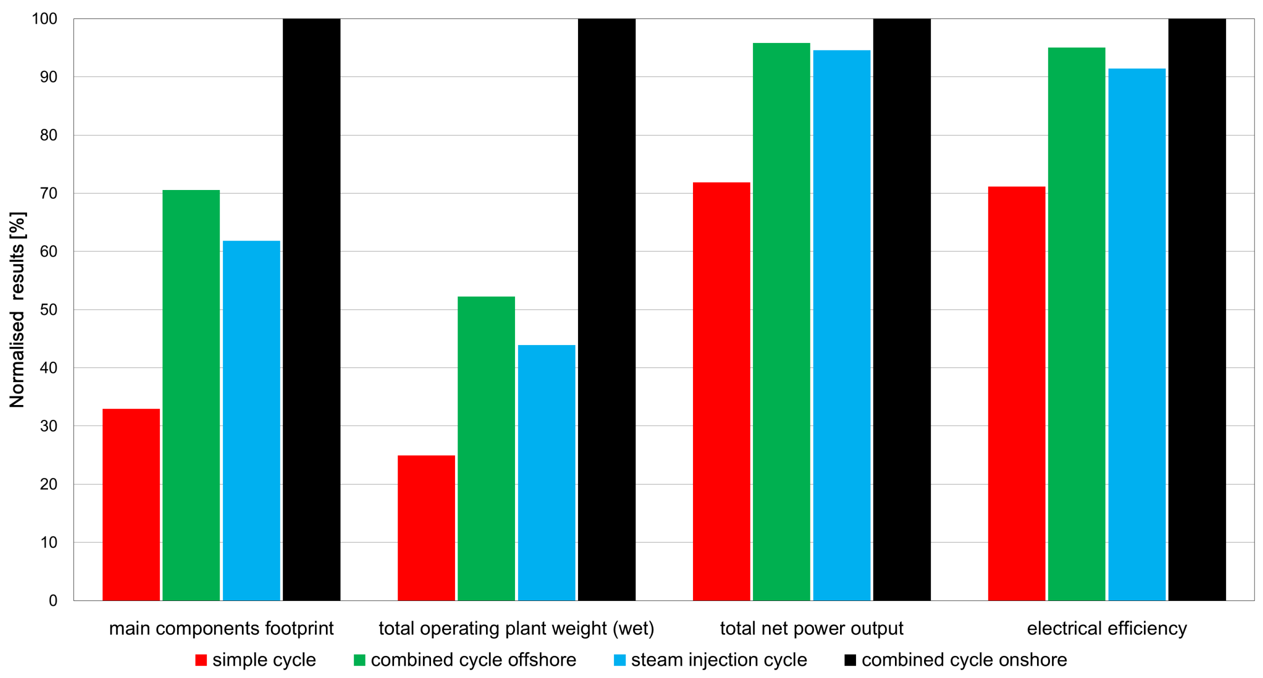

Figure 1: Selected output parameters (main component footprint, total operating plant weight, total net power output, electrical efficiency) of the four models normalized with the onshore combined cycle.

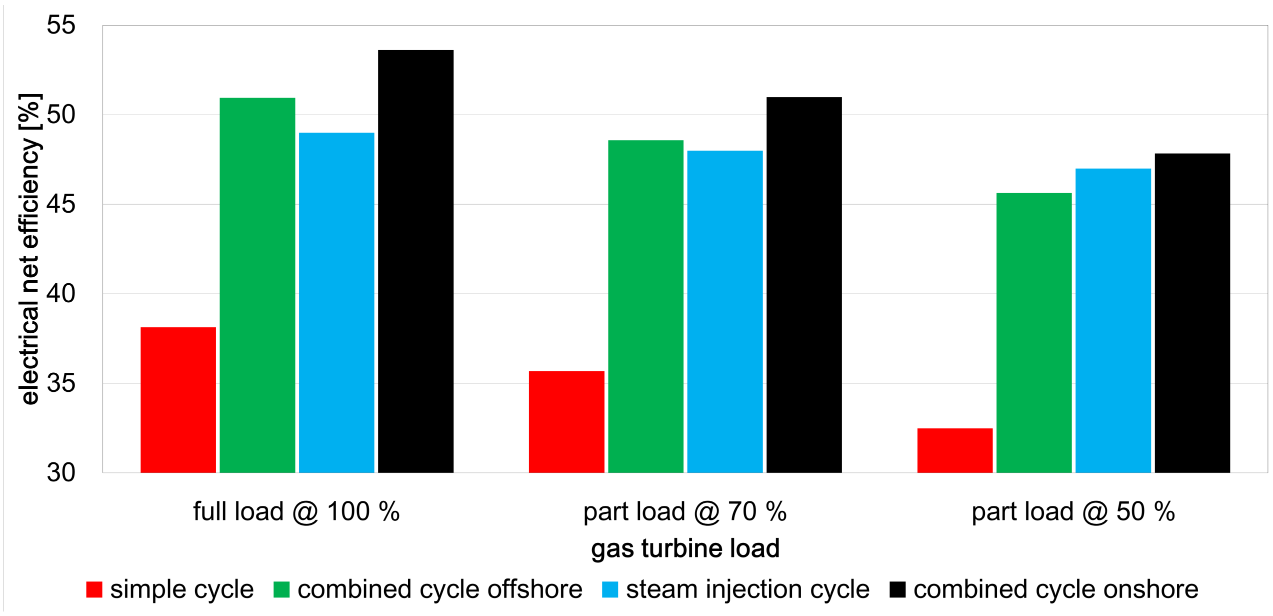

Figure 2: Electrical net efficiency of the four models at 100%, 70% and 50% gas turbine load.

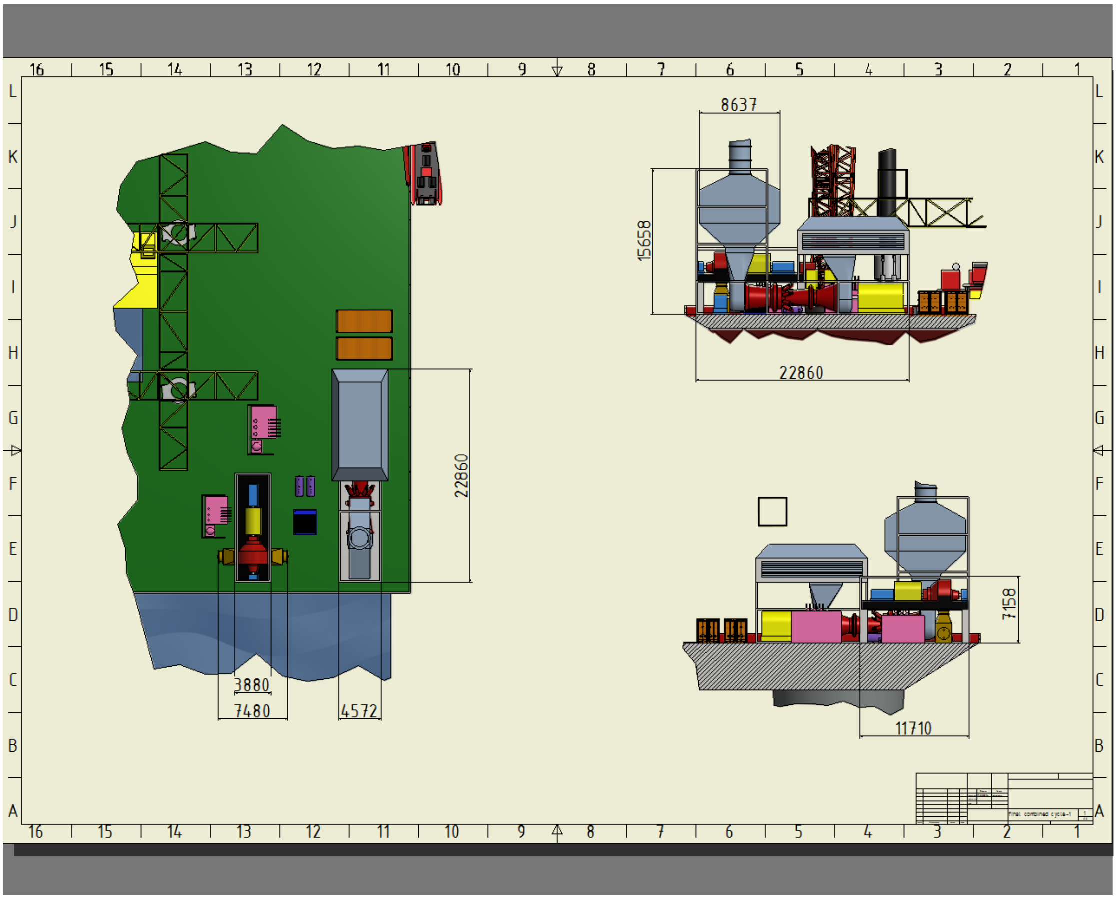

Figure 5: Detailed cutout of the offshore combined cycle on the platform.

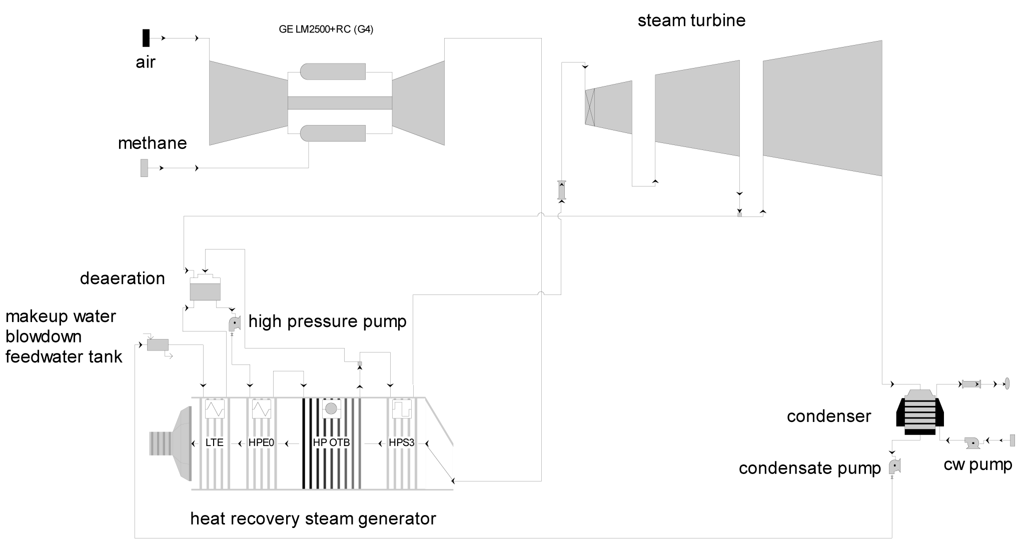

Figure 6: Detailed cutout of the offshore combined cycle on the platform.