ACER

Examples of Calculation

CO_2 emission limits in Capacity Mechanisms

based on Article 22(4) of Regulation (EU) 2019/943 and ACER's Opinion 22/2019

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Contents

Acronyms

Acronym	Meaning
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
DH	District Heating
EF	Emission Factor
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
NCV	Net Calorific Value
scm	Standard Cubic Meter
ST	Steam Turbine

1. Introduction

Following the publication of the Agency's Opinion 22/2019 (hereinafter referred as "Opinion") and upon request from stakeholders, this document provides examples of calculation of the CO_2 emission limits introduced in Article 22(4) of Regulation (EU) 2019/943. As already addressed in the Opinion, the Agency recognises the various power plant configurations across the EU and the difficulties, thereof, in implementing a uniform calculation method. Therefore, the purpose of this document is to demonstrate the rationale of the methodology applied to a number of non-trivial cases to assist stakeholders in applying the Agency's technical guidance. The following generation and production units' layouts are presented:

- Combined cycle gas turbine (CCGT) unit with supplementary firing after the gas turbine (GT)
- CCGT unit with heat extraction for district heating (DH) before the steam turbine (ST)
- Generation unit powered by co-firing of coal and biomass
- Coal-fired generation unit in a strategic reserve capacity mechanism
- Multi-shaft CCGT consisting of two GTs and one ST
- ST fed by two separate boilers with common header

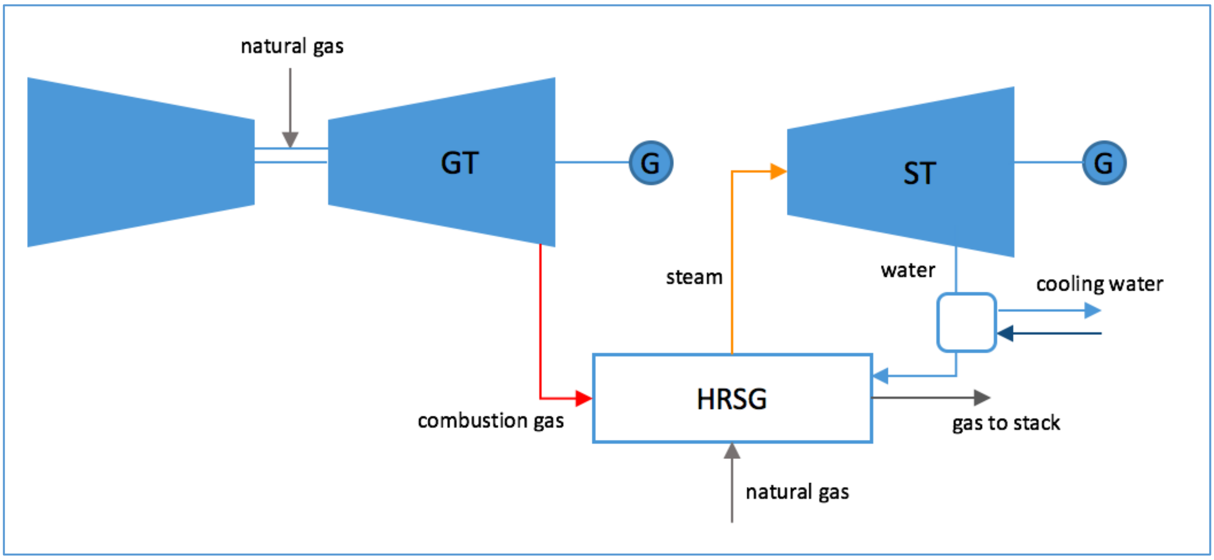
These examples were selected in order to provide stakeholders and competent national bodies with support on specific yet very common cases. If necessary, the Agency may provide assistance with the calculation of emission limits related to other types of generation units layouts, bilaterally and on a case-by-case basis. Throughout this document, terminology and definitions provided in Section 4 of the Opinion are used.

2. Examples of Calculation

2.1. CCGT unit with supplementary firing after the GT

The Opinion clarifies that, with regard to the calculation of the emission limits, generation units working in a tandem should be considered as combined. This is the case of the GT and ST of a CCGT, as specified in Section 5 of the Opinion. On top of this, Section 5 of the Opinion notes that the contribution of extra thermal input, as in the case of supplementary firing, should also be considered together with its related CO_2 emissions when calculating the design efficiency of the generation units. These principles are now applied to the following case study of a small size gas-fired CCGT unit under development, the layout of which is provided in Figure 1.

Figure 1: Simplified layout of a CCGT unit with supplementary firing.



Net electrical efficiency

In order to calculate the net electrical efficiency of the two generation units in tandem, the overall electricity production of the GT and ST after deduction of the auxiliary consumption (including fuel preparation and flue gas treatment) is divided by a quantity equal to the natural gas input in standard cubic meters (scm), converted to kWh_t by means of the Net Calorific Value (NCV) (see Annex I of the Opinion), mass density and the relevant conversion factor. The production unit that is analysed in this example is under development and therefore an EU ETS annual emission report is not yet available. It follows that nameplate numbers and values from technical specification sheets and preliminary production unit design are used, all of them referring to the operation of the production unit at nominal capacity, under standard conditions. These data are presented in Table 1.

Table 1: Example of data for calculating the net electrical efficiency of a CCGT with supplementary firing.

	Value	Unit
Fuel, GT	Natural Gas	-
Fuel consumption, GT	6,680	scm/h
Electricity generation, GT	22,600	kWhe/h
Fuel, supplementary firing	Natural Gas	-
Fuel consumption, supplementary firing	539	scm/h
Electricity generation, ST	14,700	kWhe/h
Auxiliary consumption	629	kWhe/h
NCV, Natural Gas	48	TJ/Gg
Mass density, Natural Gas	0.712	kg/scm

Before proceeding with the calculation, an evaluation on the contribution of supplementary firing is needed. Article 22(4) of Regulation (EU) 2019/943 asks for the emission limits to be calculated *"on the basis of the design efficiency of the generation unit meaning the net efficiency at nominal capacity under the relevant standards"*. It follows that the role of supplementary firing should be analysed, in relation to the CCGT design efficiency. In this example, it is assumed that the ST is sized for operating with supplementary firing and the GT operating at full load[1].

By applying the Opinion's principles, the net electrical efficiency is therefore calculated as

$$\eta_{\mathrm{des}} = \frac{(22{,}600 + 14{,}700 - 629)\ \mathrm{kWh/h}}{(6{,}680 + 539)\ \mathrm{scm/h} \cdot 48\ \mathrm{TJ/Gg} \cdot 0.712 \cdot 10^{-6}\ \mathrm{Gg/scm} \cdot 277{,}778\ \mathrm{kWh/TJ}} = 54\%^{2}$$

Specific Emissions

In order to calculate the value of *Specific Emissions* and verify compliance with the limit of 550 gCO_2/kWh, the formula introduced in Section 6.1 of the Opinion is now applied. Calculation is performed based on the input data shown in Table 2.

Table 2: Example of data for calculating the Specific Emissions of a CCGT with supplementary firing after the GT

	Value	**Unit**
Net Electrical Efficiency	54%	-
Emission Factor Natural Gas	56,100	$kgCO_2/TJ$
Fuel share Natural Gas	100%	-
Carbon captured factor	0%	-

The value of *Specific Emissions* is calculated as:

$$\text{Specific Emissions} = \frac{0.0036\ \mathrm{kWh/GJ}\ \cdot 56{,}100\ \mathrm{kgCO_2/TJ}}{0.54} = 374\ \mathrm{gCO_2/kWh}$$

It results that the CCGT unit is compliant with the emission limit on the *Specific Emissions*.

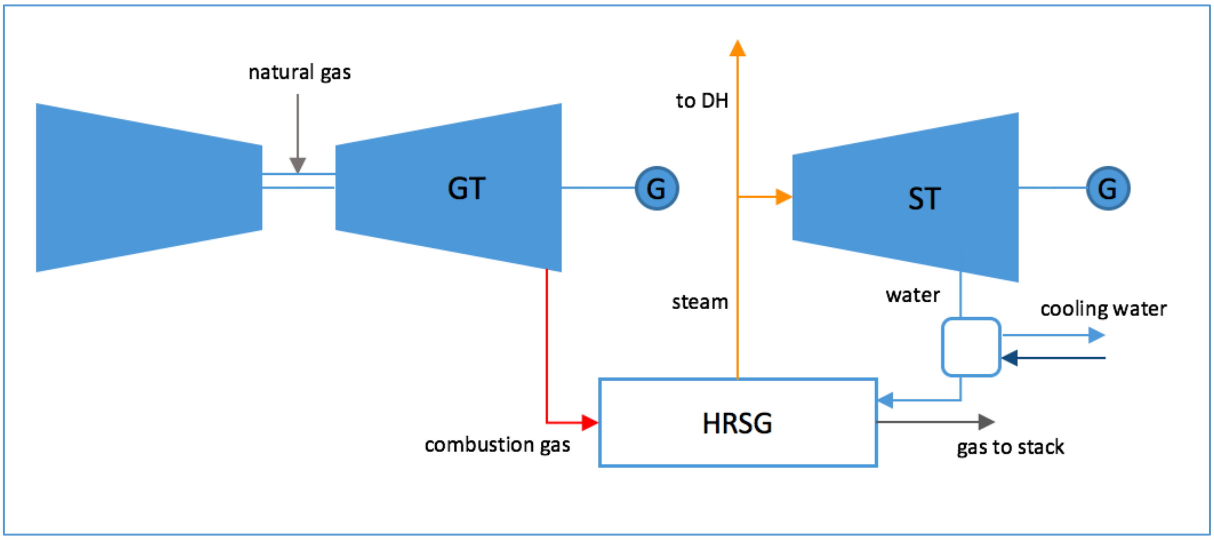
[1] In most of the combined cycles units, using supplementary firing will decrease the CCGT efficiency but the plant might need to properly respond to fluctuations of electrical load or to increase the maximum capacity to the CM contracted value. In these cases, supplementary firing should also be considered when calculating η_{des}.

[2] Please note that depending on the decimal places of the calculated values the resulting values of the Specific and Annual Emissions may vary rather considerably. This is why a common approach for all market participants should be followed. The Agency recommends to express net electrical efficiency to two decimal places (here 0.54 or 54%).

2.2. CCGT unit with heat extraction for DH before ST

The third subparagraph of Section 7.3 of the Opinion indicates that the net electrical efficiency of cogeneration units should refer to the unit producing only electricity at full load, an approach already used in the LCP BAT Conclusion[3]. This principle is applied in this example, which analyses the case of a gas-fired CCGT unit, which is under development.

Figure 2: Simplified layout of a CCGT with heat extraction for DH before ST



Net Electrical Efficiency

As in the previous example, the production unit that is analysed in this example is under development and therefore an EU ETS annual emission report is not yet available. It follows that nameplate numbers and values from technical specification sheets and preliminary production unit design are used, all of them referring to the operation of the production unit at nominal capacity, under standard conditions.

Table 3: GT data at nominal conditions for calculating the net electrical efficiency .

	Value	Unit
Fuel consumption, GT	6,680	scm/h
Electricity generation, GT	22,600	kWhe/h

In its normal operational set-up, the unit generates 32,655 kWh_t for a DH network, while the ST generates 8,200 kWh_e. However, as mentioned in the introduction to this example, the 'electricity full load' set-up has to be considered, when evaluating the design efficiency of the cogeneration unit. In the 'electricity full load' set-up, the ST generates 10,600 kWh_e and the output to DH reaches its minimum.

[3] Commission Implementing Decision (EU) 2017/1442.

Table 4: CCGT with heat extraction for DH before ST – Normal operational set-up.

	Value	**Unit**
Heat extraction to DH before, ST	15,194	kWht/h
Electricity generation, ST	8,200	kWhe/h

Table 5: CCGT with heat extraction for DH before ST – 'Electricity full load' set-up.

	Value	**Unit**
Heat extraction to DH before, ST	7,597	kWht/h
Electricity generation, ST	10,600	kWhe/h

The auxiliary consumption is expected at 1,350 kWh_e/h. The net electrical efficiency is therefore calculated as:

$$\eta_{des} = \frac{(22{,}600 + 10{,}600 - 1{,}350)\ \mathrm{kWh/h}}{6{,}680\ \mathrm{smc/h} \cdot 48\ \mathrm{TJ/Gg} \cdot 0.712 \cdot 10^{-6}\ \mathrm{Gg/scm} \cdot 277{,}778\ \mathrm{kWh/TJ}} = 50\%$$

Specific Emissions

The formula introduced in Section 6.1 of the Opinion is now applied in order to calculate the *Specific Emissions* and verify compliance with the limit value of 550 gCO_2/kWh. The following data is used, for the purpose of this calculation.

Table 6: Example of data for calculating the Specific Emissions of a CCGT with heat extraction for DH before ST.

	Value	**Unit**
Net Electrical Efficiency	50%	-
Emission Factor Natural Gas	56,100	$kgCO_2$/TJ
Fuel share Natural Gas	100%	-
Transferred CO_2 factor	0%	-

The value of *Specific Emissions* is calculated as:

$$\text{Specific Emissions} = \frac{0.0036\ \mathrm{kWh/GJ}\ \cdot 56{,}100\ \mathrm{kgCO_2/TJ}}{0.50} = 404\ \mathrm{gCO_2/kWh}$$

It results that the CCGT unit is compliant with the emission limit on the *Specific Emissions.*

2.3. Generation unit powered by co-firing of biomass and fossil fuels

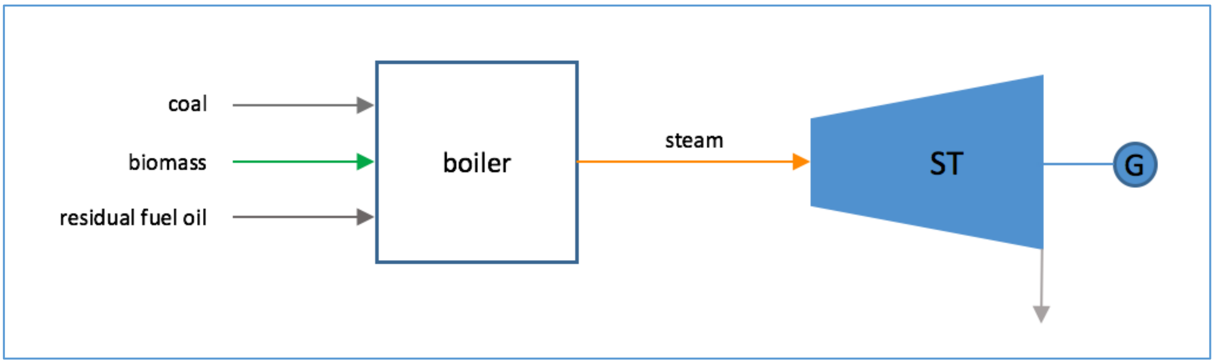
In this example of calculation, the formula introduced in Section 7.1 of the Opinion is applied. Specifically, the case of a 500 MW generation unit co-firing brown coal and solid biomass is analysed. The unit is under the EU ETS, where also a heavy fuel oil stream, used as supplementary fuel, e.g. for start-ups, is reported. The biomass used is in the form of wood chips and satisfies the sustainability criteria of Article 29 of Directive (EU) 2018/2001. Data regarding fuels and a simplified layout of the generation unit are provided in what follows.

Table 7: Example of data for calculating the fuel share of each fuel.

	EF (kgCO_2/TJ)	**NCV (TJ/Gg)**
Brown coal	99,610	18.9
Wood	0	15.6
Heavy fuel oil	73,400	45.0

	Value	**Unit**
Quantity brown coal	1,000	Gg
Quantity wood	320	Gg
Quantity heavy fuel oil	9	Gg

Figure 3: Simplified layout of a generation unit powered by co-firing of biomass and fossil fuels.



Fuel share

First of all, the fuel share of each fuel has to be calculated on the basis of the NCV, applying the formula provided in Section 7.1 of the Opinion. As an example, the calculation of the fuel share of brown coal is here shown. The rest of the fuel shares are listed in Table 8.

$$\text{fuel share}_{\text{brown coal}} = \frac{1{,}000\ \text{Gg} \cdot 18.9\ \text{TJ/Gg}}{1{,}000\ \text{Gg} \cdot 18.9\ \text{TJ/Gg} + 320\ \text{Gg} \cdot 15.6\ \text{TJ/Gg} + 9\ \text{Gg} \cdot 45.0\ \text{TJ/Gg}} = 77.8\%$$

Table 8: Calculated values of fuel shares.

	Value
Fuel share brown coal	77.8%
Fuel share wood	20.5%
Fuel share heavy fuel oil	1.7%

Specific Emissions

The formula introduced in Section 6.1 of the Opinion is now applied in order to calculate the value of *Specific Emissions* and verify compliance with the limit value of 550 gCO_2/kWh. In this example, the net electrical efficiency of the generation unit under nominal conditions (taking into account all auxiliary consumption, including fuel preparation and treatment) is obtained from the latest performance test.

Table 9: Example of data for calculating the Specific Emissions of a unit with co-firing of biomass and fossil fuels.

	Value
Net Electrical Efficiency	35%
Transferred CO_2 factor	0%

Based on the fuel shares previously calculated, *Specific Emissions* is calculated as:

$$\text{Specific Emissions} = \frac{0.0036\ \text{kWh/GJ}\ \cdot (0.778 \cdot 99{,}610 + 0.017 \cdot 73{,}400)\ \text{kgCO}_2/\text{TJ}}{0.35} = 810\ \text{gCO}_2/\text{kWh}$$

The generation unit is therefore non-compliant with the emission limit on the *Specific Emissions*. In order to evaluate its eligibility to participate in a capacity mechanism it is necessary to perform a calculation of the generation unit's *Annual Emissions*.

Annual Emissions

The formula introduced in Section 6.2 of the Agency's Opinion is now applied in order to calculate the *Annual Emissions* of the generation unit. For the purpose of this calculation, data from the previous three calendar years are needed. In this example the value of *Specific Emissions* previously calculated refers to year 2019. Values of *Specific Emissions* referring to year 2017 and 2018 are similarly calculated and reported in the following table.

Table 10: Example of data for calculating the Annual Emissions of a unit with co-firing of biomass and fossil fuels.

	2017	2018	2019	Unit
Installed capacity	500	500	500	MWe
Design electrical efficiency	35%	35%	35%	-
Electricity production	3,066	2,628	2,190	GWh
Share of coal	80.7%	78.3%	77.8%	-
Share of wood	18.4%	20.5%	20.5%	-
Share of heavy fuel oil	0.9%	1.2%	1.7%	-
Specific Emissions	834	811	810	gCO_2/kWh

The value of Annual Emissions of the generation units is therefore calculated as:

$$\text{Annual Emissions} = \frac{1}{3} \cdot \left(\frac{834\ \text{gCO2/kWhe}\ \cdot 3{,}066\ \text{GWhe}}{500\ \text{MWe}} + \frac{811\ \text{gCO2/kWhe}\ \cdot 2{,}628\ \text{GWhe}}{500\ \text{MWe}} + \frac{810\ \text{gCO2/kWhe}\ \cdot 2{,}190\ \text{GWhe}}{500\ \text{MWe}}\right)$$

The result is a value of Annual Emissions of $4{,}308\ \text{kgCO}_2/\text{kWe}$. The generation unit is therefore non-compliant with the emission limit on the *Annual Emissions* and cannot participate in a capacity mechanism.

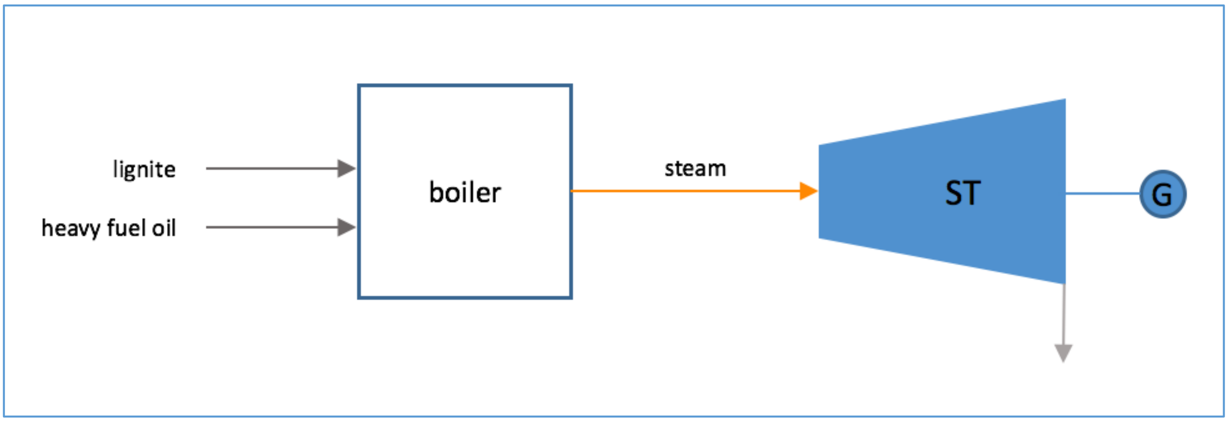
2.4. Lignite plant in a strategic reserve capacity mechanism

This example examines the reasoning behind decisions on the eligibility of a generation unit to a strategic reserves capacity mechanism. As explained in point (b) of the first Paragraph of Section 6 of the Opinion, generation units that do not comply with the limit on *Specific Emissions* and with the limit on *Annual Emissions*, could be allowed to participate in a strategic reserves capacity mechanism if the operator can firmly commit to ensure compliance with the limit value of *Annual Emissions*, during each calendar year of the delivery period. This evaluation should be based on:

i) the expected hours of activation;
ii) the maximum duration of the delivery period per activation;
iii) the generation unit's technical constraints (e.g. start-up time, ramp rate);
iv) the generation unit's *Specific Emissions*.

This example refers to a 300 MW lignite fired generation unit that operates as a base unit. A simplified layout is presented in what follows.

Figure 4: Simplified layout of a lignite plant.



Fuel shares

First, data for the calculation of the fuel shares are provided and fuel shares are calculated. The generation unit is under the EU ETS framework and therefore values of emission factors and NCV are taken from the relevant annual monitoring report.

Table 11: Example of data for calculating the fuel share of each fuel.

	EF (kgCO_2/TJ)	NCV (TJ/Gg)
Lignite	124,230	10.1
Heavy fuel oil	73,400	45.0

	Value	Unit
Quantity lignite	2,185	Gg
Quantity heavy fuel oil	7.5	Gg

$$\text{fuel share}_{\text{lignite}} = \frac{2{,}185\ \text{Gg} \cdot 10.1\ \text{TJ/Gg}}{2{,}185\ \text{Gg} \cdot 10.1\ \text{TJ/Gg} + 7.5\ \text{Gg} \cdot 45.0\ \text{TJ/Gg}} = 98.5\ \%$$

$$\text{fuel share}_{\text{heavy fuel oil}} = \frac{7.5\ \text{Gg} \cdot 45.0\ \text{TJ/Gg}}{2{,}185\ \text{Gg} \cdot 10.1\ \text{TJ/Gg} + 7.5\ \text{Gg} \cdot 45.0\ \text{TJ/Gg}} = 1.5\ \%$$

Table 12: Calculated values of fuel shares.

	Value
Fuel share lignite	98.5%
Fuel share heavy fuel oil	1.5%

Specific Emissions

Once fuel shares are known, the following data are used to calculate the value of *Specific Emissions*:

Table 13: Input data used to calculate Specific Emissions.

	Value
Net Electrical Efficiency	29%
Fuel share lignite	98.5%
Fuel share heavy fuel oil	1.5%
Transferred CO_2 factor	0%

The *Specific Emissions* value is therefore calculated as:

$$\text{Specific Emissions} = \frac{0.0036\ \text{kWh/GJ}\ \cdot (0.985 \cdot 124{,}230 + 0.015 \cdot 73{,}400)\ \text{kgCO}_2/\text{TJ}}{0.29} = 1{,}533\ \text{gCO}_2/\text{kWh}$$

The generation unit is non-compliant with the emission limit on the *Specific Emissions*. In order to evaluate its eligibility to participate in a capacity mechanism it is then also necessary to perform a calculation of the value of *Annual Emissions*.

Annual Emissions

The formula introduced in Section 6.2 of the Opinion is now applied in order to calculate the *Annual Emissions* of the generation unit. For the purpose of this calculation, data from the previous three calendar years are needed. In this example, the value of *Specific Emissions* previously calculated refers to year 2019. Values of *Specific Emissions* referring to year 2017 and 2018 are also reported in the following table.

Table 14: Example of data for calculating the Annual Emissions of a lignite unit.

	2017	2018	2019	Unit
Specific Emissions	1,526	1,527	1,533	gCO_2/kWh
Electricity production	1,840	1,524	1,708	GWh
Installed capacity	300	300	300	MWe

The value of *Annual Emissions* of the generation units is calculated as:

$$\text{Annual Emissions} = \frac{1}{3} \cdot \left(\frac{1{,}526\ \text{gCO2/kWhe}\ \cdot 1{,}840\ \text{GWhe}}{300\ \text{MWe}} + \frac{1{,}527\ \text{gCO2/kWhe}\ \cdot 1{,}524\ \text{GWhe}}{300\ \text{MWe}} + \frac{1{,}533\ \text{gCO2/kWhe}\ \cdot 1{,}708\ \text{GWhe}}{300\ \text{MWe}} \right)$$

The result is a value of *Annual Emissions* of $8{,}615\ \text{kgCO}_2/\text{kWe}$. The generation unit is therefore non-compliant with the emission limit on the *Annual Emissions*. The generation unit could be nevertheless allowed to participate in a capacity mechanism as strategic reserves, based on the Agency's provision of point (b) of the first Paragraph of Section 6 of the Opinion.

Evaluation on the admissibility in a strategic reserve capacity mechanism

It is assumed that the maximum annual requirement of the strategic reserve capacity mechanism is for the generation unit to be activated at maximum capacity, i.e. 300 MW, for a total (maximum) number of 16 activations lasting 12 hours each. These values might be defined in the terms and conditions of the capacity mechanism, published by the competent national body in the call for tenders or in the relevant contract between the capacity provider and the capacity buyer (e.g. TSO).

Table 15: Example of data for calculating the Strategic Reserve's maximum activation time.

	Value	Unit
Maximum number of activations	16	activations/year
Maximum duration of activations	12	h/activation

The admissibility of the generation unit to participate in such a strategic reserves capacity mechanism is evaluated based on the maximum equivalent full load hours (FLH_{max}) the generation unit is allowed to operate without exceeding the limit on the *Annual Emissions*. This value is provided by the following formula:

$$\mathrm{FLH_{max}} = \frac{350 \cdot 10^3}{1{,}533} = 228 \text{ hours}$$

The next step is to calculate the full load hours ($\mathrm{FLH_{required}}$) the generation unit would be required to produce, in the case the maximum number of activations with the maximum duration and maximum capacity were required. This value should be calculated taking into account the technical characteristics of the generation unit, i.e. including the time needed to reach the maximum capacity from cold start, the 12 hours maximum duration requirement per activation and the time needed to completely switch off (see Figure 5). The technical characteristics needed for the calculation are listed in Table 16.

Figure 5: Example of the operating cycle of the generation unit per activation.

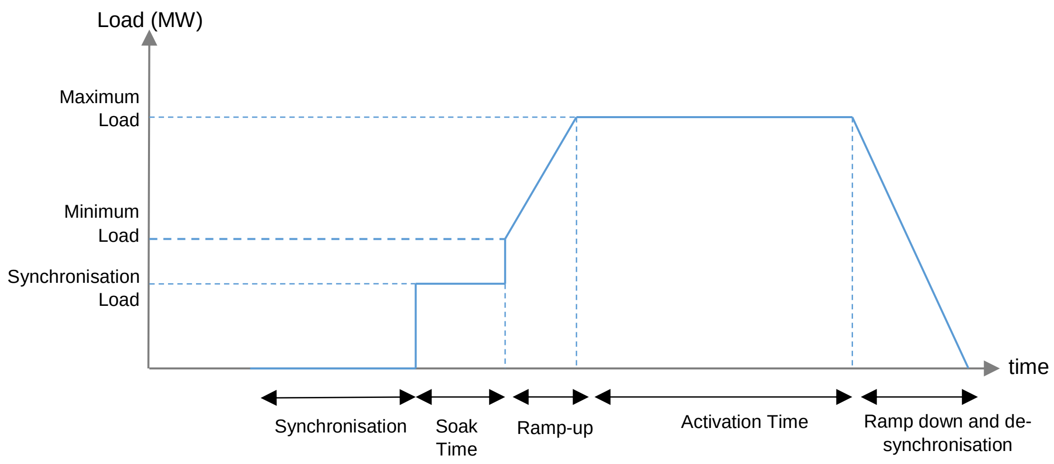


Table 16: Example of data regarding the technical constraints of the Generation Unit.

	Value	Unit
Synchronisation time	4.0	h
Synchronisation load	80	MWe
Soak time	2.0	h
Minimum load	150	MWe
Maximum load	300	MWe
Ramp up	3.0	MWe/min
Ramp down	4.0	MWe/min
Minimum on time	10	h
Ramp down and de-synchronisation time	1.3	h

Based on the data provided in Table 16, the amount of electricity that is produced per activation is calculated as[4]:

$$\text{El. production per activation} = 2\ \text{h} \cdot 80\ \text{MW} + \frac{(300 + 150)\ \text{MW}}{2} \cdot \frac{(300 - 150)\ \text{MW}}{3\ \text{MW/min} \cdot 60\ \ \text{min/h}} + 12\ \text{h} \cdot 300\ \text{MW} + 1{,}3\ \text{h} \cdot \frac{300\ \text{MW}}{2}$$

The result is a value of electricity production per activation of $4{,}143\ \text{MWhe}$. This corresponds to a value of equivalent full load hours of operation of:

$$\text{FLH}_{\text{required}} = \frac{4{,}143\ \text{MWhe} \cdot 16}{300\ \text{MWe}} = 221\ \text{h}$$

This value could allow the generation unit to participate in a strategic reserve capacity mechanism, since it is lower than the maximum allowed full load operating hours previously calculated. As explained in the Opinion, competent national body should also verify this unit's compliance by means of an ex-post validation (see Section 9 of the Opinion).

[4] Since the formula used to calculate *Annual Emissions* refers to the amount of annual electricity produced, for consistency reasons, the calculations in this example should also take into account only those periods of the activation cycle (synchronisation – soak time - ramp up – full load operation – ramp down and desynchronisation) during which the generation unit is producing electricity, i.e. the synchronisation time should not be taken into account although the unit consumes fuel and emits CO_2.

2.5. Multi-shaft CCGT consisting of two GTs and one ST

The case of a multi-shaft CCGT composed of two GTs and one ST is now analysed. This example is particularly important to understand the difference between the generation capacity that participates or is planned to participate in a capacity mechanism[5] and the generation capacity which is subject to the emission limits or, in other words, the level at which emission limits should be calculated (i.e. the generation unit level). To facilitate reading, the layout of a multi-shaft CCGT unit consisting of two GTs and one ST is provided in Figure 6 and the related data in Tables 17-19.

Figure 6: Simplified layout of a multi-shaft CCGT consisting of two GTs and one ST.

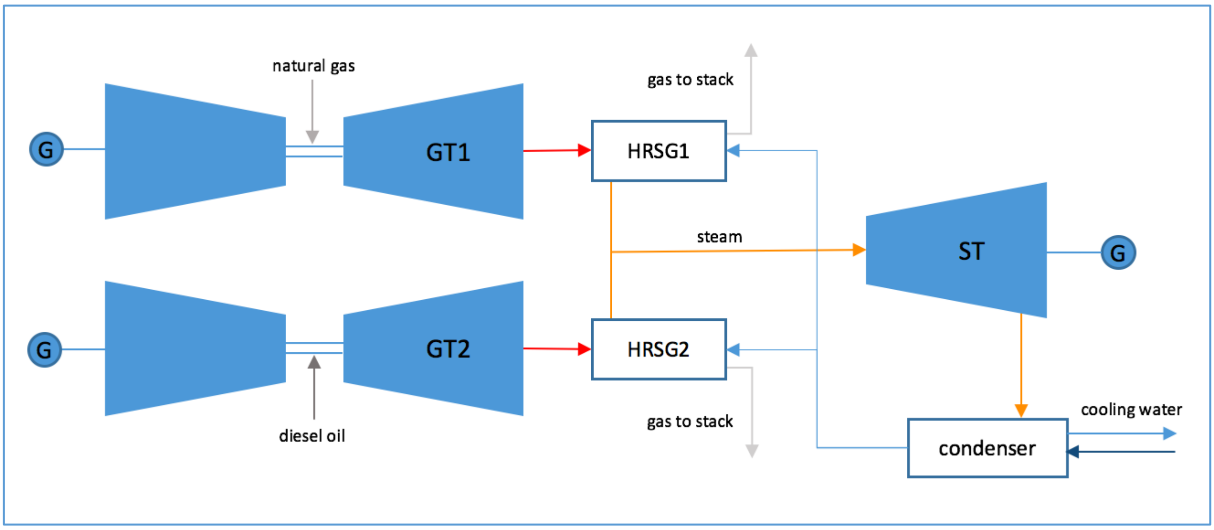


Table 17: Example of data for GT1 at nominal capacity and standard conditions.

	Value	**Unit**
Electricity generation	254	MWh_e/h
Fuel consumption	2.41	TJ/h
Fuel GT1	Natural Gas	-
Emission Factor Natural Gas	56,100	$kgCO_2/TJ$
Fuel share Natural Gas	100%	-

Table 18: Example of data for GT2 at nominal capacity and standard conditions.

	Value	**Unit**
Electricity generation	254	MWh_e/h
Fuel consumption	3.39	TJ/h
Fuel GT2	Gas/Diesel Oil	-
Emission Factor Gas/Diesel Oil	74,100	$kgCO_2/TJ$
Fuel share Gas/Diesel Oil	100%	-

Table 19: Example of data for ST at nominal capacity and standard conditions.

	Value	**Unit**
Electricity generation	282	MWh_e/h

[5] Depending on the capacity mechanism rules this could, for instance, be a generation unit, bundled products or a portfolio of production units.

According to Article 22(4) of Regulation (EU) 2019/943 and the Opinion:

- Emission limits should refer to the design conditions;
- Generation units that can be operated independently should be considered separately;
- Generation units working in a tandem should be considered together.

It follows that the calculation should be performed separately for GT1 and GT2, each one of them alone forming a tandem with the ST. The determination of the ST generation under these configurations can be done in different ways and needs to be approved by the competent national body.

Net Electrical Efficiency

As an example, the net electrical efficiency of the tandem GT1+ST is here calculated. In this example, for simplicity, it is assumed that when only one GT is operating, the output of ST is reduced by half. Auxiliary consumption is equal to 7 MWh_e/h. Calculation is performed as follows:

$$\eta_{des} = \frac{\left(254 + \frac{282}{2} - 7\right) \mathrm{MWh/h}}{2.41\ \mathrm{TJ/h}} \cdot 0.0036\ \mathrm{TJ/MWh}\ = 58\%$$

Specific Emissions

The value of net electrical efficiency is then used to calculate the Specific Emissions of such a unit:

$$\text{Specific Emissions}_{GT1+ST} = \frac{0.0036\ \mathrm{kWh/GJ}\ \cdot 56{,}100\ \mathrm{kgCO_2/TJ}}{0.58} = 348\ \mathrm{gCO_2/kWhe}$$

With a similar process, *Specific Emissions* for the GT2 in tandem with a fraction of the topping turbine ST is calculated. Results are shown in the following table:

Table 20: Summary of the values of Specific Emissions calculated for GT_1+ST and GT_2+ST

	GT1+ST	GT2+ST
Specific Emissions (gCO_2/kWhe)	348	651

While GT1+ST is compliant and can participate in a capacity mechanism, GT2+ST is not compliant with the limit on the *Specific Emissions* which is set in Article 22(4) of Regulation (EU) 2019/943 and equal to 550 gCO_2/kWhe. In order to evaluate the eligibility of the tandem of generation units GT2+ST to participate in a capacity mechanism, it is then also necessary to perform a calculation of the value of *Annual Emissions*.

Annual Emissions

The formula introduced in Section 6.2 of the Opinion is now applied in order to calculate the *Annual Emissions* of the tandem of generation units GT2+ST. For the purpose of this calculation, data from the previous three calendar years are needed.

Electricity produced by the generation unit ST has to be split into two parts in order to allocate its relative share to GT2. This is done on the basis of the energy contribution of HRSG1 and HRSG2 to the steam feeding the ST. In this example, hourly time series of the enthalpies recorded at the outlet of the two steam generators by means of a sub-metering system are used[6]. Example of these data is hereby provided.

[6] Highest granularity of data should be used in order to provide the most precise evaluation. If hourly data are not available, operators should use daily data or other aggregations. If enthalpy data are not available, GT1 and GT2 fuel consumption and efficiencies should be used as proxies to allocate ST electricity production among the two GTs.

Table 21: Example of data used for allocating ST electricity production on the basis of HRSG1 and HRSG2 energy contributions.

Date and time 2017	HRSG1		HRSG2		Energy to ST HRSG1	share HRSG1	Energy to ST HRSG2	share HRSG2
	Enthalpy (kJ/kg)	Mass flow (t/h)	Enthalpy (kJ/kg)	Mass flow (t/h)	(TJ)	(%)	(TJ)	(%)
1 Jan 00:00 01:00	3,532	400	3,490	400	1.41	50%	1.40	50%
1 Jan 01:00 02:00	3,520	400	3,592	400	1.41	49%	1.44	51%
1 Jan 02:00 03:00	3,500	400	3,445	400	1.40	50%	1.38	50%
1 Jan 03:00 04:00	3,500	400	3,526	400	1.40	50%	1.41	50%
1 Jan 04:00 05:00	3,500	400	3,467	400	1.40	50%	1.39	50%
1 Jan 05:00 06:00	3,525	400	3,691	400	1.41	49%	1.48	51%
…	…	…	…	…	…	…	…	…
				TOTAL	7,358	60%	4,905	40%

Date and time 2018	HRSG1		HRSG2		Energy to ST HRSG1	share HRSG1	Energy to ST HRSG2	share HRSG2
	Enthalpy (kJ/kg)	Mass flow (t/h)	Enthalpy (kJ/kg)	Mass flow (t/h)	(TJ)	(%)	(TJ)	(%)
1 Jan 00:00 01:00	3,768	400	3,716	400	1.51	50%	1.49	50%
1 Jan 01:00 02:00	3,752	400	3,677	400	1.50	51%	1.47	49%
1 Jan 02:00 03:00	3,659	400	3,828	400	1.46	49%	1.53	51%
1 Jan 03:00 04:00	3,489	400	3,458	400	1.40	50%	1.38	50%
1 Jan 04:00 05:00	3,743	400	3,977	400	1.50	48%	1.59	52%
1 Jan 05:00 06:00	3,687	400	3,953	400	1.47	48%	1.58	52%
…	…	…	…	…	…	…	…	…
				TOTAL	9,198	54%	7,835	46%

Date and time 2019	HRSG1		HRSG2		Energy to ST HRSG1	share HRSG1	Energy to ST HRSG2	share HRSG2
	Enthalpy (kJ/kg)	Mass flow (t/h)	Enthalpy (kJ/kg)	Mass flow (t/h)	(TJ)	(%)	(TJ)	(%)
1 Jan 00:00 01:00	3,456	400	3,569	400	1.42	49%	1.42	51%
1 Jan 01:00 02:00	3,774	400	3,924	400	1.43	49%	1.54	51%
1 Jan 02:00 03:00	3,495	400	3,720	400	1.40	48%	1.47	52%
1 Jan 03:00 04:00	3,572	400	3,774	400	1.38	49%	1.45	51%
1 Jan 04:00 05:00	3,560	400	3,609	400	1.45	50%	1.51	50%
1 Jan 05:00 06:00	3,669	400	3,710	400	1.50	50%	1.59	50%
…	…	…	…	…	…	…	…	…
				TOTAL	8,585	52%	7,835	48%

According to the values in Table 21 and the approach suggested, the share of electricity production of the ST to be allocated to the tandem GT2+ST is calculated for each year. In this example the value of *Specific Emissions* previously calculated refers to year 2019. The values of *Specific Emissions* referring to year 2017 and 2018 are also listed together with the values of installed capacity[7] and electricity production, calculated based on the hourly time series, of which an example is shown in Table 21.

Table 22: Example of data for calculating the Annual Emissions of the tandem GT2+ST.

	2017	2018	2019	Unit
Specific Emissions GT2+ST	651	651	651	gCO_2/kWh
Electricity production GT2	1,096	1,205	1,162	GWh
Electricity production ST	1,453	1,574	1,453	GWh
Share of el. production ST to GT2+ST	40%	46%	48%	-
Electricity production GT2+ST	1,677	1,873	1,859	GWh
Installed capacity GT2+ST	395	395	395	MWe

[7] As explained above, it is assumed that when only one GT is working, the output of ST, at design conditions, is reduced by half.

The value of *Annual Emissions* of the generation units is therefore calculated as:

$$\text{Annual Emissions} = \frac{1}{3} \cdot \left(\frac{651\ \text{gCO2/kWhe} \ \cdot 1{,}677\ \text{GWhe}}{395\ \text{MWe}} + \frac{651\ \text{gCO2/kWhe} \ \cdot 1{,}873\ \text{GWhe}}{395\ \text{MWe}} + \frac{651\ \text{gCO2/kWhe} \ \cdot 1{,}859\ \text{GWhe}}{395\ \text{MWe}} \right)$$

The result is a value of *Annual Emissions* of $2{,}972\ \text{kgCO}_2/\text{kWe}$. The tandem of generation units GT2+ST is therefore non-compliant with the emission limit on the *Annual Emissions*. The analysis shows that, while the tandem of generation units GT1+ST is compliant with the emission limits, the tandem of units GT2+ST is not compliant with the emission limits and therefore cannot participate in a capacity mechanism.

2.6. ST fed by multiple steam generators via steam headers

The case of cogeneration of heat and electricity by means of steam turbines being supplied with steam at various pressure levels through more than one steam generator is rather common in industrial CHP applications and DH systems. These configurations are usually customised based on the needs for heat supply. Generator units in such systems are the steam turbines. The problems in calculating the *Specific Emissions* according to Section 6.1 of the Opinion are (1) evaluating fuel shares and (2) calculating the overall net electrical efficiency. In general, calculations should be performed based on hourly (or even sub-hourly) data on the operation of the steam turbines and the relevant steam generators, so as to properly allocate the steam input to the ST from the different steam generators. In this way, fuels can be allocated accordingly and the overall net electrical efficiency can be defined. Hourly data will ensure that the allocation refers only to the hours when the steam turbine is operating (the steam generators may provide steam for heating purposes even when the steam turbine is off). A simplified example of a condensing steam turbine being supplied through a high pressure steam header by two separate boilers is provided hereafter, in order to illustrate the methogology suggested. The technical characteristics of the boilers are presented in Table 23.

Figure 7: Simplified layout of a ST fed by multiple steam generators via steam headers.

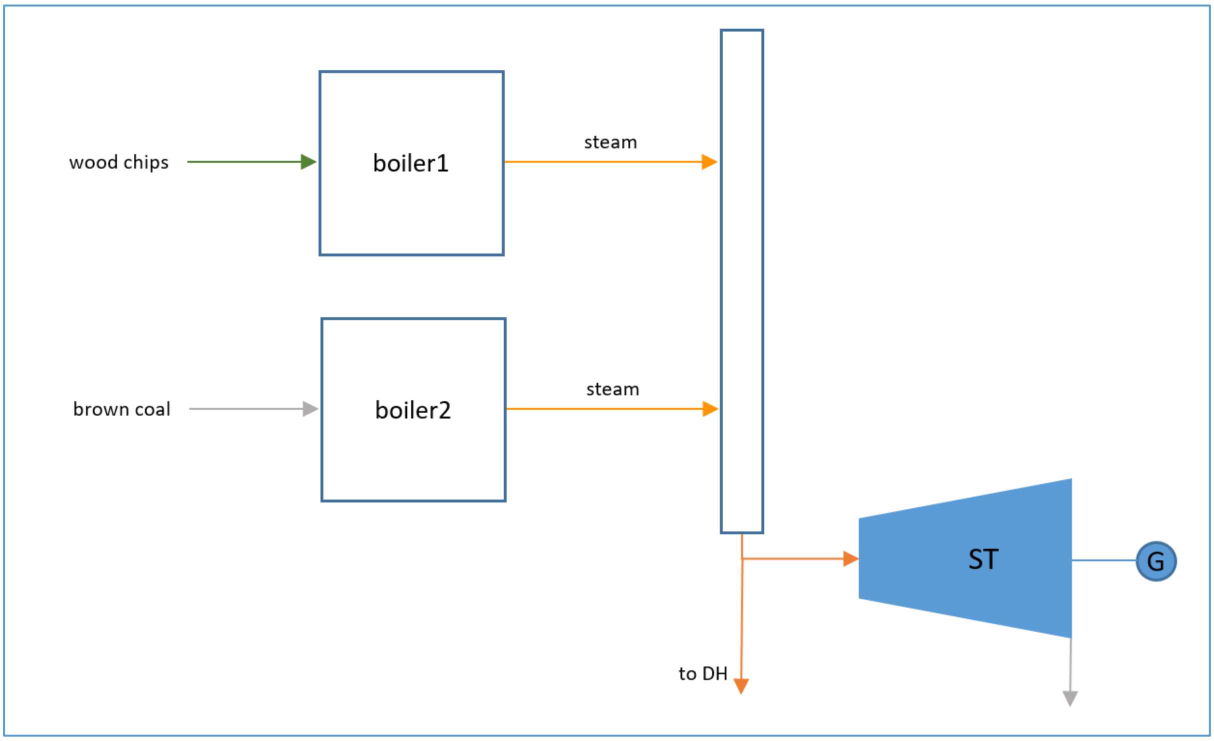


Table 23: Technical data of the two boilers.

	Boiler 1	Boiler 2	Unit
Capacity	300	400	t/h
Fuel	Wood chips	Brown coal	-
Emission Factor	0	99,610	$kgCO_2/TJ$
Net Calorific Value	15.6	18.9	TJ/kt
Design efficiency	85%	90%	-

Boiler 1 can produce 223 MWh/h of high pressure steam and Boiler 2 can produce 297 MWh/h. The steam turbine has a gross capacity of 75 MW. It is further assumed in this exampe that the auxilliary demand is 2% of the steam turbine's generator output and that heat losses of the steam distribution system from the boilers to the steam turbine also account for another 2%. The hourly operational data needed to calculate the share of each steam source (here considered as a fuel to the ST) are shown in the following table.

Table 24: Example of operational data for calculating the fuel share of the steam provided by each boiler.

Date and time 2019	ST		Boiler 1		Boiler 2		S_{F1}	S_{F2}
	Gross electricity generation (MWh/h)	Steam input[8] (MWh/h)	Steam production (MWh/h)	Fuel input (MWh/h)	Steam production (MWh/h)	Fuel input (MWh/h)	(%)	(%)
1 Jan 00:00 01:00	75	278	220	259	0	0	100%	0%
1 Jan 01:00 02:00	75	278	220	259	175	194	56%	44%
1 Jan 02:00 03:00	65	250	220	259	200	222	52%	48%
1 Jan 03:00 04:00	60	231	220	259	200	222	52%	48%
1 Jan 04:00 05:00	50	200	220	259	250	278	47%	53%
1 Jan 05:00 06:00	0	0	220	259	250	278	47%	53%
…	…	…	…	…	…	…	…	…
Total (GWh)	427	1,708	1,468	1,835	1,432	1,684	53%	47%

Being *h* the hours in which ST produces electricity, fuel shares are calculated using the following equations:

$$S_{F1} = \frac{\sum_{h=1}^{h=N} \text{quantity}_{F1,h}}{\sum_{h=1}^{h=N} (\text{quantity}_{F1,h} + \text{quantity}_{F2,h})} = 53\%$$

$$S_{F2} = 1 - S_{F1} = 47\%$$

Net electrical efficiency

Auxiliary consumption has to be taken into account, when calculating the net electrical efficiency. The net electrical efficiency can be calculated as follows:

$$\eta_e = \frac{\text{net electricity production (GWh)}}{\sum_{h=1}^{h=8760} \frac{\text{steam input to ST}_h}{(1 - \text{steam losses})} \cdot (S_{F1,h}/\eta_{\text{Boiler 1}} + S_{F2,h}/\eta_{\text{Boiler 2}})} = 23\%$$

Where *steam losses* is a decimal value indicating the losses in the steam distribution network.

Specific Emissions

The value of *Specific Emissions* is therefore calculated as follows:

$$\text{Specific Emissions} = \frac{0.0036\ \text{kWh/GJ} \cdot (0.47 \cdot 99{,}610\ \text{kgCO}_2/\text{TJ})}{0.23} = 733\ \text{gCO}_2/\text{kWhe}$$

Annual Emissions

Considering the data in Table 25 regarding the annual operation of the steam turbine, and assuming for simplicity in this example that the allocation of fuels and the net electrical efficiency are the same for all the reference years, the *Annual Emissions* is calculated.

Table 25: Example of data to calculate the value of Annual Emissions.

	2017	2018	2019	Unit
Specific Emissions	733	733	733	gCO_2/kWh
Net electricity production	419	322	386	GWh
Installed capacity (net)	73.5	73.5	73.5	MWe

[8] Calculated based on the mass flow rates and enthalpy of the steam as in the previous example.

$$\text{Annual Emissions} = \frac{1}{3} \cdot \left(\frac{733\ \text{gCO2/kWhe} \ \cdot 419\ \text{GWhe}}{73.5\ \text{MWe}} + \frac{733\ \text{gCO2/kWhe} \ \cdot 322\ \text{GWhe}}{73.5\ \text{MWe}} + \frac{733\ \text{gCO2/kWhe} \ \cdot 386\ \text{GWhe}}{73.5\ \text{MWe}} \right)$$

The results is a value of *Annual Emissions* of $3{,}746\ \text{kgCO}_2/\text{kWe}$. The generation unit is not eligible to participate in capacity mechanisms.