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Manual for Determination of Combined Heat and Power (CHP)

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Foreword

This CEN/CENELEC Workshop Agreement has been drafted and approved by a Workshop of representatives of interested parties on 2004-06-16, the constitution of which was supported by CEN and CENELEC following the public call for participation made in January 2003.

A list of the individuals and organizations which supported the technical consensus represented by the CEN/CENELEC Workshop Agreement is available to purchasers from the CEN Management Centre. These organizations were drawn from the following economic sectors: national and international energy (electricity, gas) and in particular CHP/DHC associations[1], municipalities owning/operating CHP/DHC systems, utilities owning/operating CHP/DHC systems, industries owning/operating CHP plants, manufacturers of CHP and/or DHC plants and equipment, engineering and consulting companies, industrial CHP and/or DHC users (pulp and paper industry, sugar industry).

The final review/endorsement round for this CWA was started on 2004-05-24 and was successfully closed on 2004-06-16.The final text of this CWA was submitted to CEN for publication on 2004-06-28.

This CEN/CENELEC Workshop Agreement is publicly available as a reference document from the National Members of CEN and CENELEC.

Comments or suggestions from the users of the CEN/CENELEC Workshop Agreement are welcome and should be addressed to the CEN Management Centre.

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[1] CHP/DHC = Combined heat and power / district heating and cooling

Symbols and Indices

Latin symbols	**Description**	**unit**
f	fuel energy	MWh
p	electrical/mechanical energy	MWh
q	heat energy	MWh

Greek symbols	**Description**	**units**
η	efficiency	MWh/MWh
β	power loss	MWh/MWh
σ	power-to-heat ratio	MWh/MWh

Indices	**Description**
CHP	combined heat and power
non-CHP	non combined heat and power
q	heat energy
p	electrical/mechanical capacity, electrical/mechanical energy
m	mechanical
e	electrical

1 Objective and Scope

CHP can make significant fuel and emissions savings over conventional, separate forms of power generation and heat-only boilers. The generation of electricity from power stations is generally at efficiencies in the range 30-55%, based on the Net Calorific Value (NCV) or Lower Heating Value (LHV) of the fuel. Further losses occur in the transmission and distribution of electricity to customers. This means that 45-70% of the energy content of the fuel is not usefully employed. This unutilised energy content is rejected as heat directly to the atmosphere or into seas or rivers. The generation of electricity and the recovery of heat in CHP plants typically achieve overall efficiencies of 70-90% and above, corresponding to efficiencies of heat only boilers. The higher the overall efficiency and the power to heat ratio, the more effective the CHP process.

Unlike conventional methods of electricity generation, in order to achieve such high overall efficiencies, some of the heat cogenerated in a CHP Scheme is usefully employed in industrial processes or for heating and hot water in buildings. The heat used in this way displaces heat that would otherwise have to be supplied by burning additional fuel in boilers or other direct-fired equipment and so also leads directly to a reduction in CO_2-emissions. The development of CHP plays a crucial role in the European energy policy for reducing CO_2-emissions.

The determination of CHP products (heat and power outputs) is important not only for the CHP Directive [1] but also for the European Emissions Trading Scheme [2], State Aid guidelines for environmental improvement and the energy taxation Directive [3].

The objective of the CEN/CENELEC Workshop Agreement is to present a set of transparent and accurate formulae and definitions for determination of CHP (cogeneration) energy products and the referring energy inputs. The CEN/CENELEC Workshop Agreement shall simply formulate the procedure for quantifying CHP output and inputs, such as CHP electrical energy, CHP mechanical energy, CHP heat energy and CHP fuel energy. It does not include quality rankings such as assessments of fuel savings or environmental impact.

Gathering statistics and monitoring developments in the combined heat and power sector is difficult and can contain a considerable number of uncertainties. Some CHP plants may decouple the generation of heat and power at certain times or to a certain extent and thus CHP and NON-CHP electricity and heat may be generated in the same plant.

The lack of reliable information and transparency may be considered in itself as a barrier to the further development of the technology and negatively affects the image of the CHP sector. To remove the ambiguity resulting from a lack of standardised procedures across Europe, a set of widely accepted determination rules is needed. Such rules will create greater certainty that the basic concept of CHP is understood and determined in the same way.

As a result of this requirement the CEN2) /CENELEC3) Workshop on "Manual for Determination of Combined Heat and Power (CHP)" was initiated. It ran in parallel to the discussions on the Directive on the promotion of cogeneration based on a useful heat demand in the internal energy market [1].

1.1 Relation to Annex II of CHP Directive 2004/8/EC 11 February 2004

The resulting CEN Workshop Agreement (CWA) is to provide guidance for the implementation of Annex II of the CHP-Directive and the determination of the power-to-heat ratio (see section 5).

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2) European Committee for Standardization (http://www.cenorm.be)

3) European Committee for Electrotechnical Standardization (http://www.cenelec.org)

Whereas the amount of CHP electrical/mechanical energy defined as p_{CHP} in the CWA equals E_{CHP} in the CHP Directive.

Whereas total useful heat in the CWA (q) covers heat for a justified demand regardless of the possible CHP character, in the Directive the concept of useful heat implies useful heat from CHP only.

Whereas the amount of CHP useful heat energy defined as q_{CHP} in the CWA equals H_{CHP} in the CHP Directive.

Whereas the electrical/mechanical energy-to-heat energy ratio defined as σ_{CHP} in the CWA equals the power-to-heat ratio C in the CHP Directive.

2 Reading Instructions (Route Map)

This chapter is a route map through the manual. The manual is prepared/designed to handle all kind of plants and is therefore to some extent complicated when the plant is simple.

2.1 Instructions

Start to read chapter 3 where all the expressions used in the manual are defined and chapter 4 where the plant is defined and your plant can be classified. The chapter describes the CHP-plant, the CHP-process and the non-CHP generation of heat and electrical/mechanical energy. For small and simple plants read Annex A where useful simplifications are presented. For all other plants try to find the example in Annex C which corresponds to your plant as close as possible and follow the procedure step by step.

A schematic picture of the principles of the manual is given in chapter 5. The figure 5, 6 and 7 show the principles from a general overview to detailed equations. To simplify your classification and your determination of the CHP plant see Annex C.2 for instructions to draw a CHP scheme line diagram.

In chapter 6 the CHP plant boundaries are drawn. The principle is to keep the boundaries around the CHP process itself. Here all inputs and outputs are determined. Fuel input in 6.2, electrical and mechanical energy output in 6.3 and useful heat output in 6.4. Measurements are default. In case of lack of such measurement, indirect methods for determination of energy flows can be used provided they supply the adequate accuracy. Indirect methods are described in chapter 6.2.3 and 6.4.2.

Chapter 7 gives instructions how to separate non-CHP heat and the corresponding fuel. This is necessary in plants with live steam extraction and/or auxiliary/supplementary firing.

In chapter 8 determination of CHP overall efficiency is described. How to act when the plant can not run in complete back pressure mode and how to handle the cooling steam in a extraction steam turbine on minimum load.

Chapter 9 gives instructions how to separate non-CHP electricity and the corresponding fuel.

2.2 Annexes

Read Annex A to learn about how to simplify the determinations for small and simple plants.

Read Annex B to learn about determination of the power loss coefficients for CHP processes with steam turbines.

In Annex C.1 determination examples are presented. In C.2 instruction for describing of the CHP plant is given. Here also the Tag notation used in the manual is presented.

When the principles for determination are clear collecting data is the next step. In Annex C.3 and C.4, CHP plant monitoring and metering requirements as well as how to treat uncertainties is presented.

3 Definitions

For further explanations see section 4 and subsequent sections..

Combined heat and power (CHP) or "cogeneration" is the simultaneous conversion of primary energy into mechanical and/or electrical energy and useful heat energy in one (the same) plant. Simultaneously means that the energy content of a the fuel is used for the generation of both heat and electrical/mechanical power at the same time within a thermodynamic process (the CHP process) (see Article 3 (a) in [1]).

CHP plants are plants that simultaneously can generate electrical/mechanical power as well as useful heat power. Thereby all or least at a certain extent of generated useful heat power and electrical/mechanical power can be CHP useful heat power and cogenerated (CHP) electrical/mechanical power.

Reporting Period is the period of time used for reporting and determination of data for the CHP plant.

Heat rejection facilities are devices for the diversion of heat energy by means of which heat energy is discharged unused into the environment, e.g.:

- Waste heat condensers
- Compression air coolers not connected to a heat recovery system
- Bypass facilities
- Steam condensers not connected to a heat recovery system
- Radiators
- Cooling air coolers not connected to a heat recovery system
- Lube oil coolers not connected to a heat recovery system
- Charge air coolers not connected to a heat recovery system
- Stacks
- Auxiliary coolers not connected to a heat recovery system

The term "bypass" is used for the direct diversion of the flue gases into the environment, avoiding the waste heat boiler / flue gas heat exchanger. The consequence is incomplete use of the heat in the flue gas.

3.1 Energies

Total useful heat energy (q) is the heat energy (thermal energy) supplied by a plant in a reporting period. It is heat energy supplied by a plant that would otherwise demonstrably be supplied from other sources.

Change in total useful heat energy (Δq).

Total electrical/mechanical energy (p) is defined as gross electrical/mechanical energy output of a plant in a reporting period.

Change in total electrical/mechanical energy (Δp).

Total fuel energy (f) is the total fuel energy based on lower heating value (LHV) needed in a CHP plant to generate electrical/mechanical energy and useful heat in a reporting period.

CHP useful heat energy (q_{CHP}) is the heat energy (thermal energy) supplied by a CHP process to a network or a production process in a reporting period. It is heat energy that would otherwise be supplied from other sources (see Article 3 (b) in [1]).

CHP electrical/mechanical energy (p_{CHP}) is defined as the gross electrical/mechanical energy, which is generated in direct relation to the generation of CHP useful heat (see Article 3 (d) in [1]) in a reporting period.

CHP fuel energy (f_{CHP}) is the fuel energy based on lower heating value (LHV) needed in a CHP process to co-generate CHP electrical/mechanical energy and CHP useful heat energy in a reporting period.

Non-combined useful heat energy ($q_{non\text{-}CHP}$) is the heat energy (thermal energy) supplied by a CHP plant to a network or a production process, which is not generated in direct relation to the generation of CHP electrical/mechanical energy in a reporting period.

Non-combined electrical/mechanical energy ($p_{non\text{-}CHP}$) is defined as the gross electrical/mechanical energy, which is generated in a reporting period at times when no or insufficient heat energy is required. Thus this electrical/mechanical energy is not generated in direct relation to the generation of useful heat.

Non-combined fuel energy ($f_{non\text{-}CHP} = f_{non\text{-}CHP,q} + f_{non\text{-}CHP,p}$) is the fuel energy based on lower heating value (LHV) needed in a CHP plant for non-combined generation of useful heat energy and non-combined electrical/mechanical energy generation in a reporting period.

3.2 Dimensionless Figures of Energies

Total overall efficiency of energies ($\eta_{tot} = \eta_{CHP+non\text{-}CHP,q+non\text{-}CHP,p}$) is the ratio of all energy outputs to all energy inputs of a plant in a reporting period.

Overall efficiency of energies ($\eta = \eta_{CHP+non\text{-}CHP,p}$) is the ratio of energy outputs to energy inputs of a plant excluding non-CHP heat energy and the referring non-CHP fuel energy for generation of non-CHP heat energy in a reporting period (see Article 3 (g) in [1]).

CHP overall efficiency of energies (η_{CHP}) is the ratio of CHP energy output to CHP energy inputs of the CHP plant in a reporting period.

Electrical/mechanical power-to-heat ratio (σ_{CHP}) is the ratio between gross electrical/mechanical CHP energy (p_{CHP}) to CHP useful heat energy (q_{CHP}) in a reporting period (see Article 3 (k) in [1]).

Electrical/mechanical power loss coefficient (β) is the balance between increasing heat energy recovery (Δq) and reducing electrical/mechanical energy (Δp) of CHP plants with power loss in a reporting period.

Efficiency of non-combined electrical/mechanical energy generation ($\eta_{non\text{-}CHP,p}$) is the efficiency of the electrical/mechanical energy generation, which is not generated in direct relation to the generation of useful heat energy in a reporting period.

Efficiency of non-combined heat energy generation ($\eta_{non\text{-}CHP,q}$) is the efficiency of the heat energy generation, which is not generated in direct relation to the generation of CHP electrical/mechanical energy in a reporting period.

4 Description of CHP and Non-CHP Processes

In a combined heat and power (CHP) process high overall efficiencies can be achieved whereby a share of the energy output is electrical/mechanical power.

4.1 CHP Plant

CHP power plants may generate electrical/mechanical energy as well as useful heat energy at the same time (simultaneously, see Figure 1 — Transformation of Fuel Energy in a CHP Plant). Thereby not all useful heat energy and all electrical/mechanical energy has to be generated in CHP mode. Thus:

$p = p_{CHP} + p_{non\text{-}CHP}$

$q = q_{CHP} + q_{non\text{-}CHP}$

$f = f_{CHP} + f_{non\text{-}CHP,p} + f_{non\text{-}CHP,q}$

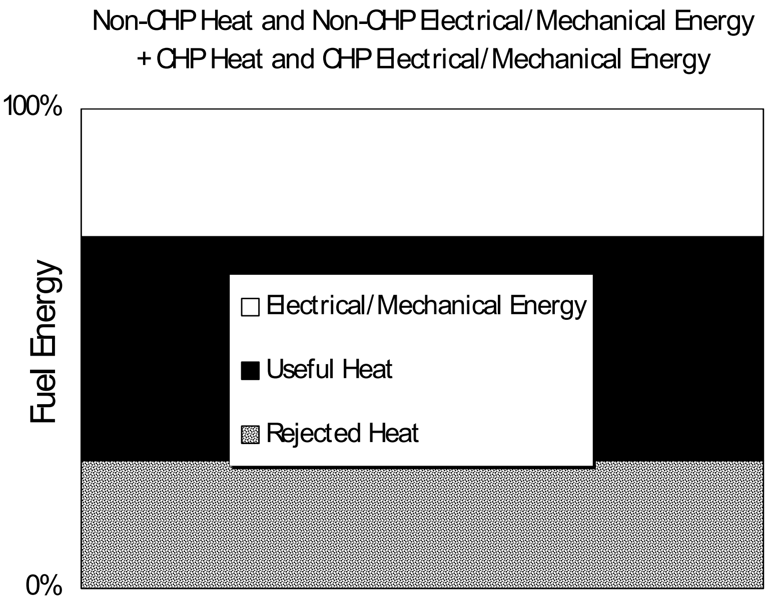

Figure 1 — Transformation of Fuel Energy in a CHP Plant

4.2 CHP Process

CHP electrical/mechanical energy is defined as the share of electrical/mechanical energy, which is at the same time generated in direct relation to the generation of useful heat energy, thus being CHP useful heat energy. Together the CHP electrical/mechanical energy and the CHP useful heat energy is the output from the CHP process as shown in (Figure 2 — Subdivision of a CHP Plant in Combined and Non-Combined Processes).

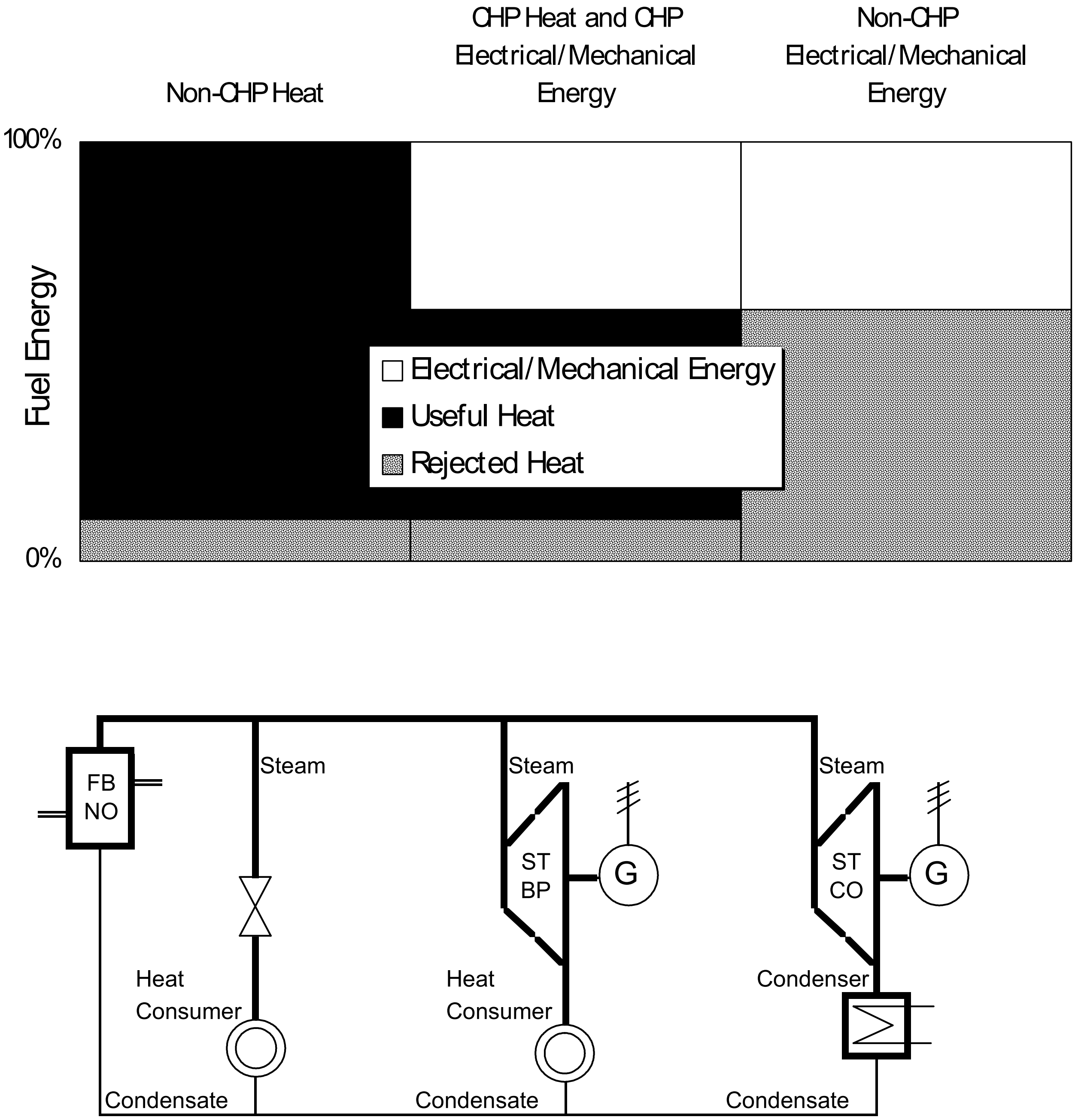

Figure 2 — Subdivision of a CHP Plant in Combined and Non-Combined Processes

4.2.1 Electrical/Mechanical Energy-to-Heat Energy Ratio

$\sigma_{CHP} = p_{CHP} / q_{CHP}$ Electrical/mechanical energy-to-heat energy ratio in MWh/MWh

4.2.2 CHP Overall Efficiency

The overall efficiency of the CHP process is defined as follows:

η_{CHP} overall efficiency of energies of CHP process in a reporting period in MWh/MWh

$\eta_{CHP} = (p_{CHP} + q_{CHP}) / f_{CHP}$

4.3 Non-Combined Heat Energy Generation

Non-Combined useful heat energy generation occurs in processes with generation of useful heat energy without upstream generation of electrical/mechanical energy (see Figure 3 — Non-Combined Heat Energy Generation with Additional Boilers), e.g. applying:

- Live steam extraction (steam extraction prior to generation of electrical/mechanical energy)
- Steam boilers without downstream (back-pressure or extraction-condensing) steam turbines
- Waste-heat boilers with auxiliary / supplementary firing without downstream (back-pressure or extraction-condensing) steam turbines However the waste heat (recovered heat) recovered from the GT exhaust gases in such boilers is an integral part of the CHP.

The heat efficiency of non-CHP processes is defined as:

$\eta_{non\text{-}CHP,q}$ Efficiency of non-combined heat energy generation in MWh/MWh

$\eta_{non\text{-}CHP,q} = q_{non\text{-}CHP} / f_{non\text{-}CHP,q}$

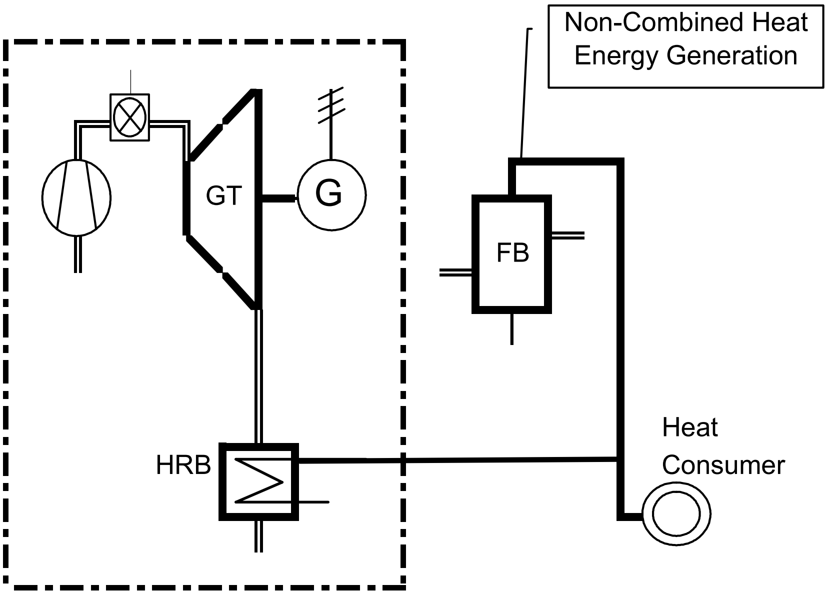

Figure 3 — Non-Combined Heat Energy Generation with Additional Boilers

4.4 Non-Combined Electrical/Mechanical Energy Generation

Non-Combined electrical/mechanical energy generation occurs in processes with insufficient or without generation of useful heat energy or in processes with heat rejection facilities, e.g. applying:

- Fuel cells, gas turbines and internal combustion engines with insufficient or without utilisation of heat thus becoming rejected heat energy instead of useful heat energy
- In the condensing part of steam cycle power plants and in combined cycle power plants with extraction-condensing steam turbines

It has to be noted that especially in the latter the non-combined power generation usually cannot be measured directly. Therefore, in this case the process must be divided into condensing (non-combined) and back pressure (combined) segments.

The electrical efficiency of non-CHP processes is defined as:

$\eta_{non\text{-}CHP,p}$ Efficiency of non-combined electrical/mechanical energy generation in MWh/MWh

$\eta_{non\text{-}CHP,p} = p_{non\text{-}CHP} / f_{non\text{-}CHP,p}$

4.4.1 Electrical/Mechanical Energy Loss

The efficiency of non-combined electrical/mechanical power generation is required for the subsequent calculation of CHP electrical/mechanical power generation and CHP fuel. The calculation method differs depending on whether for a constant fuel input an increase in useful heat output is accompanied by a reduction in electrical/mechanical power output. CHP plants where the electrical/mechanical power output remains unchanged are called Processes without Electrical/Mechanical Energy Loss (such as simple cycle gas turbine or engine based CHP). CHP plants where the increase in useful heat output is achieved at the expense of some electrical/mechanical power generation are called Processes with Electrical/Mechanical Energy Loss (such as, but not exclusively, CHP plants that include steam turbine(s) that exhaust fully or partially to a condenser). In such cases the electrical/mechanical energy loss arises because the increase in useful steam output is achieved at the expense of a reduced flow through part of the steam turbine (e.g. the LP section exhausting to the condenser), resulting in a reduced shaft power output. This reduction is the Electrical/Mechanical Energy Loss and the relationship between reduced electrical/mechanical energy output and increased steam energy output is

$\beta = -\Delta p / \Delta q$

4.4.1.1 Processes without Electrical/Mechanical Energy Loss

Assuming constant fuel energy input all processes without electricity generation subsequent to heat energy extraction do not have a electrical/mechanical energy loss. Thus for CHP plants without Electrical/Mechanical Energy Loss:

$\beta = -\Delta p / \Delta q = 0$

This refers mostly to CHP Plants without fully or partially condensing (pass-out) steam turbines like back-pressure steam turbines, but including back-pressure steam turbines, gas turbines or internal combustion engines. Moreover at constant load (fuel energy consumption) these plants can not lose electrical/mechanical energy if useful heat energy is increased (no energy loss). This is typical for back-pressure steam turbines, fuel cells, gas turbine with heat energy recovery steam generator, Internal combustion engines, etc. (see section 9.1.1). To increase the useful heat energy output these plants have to increase the fuel energy input (or reduce heat rejection). Be aware of the fact that steam extraction from heat recovery steam generators in combined cycles can also cause a electrical/mechanical power loss, even though the steam turbine is a back-pressure turbine.

4.4.1.2 Processes with Electrical/Mechanical Energy Loss

For CHP plants which include fully or partially condensing (pass-out) steam turbines (i.e. extraction-condensing steam turbines), electrical/mechanical energy generation will decline as steam extraction (generation of useful heat energy) increases for a given fuel energy consumption, so there is a balance between increasing heat energy recovery and reducing electrical/mechanical energy output. Assuming constant fuel energy input.

The relation between generation of useful heat energy and electrical/mechanical energy/power loss or vice versa is known as the energy loss coefficient (see Figure 4 — Subdivision of a CHP Plant with Electrical/Mechanical Energy Loss in Combined and Non-Combined Processes).

The electrical/mechanical power loss coefficient is defined as:

$\beta = -\Delta p / \Delta q$ electrical/mechanical power loss coefficient in a reporting period in MWh/MWh

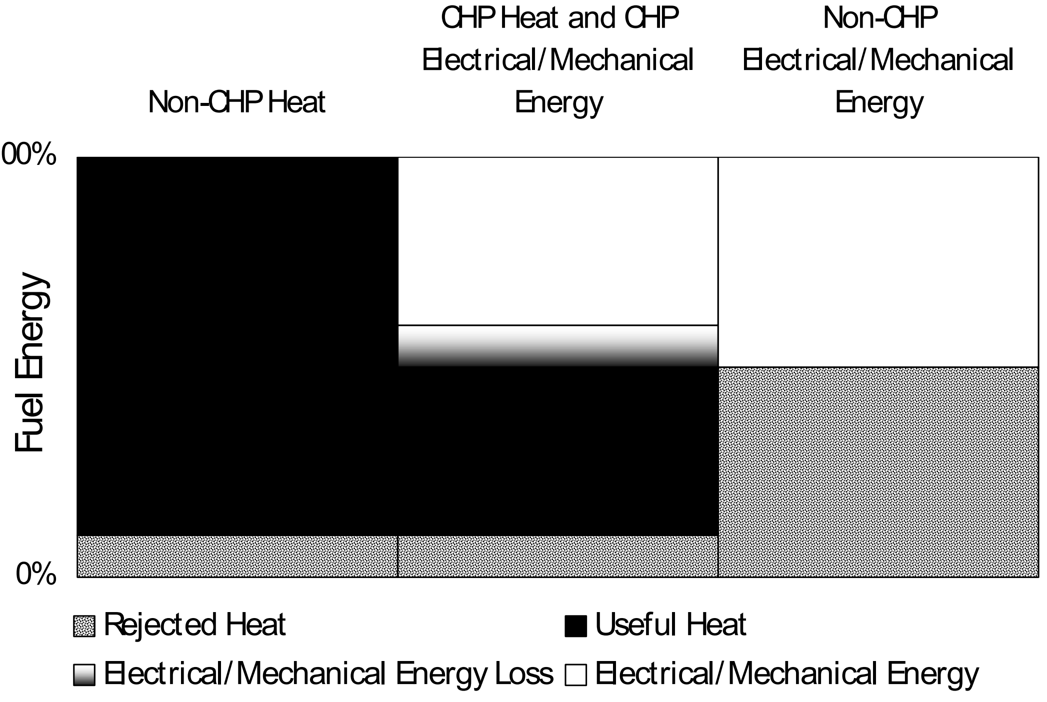

Figure 4 — Subdivision of a CHP Plant with Electrical/Mechanical Energy Loss in Combined and Non-Combined Processes

Moreover at constant load (fuel power) these plants do lose electrical/mechanical power if useful heat output is increased. These are known as plants with "power loss" since the provision of heat power has a negative effect on the electrical/mechanical power output (for the same fuel input). The electrical/mechanical power loss is typical for extraction-condensing or extraction-backpressure steam turbines. It is caused by extracting the working fluid (steam or exhaust gas) from the turbine (expander) for generation of useful heat energy. Be aware of the fact that steam extraction from heat recovery steam generators in combined cycles can also cause a electrical/mechanical power loss, even though the steam turbine is a back-pressure turbine.

5 Determination Principles

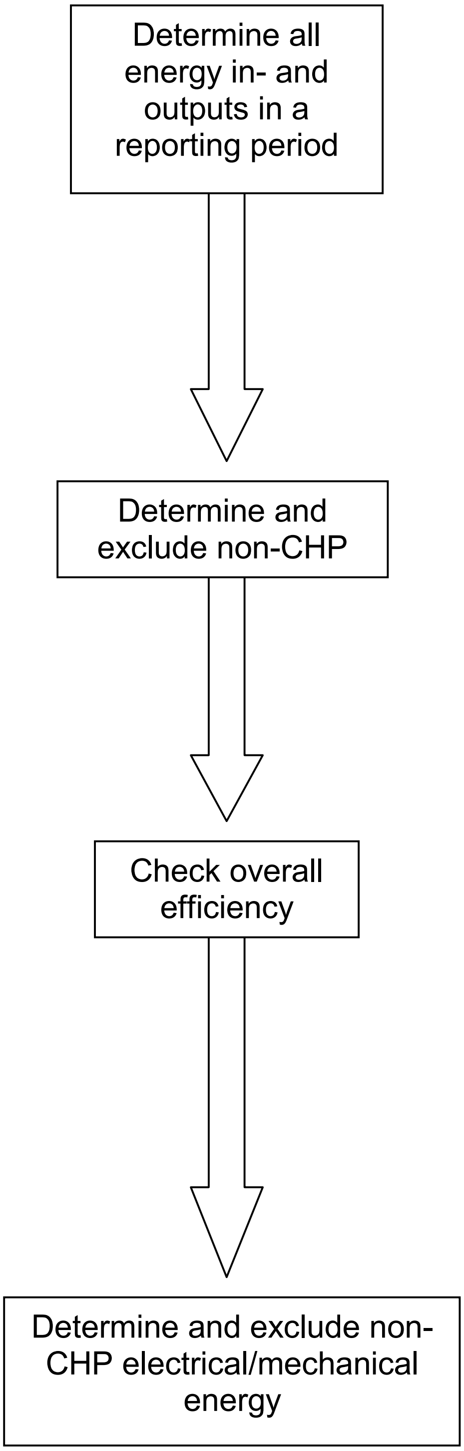

Figure 5 — Determination Principles - General

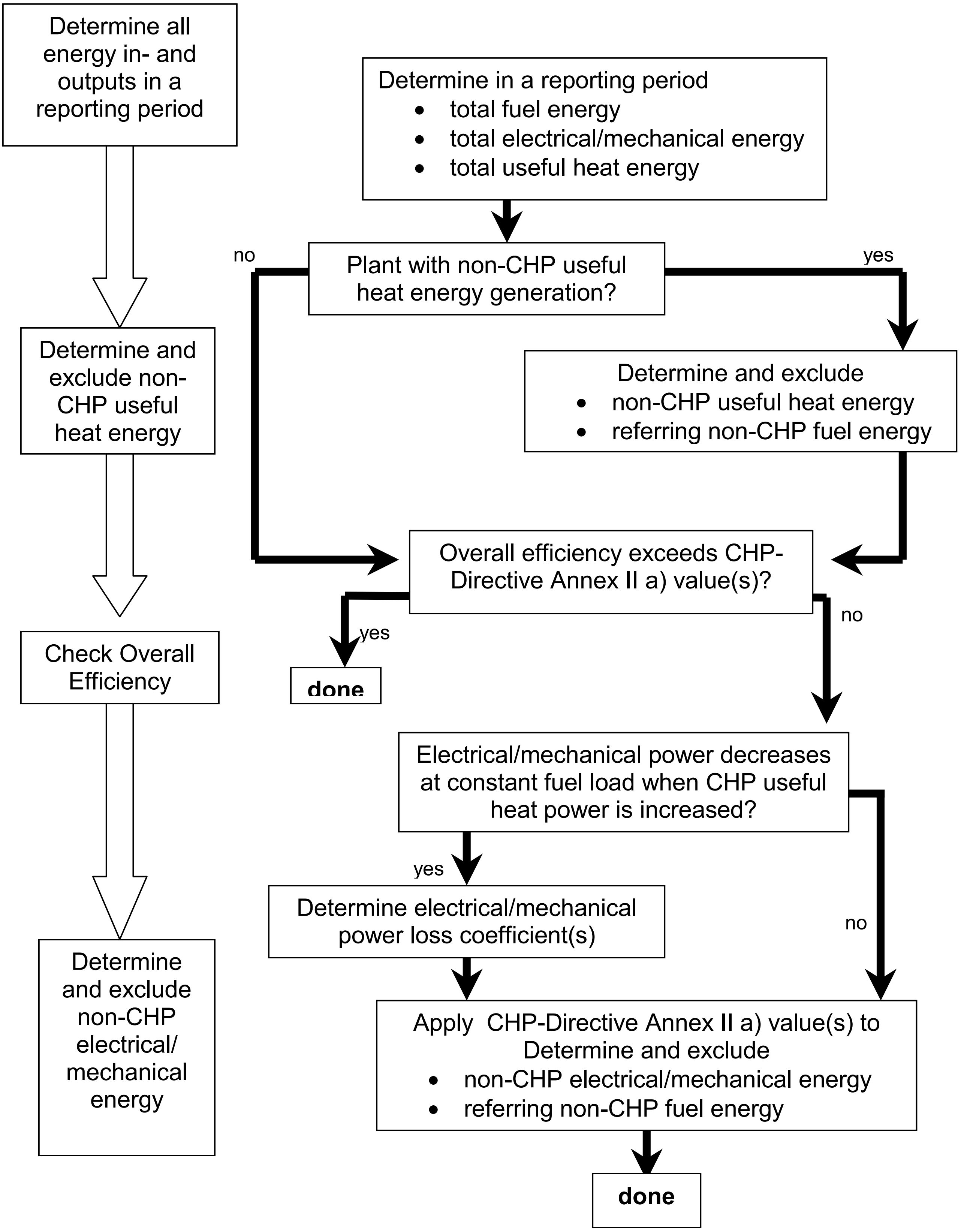

Figure 6 — Determination Principles - Detailed

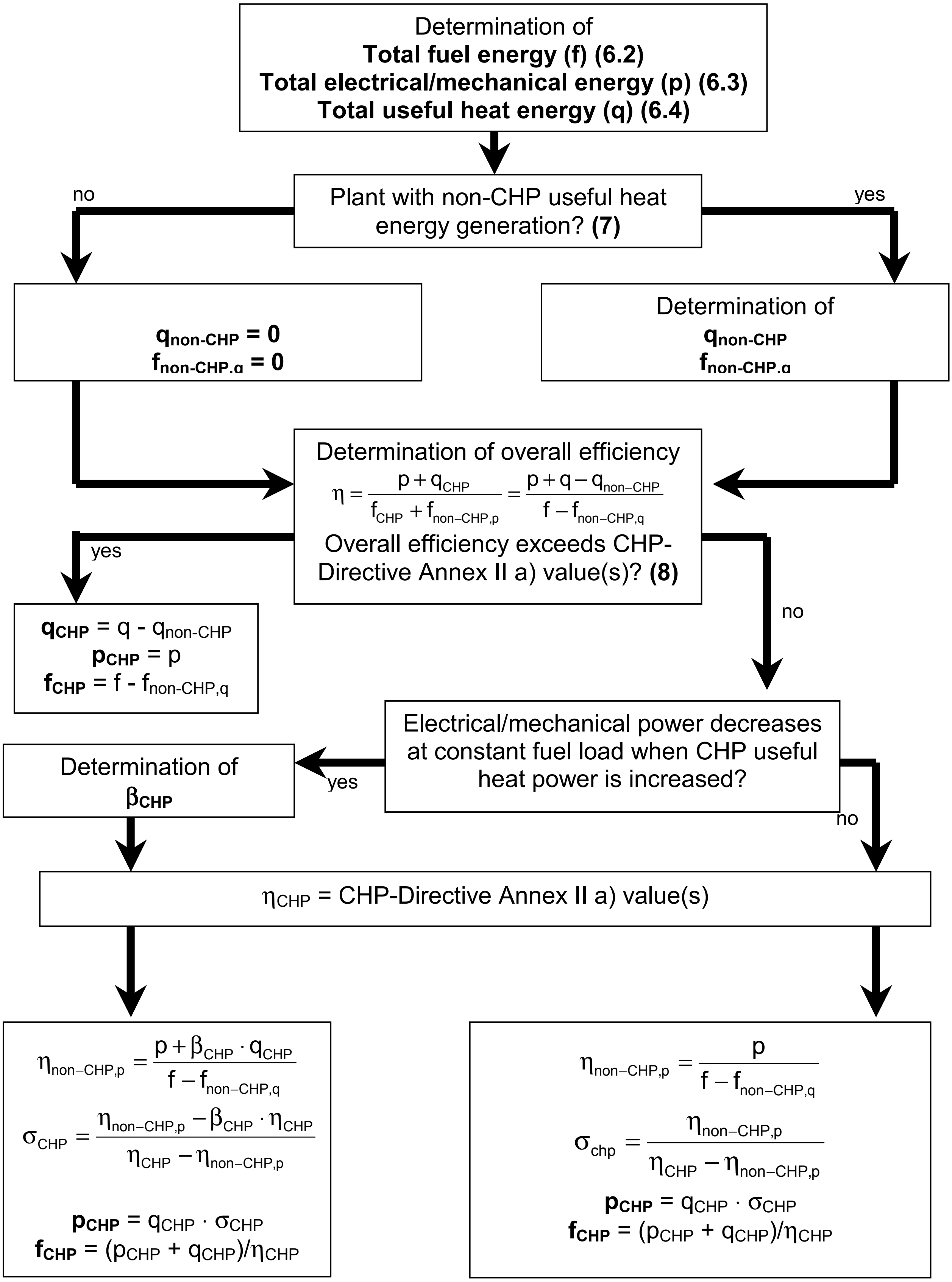

Figure 7 — Determination Principles – Equations and References

6 Determination of Energy In- and Outputs

All CHP plants must determine all energy input and outputs: f, q, p.

A CHP plant supplies energy products to a Consumer Area (see Figure 8 — CHP). The Consumer Area does not belong to the CHP Plant but consumes the energy products that are produced by the CHP Plant The two areas are not necessarily distinct geographical plot areas within the site but, rather, areas that may be conveniently represented as shown below. The consumer area is either the industrial process or for district heating the community or the public electric grid, which in all three cases consumes the energy outputs from the CHP plant.

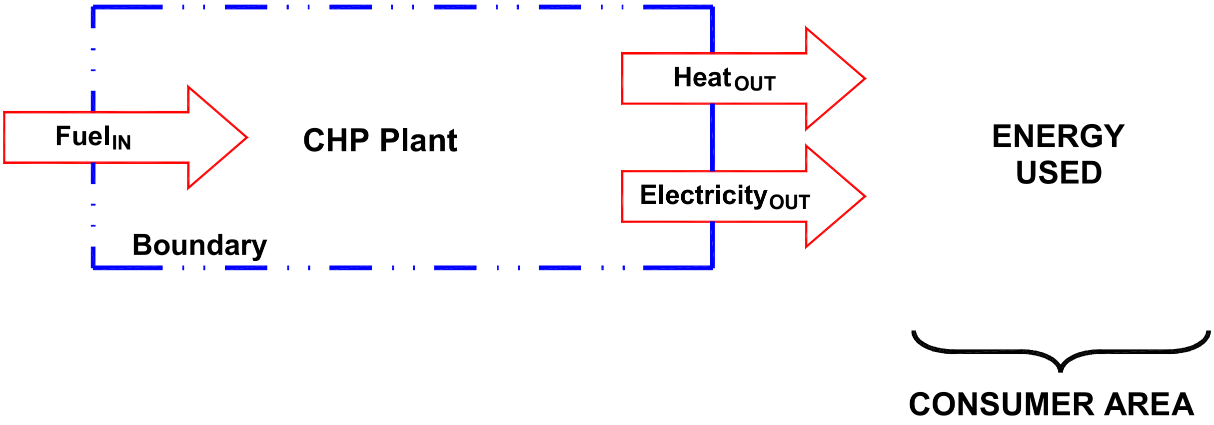

Figure 8 — CHP Site

6.1 CHP Plant Boundary

Auxiliary heat or electricity production equipment such as heat only boilers and electricity only power units that do not contribute to combined generation of heat and power must not be included in the CHP plant boundary. Therefore auxiliary (top-up) boilers, standby (back-up) boilers, process waste heat boilers and standby generators have to be excluded (see Figure 9 — Choosing the Right Scheme Boundaries in Case of Auxiliary/Standby Boilers). In case of chilling processes, these also should be placed outside the CHP boundary limit. The meters should be placed on the these boundaries.

The auxiliary or parasitic consumption of heat energy and mechanical energy of a CHP plant do not belong to its energy outputs.

However, some sites will have secondary steam turbines driving pumps or compressors delivering mechanical energy and also provide heat to the consumer area. In these cases the steam turbines and its energy outputs do not belong to the auxiliary consumption of the CHP plant but to the energy outputs. Possible determination methods for the heat and electrical/mechanical energy output are those outlined for prime movers (see section 6.3.2). The secondary steam turbines must be included in the CHP Plant boundaries (see Figure 10 — Choosing the Right Scheme Boundaries in Case of Secondary Steam Turbines). The electrical/mechanical energy outputs have to be included as energy outputs from the CHP Plant. The heat energy required to produce these additional electrical/mechanical energy outputs must be deducted from the useful heat energy output.

Where steam turbine-driven pumps or generators are driven with steam from the CHP plant, the energy flow from the CHP plant should be included in the CHP energy flow if they supply the energy to the consumer area and do not belong to the auxiliary energy consumption. For example, the steam heat power used by the steam-driven pumps or generators should be deducted from the CHP plant heat power outputs to the process and, similarly, the mechanical/electrical power output from the steam-driven pumps (see section 6.3.2) or generators should then be added to the CHP plant power outputs if they do not contribute to the auxiliary power consumption of the CHP plant but supplied to the consumer area.

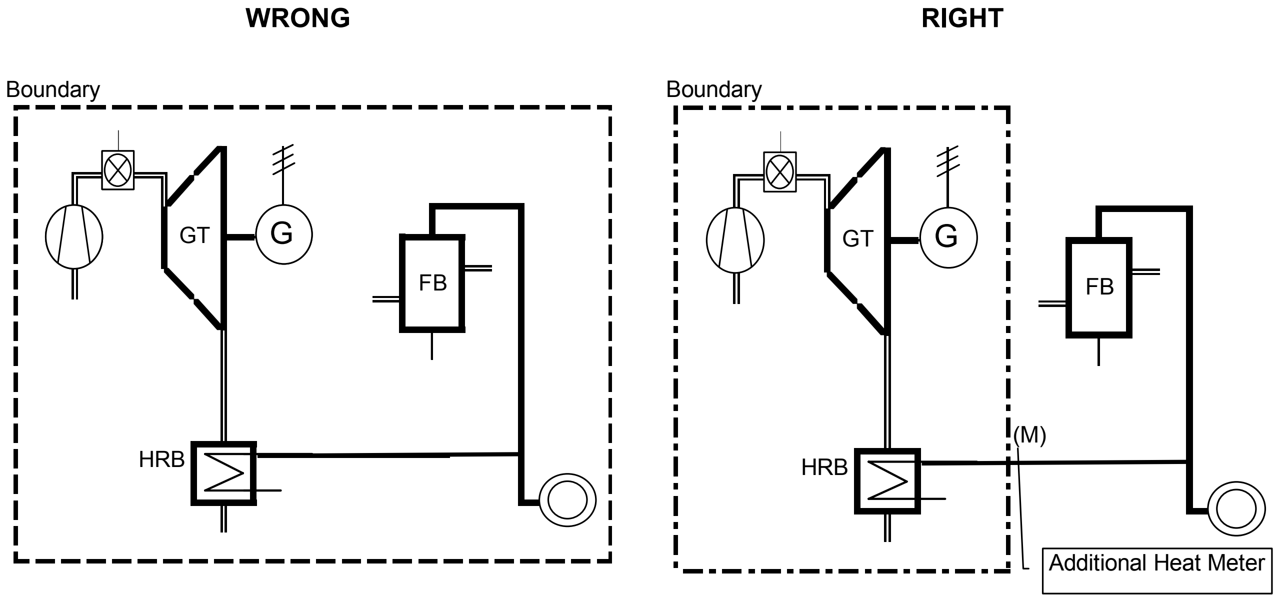

Figure 9 — Choosing the Right Scheme Boundaries in Case of Auxiliary/Standby Boilers

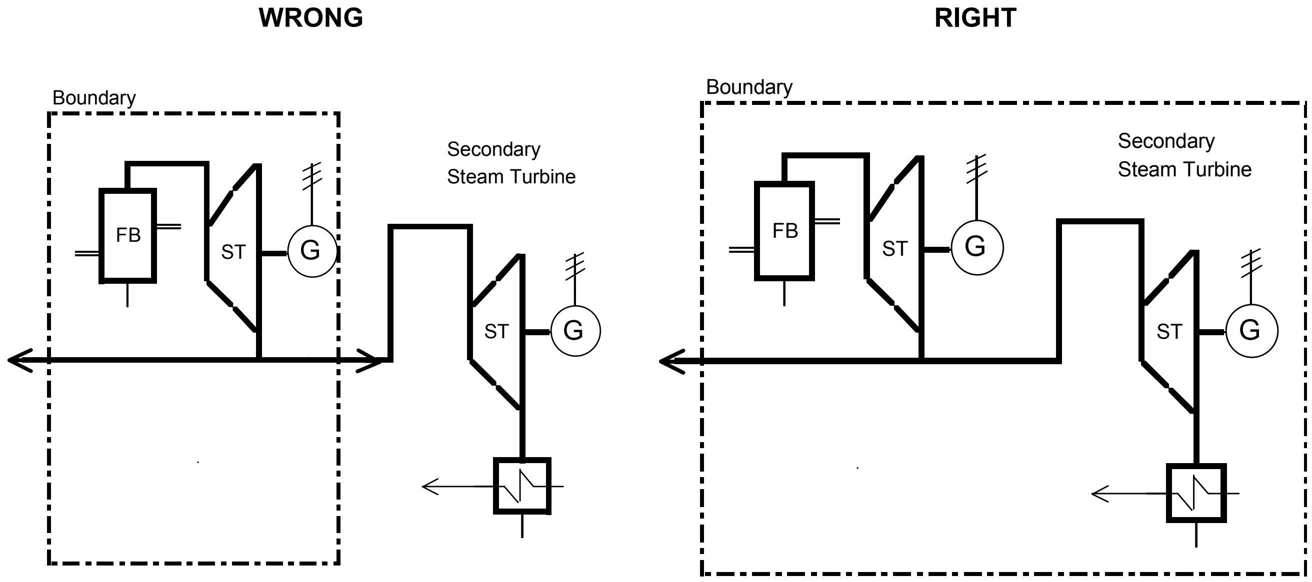

Figure 10 — Choosing the Right Scheme Boundaries in Case of Secondary Steam Turbines

Where prime movers[4] are connected in series by heat distribution systems, in combined cycle mode (where the heat from one prime mover is converted to steam to supply a steam turbine) the prime movers cannot be considered separately, even if the steam turbine is located on a different site (Figure 11 — CHP Plant Boundary).

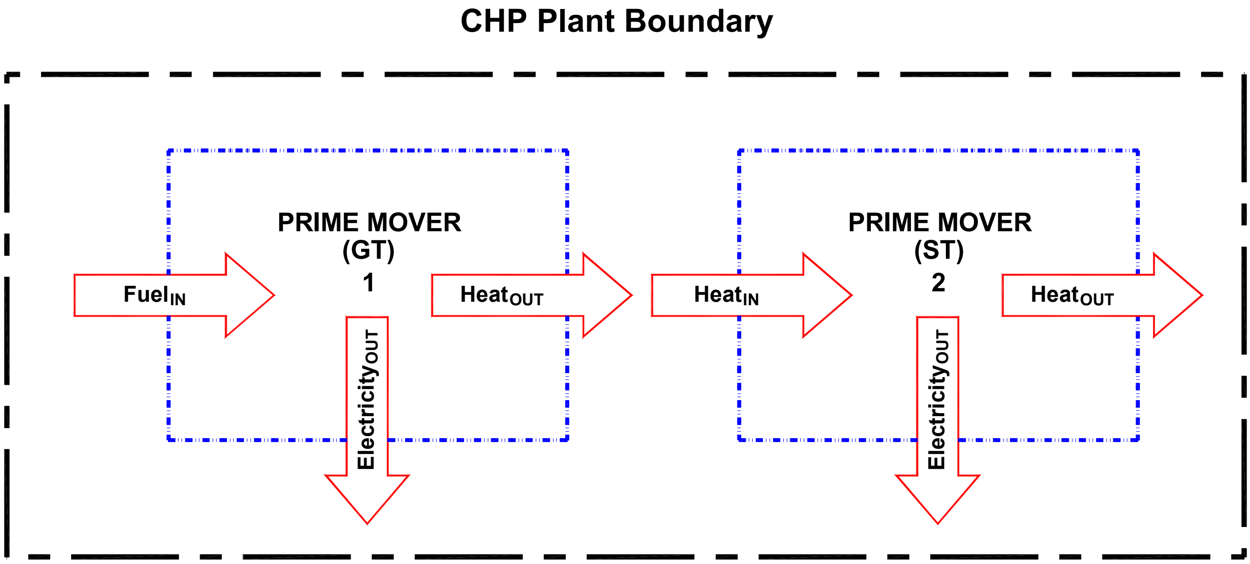

Figure 11 — CHP Plant Boundary

6.1.1 CHP Plant Area

The CHP Plant contains the main CHP Prime Mover(s) and associated heat recovery equipment.

The CHP Plant includes all prime movers, such as steam turbine-driven pumps or generators that are delivering heat and/or electrical/mechanical energy to the consumer area. These must be shown within the main CHP boundary with the appropriate connections to the consumer area.

6.1.2 Consumers Area

The consumers area consumes the CHP energy outputs. This can be the district heating network and the public electric grid when the electricity is sold on the market or industrial processes that consume heat energy and/or electrical/mechanical energy at an industrial site.

6.2 Determination of Total Fuel Energy (f)

All fuel energy inputs shall be based on net calorific value (lower heating value) and should be determined in MWh. The total fuel energy input in a reporting period is the sum of all fuel energy inputs:

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4) A machine or mechanism that converts energy.

$$f = \sum_{i=1}^{n} f_i \text{ in MWh.}$$

NOTE Indirect methods shall only be used if direct methods cannot be applied. Measurements are prescribed in all cases where this can technically been done.

6.2.1 Treatment of Recycled Fuel Energy

If a share of the energy content of the fuel energy input to the cogeneration process is recovered in chemicals and recycled this share must be deducted from fuel energy input.

EXAMPLE A CHP plant

produces

300 MWh of electricity/mechanical energy

400 MWh of useful heat

Consumes

1,000 MWh of fuel energy

Recovers

50 MWh of chemical by-products

The overall efficiency of the CHP plant is as follows:

$$\eta = \frac{300 + 400}{1000 - 50} = 73.7\%$$

6.2.2 Classification of Fuels

Fuel should for statistical purposes and for the later Annex III step of the Directive and for the Guarantee of Origin Certificate be classified into the following categories:

- Any gas
- Petroleum, or other hydrocarbon, in a liquid state
- Coal and lignite
- Coke, and semi-coke
- Petroleum coke
- Peat and oil shale
- Hydrocarbon oil
- By-products from industrial processes

- Municipal waste
- Biomass according to the Directive 2001/77/EC on the promotion of electricity from renewables [4].

6.2.3 Indirect Determination of Fuel Energy Inputs

For some fuels it may be impossible to determine their energy inputs or it may be difficult to attain a certain accuracy. This may be because measurement of mass flow is unreliable or density and/or calorific values are variable. For example, biomass and solid, liquid and gaseous waste fuels may come into this category. It may also be that the fuel is heterogeneous and contains fractions that have large particle sizes. In such cases the uncertainty associated with the fuel analysis and net calorific value may be unacceptable because of the large errors associated with trying to obtain representative samples from site and in preparing representative sub-samples for laboratory analysis. These fuels may represent the whole or only a proportion of energy inputs. In these cases indirect methods shall be permitted where direct measurement is less accurate or would impose excessive costs.

6.2.3.1 Losses Method

When one of the energy inputs of an energy system cannot be measured with sufficient certainty, the losses method can determine the missing quantity with a greater level of certainty. Essentially, the various heat losses and useful outputs are measured (or in some cases estimated); the losses are summed along with the useful outputs and the missing input component can be quantified from the compiled energy balance. The heat losses from a combustion system may include:

- Energy losses carried away in the flue gases (as sensible and latent heat)
- Chemical energy losses carried away in the flue gases (due to undeveloped heat of unburned gaseous fuel components)
- Losses in ash and dust as heat and unburned carbon (solid fuels)
- Mechanical and generation losses (for prime movers and driven machinery)
- Casing and cooling heat losses from the equipment
- Blow-down losses (for boilers)

The most important loss is the energy content of the flue gases. Determination of the flue gas losses requires analysis of the flue gas in terms of oxygen, carbon dioxide, carbon monoxide, hydrocarbons (or combustibles), sulphur dioxide and moisture, with the nitrogen content being calculated by difference. Also required is the flue gas temperature and the temperature and relative humidity of the combustion air. For direct determination of the flue gas energy content it is necessary to determine the mean flue gas velocity. Unless the flue sampling position is ideal, with an adequate number of straight undisturbed duct lengths before and after the sampling position, then a sufficiently accurate determination of mean velocity can be very difficult. In some cases a possible alternative may be to carry out a combustion calculation that avoids the need for velocity measurement. However, as a minimum, sampling and determination of the fuel moisture content will be required together with analysis for ash, carbon, hydrogen and sulphur content. In addition, either the calorific value or the mass flow of the fuel or fuels needs to be measured. In other cases, this alternative approach will not be possible because of one or more of the difficulties highlighted in 6.2.3.

Other losses may be relatively easy to determine or to make an appropriate allowance for, and in total will usually be no greater than 5%. To quantify the missing fuel energy input, the energy output as steam or hot water (boilers) or as power, (turbines or engines) must be metered. The heat in the feed-water (boilers) must also be measured and a complete energy balance constructed. If there are two fuel streams involved then the energy input from one must be measured in order to calculate the other.

6.2.3.2 Energy Balance Models

It is possible to set up a calculation routine within EMS-type packages that will use measured variables to determine the unmeasured value of heat input with a higher accuracy than direct measurement. This may be a realistic option for some CHP Plants. Systems for checking the validity of the input variables may also be included.

6.2.3.3 Standards

European and International Standards that are applicable to the determination of energy balances and efficiency of combustion plant e.g. ISO and CEN shall be used. However, it is likely that none of these will be ideal for the CHP Plant under consideration. As these Standards are primarily designed for short-term performance testing over a period of a few hours, it will be necessary to adapt them to suit monitoring of plant performance over the reporting period, using a holistic approach to determine the energy balance using all of the data that can reasonably be obtained.

6.2.4 Imported Energy

The following convention was fixed:

- waste fuels are treated as fuels (see section 6.2)
- in case of steam, hot water and hot gas a fuel equivalent is added to the fuel input of the plant (see section 6.2.5). Heat in returned condensate is not to be added to fuel inputs
- in case of returned condensate, its fuel equivalent is not taken into account in determining the fuel input. Where practicable, recovery of heat from condensate and re-use of condensate in a closed loop steam network is considered best practice. Excluding condensate heat from the total heat supplied to the user would tend not to encourage the recovery of heat from condensate*
- * Discounting the heat returned in condensate means that the whole of the energy in the steam crossing the CHP Plant boundary, above ambient temperature datum, is counted as the CHP heat output.

6.2.5 Steam, Hot Water and Hot Gas

Hot gas energy can be imported:

- from high temperature process gases manufactured by chemical reactions driven by fuel fired in reaction furnaces (e.g. steam reformer furnaces and cracking furnaces used in olefins manufacture).
- from high temperature process gases manufactured by exothermic chemical reactions (e.g. sulphuric acid manufacture).

Water and steam can be imported from any non-CHP plant (e.g., waste incineration plants, boilers, etc.) or other CHP plants.

These imported steam and or hot water must completely be used as input to the CHP plant. When it partly or completely is sold again without incorporating these energies in the CHP utility plant area to produce combined heat and power, these steam and hot water streams must be kept outside the CHP boundary area. In other words: with these imported energies CHP electricity and CHP heat must be made downstream. If that is not the case, then they may not be taken into account at all. Recovery of heat from condensate, and re-use of condensate in a closed loop steam network, is obviously best practice where possible and is excluded from this restriction.

Otherwise the equivalent fuel of n imported energies is as follows:

$$f = \frac{\sum_{i=1}^{n} \beta_i \cdot q_i}{\eta_{non-CHP,p}}$$

where the referring electrical/mechanical energy loss coefficient(s) β_ι has/have to be determined separately for each imported energy q_i (see section 9.1 and Annex B).

The table below shows power loss coefficients for different steam export/import pressures and for turbine thermodynamic efficiencies that are typical in operation for steam turbines in the size ranges shown. This Table is illustrative as the power loss coefficients are influenced by the steam turbine loading and the condition of the turbine blades.

Table 1 — Typical power loss coefficients for given steam turbines and steam pressures

Steam turbine size range	2 to <5MW$_e$	5 to <10MW$_e$	10 to <25MW$_e$	25 to <50MW$_e$	Above 50MW$_e$
Typical thermodynamic (isentropic) efficiency	65%	70%	75%	80%	84%
Steam export/import pressure					
21.7 bar	0.200	0.213	0.227	0.244	0.256
14.8 bar	0.185	0.200	0.213	0.227	0.238
11.4 bar	0.175	0.189	0.204	0.217	0.227
7.9 bar	0.164	0.175	0.189	0.200	0.213
3.8 bar	0.139	0.149	0.159	0.169	0.179
2.4 bar	0.123	0.133	0.143	0.152	0.159

In the special case that the imported steam has the same condition (pressure and temperature) as the live steam of the importing CHP plant the boiler efficiency of the CHP plant can be applied to determine the equivalent fuel of the imported steam:

$$f = \frac{\beta \cdot q}{\eta_{non-CHP,p}} = \frac{q}{\eta_{boiler}}$$

In cases where energy import does not lead to a change in electricity/mechanical energy generation (related to constant fuel energy input) ß becomes zero. Thereby the equivalent fuel f becomes zero.

EXAMPLE Steam Import into a Combined Cycle CHP Plant

To determine the fuel energy equivalent of the imported steam the power loss (power increase at constant fuel input – f1) due to steam import must be determined. These value has to determined as described in section 9.1. Moreover the efficiency of non-combined electrical/mechanical energy generation $\eta_{\text{non-CHP,p}}$ must be determined. The latter can be determined in this example as follows (see also section 9):

$$\eta_{\text{non-CHP,p}} = \frac{p + \beta_{(300°C,20bar)} \cdot q_{(300°C,20bar)} - \beta_{(440°C,100bar)} \cdot q_{(440°C,100bar)}}{f1}$$

$$\eta_{\text{non-CHP,p}} = \frac{55{,}580 + 0.30 \cdot 31{,}510 - 0.36 \cdot 46{,}860}{92{,}140} = 52{,}3\%$$

The fuel energy equivalent of the imported steam is: $f = \frac{\beta \cdot q}{\eta_{\text{non-CHP,p}}} = \frac{0.36 \cdot 46{,}860}{52.3\%} = 32{,}248 \text{ MWh}$

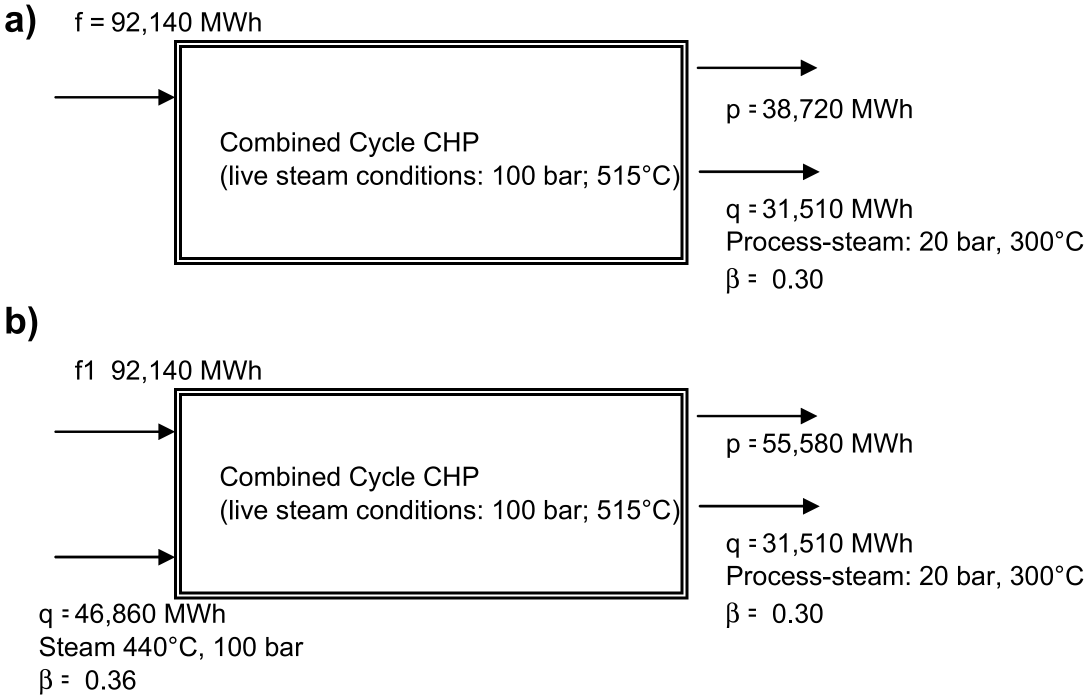

Figure 12 — Example a) Combined Cycle without Steam Import b) Combined Cycle with Steam Import

Table 2 — Combined Cycle with and without Steam Import

	a)	b)
p	38,720 MWh	55,580 MWh
q	31,510 MWh	31,510 MWh
f1	92,140 MWh	92,140 MWh
f2	0 MWh	32,248 MWh
f	92,140 MWh	124,388 MWh
σ_{CHP}	0.453	0.453
p_{CHP}	14,265 MWh	14,265 MWh

6.2.6 Justification for crediting the full heat content (above ambient temperature datum) of the steam used on site as CHP heat output without deducting all the energy in condensate returned.

6.2.6.1 Background

Where a CHP scheme generates steam that is then used on site (outside the boundaries of the CHP plant) it is good practice to return as much as possible of the condensate to the CHP plant. Returned condensate is usually hot 80-100 °C so, besides reducing the quantity if fresh treated water make-up that is required to compensate for losses, it reduces the heat (steam) requirements of the deaerator. This in turn results in a fuel saving either at the CHP plant or at the site boilers.

In order to determine the true thermal efficiency of the CHP plant the quantity (and temperature) of returned condensate must be taken into consideration. In practice this may present a number of problems, as outlined below.

6.2.6.2 Problems in accounting for energy utilised, lost or returned in condensate

1. At many sites the measurement of condensate returned from site to within the CHP boundary, and its energy content, will be problematic. One reason will be that condensate may be returned from a number of steam users in different piping systems. Consequently condensate metering may involve a number of flowmeters (and temperature measurements).

2. Strictly any condensate that is dumped for whatever reason (for example because of risk of contamination) is not part of the useful heat output to the site. Usually there will be no way to differentiate between condensate losses that occur in this way and condensate whose energy content is genuinely used within the process and therefore cannot be returned to the CHP plant (e.g. steam used for process heating by direct steam injection).

3. Where a site has steam boilers that are separate and independent of the CHP system it may often be good operating practice to return condensate preferentially to these boilers, which may be less susceptible to damage by contaminated condensate than the CHP boilers. In this case is the heat in the condensate part of the CHP output to site (outside of the CHP boundary) or is it heat returned to within a CHP/Utilities boundary?

6.2.6.3 Implications of discounting the heat in returned condensate.

The disadvantage of discounting all of the heat in the condensate returned is that it will give calculated overall efficiencies that are unrealistically high, particularly for schemes with high heat to power ratios.

Discounting the heat returned in condensate means that the whole of the energy in the steam exported to site (i.e. steam crossing the CHP plant boundary), above ambient temperature datum, is counted as the CHP heat output.

In practice for a typical level of 50-60% of hot condensate returned across the CHP boundary approximately 5-6% of the energy in the steam exported is returned.

The implications of discounting the heat returned to the CHP plant in the form of hot condensate have been examined for a number of technology options:

- Gas turbine simple cycle, low level of supplementary firing (or unfired HRB).

- Gas turbine simple cycle, high level of supplementary firing.
- Gas turbine, back-pressure steam turbine combined cycle.
- Gas turbine, pass-out/condensing steam turbine combined cycle.
- Steam cycle using back-pressure steam turbine.
- Steam cycle using pass-out/condensing steam turbine.

In summary, for gas turbine based CHP schemes discounting the heat in returned condensate will increase the heat efficiency by 2 - 3% with no supplementary firing, increasing to around 6% with maximum supplementary firing. Steam cycle CHP sites have high heat to power ratios and so discounting condensate increases the calculated heat to power ratio even further, increasing the heat efficiency by 2-9%. At sites with CHP based on reciprocating engines heat recovery is usually in the form of hot water, so condensate return is not an issue.

6.2.6.4 Conclusion

In view of the problem associated with rigorously determining the heat output, a simplified treatment was necessary, therefore the heat in returned condensate will not be taken into account in case of steam delivery (see section 6.4.1).

6.3 Determination of Total Electrical/Mechanical Energy (p)

The total electrical/mechanical energy output in a reporting period is the sum of gross electrical and equivalent mechanical gross energy output including start-up, standstill and shutdown periods:

$$p = \sum_{i=1}^{n} \left(p_{e,i} + p_{m,i}\right) \text{ in MWh}$$

NOTE Indirect methods shall only be used if direct methods cannot be applied. Measurements are prescribed in all cases where this can technically been done.

6.3.1 Determination of Total Electrical Energy (p_e)

The electrical energy output (p_e) in a reporting period is the total (gross) electricity generated without subtraction of parasitic consumption (in a reporting period). Electricity shall be measured at the outlet of the main generators.

6.3.2 Determination of Total Mechanical Energy (p_m)

Some CHP plants generate mechanical energy to drive a pump, fan or compressor directly (see Figure 13 — Electrical and Mechanical Energy). This mechanical energy is equivalent to electrical power5).

Where one of the main prime movers in a CHP plant drives a mechanical load rather than (or as well as) an electrical generator, it will usually be of sufficient importance to warrant metering of the process-side operation in terms of flow rate, temperatures and pressures. These measurements may permit the absorbed power to be determined. For a liquid pumping duty this is straightforward but for a gas compressor the determination can be quite complex, depending on the number of stages, intercooling and, sometimes, changes in molecular weight.

An alternative method is to derive the driven load from an energy balance including the fuel energy input, the energy content of the exhaust gases and, where applicable, the engine cooling circuits. This will involve exhaust gas analysis and the sensitivity to errors in oxygen content may render this approach less robust than determination of load from the process conditions.

Where the prime mover is a steam turbine, measurement of the steam flow and its inlet and exit conditions will permit the mechanical power output to be calculated.

Manufacturers' design data or, preferably, test data can provide a good basis for determining difficult power outputs. This approach may require an estimate of the fall-off in performance/efficiency since new.

If there is a back-up method of driving the mechanical load using an electric motor, the electrical input to this motor can be used to estimate the shaft power required to drive the mechanical load (using the manufacturer's figures for motor and gearing efficiencies).

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5) The majority of electricity generated in the plant that is consumed onsite is used to run electric motors used to drive pumps, fans, compressors, etc. with regard to CHP plants generating mechanical power to drive a pump, fan or compressor directly, the losses in turning mechanical energy into electrical energy and then back into mechanical energy again can be avoided. If, however, the efficiency of energy transformation in large-scale prime generator and possibly small-scale drive is taken into account, then the advantage of mechanical drives is doubtful. Therefore mechanical power is treated thermodynamically equivalent to electricity with a factor of 1.

Mechanical power used for drives that are integral to the operation of the plant prime movers (e.g. the air compressor module of a gas turbine) shall not be included as plant mechanical power outputs. The value of this energy is reflected in shaft output power and heat from the engine.

Mechanical power used for drives other than those integral to the operation of the CHP prime movers, where the alternative driver is an electric motor, may be included as plant mechanical power outputs. These may include

- steam turbine-driven boiler feed-water pumps,
- cooling water pumps,
- condensate extraction pumps,
- compressors for process air.

For these purposes, power used by electric motor drives is already included since the CHP electrical power outputs are measured at the generator terminals.

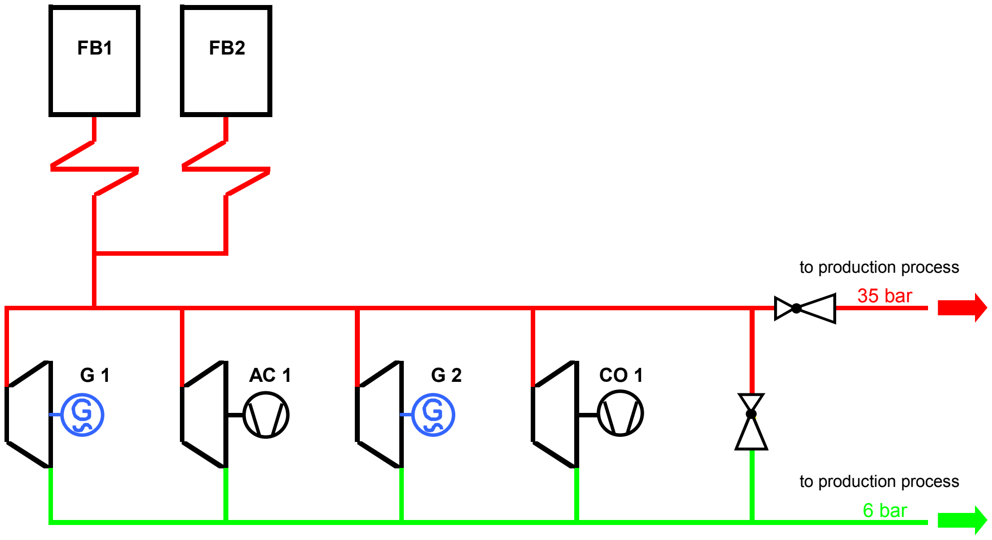

Figure 13 — Electrical and Mechanical Energy

EXAMPLE The gross electrical/mechanical energy outputs are

G 1 = 300 MWh (generator power)

G 2 = 400 MWh (generator power)

AC 1 = 100 MWh (air-compressor shaft power)

CO 1 = 200 MWh (cold-compressor shaft power)

The total electrical/mechanical energy output equals: p = 300 + 400 + 100 + 200 = 1,000 MWh

6.4 Determination of Total Useful Heat (q)

Total useful heat output in a reporting period is the registered amount of useful heat supplied from a CHP plant.

Usually, for CHP plants, heat outputs will be in the form of steam or hot water to be used in a network or a production process. Some CHP plants use part or all of the exhaust gases from a gas turbine or engine for direct heating or drying applications. CHP plants may provide heat at various pressure and temperature levels and the energy output is the sum of these heat energy outputs from the CHP plant to a network or a production process.

Useful heat output excludes heat rejected to the environment without any beneficial use. Examples include, inter alia, heat lost from chimneys or exhausts and heat rejected in equipment such as condensers and radiators. Heat exported for use to generate power on another site is not classified as a heat export but as part of the internal heat transfer within a CHP Plant. Some Schemes may export steam that was originally imported at a higher pressure as a heat input from another site. To qualify as useful heat outputs such heat must be used for process or space heating purposes. For example this applies to heat for de-aeration, condensate heating, make-up water and boiler feed-water heating used for the operation of other boilers or other energy conversion facilities in the energy sector.

The useful heat output of a CHP plant in a reporting period is the sum of all useful heat outputs.

$$q = \sum_{i=1}^{n} q_i \text{ in MWh}$$

Steam systems may provide heat at several pressure levels and the heat output is the sum of these steam energy outputs. Pressure, temperature and steam mass flow is required for outputs at each pressure level.

6.4.1 Determination of Useful Heat from Steam Delivery

Heat from steam can be used within the CHP plant before the steam is supplied to the process, and can also be returned to the CHP plant from the process as condensate after the steam has given up most, but not all, of its useful energy. In broad terms, the aim is to determine the useful heat supplied to the process (i.e. excluding the heat rejected in condensers, heat rejection radiators, and other facilities) with this objective in view:

- Where steam is used within the CHP plant for duties such as de-aeration, condensate heating, fuel drying and heating, make-up water and boiler feed-water heating, this should not be counted as part of the useful heat supplied to site
- Steam used for injection into gas turbines is not useful heat supplied to process. The value of this energy is reflected in increased power output and exhaust gas mass flow

The specific heat content (specific enthalpy) is the specific enthalpy from steam tables or steam charts (IAPWS-IF97), which have a datum of 0°C and 1.013 bar and must be measured on the point it crosses the CHP system border.

The imported energy from the returned condensate will not be taken into account.

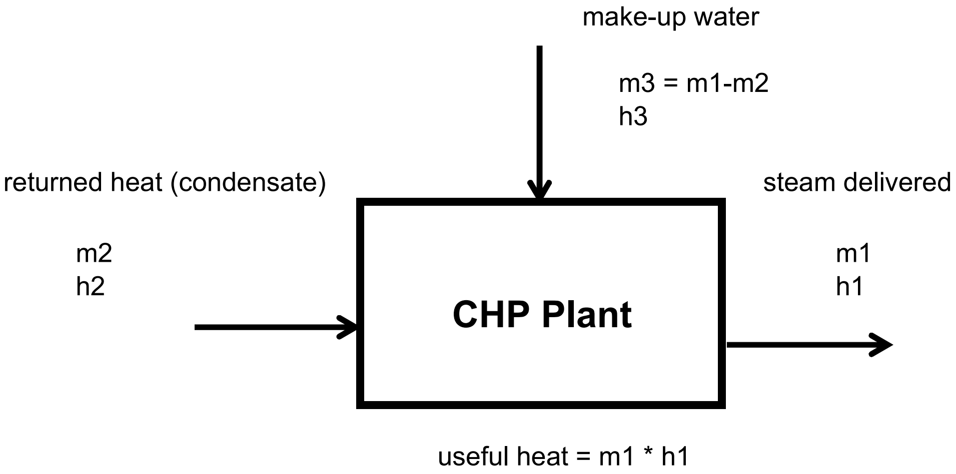

Figure 14 — Determination of Useful Heat from Steam Delivery

EXAMPLE

Table 3 — Determination of Useful Heat from Steam Delivery

	m	t	p	h	m*h
1	100 t	179.9 °C	10.000 bar	2777 kJ/kg	77.1 MWh
2	90 t	60.0 °C	1.013 bar	251 kJ/kg	6.3 MWh
3	10 t	10.0 °C	1.013 bar	42 kJ/kg	0.1 MWh

- Heat to site: q = 77.1 MWh

6.4.2 Hot Water and Thermal Fluid Systems

The useful heat output may be to hot water or heat transfer oil circulating systems that are used to transport heat for process or space heating, or for Community Heating CHP Plants. In such cases, in addition to the circulation rate, the flow (hot) and return (cool) temperatures of the circulating fluid at the CHP plant boundary are required. The mean specific heat of the circulating fluid over the working temperature range is required to determine the heat output. This must be measured with a heat meter according to the CEN 1434 standard.

CHP units smaller than 1 MWe which have no heat rejection facilities and which have also a constant power to heat ratio under all operational circumstances have to measure the electricity but the measurement of heat and fuel is not a prerequisite. If a CHP unit smaller than 1 MWe has heat rejection facilities or when the power to heat ratio is not constant under all operational circumstances then a heat meter according to CEN 1434 still must be installed, as well as the electricity and the fuel meter.

6.4.3 Direct Use of Exhaust Gases

Some CHP Plants use part or all of the exhaust gases from a gas turbine or engine for direct heating or drying applications. Where exhaust gases are used for direct heating applications, the useful heat output is the difference in heat content of the exhaust gases between entering and leaving the application. The useful energy extracted from the exhaust gases involves, as a minimum, measuring the gas temperature leaving the gas turbine or engine and the gas temperature in the flue leaving the process plant.

It is possible to determine the energy utilisation by measurement of exhaust gas velocity, composition (moisture and oxygen as a minimum) and temperatures. A wide range of instruments is available for measuring flue gas oxygen concentrations and information on the procedure can be found in ISO 12039:2001. Moisture is normally determined gravimetrically, by manual extractive absorption or condensation methods. A European Standard (EN) is currently in preparation but is not yet complete.

Flue gas velocity can be determined using velocity head methods such as pitot tubes or averaging pitots. The relevant parts of ISO 10780:1994 can be followed for the measurement procedure and instructions for calibrating pitot tubes can be found in ISO 3966:1977. However, unless the conditions for velocity measurement are exceptionally good (i.e. there should be provision of long, straight lengths of duct before and after the measuring location) these measurements are likely to have uncertainties of ±10% or more. Useful information on the number of straight unobstructed duct diameters required can be found in ISO 9096:1992. Uncertainty can also increase if gas velocities are too low, e.g. if a boiler is operating at high turndown conditions. Other options may be more reliable. The use of manufacturers' data on exhaust gas flow versus load may provide an alternative strategy.

Where all of the exhaust is used for direct heating, an energy balance around the prime mover may be possible providing that all of the other energy inputs and outputs can be reliably determined. Such a model is easily formulated and is suitable for continuous monitoring. Providing the fuel energy input is known, this information, together with the exhaust gas temperatures before and after the process heat load is sufficient to derive the heat output. This, too, can be set up as a model for continuous monitoring. If supplementary or auxiliary firing (with additional combustion air) into the engine exhaust is used, its energy input and the mixed gas temperature after the supplementary/auxiliary burner will be required.

Where only a proportion of the exhaust gas is used for direct heating it is likely that the remaining exhaust will be used for some other duty such as steam generation or water heating. In this case an energy balance that includes the boiler duty can be used to derive the direct heating duty.

7 Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

CHP plants might generate non-combined heat (see section 4.3). In this case the amount of non-combined generated heat ($q_{non\text{-}CHP}$) and the referring ($f_{non\text{-}CHP,q}$) fuel have to be determined. Both have to be subtracted from total fuel energy and total useful heat energy to determine CHP useful heat energy and CHP fuel energy plus fuel energy for NON-CHP electrical/mechanical energy generation:

$$q_{CHP} = q - q_{non-CHP}$$

$$f_{CHP} + f_{non-CHP,p} = f - f_{non-CHP,q}$$

The total non-combined generated useful heat energy of a CHP plant is the sum of all non-combined generated useful heat energy:

$$q_{non-CHP} = \sum_{i=1}^{n} q_{non-CHP,i} \text{ in MWh}$$

The total non-combined fuel energy for generation of non-combined useful heat energy of a CHP plant is the sum of all non-combined fuel energy for generation of non-combined useful heat energy:

$$f_{non-CHP,q} = \sum_{i=1}^{n} f_{non-CHP,q,i} \text{ in MWh}$$

7.1 Live Steam Extraction

Live steam extraction in this context is the extraction of steam that is unconnected with any electricity generation. Live steam extraction is rated as non-combined heat generation (see Figure 15 — Live Steam Extraction/No Live Steam Extraction). Steam generated by supplementary or auxiliary firing or in fired boilers that does not contribute to any downstream power generation (live steam extraction) can also not contribute to CHP heat energy. Steam that is generated in a heat recovery boiler using gas turbine or engine exhaust gases as the source of energy contributes to CHP heat energy.

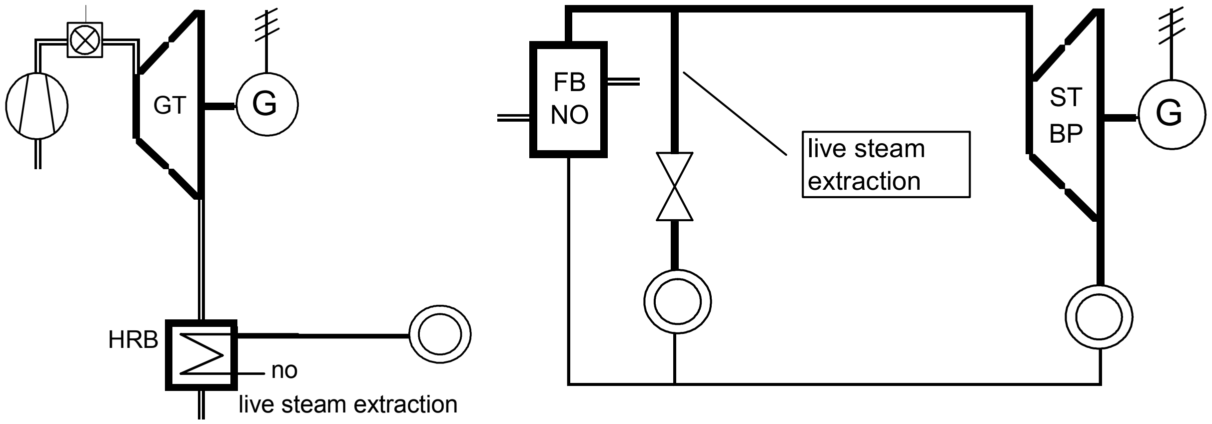

Figure 15 — Live Steam Extraction/No Live Steam Extraction

Usually the amount of heat energy ($q_{non\text{-}CHP}$) generated from live steam is metered. To determine the fuel used for live steam extraction the efficiency for non-combined heat generation should be used:

$$\eta_{non-CHP,q} = \frac{q_{non-CHP}}{f_{non-CHP,q}}$$

$$f_{non-CHP,q} = \frac{q_{non-CHP}}{\eta_{non-CHP,q}}$$

7.2 Auxiliary/Supplementary firing

If subsequent to an auxiliary[6]/supplementary[7] firing a further co-generation process takes place the fuel is to be rated as CHP fuel energy. Auxiliary/supplementary firing are rated as non-combined heat generation as long as there is no downstream co-generation process subsequent to the auxiliary/supplementary firing (see also Figure 16 — CHP and NON-CHP Auxiliary/Supplementary firing). Usually the amount of fuel energy ($f_{non\text{-}CHP}$) for these processes is metered. To determine the referring non-CHP useful heat energy the referring efficiency for non-combined heat generation has to be known:

$$\eta_{non-CHP,q} = \frac{q_{non-CHP}}{f_{non-CHP,q}}$$

$$q_{non-CHP} = f_{non-CHP,q} \cdot \eta_{non-CHP,q} \,.$$

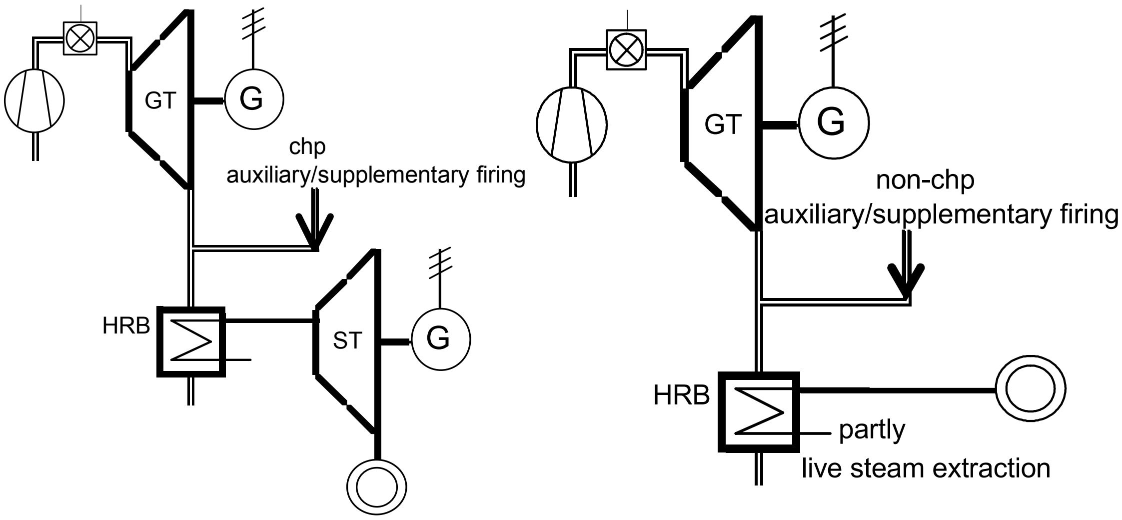

Figure 16 — CHP and NON-CHP Auxiliary/Supplementary firing

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[6] with additional air

[7] without additional air

7.3 Complex CHP plants

Complex CHP plants may consist of various combinations of CHP technologies and non-CHP technologies. To separate all non-CHP useful heat energy generation from the CHP process may require significant effort (see Figure 17 —NON-CHP Fuel Energy and NON-CHP Useful Heat Energy). In these cases, as a minimum, fuel, electricity and heat must be measured at the CHP boundary. The amount of non-CHP fuel and useful heat energy from auxiliary/supplementary firing can be determined by applying energy balances of the following kind:

$$f_{non-CHP,q} = f \cdot \frac{e_2}{e_1 + e_2} \qquad q_{non-CHP} = q \cdot \frac{e_2}{e_1 + e_2}$$

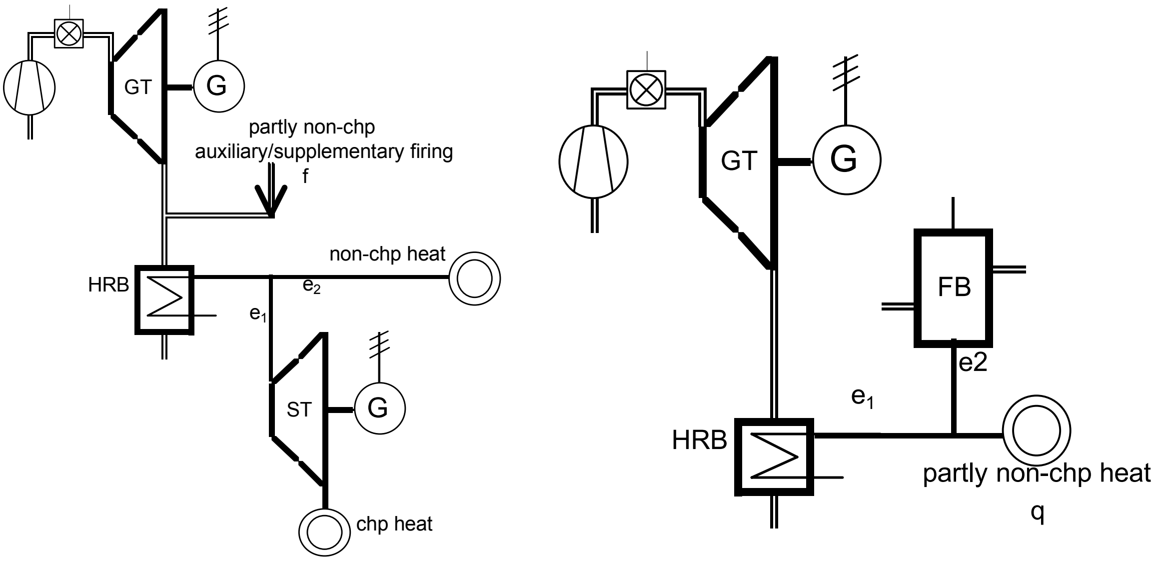

Figure 17 —NON-CHP Fuel Energy and NON-CHP Useful Heat Energy in Complex CHP Plants

8 Determination of Overall Efficiency (η)

To determine the overall efficiency (η) of a CHP plant in a reporting period the following figures must be known:

- Total useful heat energy (q) see section 6.2
- Total electrical/mechanical energy (p) see section 6.3
- Total fuel energy (f) see section 6.4
- Non-combined useful heat energy ($q_{non\text{-}CHP}$) see section 7
- Non-combined fuel energy for non-combined generation of useful heat energy ($f_{non\text{-}CHP,q}$) see section 7

CHP useful heat energy must be determined: $q_{CHP} = q - q_{non-CHP}$.

The overall efficiency is:

$$\eta = \frac{p + q_{CHP}}{f - f_{non-CHP,q}}$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

If the overall efficiency (η) achieves or exceeds the value(s) in Annex II a) of the CHP-Directive then:

$$\mathbf{q_{CHP}} = q - q_{non\text{-}CHP}$$
$$\mathbf{p_{CHP}} = p$$
$$\mathbf{f_{CHP}} = f - f_{non\text{-}CHP,q}$$

Otherwise the non-CHP electrical/mechanical energy ($p_{non\text{-}CHP}$) and the referring fuel energy ($f_{non\text{-}CHP,p}$) have to be determined see section 9.

9 Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

If the overall efficiency of the CHP plant (η) in a reporting period achieves the value(s) in Annex II a) of the CHP-Directive the CHP plant does not generate non-CHP electrical/mechanical energy ($p_{\text{non-CHP}}$) (see section 8).

The non-CHP electrical/mechanical energy ($p_{\text{non-CHP}}$) and the referring fuel energy ($f_{\text{non-CHP,p}}$) only have to be determined if the overall efficiency of the CHP plant (η) in a reporting period does to not achieve the value(s) in Annex II a) of the CHP-Directive (see section 8). In this case the CHP overall efficiency (η_{CHP}) according to Annex II of the CHP Directive will be applied to determine the power-to-heat ratio.

To determine the non-CHP electrical/mechanical energy ($p_{\text{non-CHP}}$) and the referring fuel energy ($f_{\text{non-CHP,p}}$) of a CHP plant and to isolate the CHP part the following steps have to be done:

1) Determination of power loss coefficient(s) (β_{CHP}) (see section 9.1)

2) Determination of the efficiency of non-combined electrical/mechanical energy generation:

$$\eta_{\text{non-CHP,p}} = \frac{p + \beta_{\text{CHP}} \cdot q_{\text{CHP}}}{f - f_{\text{non-CHP,q}}} \text{ respectively } \eta_{\text{non-CHP,p}} = \frac{p}{f - f_{\text{non-CHP,q}}}$$

3) Determination of the power-to-heat ratio:

$$\sigma_{\text{CHP}} = \frac{\eta_{\text{non-CHP,p}} - \beta_{\text{CHP}} \cdot \eta_{\text{CHP}}}{\eta_{\text{CHP}} - \eta_{\text{non-CHP,p}}} \text{ respectively } \sigma_{\text{CHP}} = \frac{\eta_{\text{non-CHP,p}}}{\eta_{\text{CHP}} - \eta_{\text{non-CHP,p}}}$$

This is the power-to-heat ratio of Annex II b) of the CHP Directive, to be determined for each reporting period.

4) Determination of CHP electricity/mechanical energy: $p_{\text{CHP}} = \sigma_{\text{CHP}} \cdot q_{\text{CHP}}$

5) Determination of non-CHP electricity/mechanical energy: $p_{\text{non-CHP}} = p - p_{\text{CHP}}$

6) Determination of fuel energy for non-CHP electricity/mechanical energy generation:

$$f_{\text{non-CHP,p}} = \frac{p_{\text{non-CHP}}}{\eta_{\text{non-CHP,p}}}$$

7) Determination of fuel energy for CHP electricity/mechanical energy generation:

$$f_{\text{CHP}} = f - f_{\text{non-CHP,p}} - f_{\text{non-CHP,q}} \text{ or } f_{\text{CHP}} = \frac{p_{\text{CHP}} + q_{\text{CHP}}}{\eta_{\text{CHP}}}$$

9.1 Determination of Power Loss Coefficient(s)

Where there is more than one pass-out or steam export pressure, the power loss coefficient β should be the mean of the values at each pressure level weighted in proportion to heat extraction.

$$\beta = \frac{\sum_{i=1}^{n} \beta_i \cdot q_i}{\sum_{i=1}^{n} q_i} \text{ in MWh/MWh}$$

The power loss coefficient(s) must be derived from actual measurements of the CHP Plant in question or if impossible to measure determined by calculation. The power loss coefficient depends on the pressure and temperature of the steam supplied to site, the steam turbine generating set's thermodynamic (isentropic) and mechanical efficiencies and the vacuum (or pressure) maintained in the condenser. Rigorous calculation requires knowledge of all of the above parameters.

To determine the power loss coefficient(s) by measurement during one hour of continuous operation requires some careful manipulation of the CHP operation, and requires that adequate metering of power and steam outputs is in place. Each site should decide how to carry out the test without disrupting process operations or putting plant or personnel at risk. In general, it is suggested that the start point should be with the condensers at the highest load possible. Ideally, the boilers supplying the turbine steam should be on fixed output (firing set point) to give a constant flow, pressure and temperature at the turbine inlet. The steam extraction or export can then be increased in small steps thereby reducing the flow to the condensers, and the changes in steam export and power generation observed. If some or the entire site heat load can initially be provided by standby boiler plant, which can then automatically be backed off as the extraction is increased, this will enable the test to cover the greatest operating range. It may otherwise be necessary to vent surplus steam during the test to permit a reasonable range of condenser loading to be covered.

Where there is more than one pass-out pressure it may be possible to determine the power loss coefficients ($\beta_{,i}$) for each pressure (i) by keeping the other pass-out(s) constant. Otherwise, a single experiment will enable the mean isentropic efficiency to be determined and then the individual power loss coefficients may be determined.

Determination of the power loss coefficients involves some on-site measurements. Measurements of at least two of the three mass flows (steam in, steam out and condensate out) and the power output are recommended. In addition, the pass-out steam pressure and temperature and condenser vacuum (pressure) are required. The determination requires the use of steam tables, a steam enthalpy-entropy diagram, or software such as the steam tables [5] (see Annex B)

9.1.1 Plants without Power Loss

Pants consisting of technologies listed in Annex I of the CHP-Directive except plants including extraction-condensing steam turbines could be plants falling into this category (see Figure 18 — CHP Plant without Power Loss).

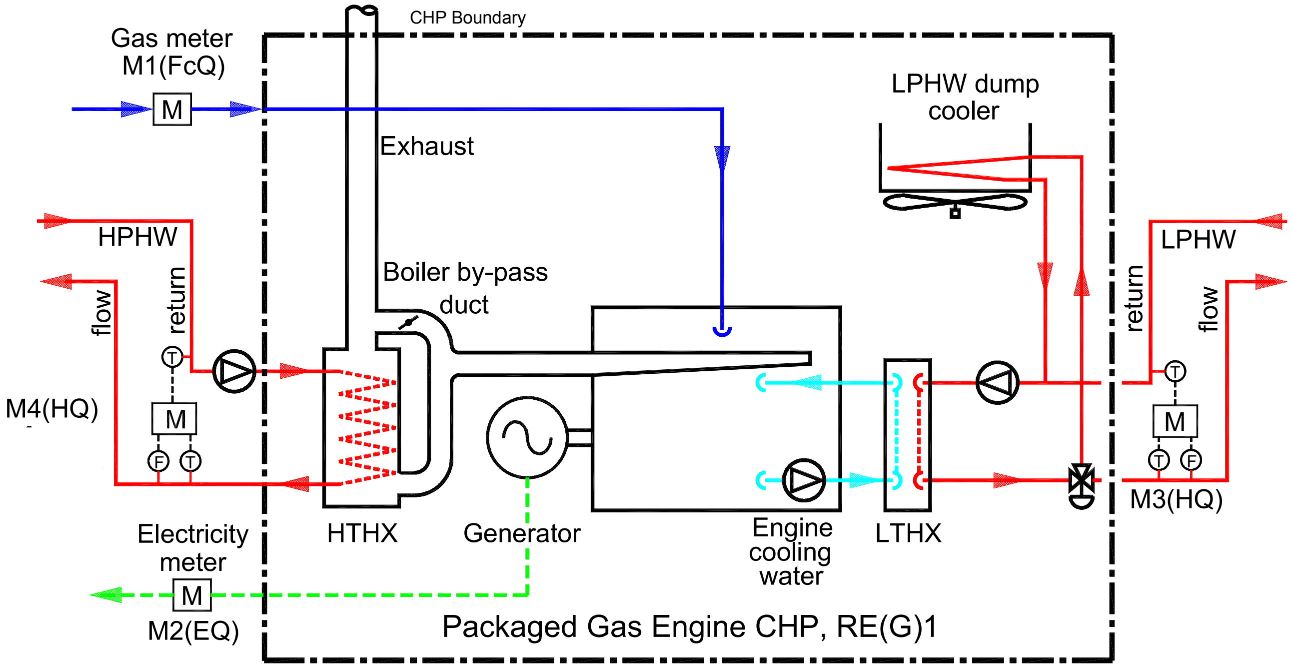

Figure 18 — CHP Plant without Power Loss

9.1.2 Plants with Power Loss

In all processes with electricity generation subsequent to heat extraction a power loss occurs (see Figure 19 — CHP Plant with Power Loss). This applies to all CHP plants comprising extraction-condensing steam turbines and combined cycles (topping cycle, e.g. GT plus bottoming cycle, e.g. ST) when heat is extracted prior the bottoming cycle.

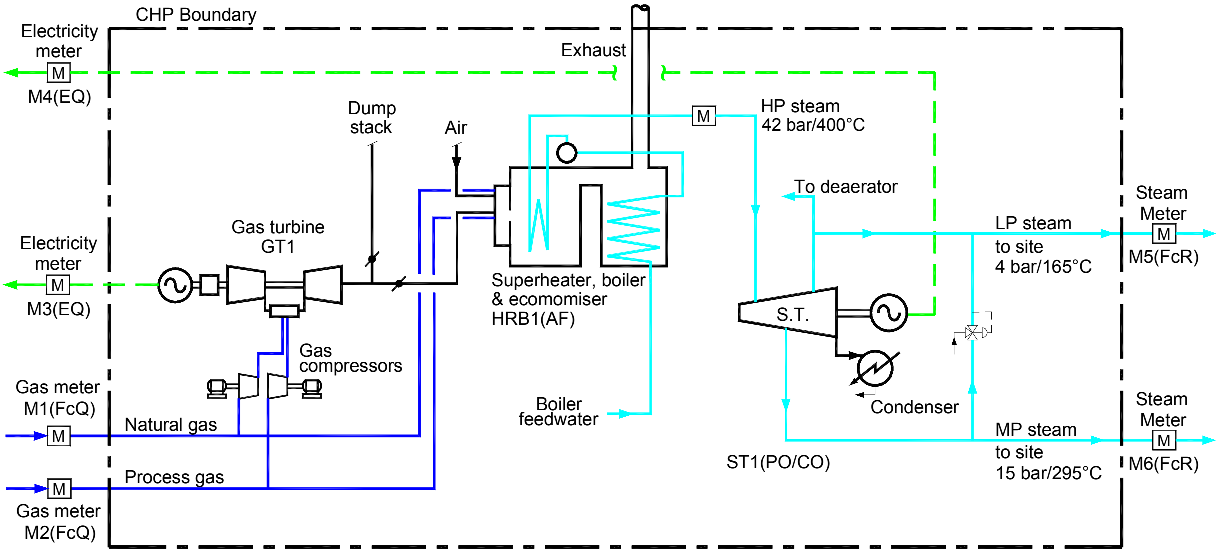

Figure 19 — CHP Plant with Power Loss

Annex A

A.1 Small Scale CHP plants

CHP Plants with a rated total gross capacity of less than 1 MWe are classified as small scale CHP plants:

$$P < 1 MWe$$

Small-scale CHP plants with no heat rejection facility (see Figure 20 — Small-scale CHP Scheme with no Heat Rejection Facility) do not have to measure the heat. When heat demand falls, a CHP Plant with no heat rejection facility must regulate its electrical/mechanical output and finally shut down, otherwise serious engine failure will occur. In these circumstances, no heat can be supplied beyond the site demand. The CHP Plant should be matched to heat demands, operating as the lead boiler in an installation, and modulating according to heat demand.

NOTE Gas turbine combined cycles with extraction-condensing steam turbines cannot be rated as plants without non-combined heat and electricity generation.

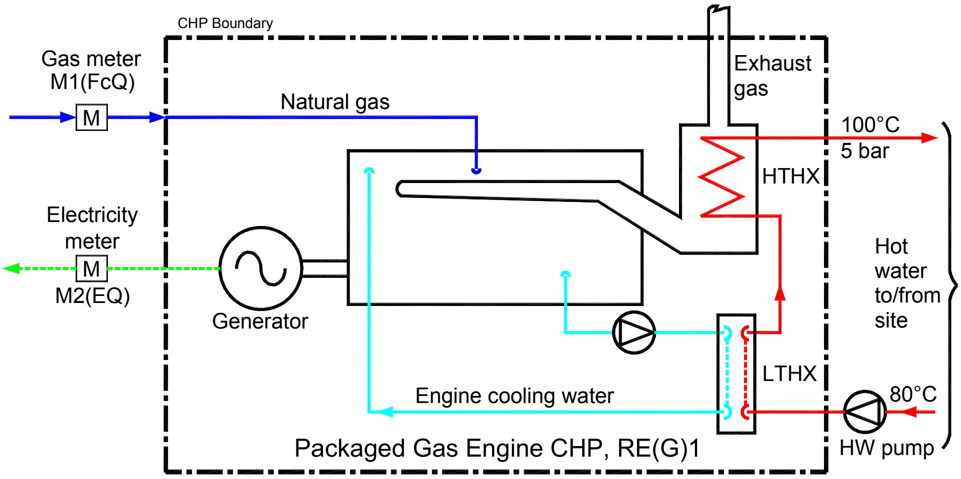

Figure 20 — Small-scale CHP Scheme with no Heat Rejection Facility

These plants have also a constant power-to-heat ratio under all operational circumstances. In this case the heat may be calculated by multiplying the measured electricity production by that constant power-to-heat ratio.

Annex B

B.1 Determination of Power Loss Coefficients by Performance Test (Example)

A test was carried out in which the two pass-out streams from the steam turbine were altered in turn whilst endeavouring to maintain a constant steam flow to the ST. The flow of LP steam to the deaerator and condensate heater was estimated at 4.0 t/h. This was assumed to remain unchanged. Since there are two pass-out streams and a condenser (vacuum exhaust) steam, we need to derive the specific electricity generation (kW per tonne/h of steam, i.e. kWh/tonne) for each stream. Therefore in order to solve for three unknowns three independent sets of data are required.

The three sets of test data are:

	A	B	C	D	P
	Total Steam	**LP steam to site**	**MP steam to site**	**Condenser steam**	**Generation**
1. Initial operation	82.9 t/h	28.0 t/h	25.5 t/h	-	10,626 kW
2. Increased MP pass-out	84.0 t/h	28.0 t/h	30.0 t/h	-	10,056 kW
3. Increased LP pass-out	83.5 t/h	33.0 t/h	25.0 t/h	-	10,255 kW

Step 1: Derive LP pass-out (= LP steam to site + 4.0 t/h) and flow of steam to condenser

Determination	= A	= B + 4 t/h	= C	= A - B - C	= P
	Total Steam	**LP pass-out**	**MP pass-out**	**Condenser steam**	**Generation**
Case 1	82.9 t/h	32.0 t/h	25.5 t/h	25.4 t/h	10,626 kW
Case 2	84.0 t/h	32.0 t/h	30.0 t/h	22.0 t/h	10,056 kW
Case 3	83.5 t/h	37.0 t/h	25.0 t/h	21.5 t/h	10,255 kW

Step 2: Normalise data to a total steam flow of 84.0 t/h (case 2)

Determination	= A * A2 / A	= B * A2 / A	= C * A2 / A	= D * A2 / A	= P * A2 / A
	Total Steam	**LP pass-out**	**MP pass-out**	**Condenser steam**	**Generation**
Case 1	84.0 t/h	32.4 t/h	25.8 t/h	25.7 t/h	10,767 kW
Case 2	84.0 t/h	32.0 t/h	30.0 t/h	22.0 t/h	10,056 kW
Case 3	84.0 t/h	37.2 t/h	25.1 t/h	21.6 t/h	10,316 kW

Step 3: Determine the kWh/tonne of steam to MP pass-out, LP pass-out and condenser by solving 3 simultaneous equations

$$X * B1 + Y * C1 + Z * D1 = P1$$

$$X * B2 + Y * C2 + Z * D2 = P2$$

$$X * B3 + Y * C3 + Z * D3 = P3$$

X	Y	Z
110.7 kWh/t	47.8 kWh/t	230.9 kWh/t

Step 4: Heat to site per tonne/h of MP and LP pass-out

	Determination	Power loss	Enthalpy	Power loss (ß)
MP power loss	Z-Y	183.1 kWh/t	841 kWh/t	0.218
LP power loss	Z-X	120.2 kWh/t	774 kWh/t	0.155

Annex C

C.1 Sample Determinations

C.1.1 Molten Carbonate Fuel Cell (MCFC) with Back-up Boiler

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set (see Figure 21 — MCFC with Back-up Boiler). In this case the useful heat energy and fuel energy from and to the back-up boiler (FB) can easily be excluded from the energy balance by adding an additional heat meter.

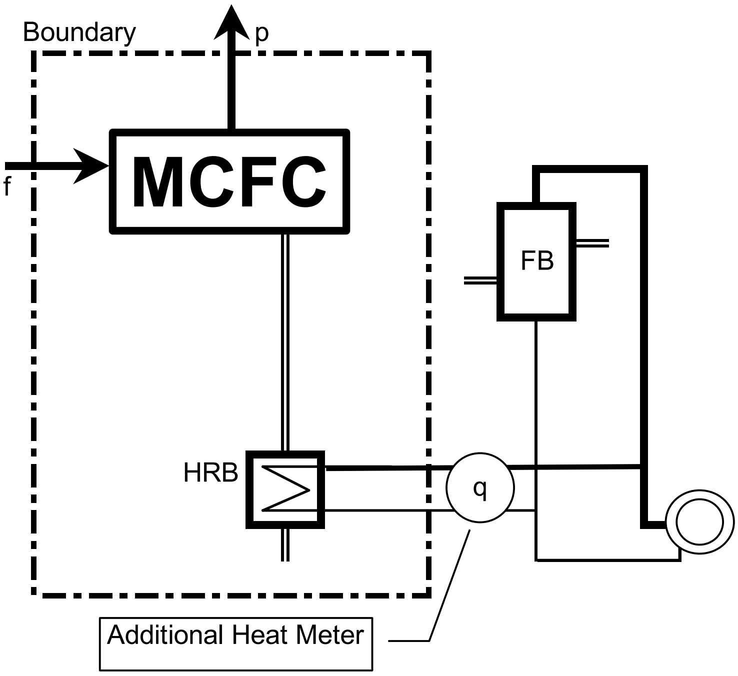

Figure 21 — MCFC with Back-up Boiler

The resulting energy in- and outputs during one year of operation in shown in Figure 22 — MCFC Energy Balance.

Figure 22 — MCFC Energy Balance

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

As the useful heat energy and fuel energy from and to the back-up boiler (FB) are not included in the boundaries and there are no further possibilities to generate non-CHP useful heat. It is a plant without non-CHP useful heat energy generation. Therefore:

$$q_{\text{non-CHP}} = 0$$
$$f_{\text{non-CHP,q}} = 0$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{chp} = q - q_{non-chp} = 624 - 0 = 624\ \text{MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{1{,}200 + 624}{2{,}500 - 0} = 73.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive fuel cells belong to type (h) therefore the threshold is 75%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction does not cause power loss as there is no downstream electricity/mechanical energy generation subsequent to generation of useful heat energy: $\beta_{CHP} = 0.0$

2) Efficiency of non-combined electrical/mechanical energy generation:

$$\eta_{non-chp,p} = \frac{p}{f - f_{non-chp,q}} = \frac{1{,}200}{2{,}500 - 0} = 48.0\%$$

3) Power-to-heat ratio: $\sigma_{chp} = \dfrac{\eta_{non-chp,p}}{\eta_{chp} - \eta_{non-chp,p}} = \dfrac{48.0\%}{75.0\% - 48.0\%} = 1.778$

4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 1.778 \cdot 624 = 1{,}109\ \text{MWh}$

5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 1{,}200 - 1{,}109 = 91\ \text{MWh}$

6) Fuel energy for non-CHP electricity/mechanical energy generation:

$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{91}{48\%} = 189\ \text{MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:

$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 2{,}500 - 348 - 0 = 2{,}311\,\mathrm{MWh}$$

Table 4 — MCFC - CHP and non-CHP Energies (Back-up Boiler Outside Boundary)

		total	CHP	non-CHP,q	non-CHP,p
q	=	624 MWh	624 MWh	0 MWh	-
p	=	1,200 MWh	1,109 MWh	-	91 MWh
f	=	2,500 MWh	2,311 MWh	0 MWh	189 MWh

C.1.2 Gas Turbine with Heat Recovery

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is no non-CHP useful heat energy generation. The energy in- and outputs during one year of operation are those shown in Figure 23 — Gas Turbine with Heat Recovery.

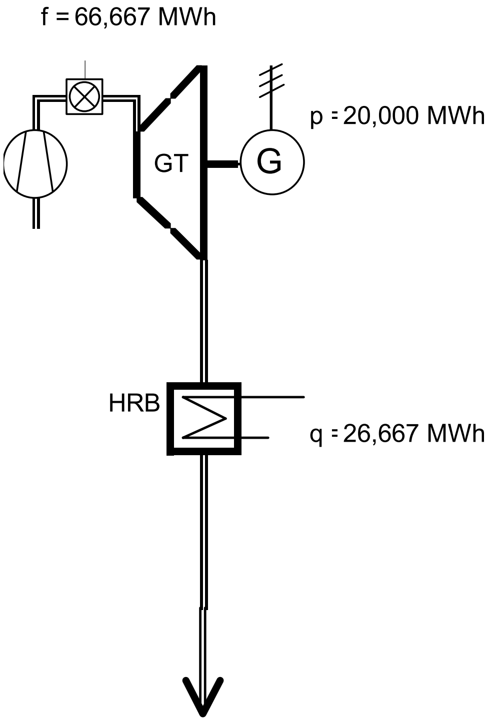

Figure 23 — Gas Turbine with Heat Recovery

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

As there are no possibilities to generate non-CHP useful heat. It is a plant with non-CHP useful heat energy generation. Therefore:

$$q_{\text{non-CHP}} = 0$$
$$f_{\text{non-CHP,q}} = 0$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{chp} = q - q_{non-chp} = 26{,}667 - 0 = 26{,}667 \text{ MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{20{,}000 + 26{,}667}{66{,}667 - 0} = 70.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a gas turbine with heat recovery belongs to type (d) therefore the threshold is 75%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction does not cause power loss as there is no downstream electricity/mechanical energy generation subsequent to generation of useful heat energy: $\beta_{CHP} = 0.0$
2) Efficiency of non-combined electrical/mechanical energy generation:
$$\eta_{non-chp,p} = \frac{p}{f - f_{non-chp,q}} = \frac{20{,}000}{66{,}667 - 0} = 30.0\%$$
3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{30.0\%}{75.0\% - 30.0\%} = 0.667$
4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.667 \cdot 26{,}667 = 17{,}778 \text{ MWh}$
5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 20{,}000 - 17{,}778 = 2{,}222 \text{ MWh}$
6) Fuel energy for non-CHP electricity/mechanical energy generation:
$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{2{,}222}{30\%} = 7{,}407 \text{ MWh}$$
7) Fuel energy for CHP electricity/mechanical energy generation:
$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 66{,}667 - 7{,}407 - 0 = 59{,}259 \text{ MWh}$$

Table 5 —Gas Turbine with Heat Recovery - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	26,667 MWh	26,667 MWh	0 MWh	-
p	=	20,000 MWh	17,778 MWh	-	2,222 MWh
f	=	66,667 MWh	59,259 MWh	0 MWh	7,407 MWh

C.1.3 Steam Backpressure Turbine

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is no non-CHP useful heat energy generation. The energy in- and outputs during one year of operation are those shown in Figure 24 — Steam Backpressure Turbine.

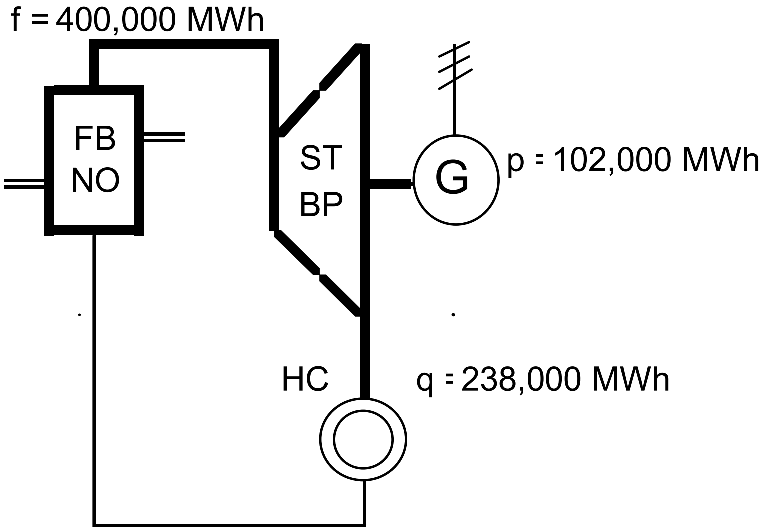

Figure 24 — Steam Backpressure Turbine

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

As there are no possibilities to generate non-CHP useful heat. It is a plant with non-CHP useful heat energy generation. Therefore:

$$q_{\text{non-CHP}} = 0$$
$$f_{\text{non-CHP,q}} = 0$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{chp} = q - q_{non-chp} = 238{,}000 - 0 = 238{,}000\,\text{MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{102{,}000 + 238{,}000}{400{,}000 - 0} = 85.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a steam backpressure turbine belongs to type (b) therefore the threshold is 75%. As the plant exceeds this threshold non-CHP electrical energy generation does not takes place.

$$q_{CHP} = q - q_{non\text{-}CHP} = 238{,}000 \text{ MWh}$$

$$p_{CHP} = p = 102{,}000 \text{ MWh}$$

$$f_{CHP} = f - f_{non\text{-}CHP,q} = 400{,}000 \text{ MWh}$$

Table 6 — Steam Backpressure Turbine - CHP and non-CHP Energies

		total	**CHP**	**non-CHP,q**	**non-CHP,p**
q	=	238,000 MWh	238,000 MWh	-	-
p	=	102,000 MWh	102,000 MWh	-	-
f	=	400,000 MWh	400,000 MWh	-	-

C.1.4 Gas Turbine with Heat Recovery and Supplementary/Auxiliary Firing

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is non-CHP useful heat energy generation caused by auxiliary/supplementary firing. Nevertheless, the non-CHP useful heat energy cannot be measured directly. Therefore it has to be included in the boundaries and excluded by calculation afterwards. The energy in- and outputs during one year of operation are those shown in Figure 25 — Gas Turbine with Heat Recovery and Supplementary/Auxiliary Firing.

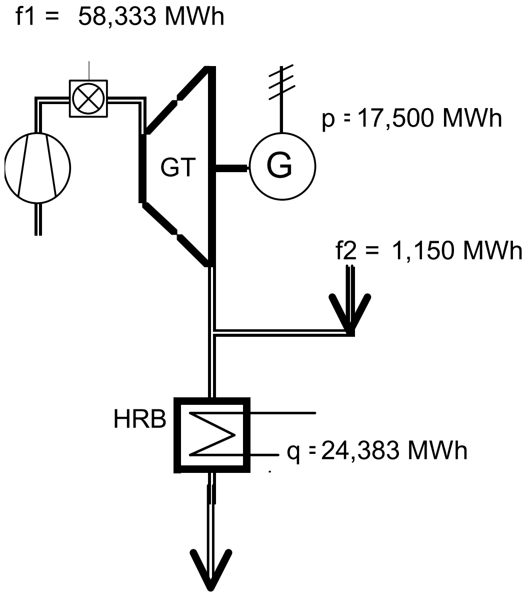

Figure 25 — Gas Turbine with Heat Recovery and Supplementary/Auxiliary Firing

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

The plant has the possibility of non-combined heat generation via supplementary/auxiliary firing. The fuel for non-CHP useful heat generation can be measured directly:

$$f_{\text{non-CHP,q}} = f2 = 1{,}150 \text{ MWh}$$

To determine the referring non-CHP useful heat energy the referring efficiency for non-combined heat generation has to be known (this is the boiler efficiency of the heat recovery steam boiler). The maximum efficiency of the heat recovery boiler of this plant derived from manufacturer's data is assumed to be:

$$\eta_{\text{HRB}} \approx \eta_{\text{non-chp,q}} = 90\%$$

$$q_{\text{non-chp}} = f_{\text{non-chp,q}} \cdot \eta_{\text{non-chp,q}} = 1{,}150 \cdot 90\% = 1{,}035 \text{ MWh} .$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{\text{chp}} = q - q_{\text{non-chp}} = 24{,}383 - 1{,}035 = 23{,}348 \text{ MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{p + q_{chp}}{(f1 + f2) - f_{non-chp,q}} = \frac{17{,}500 + 23{,}348}{59{,}483 - 1{,}150} = 70.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a gas turbine with heat recovery belongs to type (d) therefore the threshold is 75%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction does not cause power loss as there is no downstream electricity/mechanical energy generation subsequent to generation of useful heat energy: $\beta_{CHP} = 0.0$
2) Efficiency of non-combined electrical/mechanical energy generation:
$$\eta_{non-chp,p} = \frac{p}{f - f_{non-chp,q}} = \frac{17{,}500}{59{,}483 - 1{,}150} = 30.0\%$$
3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{30.0\%}{75.0\% - 30.0\%} = 0.667$
4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.667 \cdot 23{,}348 = 15{,}566 \text{ MWh}$
5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 17{,}500 - 15{,}566 = 1{,}934 \text{ MWh}$
6) Fuel energy for non-CHP electricity/mechanical energy generation:
$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{1{,}934}{30\%} = 6{,}448 \text{ MWh}$$
7) Fuel energy for CHP electricity/mechanical energy generation:
$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 59{,}483 - 6{,}448 - 1{,}150 = 51{,}885 \text{ MWh}$$

Table 7 — Gas Turbine with Heat Recovery and Supplementary/Auxiliary Firing - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	24,383 MWh	23,348 MWh	1,035 MWh	-
p	=	17,500 MWh	15,566 MWh	-	1,934 MWh
f	=	59,483 MWh	51,885 MWh	1,150 MWh	6,448 MWh

C.1.5 Combined Cycle Gas Turbine with Heat Recovery and Supplementary Firing

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is non-CHP useful heat energy generation caused by auxiliary/supplementary firing. Nevertheless, the non-CHP useful heat energy cannot be measured directly. Therefore it has to be included in the boundaries and excluded by calculation afterwards. The energy in- and outputs during one year of operation are those shown in Figure 26 — Combined Cycle with Heat Recovery and Supplementary Firing.

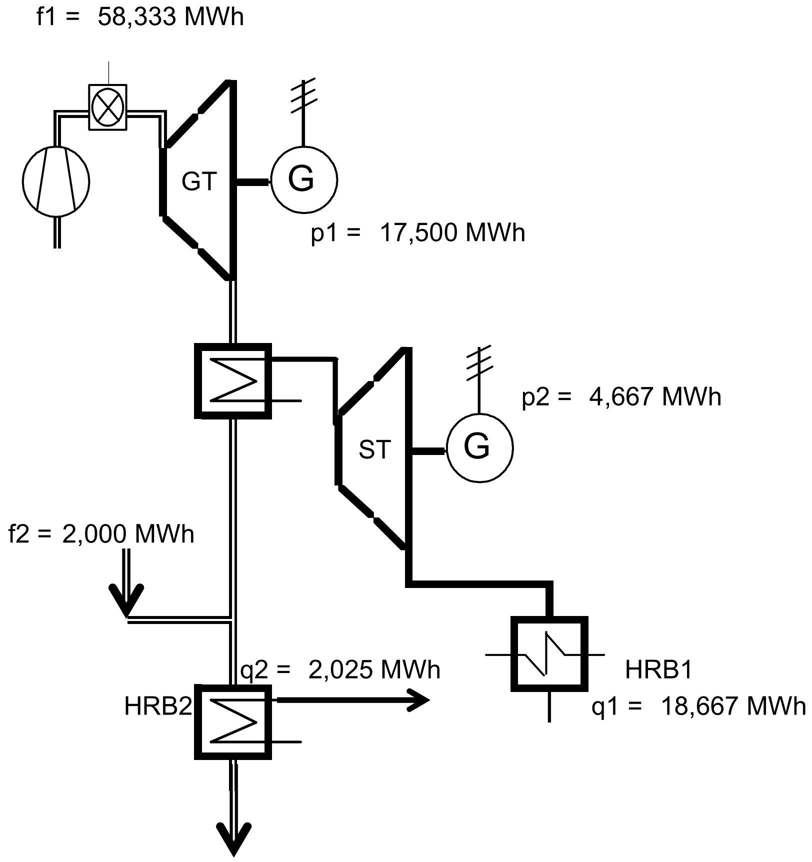

Figure 26 — Combined Cycle with Heat Recovery and Supplementary Firing

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

The plant has the possibility of non-combined heat generation via supplementary/auxiliary firing. The fuel for non-CHP useful heat generation can be measured directly:

$$f_{\text{non-CHP,q}} = f2 = 2{,}000 \text{ MWh}$$

To determine the referring non-CHP useful heat energy the referring efficiency for non-combined heat generation has to be known (this is the boiler efficiency of the heat recovery steam boiler). The maximum efficiency of the heat recovery boiler 2 of this plant derived from manufacturer's data is assumed to be:

$$\eta_{\text{HRB2}} \approx \eta_{\text{non-chp,q}} = 90\%$$

$$q_{non-chp} = f_{non-chp,q} \cdot \eta_{non-chp,q} = 2{,}000 \cdot 90\% = 1{,}800\ \text{MWh}\ .$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{chp} = q - q_{non-chp} = 20{,}692 - 1{,}800 = 18{,}892\ \text{MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{p + q_{chp}}{(f1 + f2) - f_{non-chp,q}} = \frac{22{,}167 + 18{,}892}{60{,}333 - 2{,}000} = 70.4\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a combined cycle gas turbine with heat recovery belongs to type (a) therefore the threshold is 80%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction does not cause power loss, in this back-pressure steam turbine, as there is no downstream electricity/mechanical energy generation subsequent to generation of useful heat energy: $\beta_{CHP} = 0.0$

2) Efficiency of non-combined electrical/mechanical energy generation:

$$\eta_{non-chp,p} = \frac{p}{f - f_{non-chp,q}} = \frac{22{,}167}{60{,}333 - 2{,}000} = 38.0\%$$

3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{38.0\%}{80.0\% - 38.0\%} = 0.905$

4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.905 \cdot 18{,}892 = 17{,}092\ \text{MWh}$

5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 22{,}167 - 17{,}092 = 5{,}074\ \text{MWh}$

6) Fuel energy for non-CHP electricity/mechanical energy generation:

$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{5{,}074}{38\%} = 13{,}353\ \text{MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:

$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 60{,}333 - 13{,}353 - 2{,}000 = 44{,}980\ \text{MWh}$$

Table 8 — Combined Cycle with Heat Recovery and Supplementary/Auxiliary Firing - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	20,692 MWh	18,892 MWh	1,800 MWh	-
p	=	22,167 MWh	17,092 MWh	-	5,074 MWh
f	=	60,333 MWh	44,980 MWh	2,000 MWh	13,353 MWh

C.1.6 Gas Turbine with Heat Recovery and Bypass Facility

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is no non-CHP useful heat energy generation. The energy in- and outputs during one year of operation are those shown in Figure 27 — Gas Turbine with Heat Recovery and Bypass Facility.

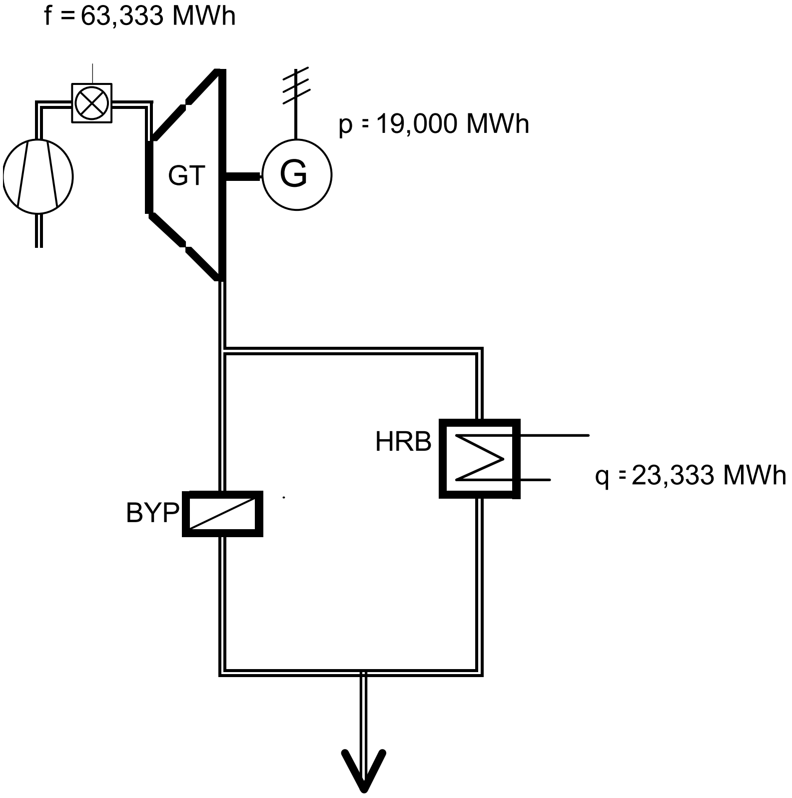

Figure 27 — Gas Turbine with Heat Recovery and Bypass Facility

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

As there are no possibilities to generate non-CHP useful heat. It is a plant without non-CHP useful heat energy generation. Therefore:

$$q_{\text{non-CHP}} = 0$$
$$f_{\text{non-CHP,q}} = 0$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{\text{chp}} = q - q_{\text{non-chp}} = 23{,}333 - 0 = 23{,}333\ \text{MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{19{,}000 + 23{,}333}{63{,}333 - 0} = 66.8\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex **II** a) of the CHP-Directive.

According to Annex **I** of the CHP Directive a gas turbine with heat recovery belongs to type (d) therefore the threshold is 75%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction does not cause power loss as there is no downstream electricity/mechanical energy generation subsequent to generation of useful heat energy: $\beta_{CHP} = 0.0$
2) Efficiency of non-combined electrical/mechanical energy generation:
$$\eta_{non-chp,p} = \frac{p}{f - f_{non-chp,q}} = \frac{19{,}000}{63{,}333 - 0} = 30.0\%$$
3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{30.0\%}{75.0\% - 30.0\%} = 0.667$
4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.667 \cdot 23{,}333 = 15{,}556\ \text{MWh}$
5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 19{,}000 - 15{,}556 = 3{,}444\ \text{MWh}$
6) Fuel energy for non-CHP electricity/mechanical energy generation:
$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{3{,}444}{30\%} = 11{,}481\ \text{MWh}$$
7) Fuel energy for CHP electricity/mechanical energy generation:
$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 63{,}333 - 11{,}481 - 0 = 51{,}852\ \text{MWh}$$

Table 9 —Gas Turbine with Heat Recovery and Bypass Facility - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	23,333 MWh	23,333 MWh	0 MWh	-
p	=	19,000 MWh	15,556 MWh	-	3,444 MWh
f	=	63,333 MWh	51,852 MWh	0 MWh	11,481 MWh

C.1.7 Gas Turbine with Heat Recovery, Bypass Facility and Supplementary/Auxiliary Firing

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is non-CHP useful heat energy generation caused by auxiliary/supplementary firing. Nevertheless, the non-CHP useful heat energy cannot be measured directly. Therefore it has to be included in the boundaries and excluded by calculation afterwards. The energy in- and outputs during one year of operation are those shown in Figure 28 — Gas Turbine with Heat Recover, Bypass Facility and Supplementary/Auxiliary Firing.

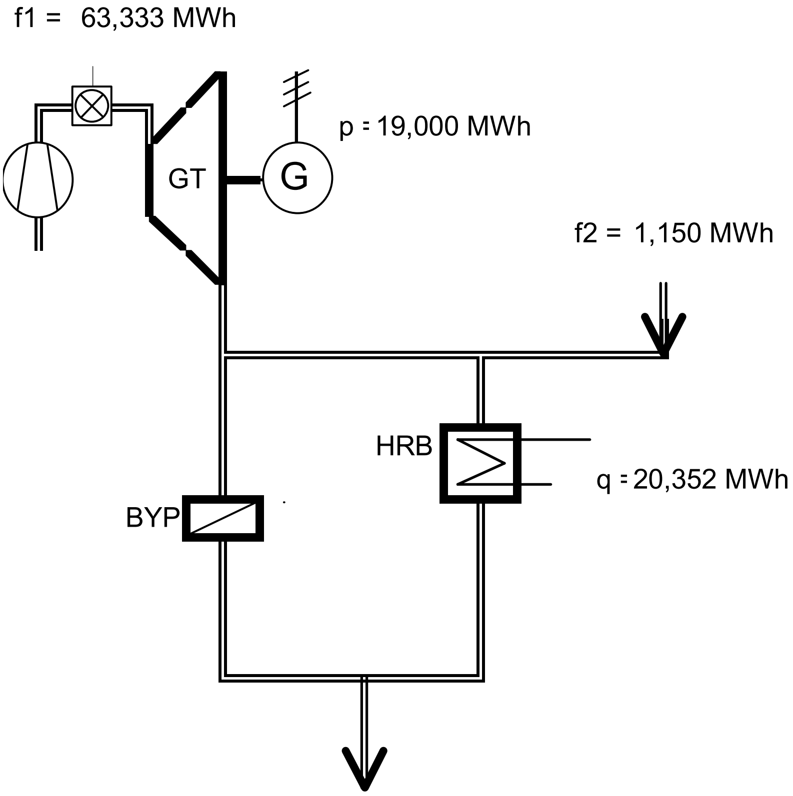

Figure 28 — Gas Turbine with Heat Recover, Bypass Facility and Supplementary/Auxiliary Firing

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

The plant has the possibility of non-combined heat generation via supplementary/auxiliary firing. The fuel for non-CHP useful heat generation can be measured directly:

$$f_{\text{non-CHP,q}} = f2 = 1{,}150 \text{ MWh}$$

To determine the referring non-CHP useful heat energy the referring efficiency for non-combined heat generation has to be known (this is the boiler efficiency of the heat recovery steam boiler). The maximum efficiency of the heat recovery boiler of this plant derived from manufacturer's data is assumed to be:

$$\eta_{\text{HRB}} \approx \eta_{\text{non-chp,q}} = 90\%$$

$$q_{\text{non-chp}} = f_{\text{non-chp,q}} \cdot \eta_{\text{non-chp,q}} = 1{,}150 \cdot 90\% = 1{,}035 \text{ MWh}.$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{chp} = q - q_{non-chp} = 20{,}352 - 1{,}035 = 19{,}317\ \text{MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{p + q_{chp}}{(f1 + f2) - f_{non-chp,q}} = \frac{19{,}000 + 19{,}317}{64{,}483 - 1{,}150} = 60.5\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a gas turbine with heat recovery belongs to type (d) therefore the threshold is 75%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction does not cause power loss, in the gas turbine, as there is no downstream electricity/mechanical energy generation subsequent to generation of useful heat energy: $\beta_{CHP} = 0.0$

2) Efficiency of non-combined electrical/mechanical energy generation:
$$\eta_{non-chp,p} = \frac{p}{f - f_{non-chp,q}} = \frac{19{,}000}{64{,}483 - 1{,}150} = 30.0\%$$

3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{30.0\%}{75.0\% - 30.0\%} = 0.667$

4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.667 \cdot 19{,}317 = 12{,}878\ \text{MWh}$

5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 19{,}000 - 12{,}878 = 6{,}122\ \text{MWh}$

6) Fuel energy for non-CHP electricity/mechanical energy generation:
$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{6{,}122}{30\%} = 20{,}407\ \text{MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:
$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 64{,}483 - 20{,}407 - 1{,}150 = 42{,}926\ \text{MWh}$$

Table 10 — Gas Turbine with Heat Recover, Bypass Facility and Supplementary/Auxiliary Firing - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	20,352 MWh	19,317 MWh	1,035 MWh	-
p	=	19,000 MWh	12,878 MWh	-	6,122 MWh
f	=	64,483 MWh	42,926 MWh	1,150 MWh	20,407 MWh

C.1.8 Combined Cycle Gas Turbine with Heat Recovery, Bypass Facility and Auxiliary Firing

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is non-CHP useful heat energy generation caused by auxiliary/supplementary firing (f3). Nevertheless, the non-CHP useful heat energy cannot be measured directly. Therefore it has to be included in the boundaries and excluded by calculation afterwards. The energy in- and outputs during one year of operation are those shown in Figure 29 — Combined Cycle Gas Turbine with Heat Recovery, Bypass Facility and Auxiliary Firing.

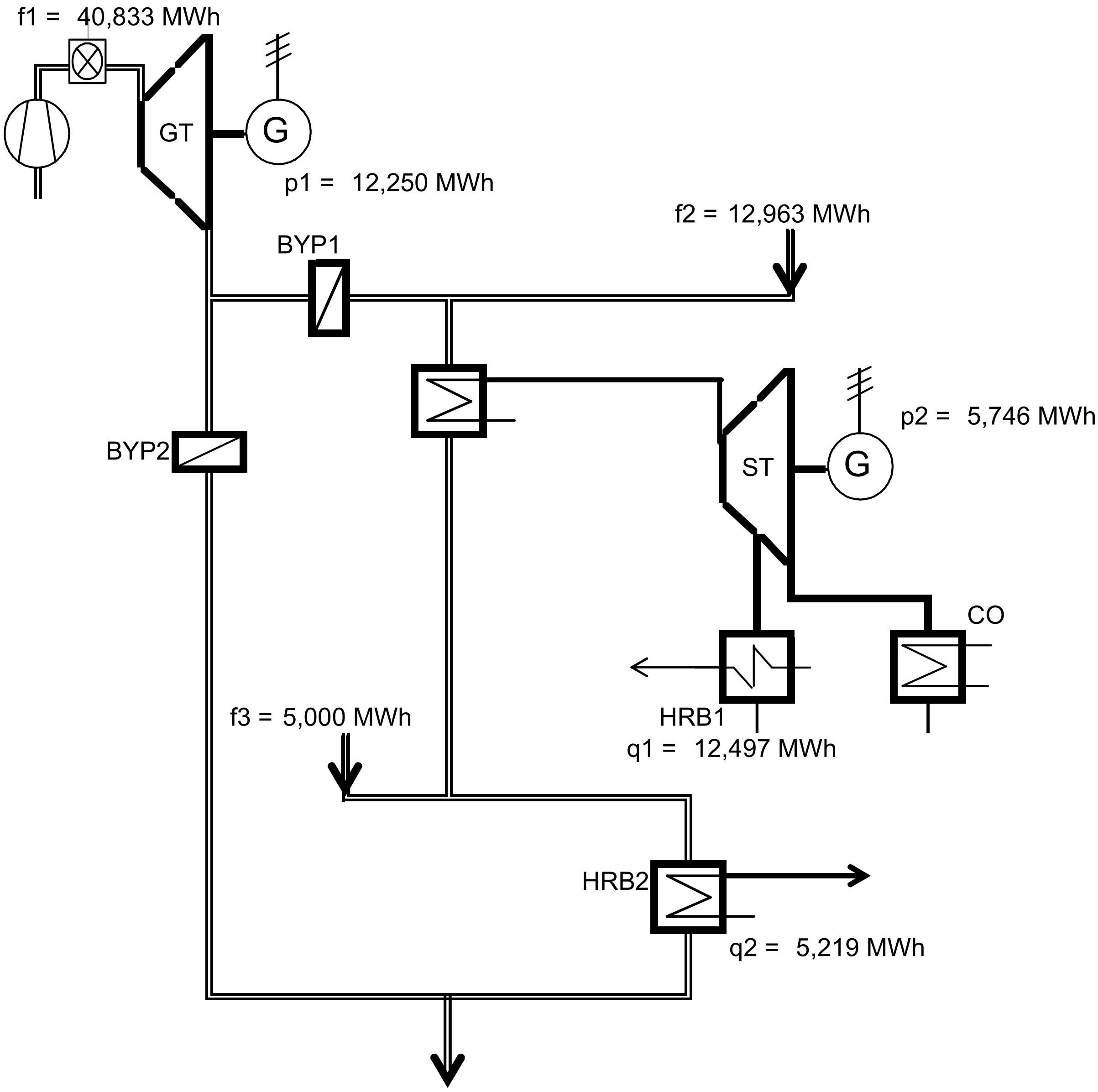

Figure 29 — Combined Cycle Gas Turbine with Heat Recovery, Bypass Facility and Auxiliary Firing

$$f = f_{CHP} + f_{non\text{-}CHP,p} + f_{non\text{-}CHP,q} = f1 + f2 + f3 = 40{,}833 + 12{,}963 + 5{,}000 = 58{,}796 \text{ MWh}$$

$$p = p_{CHP} + p_{non\text{-}CHP} = p1 + p2 = 12{,}250 + 5{,}746 = 17{,}996 \text{ MWh}$$

$$q = q_{\text{non-CHP}} + q_{\text{CHP}} = q1 + q2 = 12{,}497 + 5{,}219 = 17{,}716\ \text{MWh}$$

It must be noted that the plant may be able to operate in different configurations. For example

1) Without Steam Turbine (Gas Turbine Only)
2) Without Gas Turbine (Steam Turbine Only)
3) Without Gas and Steam Turbine (Heat Only)

If this would be the case the energy in- and outputs for these operations modes have to be determined separately. Moreover calculations have to be carried out for these operation modes separately.

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

The plant has the possibility of non-combined heat generation via supplementary/auxiliary firing (f3). The fuel for non-CHP useful heat generation can be measured directly:

$$f_{\text{non-CHP,q}} = f3 = 5{,}000\ \text{MWh}$$

To determine the referring non-CHP useful heat energy the referring efficiency for non-combined heat generation has to be known (this is the boiler efficiency of the heat recovery steam boiler). The maximum efficiency of the heat recovery boiler 2 (HRB2) of this plant derived from manufacturer's data is assumed to be:

$$\eta_{\text{HRB2}} \approx \eta_{\text{non-chp,q}} = 90\%$$

$$q_{\text{non-chp}} = f_{\text{non-chp,q}} \cdot \eta_{\text{non-chp,q}} = 5{,}000 \cdot 90\% = 4{,}500\ \text{MWh}\ .$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{\text{chp}} = q - q_{\text{non-chp}} = 17{,}716 - 4{,}500 = 13{,}216\ \text{MWh}$.

The overall efficiency is:

$$\eta = \frac{p + q_{\text{chp}}}{f - f_{\text{non-chp,q}}} = \frac{17{,}996 + 13{,}216}{58{,}796 - 5{,}000} = 58.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a combined cycle gas turbine with heat recovery belongs to type (a) therefore the threshold is 80%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction from the steam turbine (ST) by the heat recovery boiler 1 (HRB 1) does cause power loss. The power loss coefficient has been determined by performance tests as follows: $\beta_{CHP} = 0.115$.

2) Efficiency of non-combined electrical/mechanical energy generation (in this case, the power loss concerns the extraction from the turbine. The heat generated in HRB2 has no effect on power generation in the ST):

$$\eta_{non-chp,p} = \frac{p + \beta \cdot q_{chp}}{f - f_{non-chp,q}} = \frac{17{,}996 + 0.115 \cdot 13{,}216}{58{,}796 - 5{,}000} = 36.3\%$$

3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p} - \beta \cdot \eta_{chp}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{36.3\% - 0.115 \cdot 80.0\%}{80.0\% - 36.3\%} = 0.619$

4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.619 \cdot 13{,}216 = 8{,}183\ \text{MWh}$

5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 17{,}996 - 8{,}183 = 9{,}813\ \text{MWh}$

6) Fuel energy for non-CHP electricity/mechanical energy generation:

$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{9{,}813}{36.3\%} = 27{,}048\ \text{MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:

$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 58{,}796 - 27{,}048 - 5{,}000 = 26{,}748\ \text{MWh}$$

Table 11 — Combined Cycle Gas Turbine with Heat Recovery, Bypass Facility and Auxiliary Firing - CHP and non-CHP Energies

		total	**CHP**	**non-CHP,q**	**non-CHP,p**
q	=	17,716 MWh	13,216 MWh	4,500 MWh	-
p	=	17,996 MWh	8,183 MWh	-	9,813 MWh
f	=	58,796 MWh	26,748 MWh	5,000 MWh	27,048 MWh

C.1.9 Steam Condensing Extraction Turbine with Live Steam Extraction

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is non-CHP useful heat energy generation caused by live steam extraction. Nevertheless, the fuel energy for generation of non-CHP useful heat energy cannot be measured directly. Therefore it has to be included in the boundaries and excluded by calculation afterwards. The energy in- and outputs during one year of operation are those shown in Figure 30 — Steam Condensing Extraction Turbine with Live Steam Extraction.

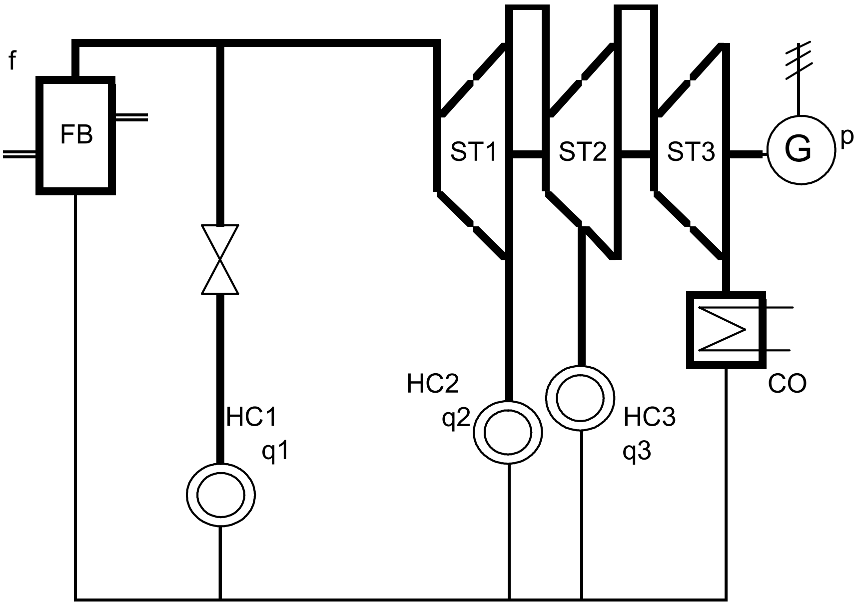

Figure 30 — Steam Condensing Extraction Turbine with Live Steam Extraction

$$f = f_{CHP} + f_{non\text{-}CHP,p} + f_{non\text{-}CHP,q} = f = 911{,}111 \text{ MWh}$$

$$p = p_{CHP} + p_{non\text{-}CHP} = p = 200{,}000 \text{ MWh}$$

$$q = q_{non\text{-}CHP} + q_{CHP} = q1 + q2 + q3 = 100{,}000 + 100{,}000 + 50{,}000 = 250{,}000 \text{ MWh}$$

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

The plant has the possibility of non-combined heat generation via live steam extraction. The non-CHP useful heat energy can be measured directly:

$$q_{non\text{-}CHP} = q1 = 100{,}000 \text{ MWh}$$

To determine the referring non-CHP fuel energy the referring efficiency for non-combined heat generation has to be known (this is the boiler efficiency of the boiler). The maximum efficiency of the boiler of this plant derived from manufacturer's data is assumed to be:

$$\eta_{FB} \approx \eta_{non-chp,q} = 90\%$$

$f_{\text{non-CHP,q}} = q_{\text{non-CHP}} / \eta_{\text{non-CHP,q}}$ = 100,000 / 90% = 111,111 MWh.

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{\text{CHP}} = q - q_{\text{non-CHP}} = q - q1$ = 150,000 MWh

Fuel for generation of CHP and non-CHP electrical/mechanical energy:

$$f_{\text{CHP}} + f_{\text{non-CHP,p}} = f - f_{\text{non-CHP,q}} = 911{,}111 - 111{,}111 = 800{,}000 \text{ MWh}$$

The overall efficiency is:

$$\eta = \frac{p + q_{\text{chp}}}{f - f_{\text{non-chp,q}}} = \frac{200{,}000 + 150{,}000}{911{,}111 - 111{,}111} = 43.8\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a steam condensing extraction turbine belongs to type (c) therefore the threshold is 80%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction causes power loss. The power loss coefficients have been determined by performance tests as follows: $\beta_{\text{CHP,2}}$ = 0.250, $\beta_{\text{CHP,3}}$ = 0.200. The mean power loss is:
$$\beta_{\text{CHP}} = \frac{\sum_{i=1}^{n} \beta_{\text{CHP,n}} \cdot q_{\text{chp,n}}}{q_{\text{chp}}} = \frac{50 \cdot 0.200 + 100 \cdot 0.250}{150} = 0.233$$

2) Efficiency of non-combined electrical/mechanical energy generation:
$$\eta_{\text{non-chp,p}} = \frac{p + \beta_{\text{CHP}} \cdot q_{\text{chp}}}{f_{\text{chp}} + f_{\text{non-chp,p}}} = \frac{200{,}000 + 0.233 \cdot 150{,}000}{800{,}000} = 29.4\%$$

3) Power-to-heat ratio: $\sigma_{\text{chp}} = \frac{\eta_{\text{non-chp,p}} - \beta \cdot \eta_{\text{chp}}}{\eta_{\text{chp}} - \eta_{\text{non-chp,p}}} = \frac{29.4\% - 0.233 \cdot 80\%}{80.0\% - 29.4\%} = 0.212$

4) CHP electricity/mechanical energy: $p_{\text{chp}} = \sigma_{\text{chp}} \cdot q_{\text{chp}} = 0.212 \cdot 150{,}000 = 31{,}728 \text{ MWh}$

5) Non-CHP electricity/mechanical energy:
$$p_{\text{non-chp}} = p - p_{\text{chp}} = 200{,}000 - 31{,}728 = 168{,}272 \text{ MWh}$$

6) Fuel energy for non-CHP electricity/mechanical energy generation:
$$f_{\text{non-chp,p}} = \frac{p_{\text{non-chp}}}{\eta_{\text{non-chp,p}}} = \frac{168{,}272}{29.4\%} = 572{,}840 \text{ MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:

$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 911{,}111 - 572{,}840 - 111{,}111 = 227{,}160 \text{ MWh}$$

Table 12 — Steam Condensing Extraction Turbine with Live Steam Extraction - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	250,000 MWh	150,000 MWh	100,000 MWh	-
p	=	200,000 MWh	31,728 MWh	-	168,272 MWh
f	=	911,111 MWh	227,160 MWh	111,111 MWh	572,840 MWh

C.1.10 Steam Condensing Extraction Turbine with Heat Recovery from Flue Gas

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case there is no non-CHP useful heat energy generation. The energy in- and outputs during one year of operation are those shown in Figure 31 — Steam Condensing Extraction Turbine with Heat Recovery from Flue Gas.

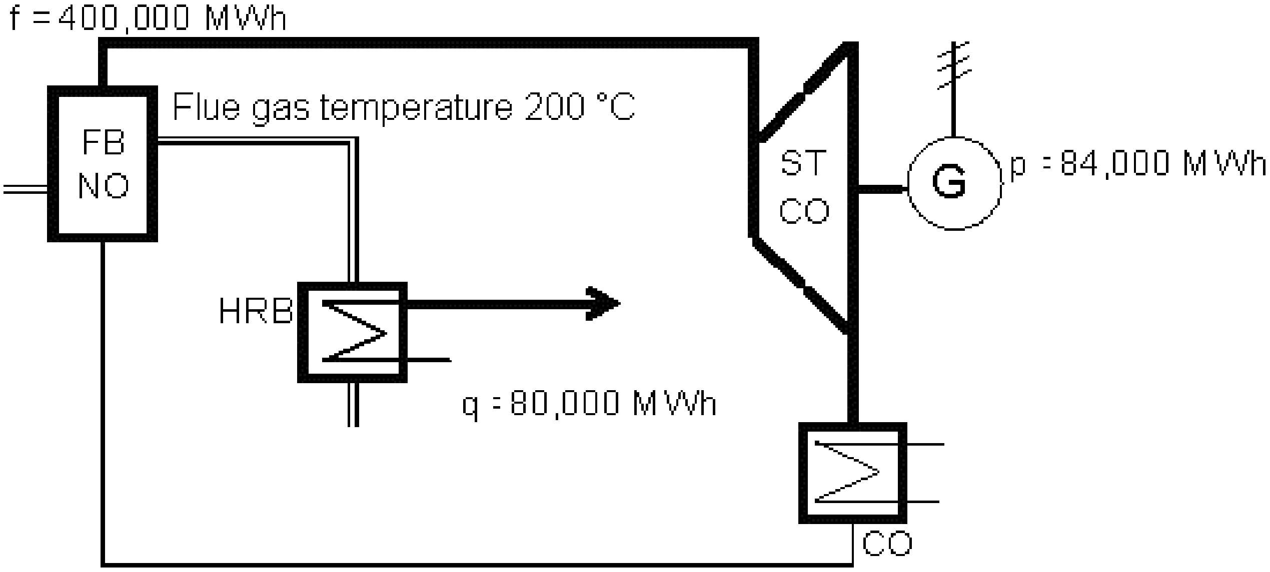

Figure 31 — Steam Condensing Extraction Turbine with Heat Recovery from Flue Gas

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

As there are no possibilities to generate non-CHP useful heat. It is a plant without non-CHP useful heat energy generation. Therefore:

$$q_{\text{non-CHP}} = 0$$
$$f_{\text{non-CHP,q}} = 0$$

Step 3: Determine overall efficiency

The plant does not have the possibility of non-combined heat generation, therefore the total useful heat is CHP useful heat energy: $q_{CHP} = q = 80{,}000$ MWh

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{84{,}000 + 80{,}000}{400{,}000 - 0} = 41.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a steam condensing extraction turbine belongs to type (c) therefore the threshold is 80%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction causes power loss, due to additional steam required for combustion air preheating (in power plant without combustion air preheating by means of steam extraction the power loss may be zero). The power loss coefficient has been determined by performance tests in this case as follows: $\beta_{CHP} = 0.200$.

2) Efficiency of non-combined electrical/mechanical energy generation:

$$\eta_{non-chp,p} = \frac{p + \beta_{CHP} \cdot q_{chp}}{f_{chp} + f_{non-chp,p}} = \frac{84{,}000 + 0.200 \cdot 80{,}000}{400{,}000} = 25.0\%$$

3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p} - \beta \cdot \eta_{chp}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{25.0\% - 0.200 \cdot 80.0\%}{80.0\% - 25.0\%} = 0.164$

4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.164 \cdot 80{,}000 = 13{,}091\,\text{MWh}$

5) Non-CHP electricity/mechanical energy: $p_{non-chp} = p - p_{chp} = 84{,}000 - 13{,}091 = 70{,}909\ \text{MWh}$

6) Fuel energy for non-CHP electricity/mechanical energy generation:

$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{70{,}909}{25.0\%} = 283{,}636\ \text{MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:

$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 400{,}000 - 283{,}636 - 0 = 116{,}364\ \text{MWh}$$

Table 13 — Steam Condensing Extraction Turbine with Heat Recovery from Flue Gas Extraction - CHP and non-CHP Energies

		total	Chp	non-CHP,q	non-CHP,p
q	=	80,000 MWh	80,000 MWh	-	-
p	=	84,000 MWh	13,091 MWh	-	70,909 MWh
f	=	400,000 MWh	116,364 MWh	-	283,636 MWh

C.1.11 Combined Cycle with Complex Common Steam Header

Step 1: Determine energy in- and outputs

To determine the energy in- and outputs first of all the right boundaries have to be set. In this case non-CHP useful heat energy generation is possible. Nevertheless, neither the fuel energy for generation of non-CHP useful heat energy nor the non-CHP useful heat energy can be measured directly. Therefore it has to be included in the boundaries and excluded by calculation afterwards. The energy in- and outputs during one year of operation are those shown in Figure 32 — Common Steam Header.

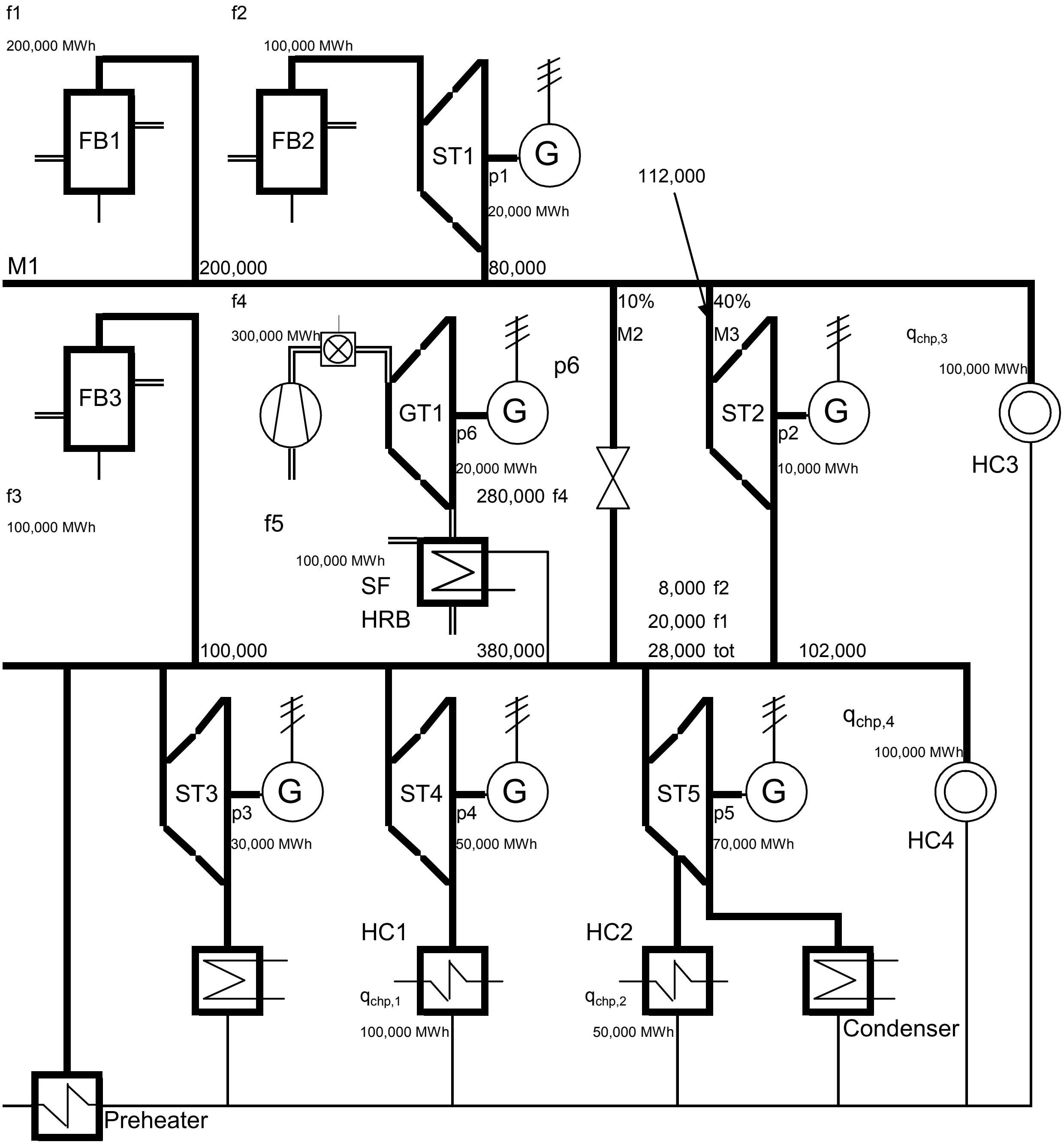

Figure 32 — Common Steam Header

Total useful heat energy:

q = q1 + q2 + q3 + q4 = 100,000 + 50,000 + 100,000 + 100,000 = 350,000 MWh

Total electrical/mechanical energy:

p = p1 + p2 + p3 + p4 + p5 + p6 = 20,000 + 10,000 + 30,000 + 50,000 + 70,000 + 20,000 = 200,000 MWh

Total fuel energy:

f = f1 + f2 + f3 + f4 + f5 = 200,000 + 100,000 + 100,000 + 300,000 + 100,000= 800,000 MWh

Step 2: Determination of NON-CHP Useful Heat Energy and Referring Fuel Energy

Non-CHP useful heat energy can be generated in HC3 and HC4. The fuel energy is supplied in FB1, FB3 and FB5. For determination of non-CHP useful heat energy and the referring fuel energy three additional mass flow meters (M1, M2 and M3) have to be installed. Together with the approaches explained in section 7.3 the non-CHP useful heat can be determined as follows:

$$q_{non-chp,3} = q3 \cdot \frac{200{,}000}{200{,}000 + 80{,}000} = 100{,}000 \cdot 0.71 = 71{,}429 \text{ MWh}$$

The non-CHP useful heat energy for HC4 is determined in a similar way (see also Figure 32 — Common Steam Header), leading to:

Table 14 — Common Steam Header - Non-CHP useful Heat Energy and Fuel Source

Heat	non-CHP share	Energy in MWh	Fuel Source
3	0.71	71,429	1
4	0.03	3,279	1
4	0.16	16,393	3
4	0.16	16,393	5
sum		107,494	

As a consequence the non-CHP useful heat energy is:

$$q_{non\text{-}CHP} = q_{non\text{-}CHP,3} + q_{non\text{-}CHP,4} = 71{,}429 + 36{,}066 = 107{,}494 \text{ MWh}$$

To determine the referring non-CHP fuel energy the referring efficiency for non-combined heat generation has to be applied. The efficiency for non-combined heat generation is assumed to be:

$$\eta_{non-chp,q} = 90\%$$

$$f_{non\text{-}CHP,q} = q_{non\text{-}CHP} / \eta_{non\text{-}CHP,q} = 107{,}494 / 90\% = 119{,}438 \text{ MWh.}$$

Step 3: Determine overall efficiency

CHP useful heat energy: $q_{CHP} = q - q_{non\text{-}CHP}$ = 350,000 – 107,494 = 242,506 MWh

Fuel for generation of CHP and non-CHP electrical/mechanical energy:

$$f_{CHP} + f_{non\text{-}CHP,p} = f - f_{non\text{-}CHP,q} = 800{,}000 - 119{,}438 = 680{,}562 \text{ MWh}$$

The overall efficiency is:

$$\eta = \frac{p + q_{chp}}{f - f_{non-chp,q}} = \frac{200{,}000 + 242{,}506}{800{,}00 - 119{,}438} = 65.0\%$$

The determined overall efficiency (η) has to be compared with the value(s) in Annex II a) of the CHP-Directive.

According to Annex I of the CHP Directive a steam condensing extraction turbine belongs to type (c) therefore the threshold is 80%. As the plant runs short of this threshold non-CHP electrical energy generation takes place and has to be determined.

Step 4: Determination of NON-CHP Electrical/Mechanical Energy and the Referring Fuel Energy

1) Heat extraction causes power loss. The power loss coefficients have been determined by performance tests as follows: $\beta_{CHP,1} = \beta_{CHP,2} = 0.200$, $\beta_{CHP,3} = 0.300$, $\beta_{CHP,4} = 0.250$. The mean power loss is:

$$\beta_{CHP} = \frac{\sum_{i=1}^{n} \beta_{CHP,n} \cdot q_{chp,n}}{q_{chp}} = \frac{(100{,}000 + 50{,}000) \cdot 0.20 + 28{,}571 \cdot 0.30 + 63{,}934 \cdot 0.25}{242{,}506} = 0.225$$

2) Efficiency of non-combined electrical/mechanical energy generation:

$$\eta_{non-chp,p} = \frac{p + \beta_{CHP} \cdot q_{chp}}{f_{chp} + f_{non-chp,p}} = \frac{200{,}000 + 0.225 \cdot 242{,}506}{800{,}000 - 119{,}438} = 37.4\%$$

3) Power-to-heat ratio: $\sigma_{chp} = \frac{\eta_{non-chp,p} - \beta \cdot \eta_{chp}}{\eta_{chp} - \eta_{non-chp,p}} = \frac{37.4\% - 0.225 \cdot 80\%}{80.0\% - 37.4\%} = 0.456$

4) CHP electricity/mechanical energy: $p_{chp} = \sigma_{chp} \cdot q_{chp} = 0.456 \cdot 242{,}506 = 110{,}484 \text{ MWh}$

5) Non-CHP electricity/mechanical energy:

$$p_{non-chp} = p - p_{chp} = 200{,}000 - 110{,}484 = 89{,}516 \text{ MWh}$$

6) Fuel energy for non-CHP electricity/mechanical energy generation:

$$f_{non-chp,p} = \frac{p_{non-chp}}{\eta_{non-chp,p}} = \frac{89{,}516}{37.4\%} = 239{,}325 \text{ MWh}$$

7) Fuel energy for CHP electricity/mechanical energy generation:

$$f_{chp} = f - f_{non-chp,p} - f_{non-chp,q} = 800{,}000 - 239{,}325 - 119{,}438 = 441{,}237 \text{ MWh}$$

Table 15 — Common Steam Header - CHP and non-CHP Energies

		total	CHP	non-CHP,q	non-CHP,p
q	=	350,000 MWh	242,506 MWh	107,494 MWh	-
p	=	200,000 MWh	110,484 MWh	-	89,516 MWh
f	=	800,000 MWh	441,237 MWh	119,438 MWh	239,325 MWh

C.2 CHP Plant Descriptions

A CHP Scheme Line Diagram showing the CHP plant and its relationship to the site as a whole is required. The diagram should include all the main plant items that lie within the CHP plant boundary, their interconnections, and piping and cables carrying fuel and energy inputs, power and heat outputs (steam, hot water and exhaust gas, as applicable). All lines should clearly indicate the fluid or service carried. In the case of steam and hot water, the notation should include the working pressure and temperature.

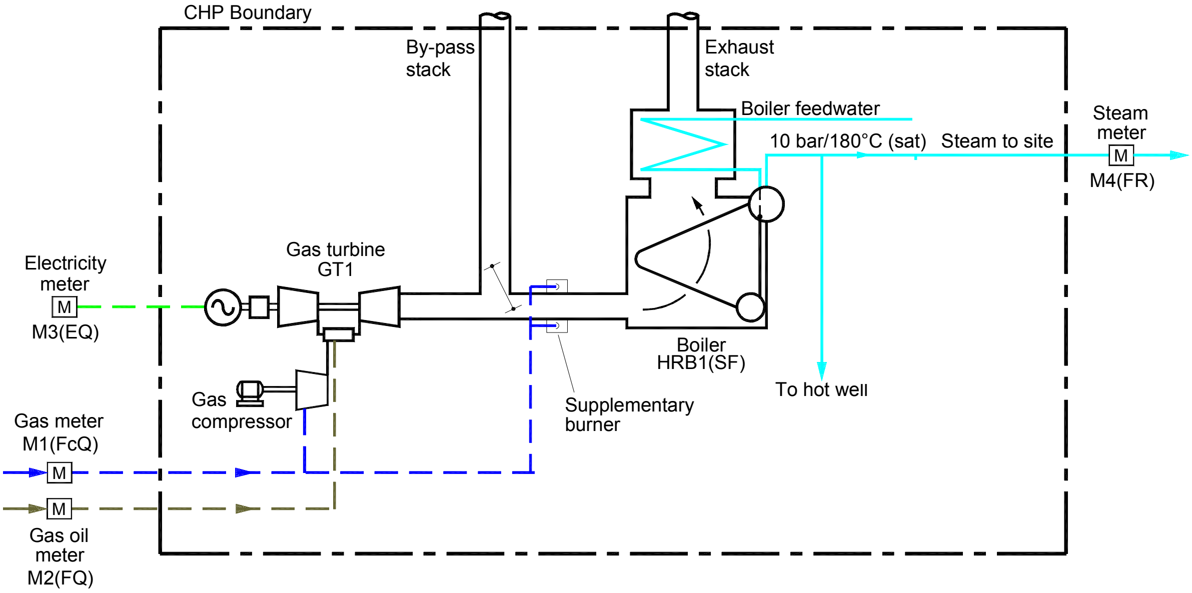

Figure 33 — CHP Scheme Line Diagram

All main equipment items and metering stations should be identified on the CHP Scheme Line Diagram with simple Tag Numbers. Equipment Tags should consist of a simple prefix (as indicated below) followed by a number, e.g. GT1, GT2, ST1, HRB1. Where appropriate a suffix indicating the sub-type of machine should be added, e.g. ST1 (CO), ST2 (PO/CO), RE1 (G), RE2 (DF). Similarly, Meter Tags should be M1(FcQ), M2 (TR) etc.

Table 16 — Suggested Tag Notation

Prefix	Equipment type	Suffix	Sub-type
BYP	Bypass facility		
GT	Gas turbine		
RE	Reciprocating engine	(G)	Gas engine
		(D)	Diesel engine
		(DF)	Dual fuel
		(HFO)	Heavy fuel oil
ST	Steam turbine	(BP)	Back pressure
		(PO)	Pass-out
		(PI)	Pass-in
		(CO)	Condensing
HRB	Heat recovery boiler	(S)	Steam
		(W)	Hot water
		(SF)	Supplementary firing
		(AF)	Auxiliary firing
FB	Fired boiler	(NO)	Normally operating
		(HS)	Hot standby
		(CS)	Cold standby
M	Metering station	(F)	Flow / (Fc) flow (corrected)
		(E)	Electric Power
		(H)	Heat
		(T)	Temperature
		(P)	Pressure
		(An)	Analyser
		(I)	Indicator
		(R)	Recorder
		(W)	Weight
		(Q)	Totaliser
HC	Heat consumer		

C.3 CHP Plant Monitoring

CHP Schemes should measure and monitor to the specified standard of accuracy all fuel and energy inputs, and power and heat outputs.

It is recognised that where a heat output is not sold, e.g. heat supplied to site, it is often not monitored. In such cases, monitoring should be installed for the purposes of this CWA. Where inadequate, or no meters are in place an estimate of steam/heat flow based on indirect methods is acceptable.

Some CHP inputs and outputs cannot be metered directly. Examples include fuels of variable calorific value, the use of exhaust gases for drying, and mechanical outputs from prime movers or subsidiary steam turbine drives.

- Refer to 6.2.3 for guidance on indirect determination of energy inputs.

C.3.1 General Metering Requirements

An appropriate level of metering is nothing more than good practice, in terms of monitoring and improving CHP Scheme performance (see Figure 19 — CHP Plant with Power Loss).

The metering installation should be designed, manufactured and installed to an acceptable standard and sound practice as given by European (EN), or International (ISO) Standards or Guides.

Where commercial transactions or tax arrangements are based on metered or measured quantities (e.g. custody transfer of fuel), such metering (the meter from which you are billed) or measurement will normally be regarded as sufficient.

For all other metering arrangements (other than above) should be made according to European or member states recommended good practices, and should cover the read the following requirements:

- Validation procedures for the monitoring system should be in place either by direct calibration or by validating each of the components within the measurement system

- Periodic calibration should be carried out by the European Accreditation Service accredited organisations working within the scope of European Accreditation of Measurement and Sampling procedures

- To ensure that monitoring system uncertainties are maintained within the meter's specification the frequency of calibration should be at least once every five years, or earlier if this is recommended by the manufacturers' instructions.

- Metering should be tamper-proof

C.3.1.1 Measurement requirements

1) Fuel, heat and electricity/mechanical energy, steam, condensate return and make up water must be measured.

2) Measurements must be done with calibrated energy and flow, pressure and temperature and torque meters.

3) Only with small scale CHP units below 1 MWe and having a fixed power to heat ratio and a fixed power to fuel ratio the electricity may be measured alone. If there is at small scale CHP units below 1

MWe only a fixed power to heat ratio and not a fixed fuel to electricity ratio then also the fuel input has to be measured. In all other cases the three energy flows (fuel, heat and electricity/mechanical energy) must be measured.

4) Mechanical energy must be measured by means of a torque meter.

5) Fuel consumption, heat produced and electrical/mechanical energy produced must be measured during the reporting period, this is one complete calendar year. All hours of a year must be included. Fuel input must be measured by measuring the fuel input mass flow, used in that period.

6) Steam imported and steam delivered must be measured. Steam imported and steam delivered must be measured on the CHP boundary. Steam mass flow, steam pressure and steam temperature must be measured.

7) The mass flow of the condensate return and the mass flow of make up water must be measured. Condensate return and make up water must be measured on the CHP boundary. The temperature of the condensate return must also be measured.

8) The meters must fulfill the requirements of the European Measurement Directive and must fulfill the relevant European standards, like the EN 1434.

9) Fuel input, heat output and electricity output steam, condensate return and make up water must be measured on the CHP boundary.

10) Power loss coefficients during full burner(s) load and during part load of the burner(s) must be measured by means of a 1hr test. This 1 hr test must be done under conditions as close to the design mode as possible.

11) Fuel inputs of auxiliary firing and supplementary firing devices and their heat and electricity outputs must be measured separately by means of specific tests.

12) The efficiency of auxiliary firing and supplementary firing devices must be measured by means of a 1 hr test under full load burner conditions and under part load burner conditions. This 1 hr test must be done under conditions as close to the design mode as possible.

C.3.1.2 Calculation requirements

1) The measured fuel mass must be multiplied with the Lower Caloric Value of the fuel in order to find the energy content of the fuel input.

2) σ_{CHP} (the “C” form the Directive Annex IIb) must be calculated, based on the measured values for fuel, heat and electricity/mechanical energy.

3) Electrical, heat and total efficiencies must be calculated based on the measured values for fuel, heat and electricity/mechanical energy.

4) Electrical, heat and total efficiencies must be calculated during operating conditions, based on the measured values for fuel, heat and electricity/mechanical energy.

5) p_{CHP} must be calculated by multiplying σ_{CHP} with q_{CHP}

6) $p_{non\text{-}CHP}$ must be calculated by extracting p_{CHP} from p

7) $f_{non\ CHP,p}$ must be calculated by dividing $p_{non\text{-}CHP}$ by $\eta_{non\text{-}CHP,p}$

8) f_{CHP} must be calculated by extracting $f_{non\text{-}CHP,q}$ and $f_{non\text{-}CHP,\ p}$ from f.

9) Allocated fuel to the imported steam must be calculated with the following formulae $f = \frac{\beta \cdot q}{\eta_{non-CHP,p}}$.

C.4 How to Deal with Uncertainties

The expression of uncertainty is an essential indicator of the quality of the monitoring of performance (energy inputs and outputs). Therefore determined values of energy inputs and outputs should meet reasonable standards. It should be noted that fossil fuel energy can be assessed in multiplying their mass or volume by their specific average lower heating value as given by the supplier or by representative sampling calorimetric measurements.

References

1) EC: Directive of the European Parliament and of the Council on the promotion of cogeneration based on a useful heat demand in the internal energy market. April 2004

2) EC: Directive of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowance trading within the Community. October 2003

3) EC: Council Directive restructuring the Community framework for the taxation of energy products and electricity. October 2003

4) EC: Directive of the European Parliament and of the Council on the promotion of electricity produced from renewable energy sources in the internal electricity market. September 2001

5) IAPWS-IF97: Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam

6) EN (ISO) 13005: Guide to Expression of Uncertainty in Measurement.

7) ISO 1988: Hard Coal Sampling.

8) ISO 9096: Method for the Manual Gravimetric Determination of Concentration and Mass Flow Rate of Particulate Material in Gas Carrying Ducts.

9) ISO 13909: Parts 1-8, Coal Sampling.

10) ISO 10780: Stationary Source Emission - Measurement of Velocity and Volume Flow Rate of Gas Streams in Ducts.

11) ISO 12039: Stationary Source Emissions - Determination of the Volumetric Concentration of Carbon Monoxide, Carbon Dioxide and Oxygen.

12) ISO 31: Quantities and units

NOTE ISO refers to the International Standards Organisation.

EN refers to the European Standards Organisation.