

Gas turbine vs. gas engine

MAN Energy Solutions

Future in the making

A comparative study of efficiency
and flexibility in combined heat and
power applications

Gas turbine, gas engine, combined heat and power, steam generation, hot water generation, flexibility

This study compares a MAN gas turbine and a MAN gas engine of the same output class in three different CHP processes involving steam and hot water generation. The aim of the study is to define the pros and cons of the different power generators used for the CHP processes examined in order to help buyers choose turbine or engine technology depending on the application. The gas turbine, with its low power-to-heat ratios and high steam parameters, is generally the more economical alternative. Steam generation is also economically feasible with gas engines, but high steam parameters can limit the overall fuel utilization and thus the profitability. Gas engine solutions, particularly in the case of higher steam parameters, require the parallel generation of hot water to be economical.

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Introduction

Setting aside renewable energy technologies, electricity production using gaseous fuels and combined heat and power (CHP) offers the greatest potential for CO₂ reduction. That is why these technologies will become more important in future. Combining both of these technologies enables maximum fuel utilization and minimal emissions at the same time.^{1, 2, 3}

MAN Energy Solution's product range includes gas turbines from 6 to 12 MW and gas engines from 7 to 20 MW,

making MAN Energy Solutions a leading supplier of highly efficient CHP systems. These powerful power generators enable extremely flexible and efficient CHP systems.

As a result, powerful prime movers are available, which enable extremely flexible and equally efficient CHP systems.

Typical authorization procedures make it virtually impossible to leave the technological design of CHP systems undefined until the tender phase. This is why, in the

development of a project, it is essential to analyze and assess the suitability of potential technologies in extensive conceptual studies. Studies comparing gas turbines and gas engines in CHP applications are already available.⁴

This study relates to processes involving the supply of steam, which are typical for a variety of industrial applications. Steam generation on two different pressure levels and hot water generation are examined for variable power-to-heat ratios.



Solvay GmbH's gas turbine plant in Rheinberg operates a MAN MGT6000

1.1. The approach: Three CHP process scenarios

The MAN MGT6000 gas turbine and the MAN 12V35/44G TS gas engine are compared to each other as prime movers in three different process scenarios with the same electrical output. In this case, “same electrical output” means that the gas engine is operated at approximately 90 % partial-load. This would certainly be unusual for a real application, but is required for comparative purposes and has no impact on the quality of the results.

The power-to-heat ratio was adjusted in each scenario to examine the flexibility of the configuration. The background here is that a system usually has to be economical over a wider operating range and not just at a single defined load point. Heat generation was increased as required using a duct burner in front of the waste heat boiler to lower the power-to-heat ratio.

For this study, the primary energy savings were considered as a measure of cost-effectiveness. These are calculated by comparing the savings from the CHP process to two separate processes for power and heat generation. Economically viable CHP processes always display clearly positive primary energy savings. EU directives define a process as “highly efficient” when it has primary energy savings of at least 10 % compared to equivalent processes. This is often used as a criterion for funding.

Fuel costs usually constitute more than 80 % of generation costs, which makes the primary energy savings a good indicator of system efficiency and cost-effectiveness. A simple example gives a sense of the level of primary energy savings: A reference CHP process with 45 % electric and

45 % thermal efficiency achieves primary energy savings of 25 %. This would be a typical case for a CHP system with a gas engine in a district heating application.

The study explicitly does not claim to illustrate optimized system configurations but is instead intended to compare the quality of various concepts and to demonstrate the potential for primary energy savings and the flexibility with regard to the power-to-heat ratio. An optimized system concept must always be developed for the specific individual conditions of each project. Consideration must be given to project specific economics as well as requirements regarding availability, maintenance, emissions, etc.

1.2. The power generators

The gas turbine

The MAN MGT6000 is one of the world's most advanced industrial gas turbines in the 6 MW class. Based on decades of experience, MAN Energy Solutions has developed its own range of modern gas turbines which combine the advantages of industrial gas turbines with those of aeroderivatives. The MAN MGT6000 single-shaft gas turbine has a compact design and high power density. It is built for power generation, with high overall efficiency in CHP and power, and low emissions as required by stringent environmental standards (NO_x/CO : 30 mg/Nm³ at 15 % O₂, dry at 50 – 100 % load).

The MAN MGT6000 has a modular structure that ensures easy access for maintenance and, with 40,000 EOH (equivalent operating hours), provides sufficiently long service intervals between two main inspections (Fig. 1).

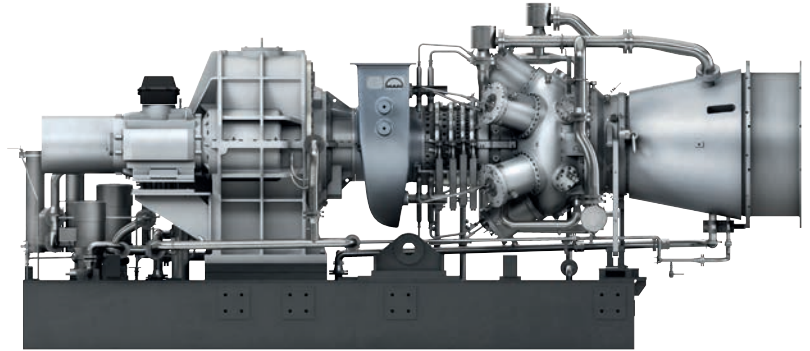


Fig. 1: MAN MGT6000 gas turbine

The gas engine

The MAN 12V35/44G TS gas engine is a highly efficient, two-stage turbocharged, medium-speed engine with a rated speed of 750 rpm. The gas engine features gas valves upstream of every cylinder (port injection) and prechambers with spark plugs to ensure optimum carburation and combustion. The high charging air pressures due to the two-stage turbocharging enable a high power density of more than 600 kW/cylinder and optimum heat extraction, particularly in district heating applications.

The engine also boasts the best electrical efficiency in its class thanks to the moderate speed of 750 rpm and its modern design (Fig. 2).

The electrical output at the alternator terminals of the two power generators is 6.63 MW for all simulations.

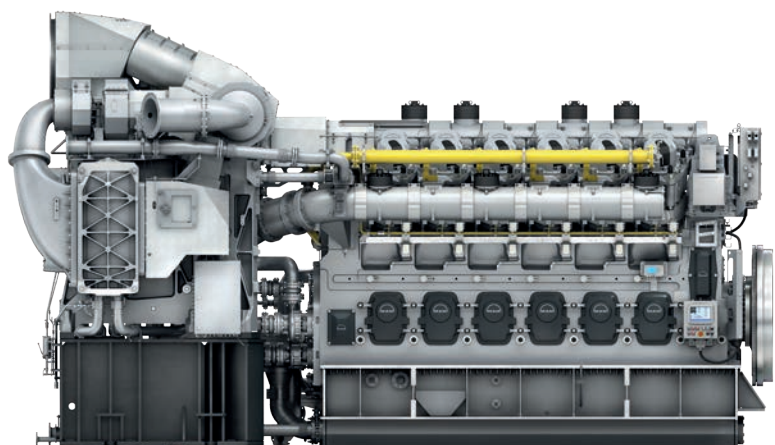


Fig. 2: MAN 12V35/44G TS gas engine

1.3. The three system configurations examined

The three different configurations are referred to as **CHP 1**, **CHP 2** and **CHP 3**:

CHP 1: CHP system with power generation and 8 bar(a) saturated steam generation (170 °C) (Fig. 3)

CHP 2: CHP system with power generation, 8 bar(a) saturated steam generation and additional hot water generation (60/130 °C) (Fig. 4)

CHP 3: CHP system with power generation, 15 bar(a)/240 °C superheated steam generation and additional hot water generation (60/130 °C) (Fig. 5)

The configurations consist of:

- Power generator for the electric alternator
- Feed water tank (deaerator) and feed water preheater
- Waste heat boiler for steam generation
- Additional heat exchangers in the exhaust gas route (economizer) and for the engine solution for recovering heat from engine cooling water and engine lubricating oil

Table 1 and 2 present the boundary conditions and assumptions. A hot water requirement of 6 MW was assumed for the CHP 2 process. For the CHP 3 process, this requirement is only 3 MW since more energy is converted into steam as a result of the higher steam parameters. The connection of the feed water preheater upstream of the steam generator is the same for all processes (Fig. 3). Condensate is returned to the feed water tank. The make-up water is preheated in a heat exchanger connected between the feed water tank and the economizer.

Boundary conditions and characteristic data of the power generators

Ambient temperature	[°C]	15
Site elevation	[m]	0
Ambient air pressure	[kPa]	101.3
Relative air humidity	[%]	60
Natural gas net calorific value	[kJ/kg]	48,000

Power generator	Gas turbine	Gas engine
Model	MAN MGT6000	MAN 12V35/44G TS
Load	100	91.4
Electrical output	6.63	6.63
Electrical efficiency	32.2	45.2
Exhaust gas temperature	505	315
Exhaust gas mass flow	26.2	11.78

Table 1

Heat generation process parameters

Steam parameters for CHP 1 and 2	[bar(a)/°C]	8/170
Steam parameters for CHP 3	[bar(a)/°C]	15/240
Feed water temperature to the waste heat boiler	[°C]	103
Make-up water temperature	[°C]	20
Share of condensate return	[%]	80
Condensate return temperature	[°C]	90
Hot water return and flow temperature	[°C/°C]	60/130
Th. output of hot water in CHP 2	[MW]	6
Th. output of hot water in CHP 3	[MW]	3

Table 2

Nomenclature

CHP_P η	[%]	Electrical efficiency of the CHP system
CHP_H η	[%]	Heat generation efficiency of the CHP system
η CHP	[%]	Total efficiency/fuel utilization
Power-to-heat ratio		Ratio of electrical to total thermal output
P _{net}	[MW]	Net electrical output of the CHP system
Q _{steam}	[MW]	Thermal power of steam generation
Q _{HW}	[MW]	Thermal power of hot water generation
Q _{fuel}	[MW]	Fuel heat input
PES	[%]	Primary energy saving
Ref_H η	[%]	Reference efficiency of a boiler 90 %
Ref_P η	[%]	Reference efficiency for power generation with natural gas 53 %

Table 3

CHP 1

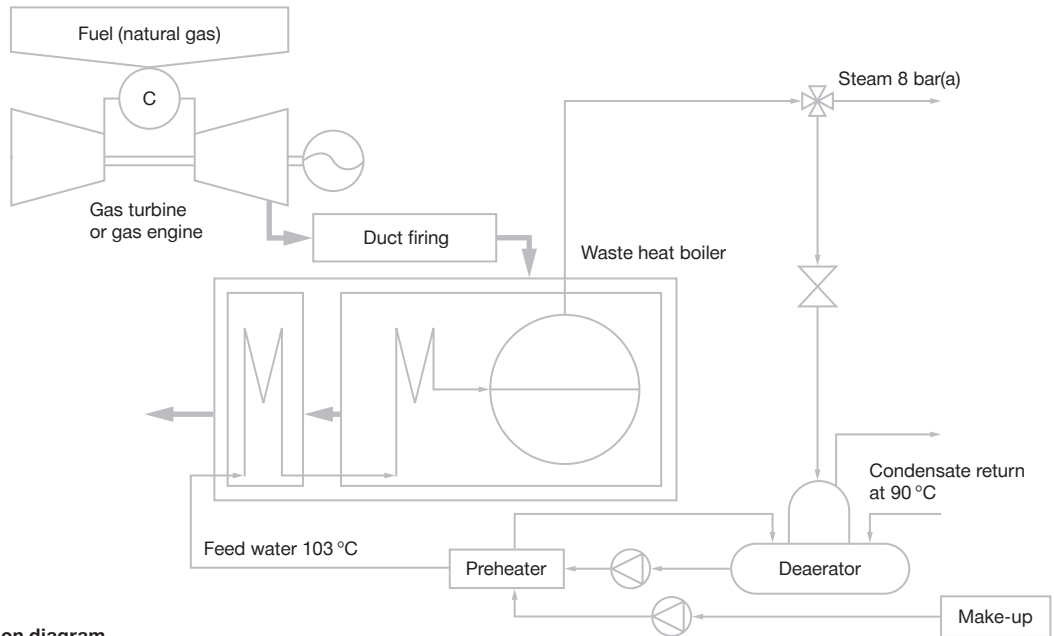


Fig. 3: CHP 1 configuration diagram

CHP 2

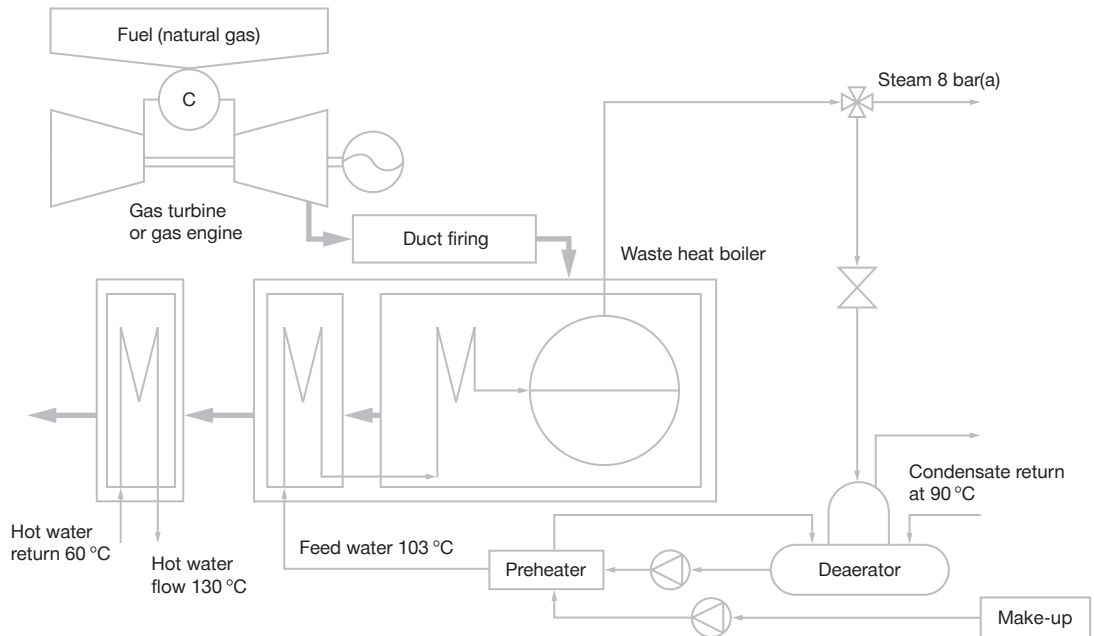


Fig. 4: CHP 2 configuration diagram

The CHP 2 and CHP 3 processes generate hot water in addition to steam. Additional heat exchangers are installed in the exhaust gas route for this purpose. In addition to the exhaust gas heat, the gas engine provides

lubricating oil heat of approximately 750 kW at a level of 70°C. More than 2 MW of heat can be extracted from the engine cooling water and intercooler at temperatures of up to 110°C.

The CHP 3 process differs from CHP 2 as a result of the higher steam parameters (15 bar(a) and 240°C) and the lower hot water output of only 3 MW (Fig. 4 and 5).

CHP 3

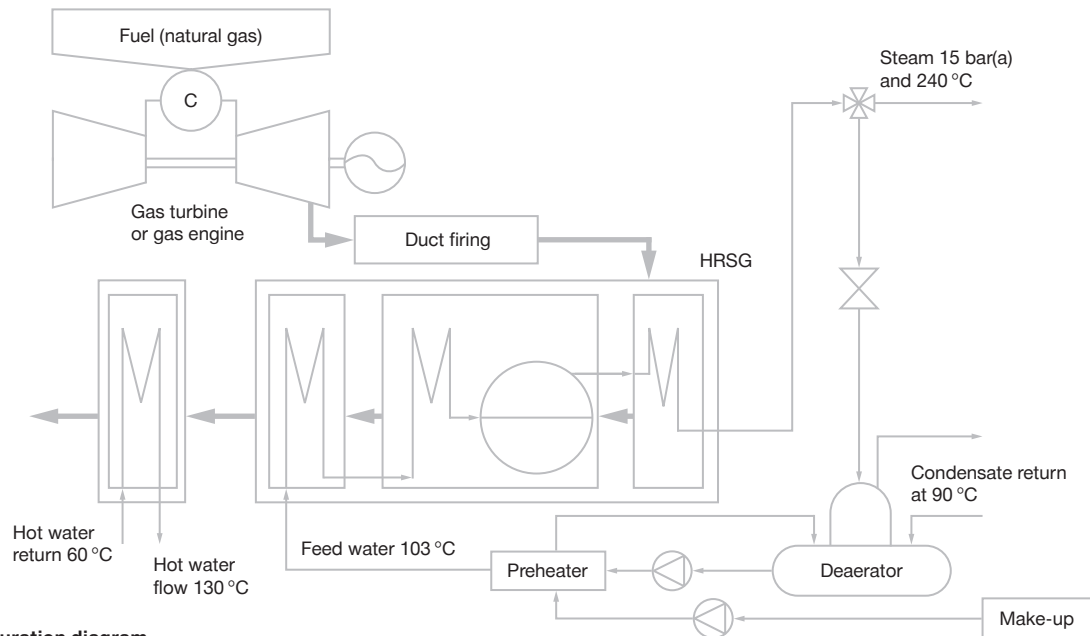


Fig. 5: CHP 3 configuration diagram

1.4. Thermodynamic calculation and simulation

The three configurations were modeled and calculated using the GateCycle™ software.

The parameters are calculated on the basis of known formulae:

Power-to-heat ratio

$$\sigma = \frac{P_{\text{net}}}{\dot{Q}_{\text{steam}} + \dot{Q}_{\text{hot water}}}$$

Efficiency of CHP 1

$$\eta_{\text{CHP 1}} = \frac{P_{\text{net}} + \dot{Q}_{\text{hot water}}}{\dot{Q}_{\text{fuel_CHP 1}}}$$

Efficiency of CHP 2 and 3

$$\eta_{\text{CHP 2+3}} = \frac{P_{\text{net}} + \dot{Q}_{\text{steam}} + \dot{Q}_{\text{hot water}}}{\dot{Q}_{\text{fuel_CHP 2+3}}}$$

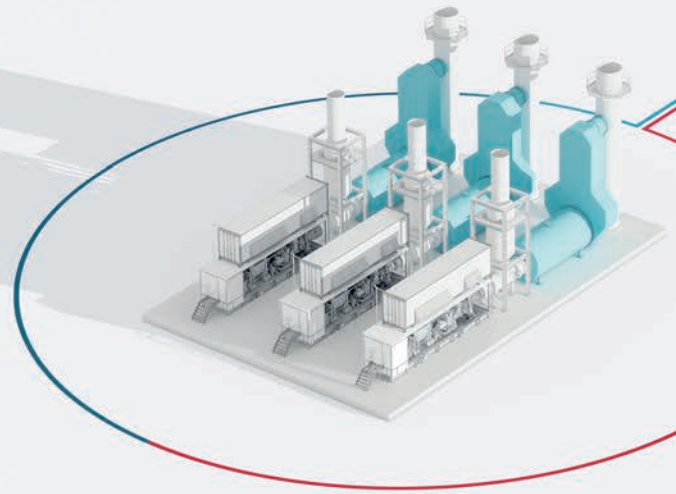
Net electrical output

$$P_{\text{net}} = P_{\text{generator}} - P_{\text{own consumption}}$$

PES (primary energy savings)

$$\text{PES} = \frac{1}{\frac{\text{CHP_H}\eta}{\text{Ref_H}\eta} + \frac{\text{CHP_P}\eta}{\text{Ref_P}\eta}}$$

Results of the calculations and analysis



2.1. Results and analysis of scenario CHP 1 (Fig. 6)

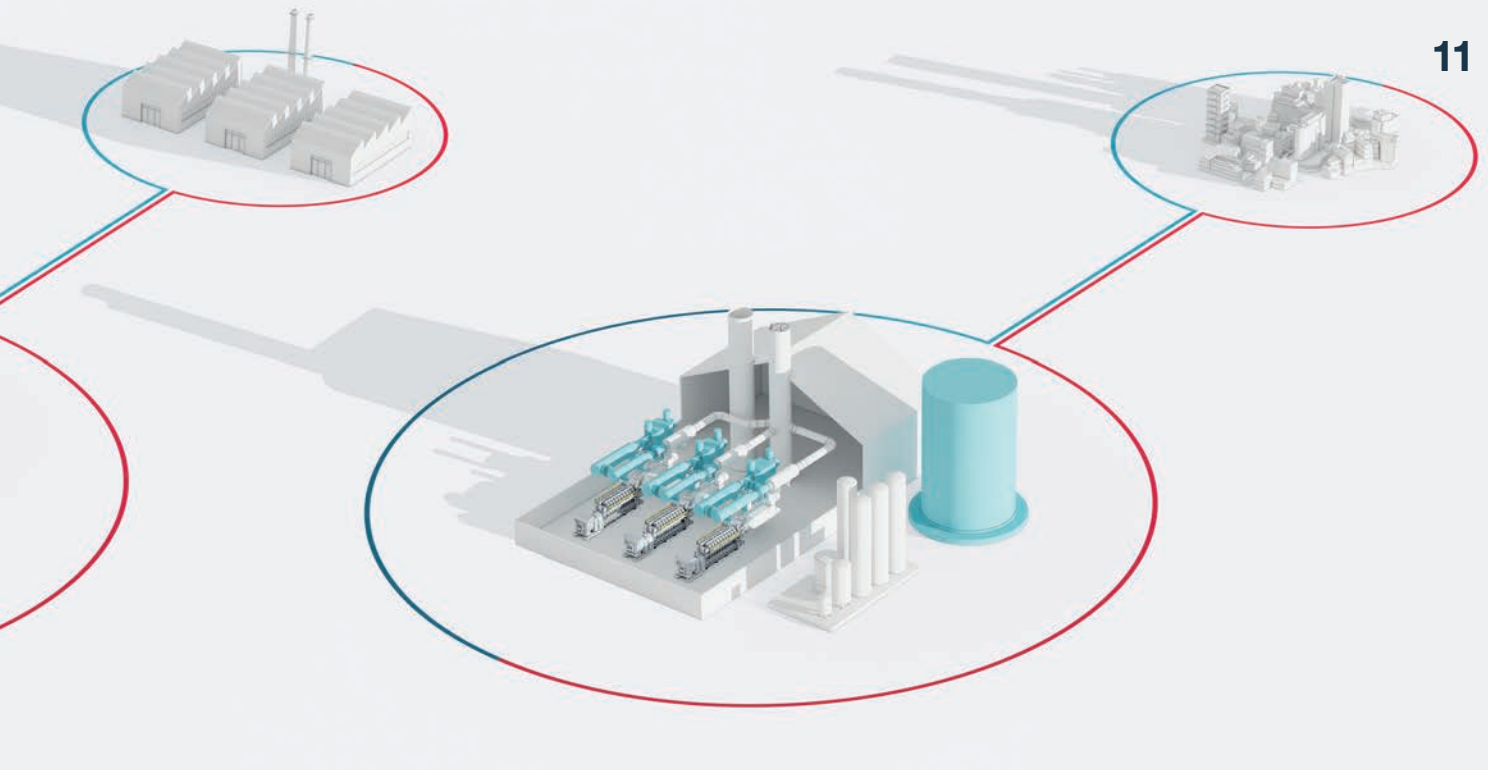
The results show decreasing total efficiencies as the power-to-heat ratio increases. At its best point, the gas engine process achieves a total efficiency of less than 75 %, and the primary energy savings are below 5 %. Only the gas turbine process achieves an overall efficiency of above 80 % and primary energy savings of more than 10 % at power-to-heat ratios of below 0.7.

The gas engine is therefore unlikely to enable an economical system as the high exhaust gas temperature of more than 130 °C downstream of the economizer already indicates.

The gas turbine is only able to provide attractive parameters for power-to-heat ratios between 0.3 and 0.6. With power-to-heat ratios of more than 0.8, the overall efficiency drops below 70 %, making the application uneconomical. The point where the curves intersect at a power-to-heat ratio of ~ 0.9 is striking. Below 0.9, the gas turbine is the better solution; above 0.9, the gas engine takes the lead.

Figure 7 shows the development of steam generation and the exhaust gas temperature after the duct burner. The steam output varies between 22 and 5 MW over the range of the power-to-heat ratio considered, which corresponds to steam generation of 32.3 t/h to 5.7 t/h. Below a power-to-heat ratio of 0.64, duct firing is required in the gas turbine process in order to achieve the steam output. Not all of the available steam can be used above a power-to-heat ratio of 0.64.

The gas engine always requires duct firing in the range of the power-to-heat ratio, as not enough steam can be generated otherwise due to the relatively low exhaust gas heat. However, only a minimum power-to-heat ratio of 0.54 is possible with the gas engine. With this power-to-heat ratio, the exhaust gas temperature is approximately 1050 °C after the duct burner and the residual oxygen content is only around 3 %. For technical reasons, a further increase in duct firing is therefore not possible.



Left: CHP with turbines, right: CHP with engines

Conclusions of simulation CHP 1

- With power-to-heat ratios of < 0.9, the gas turbine (MAN MGT6000) is the most efficient solution.
- With power-to-heat ratios of > 0.9, the gas engine (MAN 12V35/44G TS) is the most efficient solution.
- The primary energy savings for the gas engine solution are always positive.
- The primary energy savings for the gas turbine solution only become positive at power-to-heat ratios of < 0.9 but then reach a significantly higher level of > 10 %.
- With power-to-heat ratios of < 0.54, the gas engine process is unable to meet the steam requirements since the residual oxygen content in the exhaust gas is not sufficient for the increased duct firing.

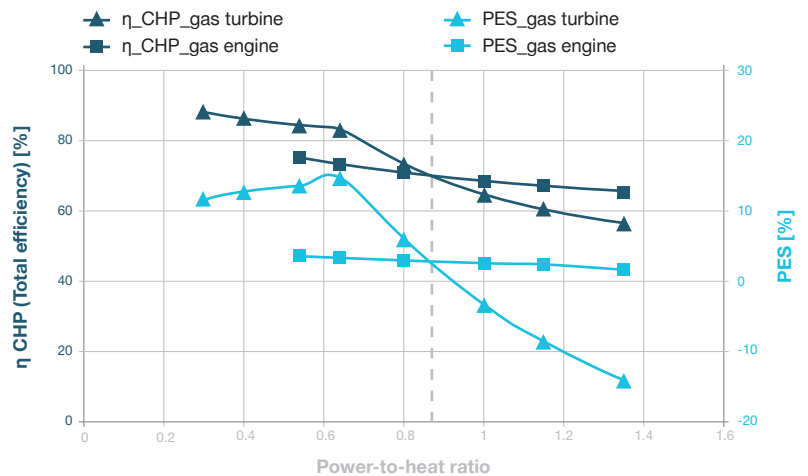


Fig. 6: Results of CHP 1 (8 bar saturated steam generation)

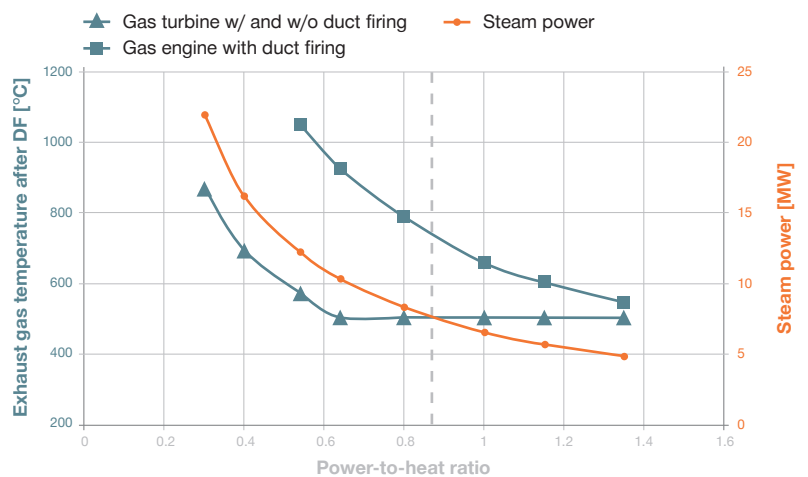


Fig. 7: Analysis of CHP 1 (8 bar saturated steam generation)

2.2. Results and analysis of scenario CHP 2 (Fig. 8)

The results of the second scenario are more attractive overall. In contrast to the first scenario, both processes now achieve a total efficiency of more than 80 % and primary energy savings of more than 10 %, namely for power-to-heat ratios of less than 0.7. The highest primary energy savings are achieved by the gas engine with approximately 20 % at power-to-heat ratios of above 0.8. The efficiency drops as the power-to-heat ratio increases, but only slightly for power-to-heat ratios ranging from 0.35 to 0.65.

In contrast to the curves in scenario 1, there is no point where the overall efficiency curves intersect in scenario 2.

The primary energy savings and the overall efficiency with the gas engine are higher than for the gas turbine across the entire range of power-to-heat ratios.

As the power-to-heat ratio increases, the steam output decreases from 20 MW to almost 0 MW since the thermal output of hot water generation is kept constant at 6 MW. Auxiliary combustion is always required for the gas engine; this is only necessary for the gas turbine at power-to-heat ratios of < 0.64.

As in scenario CHP 1, the technically feasible extent of auxiliary combustion for the gas engine is limited to power-to-heat ratios of > 0.36.

Conclusions of simulation CHP 2

- With power-to-heat ratios of > 0.6, the gas engine is the most efficient solution because the heat from the lubricating oil and intercooler can be used to generate hot water. Attractive values of 17 – 20 % can be achieved for the primary energy savings.
- With power-to-heat ratios between 0.6 and 0.36, both solutions achieve a similar total efficiency but significantly increased auxiliary combustion is required for the gas engine.
- With power-to-heat ratios between 0.2 and 0.4, a high overall efficiency of approximately 90 % can be achieved for the gas turbine process.
- With power-to-heat ratios of < 0.36, no solution is possible with the gas engine since the residual oxygen content in the exhaust gas is not sufficient for the required auxiliary combustion.

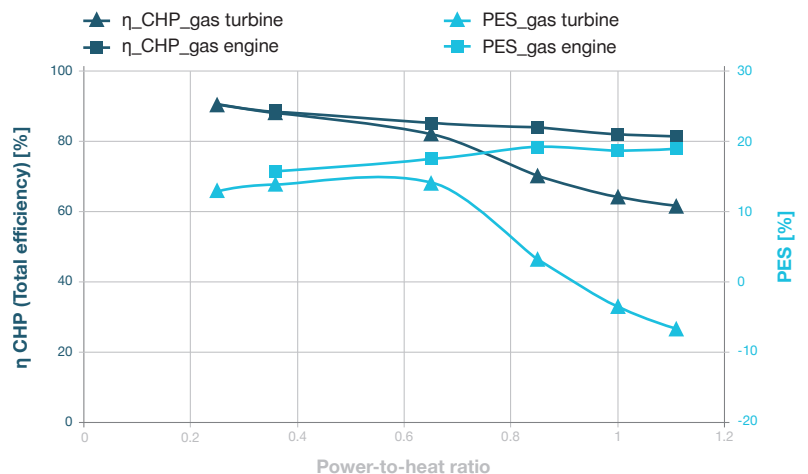


Fig. 8: Results of CHP 2 (8 bar saturated steam generation and 6 MW hot water generation)

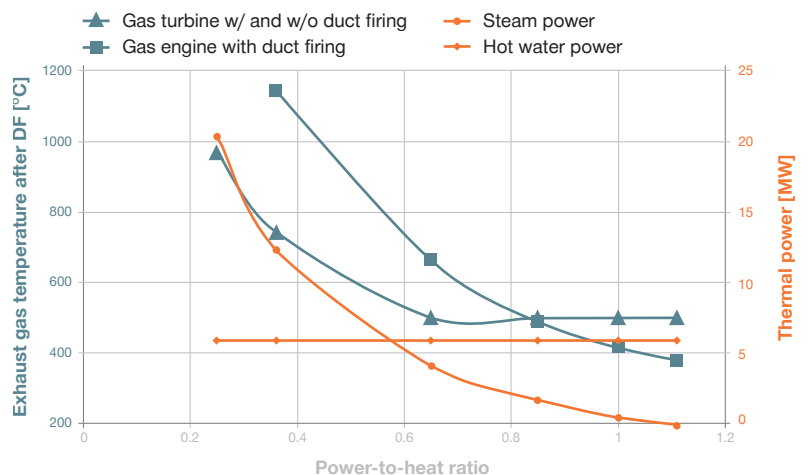


Fig. 9: Analysis of CHP 2 (8 bar saturated steam generation and 6 MW hot water generation)

2.3. Results and analysis of scenario CHP 3 (Fig. 10)

The results of the third scenario with 15 bar steam generation and 3 MW hot water generation differ considerably from the second scenario, since the higher steam pressure and the superheating cause a clear shift in heat transfer. This has a significant impact on the gas engine process in particular, as the lubricating oil heat and the engine cooling water heat cannot be used to the same extent as in the second scenario.

Only the gas turbine achieves an overall efficiency of above 80 %, at power-to-heat ratios of less than 0.7. The gas engine always remains below an overall efficiency of 80 %, and the primary energy savings are virtually constant in the low range of 7 %.

The steam output decreases from 23.3 to 1.4 MW as the power-to-heat ratio increases. The thermal output of hot water generation is kept constant at 3 MW. Auxiliary combustion is always required for the gas engine; this is only necessary for the gas turbine at power-to-heat ratios of < 0.6. As is the case for the first two scenarios, the technically feasible output of the auxiliary combustion is limited for the gas engine, for CHP 3 at a power-to-heat ratio of 0.43.

As in scenario 1, there is also a point where the curves intersect in scenario 3, this time at a power-to-heat ratio of ~ 0.8. Below 0.8, the gas turbine process is better; above 0.8, the gas engine takes the lead.

Conclusions of simulation CHP 3

- With power-to-heat ratios of < 0.8 the gas turbine enables the most efficient solution; duct firing is only required at a power-to-heat ratio of < 0.6. High efficiencies of approx. 90 % are being achieved.
- With power-to-heat ratios of > 0.8 the gas engine enables the most efficient solution as only moderate duct firing is required.
- The higher steam parameters compared to CHP 2 (8 ->15 bar) require increased duct firing for the gas engine. As a result, it is no longer possible to use the heat from the lubricating oil and intercooler in full, and the overall efficiency decreases by approximately eight percentage points for the gas engine compared to scenario CHP 2.

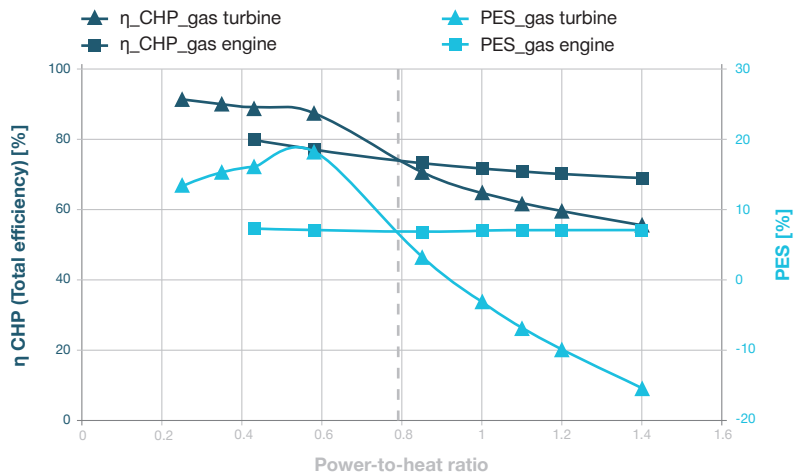


Fig. 10: Results of CHP 3 (15 bar steam generation and 3 MW hot water generation)

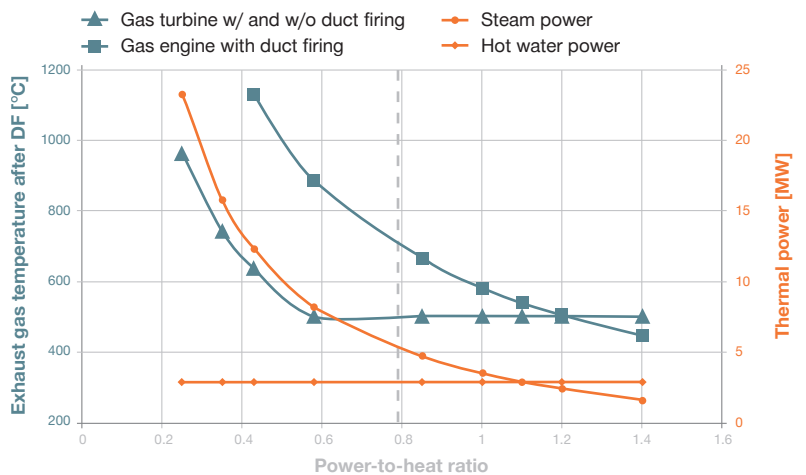


Fig. 11: Analysis of CHP 3 (12 bar steam generation and 3 MW hot water generation)

Conclusions

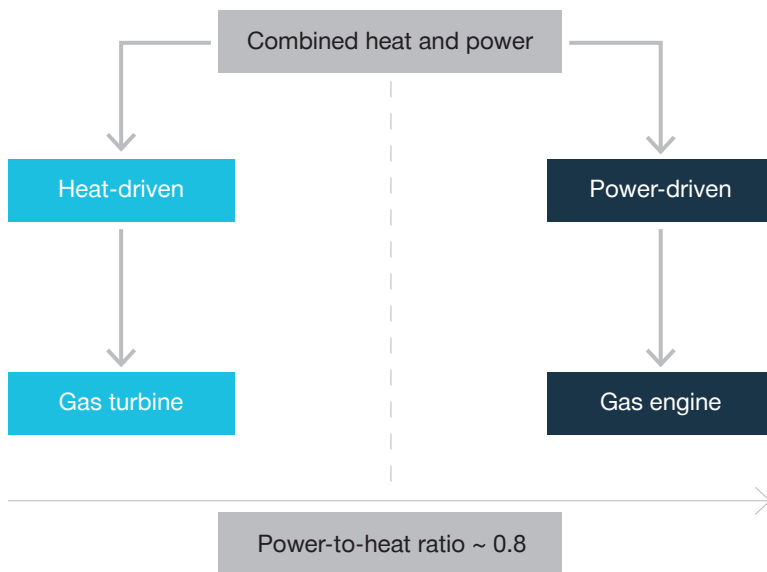


Fig. 12: Simplified summary

In scenarios CHP 1 and CHP 3, the heat sources of gas engine lubricating oil and cooling water cannot be utilized at all or only partially. For this reason, the gas turbine is the more efficient solution for power-to-heat ratios of less than 0.8.

In scenario CHP 2, both units achieve a similar overall efficiency in a power-to-heat ratio range of 0.4 to 0.7 since the heat sources of gas engine lubricating oil and intercooler can be used for hot water generation.

With power-to-heat ratios of $< \sim 0.4$, the gas engine generally does not allow for a useful configuration since the oxygen content in the exhaust gas does not permit sufficient duct firing.

With power-to-heat ratios of $> \sim 0.8$, the systems with gas engine generally achieve improved total efficiencies and also considerably higher primary energy savings.

In all three cases, the overall efficiency curve of the gas engine process with regard to the power-to-heat ratio is rather flat compared to the curve of the gas turbine process, i.e. the gas engine is more advantageous at high power-to-heat ratios and where there are high requirements for the variability of the power-to-heat ratio. However, the gas turbine solutions in scenarios CHP 1 and CHP 3 achieve higher values for the primary energy savings in this comparison with low power-to-heat ratios.

With low power-to-heat ratios and high steam parameters, the gas turbine is generally the more economical alternative. Economically viable steam generation is possible with gas engines but high steam parameters can limit the overall fuel utilization and therefore the cost-effectiveness. In order to be economical, gas engine solutions require hot water to be generated in parallel, particularly in the case of higher steam parameters.

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