

Thermodynamic simulation analysis of a multifuel CHP plant basing on the technological diagram of Avedøre unit 2

ANDRZEJ ZIĘBIK^{1*}
DAMIAN SZEGDA¹
BJØRN QVALE²
BRIAN ELMEGAARD²

¹ *Silesian University of Technology, Institute of Thermal Technology,
Konarskiego 22, 44-100 Gliwice, Poland*

² *Technical University of Denmark, Energy Engineering Section, 2800
Lyngby, Denmark*

Abstract The paper presents the results of a simulative thermodynamic analysis of a multifuel CHP plant basing on the technological diagram of Avedøre 2. Calculations have been carried out for the operation of Avedøre 2 plant in the district heating mode. Several variants of simulation have been considered, determined by the choice of operation of the respective plants, viz. main boiler fired with natural gas, main and biomass boiler, main boiler and GT plant, joint operation of the main and biomass boiler and GT plant, main boiler (fired with heavy fuel oil or/and wood chips) and biomass boiler and GT plant. For each variants a diagram of iso-fuel curves has been developed, illustrating the variability of useful effects (power output and district heat) at various loads of the CHP steam part. In case of the variant in which the main boiler and GT are in operation with natural gas as fuel the exemplary energy indices were determined.

Keywords: Multifuel CHP; Thermodynamic simulation; Indices of cogeneration

*Corresponding author. E-mail address: andrzej.ziebig@polsl.pl

Nomenclature

$CHPH\eta$	–	heat efficiency of cogeneration process
$CHPE\eta$	–	electrical efficiency of cogeneration process
\dot{E}_{ch}	–	flux of chemical energy
P	–	power rating
\dot{Q}	–	flux of heat
$Ref H\eta$	–	efficiency reference value for separate heat production
$Ref E\eta$	–	efficiency reference value for separate electricity production

Greek symbols

ε	–	index of own consumption
η	–	efficiency
σ	–	index of cogeneration

Subscripts

CHP	–	combined heat and power
E	–	energy
el	–	electricity
hp	–	heating plant
pp	–	power plant
te	–	transportation of electricity
th	–	transportation of heat
s	–	separate production

1 Introduction

The most modern power unit all over the world is the Avedøre Unit 2. It can operate both in the condensation mode and the district heating mode (back-pressure mode). The thermodynamic simulation analysis concerns the latter option. Because of difficulties concerning operation data many assumptions had to be made: some of the data have been taken directly from the Avedøre Unit 1 steam cycle (due to the similarities between steam cycles of these two plants), a certain amount of data has been taken from articles written about Avedøre 2 [5, 6, 8, 9] and another part of data has been assumed as approximations. Simulations of Avedøre 2 have been carried out for possible plant configurations (i.e. the main and biomass boiler in operation) and the results obtained from them reflect the operational capabilities of the plant.

The mentioned simulations have been carried out using the software DNA (Dynamic Network Analysis) developed at the Energy Engineering Section of the TU Denmark [2, 3, 4]. The component library of the DNA contents models of boilers, heat exchangers, turbines, compressors, burn-

ers, pumps, deaerators, condensers, separators, gasifiers and more. The obtained results help to evaluate the energy effects of Avedøre CHP operation suggested by the Institute of Thermal Technology of SUT Gliwice in Poland [10, 11].

2 Short description of the Avedøre 2 multifuel CHP plant

The Avedøre Unit 2 (Fig. 1) power rating amounts to 575 MW_{el} and a heating capacity of 545 MW_{th} . It was designed in order to ensure optimal conditions among others from the view of flexibility in application of fuels (hard coal, natural gas, heavy fuel oil, straw and wood pellets).

The main part of Avedøre 2 is a power plant with advanced super critical steam parameters, namely 300 bar and $580/600 \text{ }^\circ\text{C}$. This part of the plant can be fired with wood pellets, coal, natural gas or oil. The second module is a biomass plant burning straw in a separate boiler. Finally, the third part of the plant is the gas turbine plant. Two aero-derivative gas turbines are used for electricity generation and for feed water preheating.

The multifuel Avedøre 2 has unique operational capabilities because the steam turbine plant, biomass boiler and two gas turbines with their heat recovery units are integrated in one process. This means that the steam turbine plant has to be in operation when either the biomass boiler or the gas turbines, including their heat recovery units, are operated. But the concept is designed to be very flexible, allowing the load of the steam turbine plant, biomass boiler and the gas turbines to be varied within a very wide range, independently from each other. Avedøre 2 achieves a high efficiency over a wide load range, independent of changes in fuel constraints such as price and availability.

3 Thermodynamic simulation of Avedøre unit 2 operation as a multifuel CHP plant

3.1 District heating mode – general description

Avedøre 2 can be operated in various configurations and modes, depending on the availability of fuels, their prices and the prices of electricity and heat. In the district heating mode Avedøre 2 produces heat and electricity, and the quantity of this production depends on the plant configuration,

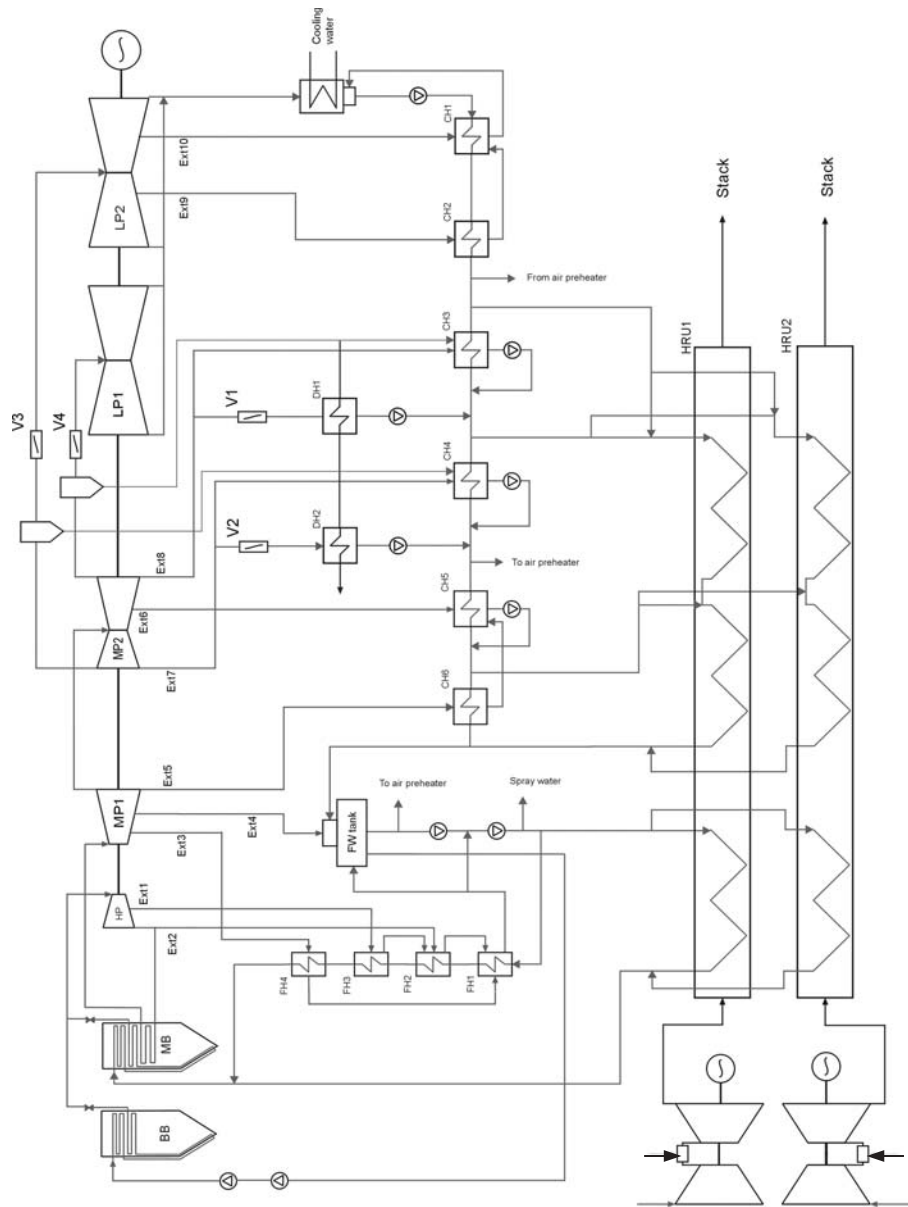


Figure 1. Avedøre Unit 2 schematic diagram: MB – main boiler, BB – biomass boiler, HRU – heat recovery unit, DH – district heating.

load, fired fuel type, and temperature of the district heating water. To obtain a plant production change depending on different configurations and fuel type, iso-fuel curves have been calculated. All of these curves have been calculated at 100/50 °C district heating water temperatures, and the amount of the district heat production has been controlled by changing the district heating water mass flow rate and the V1, V2, V3 and V4 valves operation. In order to achieve the full back-pressure mode, valves V1 and V2 have to be fully open and valve V3 and V4 have to be closed. The total plant efficiency evaluation (Energy Utilization Factor [7]):

$$EUF = \eta_{E\text{ CHP}} = \frac{\dot{P} + \dot{Q}}{\dot{E}_{ch}}. \quad (1)$$

Electrical efficiency is analysed, too.

3.2 Sole operation of the main boiler (natural gas firing)

When the main boiler is operated alone the steam plant load is lowered to 88% due to the lower live steam flow (295.1 kg/s). Live steam parameters are reduced to 580 °C and 260 bar at this load, but the main boiler steam production is kept at a maximum flow of 295.1 kg/s (full firing). The feed water temperature before the boiler is 305.3 °C at 88% load and it is decreasing down to 264 °C at the minimum boiler load which has been assumed to be 40%. In the Tab. 1 calculated data at 88% load operation have been shown, and the plant part load simulation results (iso-fuel curves) have been shown in the Fig. 2.

Table 1. Sole operation of the main boiler.

Parameter	DH Mode
Net power output [MW]	323
District heat [MJ/s]	420
Net electrical efficiency [%]	40.3
Total plant efficiency [%]	92.6
Consumption of chemical energy of fuels [MJ/s]	802
Feed water temperature [°C]	305.3

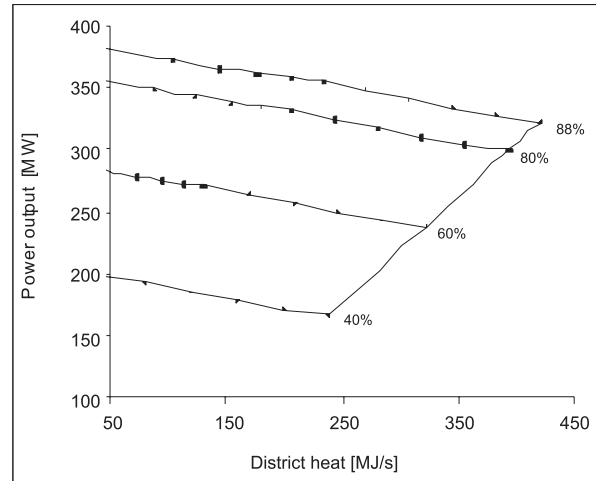


Figure 2. Calculated iso-fuel curves (sole operation of the main boiler).

3.3 Operation of the main and biomass boilers

When both the main and biomass boilers are in operation the steam plant can be operated at a full 100% load. At such load the steam parameters before the steam turbine are 296.7 bar and 580 °C, and the biomass boiler can produce up to 40 kg/s with the main boiler of 295.8 kg/s of steam at these parameters. The feed water temperature before the main boiler is 316.5 °C at full load down to 268.5 °C at the minimum load, whereas before the biomass boiler it is 230 °C at full load down to 181.5 °C at minimum of 40% load.

Two simulations have been carried out. In the first simulation it has been assumed that the biomass boiler steam production is constant 40 kg/s at all loads, and the part load operation is realized by the main boiler steam production decrease. In the second one the main boiler is operating with the constant steam production and the part load operation is realized by the biomass boiler steam production decrease. Results of simulation (iso-fuel curves) have been shown in Fig. 3 and Tab. 2.

3.4 Operation of the main boiler with gas turbines

When the gas turbines are in operation, a part of the condensate and feed water is preheated by the flue gases from gas turbines, which leads to a lower steam flow to the steam turbine extractions. The calculated extrac-

Table 2. Both boilers in operation plant.

Parameter	DH Mode
Net power output [MW]	365
District heat [MJ/s]	475
Net electrical efficiency [%]	40.2
Total plant efficiency [%]	92.4
Consumption of chemical energy of fuels [MJ/s]	909
Feed water temperature before the main boiler [°C]	316.5
Feed water temperature before the biomass boiler [°C]	230

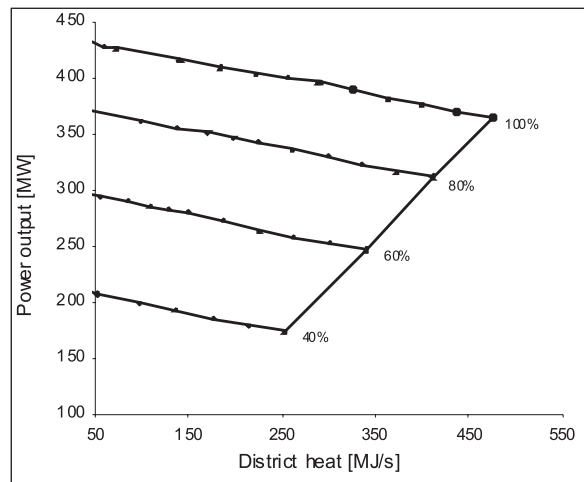


Figure 3. Calculated iso-fuel curves (the main and biomass boiler in operation).

tion steam flow to the deaerator is decreasing to almost zero because the temperature of the condensate coming into the deaerator is close to the saturation temperature at the deaerator pressure. As a result of this the minimum load of the steam plant is about 53% in this operation type. In the load range from about 71% to 88% the feed water temperature before the main boiler is kept at maximum 320 °C temperature level, and below 71% load the feed water temperature is decreasing down to 316.4 °C. This temperature is controlled by a partly or fully opened extraction valve 1. The plant efficiency is increased when the condensate from the feed water

heaters is redirected between the booster and the feed water pumps instead to the deaerator. Figure 4 presents the results of simulation (iso-fuel curves) in the case of main boiler and gas turbines plant operation for the parameters presented in Tab. 3.

Table 3. The main boiler and the gas turbines module in operation.

Parameter	DH Mode
Net power output [MW]	451
District heat [MJ/s]	492
Net electrical efficiency [%]	43.7
Total plant efficiency [%]	91.5
Consumption of chemical energy of fuels [MJ/s]	1 031
Feed water temperature before the main boiler [°C]	316.5

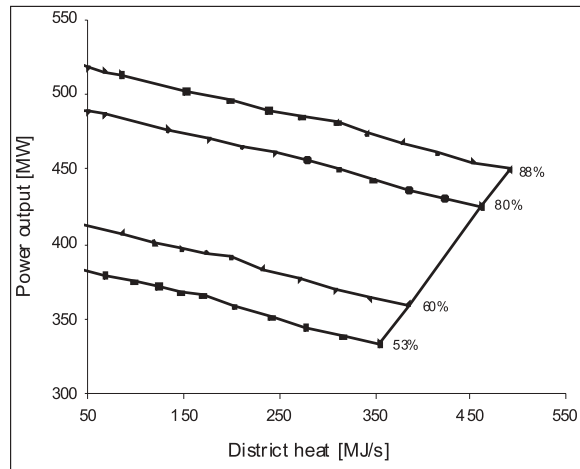


Figure 4. Calculated iso-fuel curves (the main boiler with gas turbines in operation).

3.5 Operation of the main and biomass boilers with gas turbines

When all the plant modules are in operation at full load Avedøre 2 achieves a maximum power output in the condensation mode, but as shown in Tab. 4

the total net efficiency is slightly lower than the efficiency when the plant is operated without the biomass boiler. The reason for this is that the feed water for the biomass boiler does not pass through the feed water heater train and in the end its temperature is lower than for the main boiler. The lower biomass boiler efficiency also contributes to that.

The main boiler's feed water temperature is kept constant at 320 °C in the case of all loads, and the minimum load in this type of Avedøre 2's operation has been evaluated to be at about 55%. Results of simulation (iso-fuel curves) have been presented in Fig. 5 for the parameters from Tab. 4.

Table 4. All modules in operation.

Parameter	DH mode
Net power output [MW]	498
District heat [MJ/s]	556
Net electrical efficiency [%]	43.2
Total plant efficiency [%]	91.5
Consumption of chemical energy of fuels [MJ/s]	1152
Feed water temperature before the main boiler [°C]	320
Biomass boiler feed water temperature [°C]	230

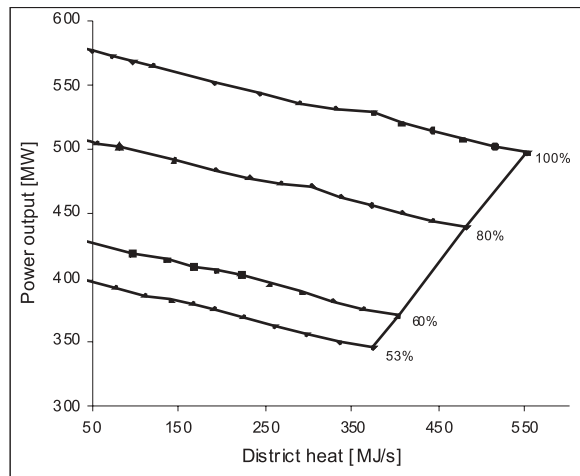


Figure 5. Calculated iso-fuel curves (all the plant modules in operation).

3.6 Operation of the main and biomass boiler with gas turbines (heavy fuel oil or/and wood chips fired in the main boiler)

When heavy fuel oil or/and wood chips are fired in the main boiler, the steam parameters are lowered to 540/540 °C. It has also been assumed that the hot reheat temperature is decreasing from 540 to 500 °C in the load range between 80 to 40%. The main boiler efficiency is also lowered, and it has been assumed that it is decreased to 92% in this case due to co-combustion of biomass. Also the auxiliary power consumption is increased due, for instance, to the mill operation. The increase in the auxiliary power consumption has been estimated to be 1.4 MW higher comparing to the pure natural gas firing operation. Figure 6 presents iso-fuel curves obtained by means of simulation for the parameters from Tab. 5.

Table 5. Calculated plant operational data in back-pressure mode (heavy oil or/and wood chips firing).

Parameter	DH mode
Net power output [MW]	470
District heat [MJ/s]	545
Net electrical efficiency [%]	41.0
Total plant efficiency [%]	88.5
Consumption of chemical energy of fuels [MJ/s]	1147
Feed water temperature before the main boiler [°C]	320
Biomass boiler feed water temperature [°C]	230

4 Energy effects of Avedøre 2 cogeneration

4.1 Evaluation of savings of chemical energy of fuel

Savings of the chemical energy of fuel have been evaluated by comparing its consumption in heating plant and power station operated separately with its consumption at Avedøre 2. Such a comparison is carried out basing on the assumption that the demand for heat and electricity (loco consumer) are the same in both cases of production. Savings of the chemical energy of

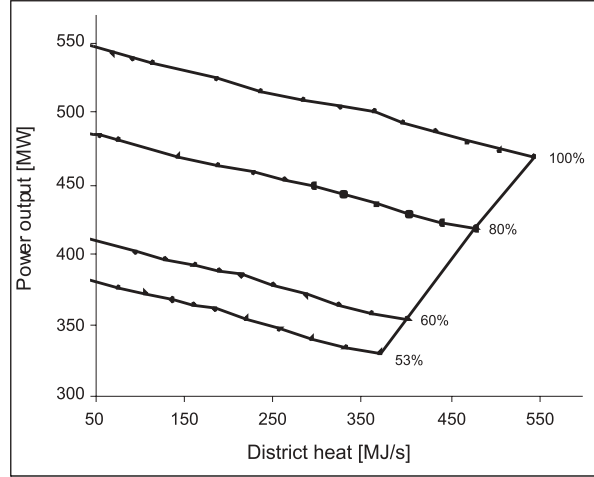


Figure 6. Calculated iso-fuel curves (heavy oil or/and wood chips firing).

fuels achieved thanks to cogeneration:

$$-\Delta \dot{E}_{ch} = \dot{E}_{ch,s} - \dot{E}_{ch,CHP} \quad (2)$$

$$\begin{aligned} -\Delta \dot{E}_{ch} = \dot{Q} \left[\frac{\eta_{th}}{\eta'_{th} \eta_{hp}} - \frac{1}{\eta_{E,CHP}} \right] + \\ + P \left[\frac{\eta_{te}(1 - \varepsilon_{el})}{\eta'_{te} \eta_{E,pp}} - \frac{1}{\eta_{E,CHP}} \right]. \end{aligned} \quad (3)$$

Savings of the chemical energy of fuel related to district heat achieved by Avedøre 2 operation, assuming, that the efficiency of heat and energy transport is the same in both cases, have been evaluated by the following equation [11]:

$$\begin{aligned} \frac{-\Delta \dot{E}_{ch}}{\dot{Q}} = \frac{1}{\eta_{E,hp}} - \frac{1}{\eta_{E,CHP}} + \\ + \sigma \left(\frac{1 - \varepsilon_{el}}{\eta_{E,pp}} - \frac{1}{\eta_{E,CHP}} \right). \end{aligned} \quad (4)$$

Data taken into calculations have been shown in Tab. 6. The net energy efficiency of the power plant has been taken for combined steam and gas power plant because current calculations are concerning Avedøre 2 at

operation on natural gas (without biomass boiler operation). The energy efficiency of heat generating plant has been taken for gas fired heating plant. Calculated data for this kind of operation have been shown in Tab. 6.

Table 6. Data applied in the calculations.

Parameter	Value
Gross total energy efficiency of Avedøre 2 [%]	93.3
Net energy efficiency of a power plant [%]	53
Net energy efficiency of a heat generating plant [%]	90
Coefficient of own electricity consumption [%]	4.2
Coefficient of co-generation [-]	0.95

$$\frac{-\Delta \dot{E}_{ch}}{\dot{Q}} = 0.743.$$

Comparing to hard coal fired CHP plants [10,11] calculated values are very high. The reason of this lies in high efficiency of the Avedøre 2 plant and combustion of natural gas.

4.2 Primary Energy Savings (PES)

Using original notation, according to the Directive of the UE concerning the promotion of cogeneration, the relative savings of the chemical energy of primary fuels is as follows [1]:

$$PES = \left[1 - \frac{1}{\frac{CHPH\eta}{RefH\eta} + \frac{CHPE\eta}{RefE\eta}} \right] \times 100\% . \quad (5)$$

Equation (5) is practically reduced to the relations:

$$PES = \frac{-\Delta E_{ch}}{E_{chr}} . \quad (6)$$

$$PES = \frac{\frac{1}{\eta_{Ehp}} - \frac{1}{\eta_{ECHP}} + \sigma \left(\frac{1-\varepsilon_{el}}{\eta_{Epp}} - \frac{1}{\eta_{ECHP}} \right)}{\frac{1}{\eta_{Ehp}} + \sigma \frac{1-\varepsilon_{el}}{\eta_{Epp}}} . \quad (7)$$

Introducing numerical data taken from Tab. 6 we get $PES = 0.2615$. The high value of the PES index, considerably exceeding the limiting value

of 10%, quoted in the EU Directive concerning the promotion of cogeneration, proves the high energy effectiveness of the cogeneration system at Avedøre 2.

4.3 Partial efficiencies of heat and electricity production

The division of the consumption of chemical energy of fuel in CHP between the production of heat and electricity is connected with the determination of the partial efficiencies of heat and electricity production. In order to determine these partial efficiencies in the cogeneration process the method of avoided input fuels has been applied. This method is also called *method of a substituted process* [12]. As the electricity produced in a CHP substitutes the electricity from the system power plants, it should be charged with such a consumption of chemical energy of the fuel as in substituted power plants.

Substituted power in a system power plant results from the condition of equality of the electric power rating at the end-user:

$$P_{CHP} (1 - \varepsilon_{el}) \eta_{te} = P_{pp} \eta'_{te}. \quad (8)$$

From the principle of avoided fuel in substituted process one can write:

$$E_{ch\ CHP} = \frac{P_{pp}}{\eta_{Epp}}. \quad (9)$$

Assuming that $\eta_{te} = \eta'_{te}$, the gross partial energy efficiencies of electricity production and heat is as follows:

$$\eta_{E\ el\ CHP} = \frac{P_{CHP}}{E_{ch\ CHP}} = \frac{\eta_{Epp}}{(1 - \varepsilon_{el})}, \quad (10)$$

$$\eta_{E\ h\ CHP} = \frac{\eta_{E\ CHP}}{1 - \sigma \left[\frac{\eta_{E\ CHP} (1 - \varepsilon_{el})}{\eta_{Epp}} - 1 \right]}. \quad (11)$$

$$\eta_{E\ el\ CHP} = 0.553 \quad ; \quad \eta_{E\ h\ CHP} = 2.713 .$$

This last efficiency is physically correct because the CHP cycle results from the combined cycle of the heat engine with a heating pump whose energy efficiency is always higher than one. Calculated values of partial efficiencies are much higher than for conventional hard-coal fired CHP plants due to the combined steam and gas cycle fired with natural gas.

5 Conclusions

This paper shows that Avedøre 2 is a very modern CHP plant, achieving a very high efficiency, especially when gas turbines are operated. The energy effects of cogeneration of Avedøre 2 have been calculated in comparison to a high efficiency combined steam and gas power plants (electrical efficiency of 53%), even though the calculated savings of chemical energy of fuel are very high ($-\Delta\dot{E}_{ch}/\dot{Q} = 0.743$). Also calculated partial efficiencies of heat and power production ($\eta_{ElCHP} = 0.553$, $\eta_{hCHP} = 2.713$) are much higher than in traditional conditions. This leads to ecological superiority of Avedøre 2 operation. When Avedøre 2 is burning biomass (straw and wood pellets) these effects are even greater, because combustion of biomass reduces CO₂ emissions.

Analysis of the index PES, introduced by the EU Directive in 2004/8/EC, indicates that Avedøre 2 fully satisfies the criterion of *high efficient cogeneration*. If the main boiler and GT plant operate and natural gas is used as the fuel the index PES amounts to about 26%. In comparison index PES in the case of classical back-pressure CHP fired with coal amounts to 17% when Energy Utilization Factor EUF = 80% and index of cogeneration $\sigma = 0.4$. In pursuance of EU Directive [1] the criterion of high efficient cogeneration has to obey the condition $PES \geq 10\%$.

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References

- [1] Directive 2004/8/EC of the European Parliament and the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market.
- [2] ELMEGAARD B.: *The Engineer's "DNA by Example"*, Technical University of Denmark.
- [3] ELMEGAARD B.: *Simulation of Boiler Dynamics – Development, Evaluation and Application General Energy System Simulation Tool*, PhD thesis, Technical University of Denmark, 1999.
- [4] ELMEGAARD B. AND HOUBAK N.: *Simulation of the Avedøreværket Unit 1 Cogeneration Plant with DNA*, Department of Mechanical Engineering, Technical University of Denmark.

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- [5] FARMER R.: *Avedøre CHP-DH station powered by three different generating technologies*, Gas Turbine World, September-October 1999.
 - [6] HANSEN S. AND SØRENSEN H.D.: *Process design and optimization of the Avedøre 2 Multifuel Power Plant*, Proceedings of ECOS 2003 Copenhagen, Denmark, June 30 – July 2, 2003.
 - [7] HORLOCK J.H.: *Cogeneration. Combined heat-and-power (CHP)*, Krieger Publishers Company, Malabar, Florida, 1997.
 - [8] Modern Power Systems. *Avedøre 2 sets new benchmarks for efficiency, flexibility and environmental impact*, January 2000.
 - [9] Modern Power Systems. *Parallel powering for Avedøre 2 power plant*, May 1996.
 - [10] SZARGUT J. AND ZIĘBIK A.: *Fundamentals of thermal engineering*, Wydawnictwo Naukowe PWN, Warszawa 2000 (in Polish).
 - [11] ZIĘBIK A.: *A Survey of energy and ecological effects concerning various ways of the realization of co-generation in Poland*, Proceedings of ECOS 2003 Copenhagen, Denmark, June 30 – July 2, 2003.