Hybrid trigeneration concepts for power, steam and hot water production

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Abstract

The cogeneration systems are well known as highly efficient solutions with high savings, low costs in operation and very interesting flexibility. This important flexibility enables covering the daily fluctuations of power and heat demands.

In order to increase the efficiency, the flexibility and the economic benefits, some advanced cogeneration solutions are introduced. It is defined as the combination of gas turbines, gas engines and also batteries. These solutions are named hybrid cogeneration systems.

The technical and economic evaluations of the hybrid cogeneration systems are for power, steam and hot water production. The study compares the performances of hybrid concepts and the standard solutions. This study uses gas turbines and gas engines of the MAN Energy Solutions portfolio.

Introduction

The combined heat and power system known as the simultaneous generation of multiple forms of useful energy (usually mechanical and thermal) in a single integrated system with one fuel source, has become one of the most serious and attractive solutions. These systems are economically attractive with high flexibility and low emissions [refs 1-17]. These systems operate with different prime movers. They can be gas turbines, gas engines, steam turbines, micro-turbines and fuel cells.

Concerning the gas turbines and gas engines, in the first step, these prime movers generate electrical power. In the second step, the exhaust gases of these prime movers drive waste heat recovery units for steam production, hot water production or heating thermal oil. Such systems are well-used in food industries, refineries, paper mills, textiles, etc.

In general, the cogeneration systems can be in heat driven or in power driven configurations. In order to get more efficient configurations and more benefits, the combined heat and power systems were improved during the last ten years. One of the most important improvements is the combination of these systems with renewable solutions, as solar systems, geothermal, etc.

There is also a new attractive combination which is using two different prime movers as the case of gas turbine and gas engine, particularly for a trigeneration system. This combination can be defined as follows: the gas turbine generates electrical power in one hand. On the other hand it drives a waste heat recovery unit for steam production.

Concerning the gas engine, it can also generate power and drive a boiler for hot water or thermal oil production. Such a solution can be very interesting for a cogeneration system that can be power driven and heat driven at the same time. Additional to such a combination, the introduction of batteries for electrical power storage showed for solely power generation systems some economic benefits by saving the yearly fuel consumption.

The topic in this paper concerns the evaluation and the comparison of four combined heat and power systems for power, steam and hot water production. Such systems are typical of many production sites of car manufacturers.

The electrical power, steam and hot water demands used in this study are very realistic. Basically, the electrical power and hot water demands for day time are different than for night time. However, steam production is constant during day and night times.

The prime movers used in this study are from MAN Energy Solutions portfolio. Only the gas turbine class up to a little more than 13MW was used, with standard characteristics based on which is available in the market.

The first system evaluated uses two identical gas engine classes 10MW in part load. One engine drives a waste heat recovery unit for steam production with supplementary firing. The second engine drives a boiler for hot water production.

The second system corresponds to the use of one gas turbine class about 13MW. This gas turbine drives two waste heat recovery units at the same time, the first one is for steam generation and the second one is for hot water production. Supplementary firing is also used during night time.

The third system is a hybrid solution that combines gas turbine and gas engine. The gas turbine used is a single shaft, 6MW class, model MGT6000. It drives a waste heat recovery unit for steam generation with and without supplementary firing. The gas engine is 10MW class, model 20V35/44G. This engine drives a waste heat recovery unit for hot water production without supplementary firing.

The fourth system evaluated is identical to the third one, but with additional batteries units for electrical power storage. The batteries are charged during the day time and discharged during the night time.

During the night time, the gas engine is stopped and its power production is covered by the batteries in one hand. On the other hand, the boiler driven by the gas engine operates in conventional mode with supplementary firing post in order to fulfil the hot water demand.

Technical boundary conditions of the study

Tables 1, 2, 3 and 4 provide the main boundary conditions used in technical and economical calculations of the study.

Concerning the gas engine, it is possible to use the available heat of the lubrication oil and also the cooling heat of the first cooling stage.

Parameters	Data
Electrical Power demand_day time (MW)	12.6
Electrical Power demand_night time (MW)	7.68
Steam Demand day and night times (t/h)	15
Steam Pressure (bara)	10
Feed water Temperature inlet HRSG (°C)	90
Make up water temperature (°C)	20
Condensate return fraction of all CHP systems	80%
Condensate return temperature (°C)	90
Hot water demand day time (MW)	4.9 to 5.6
Hot water demand night time (MW)	1.1
Hot water inlet Temperature_Boiler (°C)	60
Hot water outlet Temperature_Boiler (°C)	110
Average Ambient Temperature at day time (°C)	15
Average Ambient Temperature at night time (°C)	10

Table 1: Boundary conditions of electrical power, steam and hot water processes of the CHP systems studied

Parameters	Data	
Altitude (m)	0	
Ambient pressure (kPa)	101,3	
Relative Humidity	60%	
Inlet Pressure losses (kPa)	0.75	
Outlet Pressure losses (kPa)	2.5	
Lower Heating Value (Nat. gas), (kJ/kg)	48000	
Prime mover	Gas Turbine	
Gas Turbine model	MGT6100	
Load (%)	100%	100%
Ambient Temperature (°C)	10	15
Electrical power output (MW)	6.68	6.4
Electrical Efficiency (%)	31.8	31.4
Exhaust Temperature (°C)	500	506
Exhaust gas flow (kg/s)	26.9	26.2

Table 2: Parameters of the MGT6000

The technical performances are provided at yearly average ambient temperature of 15°C for the day time and at an average ambient temperature of 10°C for the night time. These average ambient temperatures correspond to the European continent.

Parameters	Data	
Altitude (m)	0	
Ambient pressure (kPa)	101,3	
Relative Humidity	60%	
Inlet Pressure losses (kPa)	0.75	
Outlet Pressure losses (kPa)	2.5	
Lower Heating Value (Nat. gas), (kJ/kg)	48000	
Prime mover	Gas Turbine	
Gas Turbine model	Class ≥ 13 MW	
Ambient Temperature (°C)	10	15
Electrical power output (MW)	7.68	12.6
Electrical Efficiency (%)	29.2	33.3
Exhaust Temperature (°C)	447	489
Exhaust gas flow (kg/s)	39.3	47.1

Table 3: Parameters of a gas turbine with an electrical power output ≥ 13 MW

Parameters	Data				
Load	10%	59%	60%	64%	69%
Elect. Power output (MW)	1.0	6.2	6.3	6.68	7.2
Electrical Efficiency	20.2%	43.1%	43.2%	43.5%	44.0%
Exhaust temperature (°C)	358	394	393	390	387
Exhaust gas flow (kg/s)	3.8	10.4	10.5	11.0	11.9
Lub. Oil Heat capacity (kW)	599	830	831	836	837
*HT_Heat Circuit (kW)	-	716	746	876	1066

Table 4: Parameters of the 20V35/44G

Analysis of thermodynamic features

All the thermodynamic calculations of the combined heat and power systems were carried out by models build with GateCycleTM software. The main parameters were calculated with the known equations:

$$PHR=\frac{Pel}{(Qsteam+Qhw)} \qquad (1)$$

$$\eta\_(e\ CHP)=\frac{Pel}{(QFuel\_CHP)} \qquad (2)$$

$$\eta\_CHP=\frac{(Pel+Qsteam+Qhw)}{(QFuel\_CHP)} \qquad (3)$$

All parameters of these formulas were defined in the Nomenclature.

Description of the CHP: Eng

The first CHP system evaluated in this study is based on the use of two gas engines class 10MW model 20V3544G with the first gas engine driving a steam boiler. The supplementary firing for this gas engine´s boiler is needed day and night because the steam demand is constant. The heat of the lubrication oil and the HTf the gas engine are not used for steam generation.

The second gas engine drives a boiler for hot water production at 110°C. The gas engine of this solution operates at part load during day and night times.

Concerning the water treatment section of steam process, it is the same one for all CHP systems evaluated in this study. It is considered as a standard configuration. The condensate return share is back to the deaerator. The lost steam share in the industrial process, is taken from the makeup water tank and heated with a heat exchanger driven by the outlet feed water from the deaerator tank.

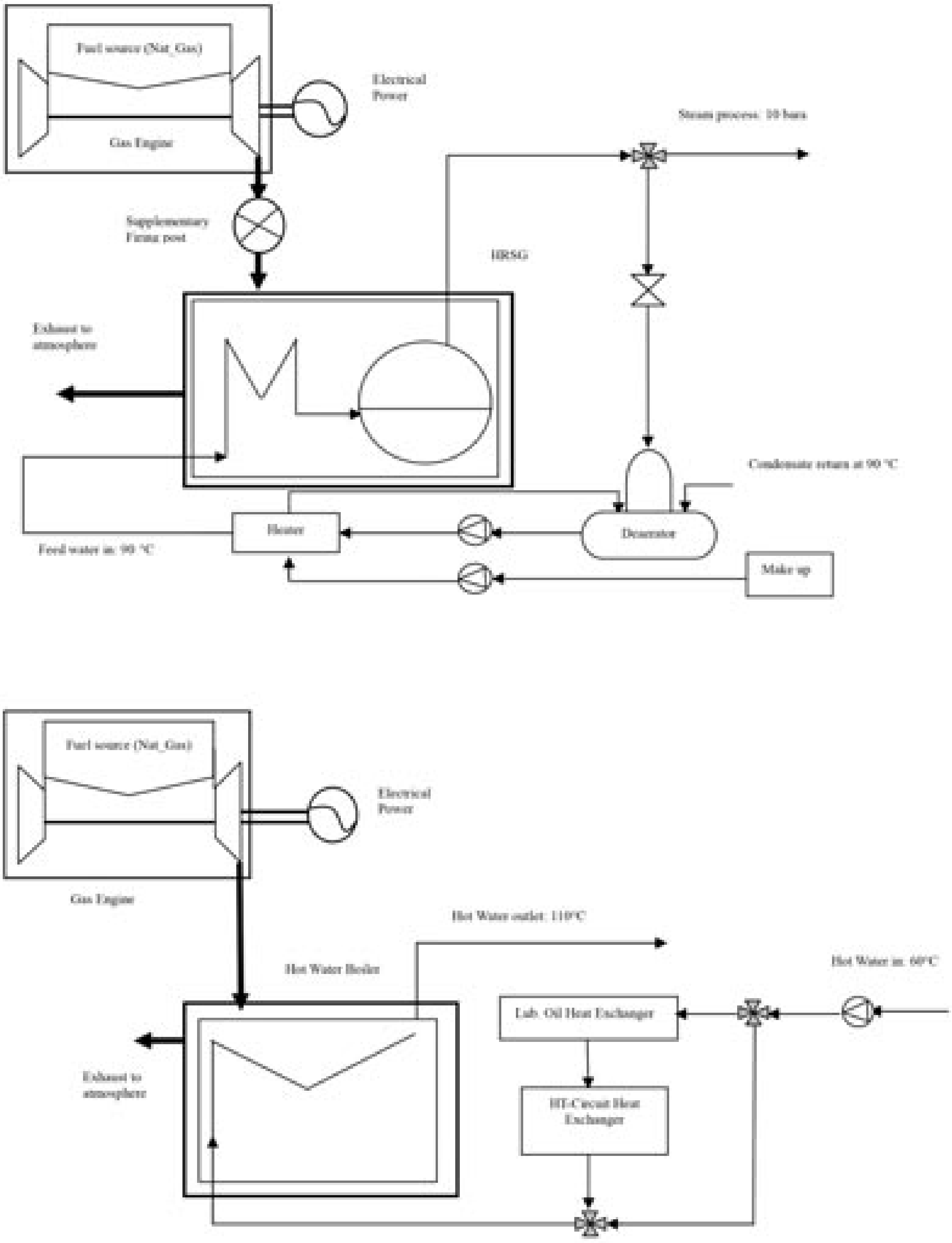

Figure 1: Configuration of CHP: Eng,
Combined power, steam and hot water production with two gas engines class 10 MW, model: 20V3544G

Description of the CHP: GT

The second combined heat and power system evaluated is based on the use of one standard gas turbine class > 13MW.

The gas turbine operates at part load day and night. The exhaust heat of this gas turbine is used in the first step for steam generation and in the second step for hot water production. The system operates without supplementary firing in the day time but in the night time supplementary firing is used in order to cover steam and hot water demands. The reason for that is the low exhaust heat capacity available from the gas turbine side which is due to the low load of the gas turbine during the night time.

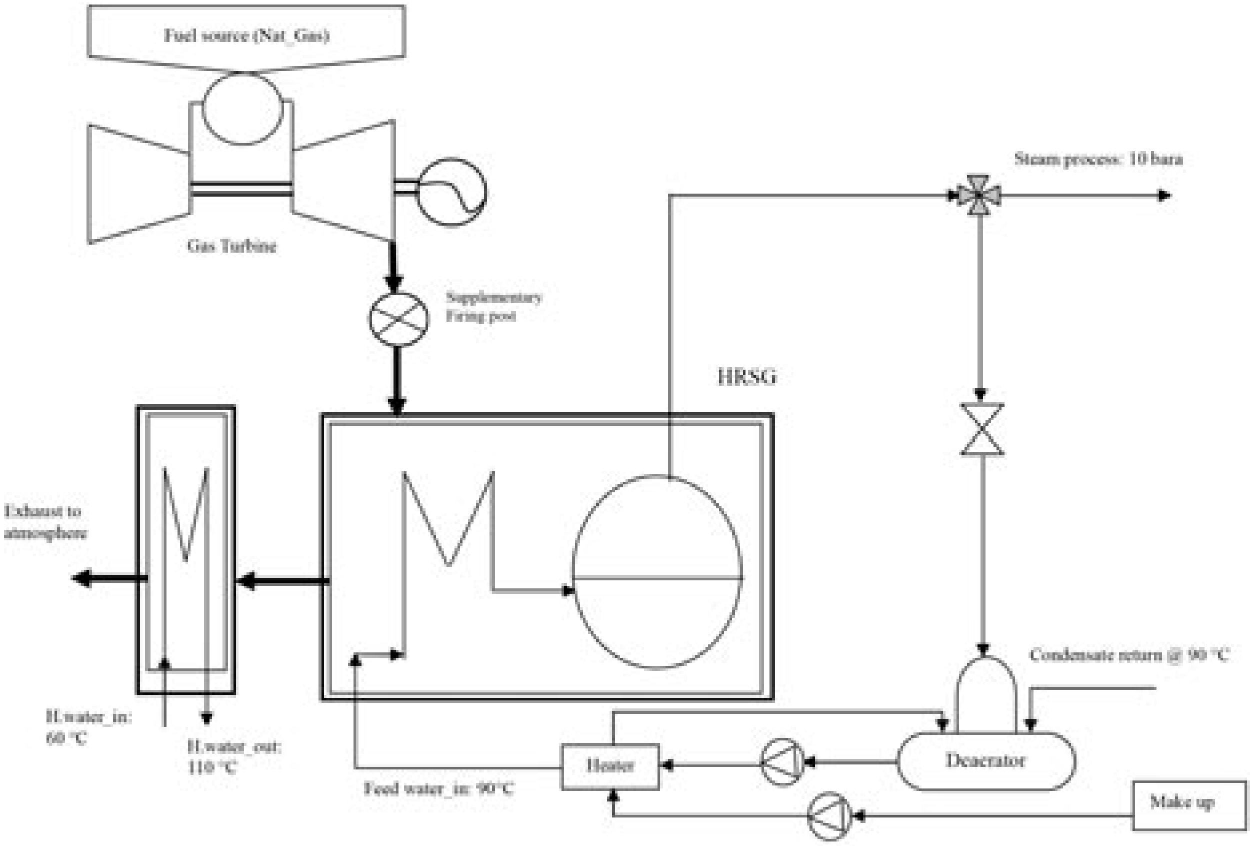

Figure 2: Configuration of CHP: GT, Combined power, steam and hot water production with one gas engine class ≥ 13 MW

Nomenclature

CHP: Eng	Conventional combined electrical power, steam and hot water generations by two gas engines combined heat and power system: electrical power, steam and hot water generations
CHP: GT	Conventional combined electrical power, steam and hot water generations with one gas turbine
CHP: GT+Eng	Hybrid combined electrical power, steam and hot water generations with one gas turbine and one gas engine
CHP: Eng+GT+B	Hybrid combined electrical power, steam and hot water generations with one gas turbine, one gas engine and batteries for electrical power storage
η CHP	Overall combined heat and power efficiency (%)
η_e CHP	Electrical efficiency of combined heat and power (%)
HRSG	Heat recovery steam generator
P_{el}	Electrical power output of combined heat and power system (MW)
PHR	Electrical power to heat process capacity ratio
Q_{steam}	Thermal power of steam generation (MW)
Q_{hw}	Thermal power of hot water production (MW)
Q_{fuel_CHP}	Thermal power of the fuel consumption of the CHP system (MW)

* HT_Heat Circuit The internal heat capacity of the first stage circuit to be dissipated

Description of the CHP: GT+ENG

The third solution is a hybrid combined heat and power system.
It is the combination of two different prime movers:
the MAN gas turbine class 6MW, model: MGT6000 and the MAN gas engine class 10MW, model: 20V3544G.

The heat lubrication oil and the heat of the first internal cooling stage of the gas engine are used for hot water production. The gas turbine operates continuously at full load and drives a boiler for steam generation at 10 bara without supplementary firing.
Concerning the gas engine it operates at two different loads. It produces an electrical power output around 6MW in the day time and just 1MW in the night time. It drives a boiler for hot water production without supplementary firing. The hot water production fluctuates significantly between the day and night times.

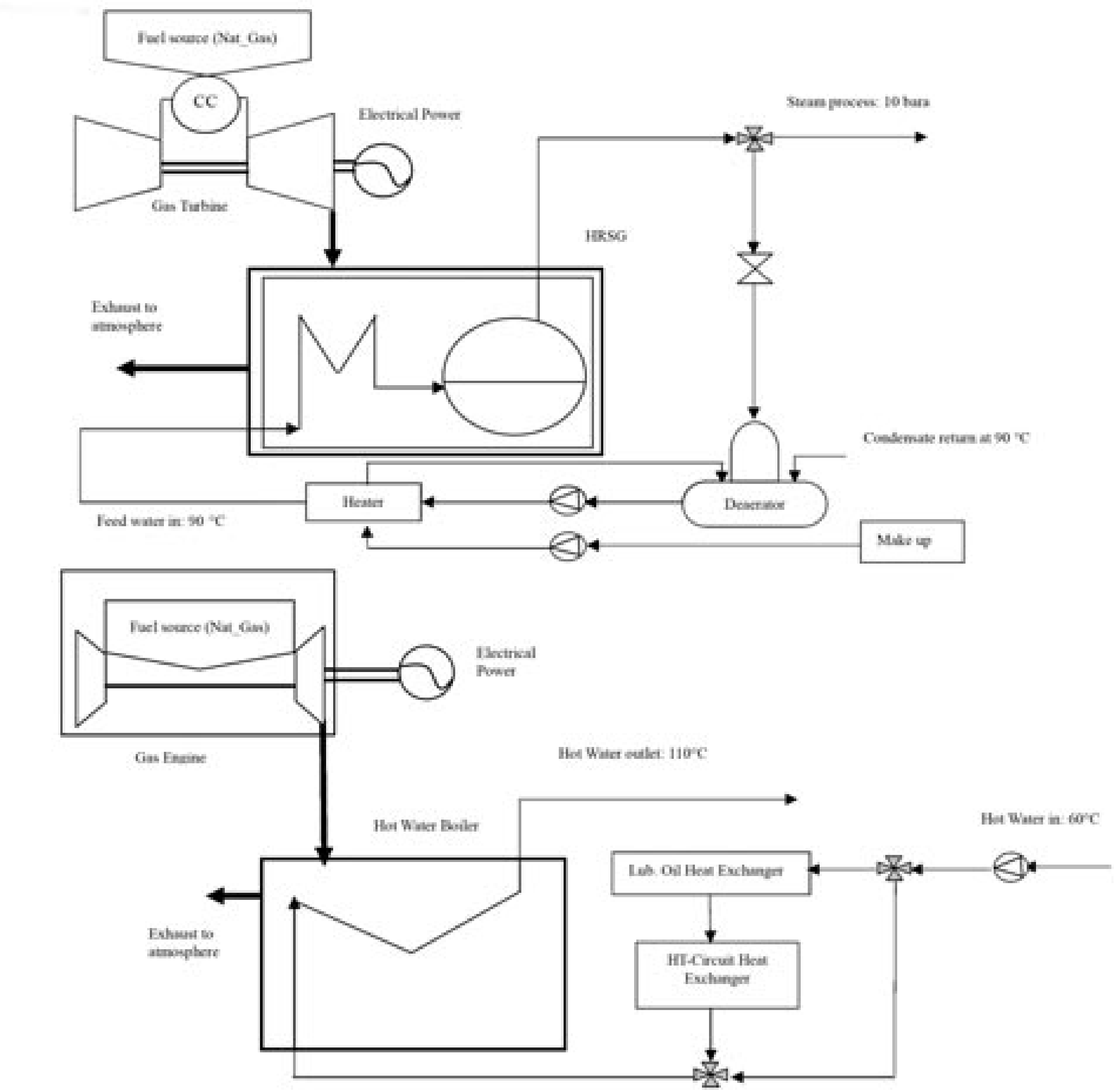

Figure 3: Configuration of Hybrid CHP: GT+Eng, for electrical Power, Steam and Hot water generations

Description of the CHP: GT+ENG+B

The fourth option is a hybrid combined heat and power system with batteries.
This solution is identical to the third one but with additional batteries modules used for electrical power storage.

The batteries operate with one cycle per day. They are charged by the gas engine during the day time. In this period the gas engine produces an excess of power equal to 1MW in order to charge the batteries. In this case hot water production will be little higher than the other systems evaluated.
During the night time, the gas engine is shut down and the batteries are discharged.
The hot water boiler driven by the gas engine during the day time operates in conventional mode at night time by the integration of supplementary firing.

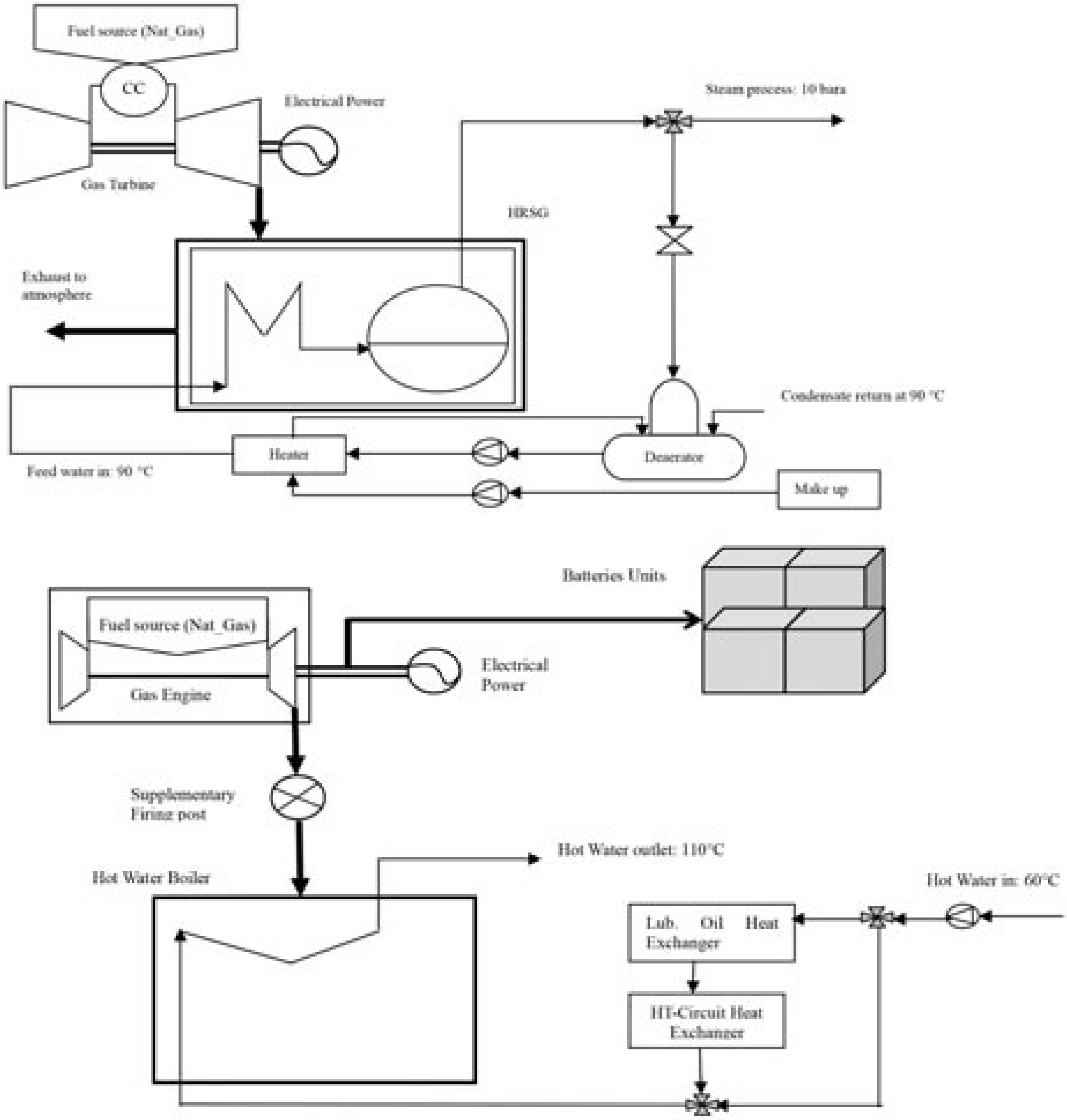

Figure 4: Configuration of Hybrid CHP: GT+Eng+B, for electrical Power, Steam and Hot water generation

Analysis of the technical performances of the evaluated CHP systems

In Table 1 of the technical boundary conditions, the electrical power, steam and hot water demands of the study were specified for the day and night times. Based on these, the PHR were evaluated.

CHP system	PHR	
	Day Time	Night Time
CHP: GT+Eng+B	0.84	0.66
CHP: GT+Eng	0.81	
CHP: Eng		
CHP: GT		

Table 5: Daily PHR variations

The PHR defines if the system operates in power driven or heat driven configuration. Based on some studies [1], when the PHR is lower than 0,8 the system is in heat driven mode and if the PHR is higher than 0,8 the CHP system is in power driven mode. The results of Table 5 provide the following information:

- In the day time, the CHP systems evaluated are in power driven configuration
- In the night time, the CHP systems operate in heat driven mode.

Parameters	Day Time	Night Time
Ambient Temperature (°C)	15	10
Load Gas Engine of Steam process	60.40%	64.10%
Electrical Power output Gas Engine of Steam Process (MW)	6.3	6.68
Load Gas Engine of Hot Water Process	60.40%	10.20%
Electrical Power output of Gas Engine of Hot Water Process (MW)	6.3	1
Electrical Power output CHP: Eng (MW)	12.6	7.68
Electrical Efficiency Gas Engine of Steam Process Gas Turbine	43.20%	43.50%
Electrical Efficiency Gas Engine of Hot Water Process	43.20%	20.20%

Table 6: Different electrical power outputs and the electrical efficiencies of the CHP: Eng

Parameters	Day Time	Night Time
Ambient Temperature (°C)	15	10
Load Gas Turbine	78%	47%
Electrical Power output Gas Turbine (MW)	12.6	7.68
Electrical Power output CHP: GT (MW)	12.6	7.68
Electrical Efficiency Gas Turbine	33.30%	29.20%

Table 7: Electrical power outputs and the electrical efficiency of the Gas Turbine class ≥ 13 MW of the CHP: GT

These results are due to the fluctuations of the electrical power demand and also the total thermal power of steam and hot water processes.

Tables 6, 7, 8 and 9 provide the electrical power outputs and the electrical efficiencies of the prime movers used in the different combined heat and power systems studied.

Concerning the MAN gas turbine class 6MW used in the CHP: GT+Eng+B and CHP: GT+Eng, it operates continuously in full load during the day and the night times.

The MAN gas engine class 10MW, during day time, it operates in part load for the CHP: GT+Eng+B, CHP: GT+Eng and CHP: Eng (between 59 and 69% load). However during night time, the gas engine is shut down for CHP: GT+Eng+B due to the use of batteries and it operates at 10% load for CHP: GT+Eng and CHP: Eng.

For the CHP: GT, a standard Gas Turbine class ≥ 13MW is used and it operates at 78% load during the day time and 47% load during the night time.

Table 10 provides the steam production at 10 bara for all CHP systems evaluated in this study. The steam production is constant at 15.5t/h which corresponds to a steam thermal power of 10.6MW. As it was mentioned in the description of all CHP systems, for CHP: GT+Eng+B and CHP:

Parameters	Day Time	Night Time
Ambient Temperature (°C)	15	10
Load Gas Turbine	100%	
Electrical Power output Gas Turbine (MW)	6.4	6.68
Load Gas Engine	59.5%	10.2%
Electrical Power output Gas Engine (MW)	6.2	1.0
Electrical Power output CHP: GT+Eng (MW)	12.6	7.68
Electrical Efficiency Gas Turbine	31.4%	31.8%
Electrical Efficiency Gas Engine	43.1%	20.2%

Table 8: Different electrical power outputs and the electrical efficiencies of the CHP: GT+Eng

Parameters	Day Time	Night Time
Ambient Temperature (°C)	15	10
Load Gas Turbine	100%	
Electrical Power output Gas Turbine (MW)	6.4	6.68
Load Gas Engine	69.1%	0%
Electrical Power output Gas Engine (MW)	7.2	Shut down
Electrical Power output Batteries (MW)	-1	1
Electrical Power output CHP: GT+Eng+B (MW)	12.6	7.68
Electrical Efficiency Gas Turbine	31.4%	31.8%
Electrical Efficiency Gas Engine	44.0%	Shut down

Table 9: Different electrical power outputs and the electrical efficiencies of the CHP: GT+Eng+B

Parameters	Steam Production at 10 bara in the day and night times (t/h)	Thermal Power of steam production in the day and night times (MW)
CHP: GT+Eng+B	15.5	10.6
CHP: GT+Eng		
CHP: Eng		
CHP: GT		

Table 10: Steam production at 10 bara for all CHP systems evaluated

GT+Eng, the steam production is from the steam boiler driven by the gas turbine class 6MW without supplementary firing during the day and night times.

For the CHP: Eng, the steam production is carried out by a boiler driven by a 20V35/44G engine (class 10MW). This steam boiler operates with a supplementary firing post (medium size) in order to fulfil the steam demand of 15.5t/h. The supplementary firing is used during the whole day.

Parameters	CHP: GT+Eng+B	CHP: GT+Eng, CHP: Eng, CHP: GT
Hot Water production at 110°C in the day time, (t/h)	96.5	84.0
Thermal Power of Hot Water in the day time (MW)	5.6	4.9
Hot Water production at 110°C in the night time (t/h)	19.7	
Thermal Power of Hot Water in the night time (MW)	1.1	

Table 11: Hot water production at 110°C for all CHP systems evaluated

Concerning the CHP: GT, supplementary firing (small size) is not used in the day time for steam production. However in the night time the supplementary firing is needed. Table 11 provides the production and thermal power of hot water at 110°C for all the CHP systems evaluated in this study. During the day time, the hot water production for CHP: GT+Eng+B is 96.5t/h but for CHP: GT+Eng, CHP: Eng and CHP: GT, it is 84.0t/h.

This difference is due to the load of the gas engine which is around 69% for CHP: GT+Eng+B and it is around 60% for CHP: GT+Eng, CHP: Eng, CHP: GT. The gas engine operates at higher load in the day time for CHP: GT+Eng+B (1MW of excess in electrical power production) in order to charge the batteries. At 69% load the total thermal power of the exhaust gas and the gas engine auxiliaries is higher than at 60% load which helps hot water production. At night time, the hot water production at 110°C is much lower than in the day time, it is 19.7t/h for all CHP systems studied.

Figure 5 shows the daily fluctuations of the electrical power demand, the electrical power output of the hybrid CHP solution with batteries (CHP: GT+Eng+B) and the state of the charge of the batteries.

As it was mentioned in the table of the technical boundary conditions, in the night time, the electrical power demand is 7,68MW and during the day time, it is 12,6MW. The electrical power output of the CHP: GT+Eng+B in the day time is 1MW more than the demand because in this time the batteries are in charging mode. The charging phase of the batteries is carried out by the gas engine. During the night time, the gas engine is shut down and the batteries are discharged. At this time, the total electrical power of the gas turbine and the batteries output cover the demand.

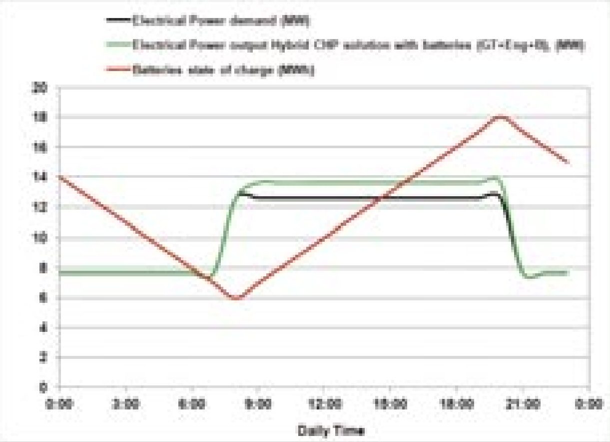

Figure 5: Daily variation of electrical power profiles

Figure 6 provides the daily fuel consumption of all CHP systems evaluated. The daily fuel consumption of the hybrid CHP system with batteries (719MWh), is the lowest one. It is 3% lower than that one of CHP: GT+Eng, 9% lower than that of CHP: Eng and 12% lower than that of CHP: GT. The interesting fuel savings of the CHP: GT+Eng+B compared to the other systems is mainly due to the use of batteries during the night time. By considering the yearly operating time of 350 days, these fuel savings become very important share in the total operating cost of the CHP plant.

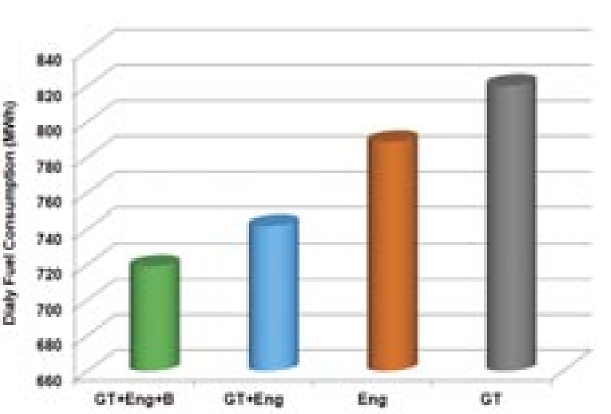

Figure 6: Daily fuel consumption of the CHP systems studied

Figure 7 provides the profile of the electrical efficiency of each CHP system during a complete day. From a general view, the electrical efficiencies of the hybrid combined heat and power systems CHP: GT+Eng+B (hybrid with batteries) and CHP: GT+Eng (hybrid without batteries) are the highest one in the whole day.

In the day time, the electrical efficiency of the hybrid solution CHP: Eng is 36.2%, it is the highest one, it is little higher than those of CHP: GT+Eng+B and CHP: Eng (solution with two gas engines class 10MW) which are around 34.3%. The electrical efficiency of CHP: GT (solution with one gas turbine class ≥ 13MW), it is around 33.3%.

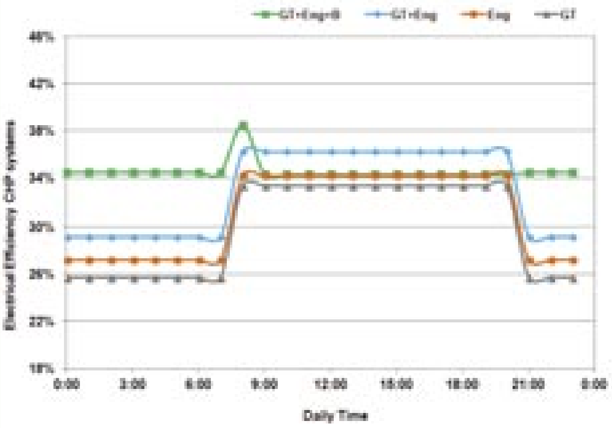

Figure 7: Profile of the electrical efficiency of the CHP systems during the day and the night time

In the night time, the electrical efficiencies of the CHP: GT+Eng+B and CHP: GT+Eng are also the highest one, particularly the electrical efficiency of CHP: GT+Eng+B, it is around 34.5%. The electrical efficiency of CHP: GT is the lowest one. It is around 25.7%. The high electrical efficiency of CHP: GT+Eng+B during the night time, is mainly due to the use of batteries. In this period the batteries are discharged and cover 13% (1MW) of the total electrical power demand (7.68MW). The rest is covered by the gas turbine class 6MW.

These evaluations show that in power driven (day time) and heat driven (night time), the hybrid CHP solutions have the highest electrical efficiencies.

Figure 8 presents the profiles of the overall CHP efficiencies of the CHP systems studied. The evolution of this parameter in the whole day is almost identical to the electrical efficiency.

During the day time, the hybrid CHP systems with and without batteries have the highest overall efficiencies. The overall CHP efficiency of the CHP: GT+Eng is around 80.8%, it is little higher than that of CHP: GT+Eng+B which is around 78.4%. The CHP efficiency of CHP: Eng is around 76.4%. In this period, the CHP efficiency of CHP: GT is 74.3%, it is the lowest one.

Concerning the night time, the overall CHP efficiency of the hybrid CHP: GT+Eng+B is the highest one. It is around 86.9%. The overall CHP efficiency of the CHP: GT+Eng is around 73.6%. However, the CHP efficiencies of CHP: Eng and CHP: GT are lower than 70%. The lowest CHP efficiency is that of CHP: GT, it is around 64.8%. The high overall CHP efficiency of CHP: GT+Eng+B is mainly due to the use of batteries modules in one hand. On the other hand the low fuel consumption of the hot water boiler which operates in conventional mode (night time) doesn't have a significant impact on the overall CHP efficiency.

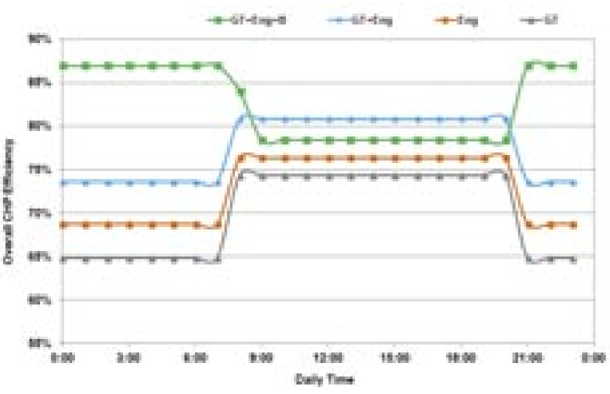

Figure 8: Profile of the overall CHP efficiency of the CHP systems evaluated during the day and the night time

As for the electrical efficiency, the evaluation of the overall CHP efficiency shows that in power driven (day time) and heat driven (night time), the hybrid CHP solutions have the highest overall CHP efficiencies.

Analysis of the economical performances of the evaluated CHP systems

An economical evaluation was performed with the specified boundary conditions of Table 12 in order to show if all these systems are viable and attractive.

Figure 9 provides the net yearly savings of all CHP systems studied. Basically the net savings consider the total operating cost of each solution (total yearly fuel consumption, service and maintenance: OPEX) in one hand. On the other hand the savings calculations are done by a comparison to a conventional solution. This standard conventional solution is defined by producing steam and hot water by conventional boilers and to buy electricity from the public grid.

Figure 9 shows also that the net yearly savings of the hybrid CHP solution with batteries (around 4.7 M€) are the highest one. The net yearly savings of the hybrid system without batteries (Eng+GT), the CHP: Eng and the solution with one gas turbine (CHP: GT) are respectively: 4.3 M€, 3.5 M€ and 3.6 M€.

Parameters	**Data**
Electricity price	110 €/MWh
Natural Gas Price	34 €/MWh
Yearly operating time	8400 hours (350 days)
Interest Rate	5%
Conventional Boiler Efficiency	90%
Batteries cost for CHP: GT+Eng+B1	480 €/kWh (actual cost)
Batteries cost for CHP: GT+Eng+B2	300 €/kWh
Batteries cost for CHP: GT+Eng+B3	100 €/kWh

Table 12: Economical boundary conditions of the study

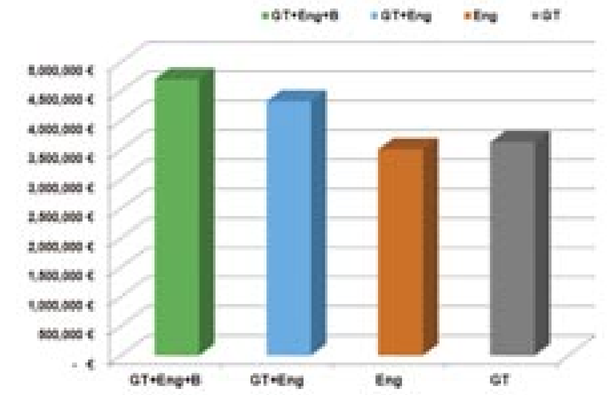

Figure 9: Net yearly savings of the CHP systems evaluated

The conventional solution has total yearly costs around 14.0M€. This is based on the specified economical boundary conditions shown in Table 12. The comparison of the yearly operating costs of the conventional option and the CHP systems studied is provided in Table 13. This comparison confirms that the yearly benefits of the hybrid CHP solution is the highest one.

CHP systems	Savings difference compared to the conventional solution
GT+Eng+B	33.2%
GT+Eng	31.2%
Eng	25.4%
GT	26.3%

Table 13: Savings difference in yearly operating costs between conventional option and the evaluated CHP systems

Figure 10 shows the payback time for all CHP systems evaluated. The payback time for the hybrid solution with batteries was evaluated with three different batteries costs mentioned in the Table 12. The actual batteries costs are the highest (B1), B2 is an intermediate cost which is expected in few years time. B3 corresponds to the lowest batteries cost that is expected after 6 years. The hybrid CHP solutions without batteries and with batteries (B3) have the shortest payback time around 4 years. This is not only driven by the low investment (CAPEX) but also due to the higher net savings (Figure 9). The CHP solution with just one gas turbine has also a short payback time around 4.2 years. This is mainly due to the lowest investment of this solution.

The payback time of the hybrid CHP systems with batteries (batteries costs: B1 and B2) and CHP: Eng have longer payback times between 5 and 6 years. This is mainly due to the high investments of these options.

Discussion and analysis of the results

The technical and economical results obtained show that:

- The hybrid combined heat and power systems with or without batteries are the most efficient solutions in power driven and heat driven configurations. This is particularly the case for the hybrid CHP solution with batteries.

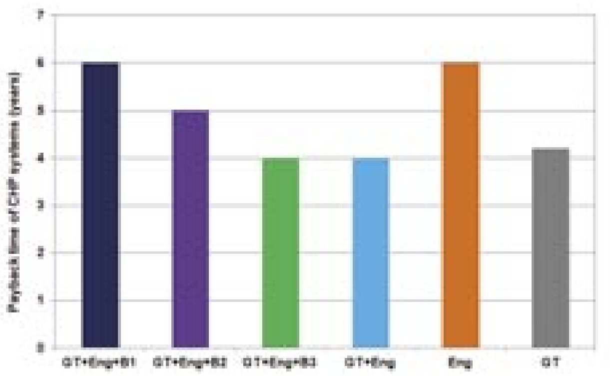

Figure 10: Payback time of the CHP systems evaluated

- The daily fuel savings of the hybrid CHP solution with batteries is the highest one. The use of the batteries modules is the main reason.
- The net yearly savings of the hybrid CHP with batteries is the highest one. This is mainly due to the heat processes (mainly the hot water production) and also to the electrical power generation as follows:
  - During the day time, the excess of electrical power production for charging the batteries implies little more production of hot water
  - Discharging the batteries in the night time to cover the total electrical power demand
- The hybrid CHP systems without batteries and with batteries (batteries cost not more than 100 €/kWh) have the shortest payback times, which is around 4 years. However, with the current batteries cost of 480 €/kWh, the hybrid CHP solution using batteries, has a payback time around 6 years which is identical to the gas engines solutions. It is not attractive at this time.
- Concerning the standard option based on the use of one gas turbine with power class > 13MW, it has an attractive payback time (between 4 and 5 years), mainly due to the low CAPEX of this solution.
- The hybrid CHP solution with batteries is expected to be very attractive in 6 years time and later and little later when batteries cost lower than 100 €/kWh are anticipated.

Conclusion

In general, industries are looking for efficient combined heat and power solutions which are economically attractive. These solutions have high flexibility and are driven by greenhouse emissions concerns. This is one of the main objectives of this study.

A comparative study carried out with the four combined heat and power solutions:

- Conventional CHP with only gas turbine
- Conventional CHP with only gas engine
- Hybrid CHP solution with gas turbine and gas engine
- Hybrid CHP solution with gas turbine, gas engine and batteries

These solutions are exemplary at satisfying the electrical power, steam and hot water production. The hybrid concepts evaluated are the most efficient options technically and economically compared to the conventional CHP systems evaluated.

The hybrid CHP solution with batteries has the highest efficiencies and the capability of a fast start-up and following fluctuating loads.

The actual battery costs are an important factor and not in the favour of an attractive economical hybrid concept, however in the future, it will be essential to consider such a solution for certain profiles of power and heat processes as it is the case of the automotive production sites. ■

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Current responsibilities:

Since 2001 in MAN Diesel & Turbo:

- Designing, simulating and modelling the thermodynamic cycles of combined heat and power systems (steam, heating, cooling and power) and combined cycle for power generation
- Proposing the most efficient, innovative, flexible and economical combined heat and power solutions for the customers

Biographical summary:

- PHD, Doctor in process engineering, Polytechnic Institute of Toulouse, France (1999-2004)
- R&D Master in Perpignan University, France (1998-1999)
- Engineer´s degree in Mechanical and Thermal engineering, Mechanical Institute, Algiers, Algeria (1991-1996)
- R&D and Project Engineer in combined heat and power by solar thermal, Solar Millennium (Solitem group section in Aachen), 2008–2011:
- Research and development, design, simulation and optimization of solar power, steam, heating and cooling systems based on the design and the use of parabolic trough collectors technology.
- R&D Engineer in solar thermal field, CSEM, Swiss Center of Energy & Electronics (Switzerland & United Arab Emirates), 2006–2007.
- Contribution in the design of an innovative solar flat collectors and storage at high temperature with PCM for solar cooling and heating purposes, used for small and medium capacities.

Questions and Answers

The following questions were raised during and after the presentation at the IDGTE Gas Turbine Papers Day at the University of Lincoln on 6 November 2018.

Dr Saidi has provided the following written replies.

Q Is the service costs of the Batteries and the other components included in the economical evaluation?

A All the service costs of the combined heat and power systems evaluated were considered even the batteries. The batteries operate with one cycle per day (charging and discharging). The batteries life time is around 10 years. This corresponds to the highest quality of batteries available in the market.

Q Why do the hybrid solutions with or without batteries generate the highest net savings and at the same time they don't have the lowest service costs?

A The Hybrid CHP solutions are more efficient than the standard CHP solutions and particularly that one with batteries included.

On the other hand these solutions generate higher fuel savings compared to the standard CHP options. The service costs have really low impact on the generated savings of Hybrid solutions. The use of batteries in the Hybrid CHP solution provide additional interesting savings.

The first share of these savings is due to the Hot water production during the day time (charging the batteries by the gas engine). The second share of these savings is due to power generation during the night time (discharging the batteries).

Q The hybrid CHP solution with batteries have higher savings but not really the lowest payback time with the actual batteries cost?

The actual high cost of the batteries is the main reason why the CAPEX of the Hybrid Solution is the highest one. The consequence of that is: the payback time of the CHP hybrid solution is around 6 years.

However in 5 or 6 years, the use of batteries for power generation and CHP fields will be more common and the expected batteries cost will be in the range of 100 €/kWh. In this case the hybrid CHP option with batteries can have the shortest payback time which is around 4 years. This is identical to the Hybrid option without batteries. The standard gas turbine solution (class > 13MW) has also a short payback time between 4 and 5 years. It is mainly due to the lowest CAPEX of this solution.

Q There is no indicative data concerning CAPEX costs in the paper.

There is no numbers concerning the CAPEX of the shown CHP solutions because it was restricted by the Leaders of the Gas Turbine department in MAN Company due to the available internal rules.

Q The cost of the batteries is stated to be 480 Euro/kWh at the present time. A car is now available in the UK from Hyundai with a selling list price of approx. 37400 euro and a battery capacity of 64kWh.

Based on these figures the battery cost is 30720 Euro. This seems a high proportion of the total cost of the car.

Are automobile batteries different or cheaper or are we already below the 480 euro/kWh cost?

First of all the batteries used in the power generation field are manufactured to a higher quality than those used for cars. The batteries considered for the study operate with one cycle per day. These devices are charged and discharged one time per day. The life time of such batteries is estimated to 10 years.

However the batteries of cars are able today to have a range of 200 – 300 km. The normal use of such batteries with cars means that such equipment will be charged 2 times or maximum 3 times per week because a normal user will not drive every day 200 km.

This implies that there is around 10 cycles per month for the batteries of cars which is three times less than those for power plant or for the study.

The main consequences is that for the cars batteries the life time will be easily between 10 and 20 years and the investment in the cars batteries is also much lower than 480 Euro/kWh.