CO_2 emission allocation in CHP systems and recomendations

BSR LTDH project

LowTEMP Training Package - 9

Interreg Baltic Sea Region
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

LowTEMP training package - OVERVIEW

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Introduction

- Intro Climate Protection Policy and Goals
- Intro Energy Supply Systems and LTDH
- Energy Supply Systems in Baltic Sea Region

Energy Strategies and Pilot Projects

- Methodology of Development of Energy Strategies
- Pilot Energy Strategies – Aims and Conditions
- Pilot Energy Strategy – Examples
- Pilot Testing Measures
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- Economic efficiency and funding gaps
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- Combined heat and power (CHP)
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Best Practice

- Best Practice I
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Motivation

The CO2 emission allocation methods are very important **energy-policy tools** and they are developed to **support energy-systems planning** as well as **decision-making** and **policy development** at both governmental, regional and industrial levels.

Cogeneration systems produces electric energy and heat but heat can be produce from fossil fuels or electricity with efficiency more than

95%

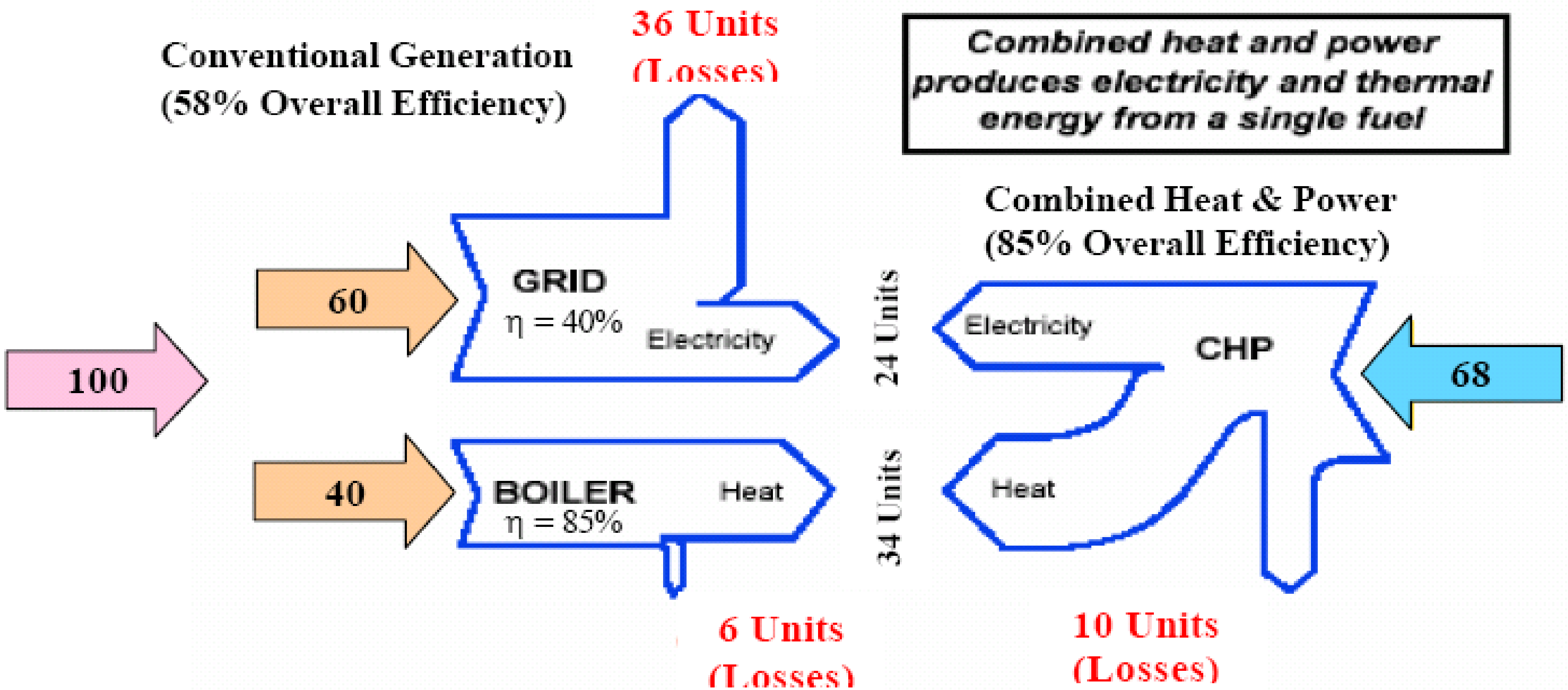
electric energy is produced from fossil fuels/heat with efficiency up to

45%

How much of emission should we allocate to energy and heat production ?

Figure 1: Emissions from the largest lignite-fired power plant in Belchatów (PL)
Source: M. Dzierzgowski, IMP PAN

Cogeneration - advantage



Energy efficiency advantage of a cogeneration system (UNESCAP, 2000)

Source: UNESCAP, 2000

Sources of emission and their GWP

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Głobal Warming Potential

The combustion of fossil fuels results in emissions of the greenhouse gases, including mainly carbon dioxide, methane, nitrous oxide and other. The **emissions of these gases are converted to CO2e** by multiplying the amount of GHG by their Global Warming Potential (GWP).

GWP is calculated to **reflect how long gas remains, on average, in the atmosphere and how strongly it absorbs energy** i.e. it refers to the total contribution to global warming that results from the emission of one unit of that gas relative to one unit of the reference gas – CO_2.

Examples:

GWP CO_2 equals (by definition) 1
Methane (CH_4) : 28–36
Nitrous Oxide (N_2O) : 265–298.

CO2
CO
CH4
N2O
Nox
SO2

Methods for assessing GHG emissions

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There are two **principal methods for assessing GHG emissions** from stationary combustion sources:

- Direct measurement
- Analysis of fuel input

Direct measurement of CO_2 emissions can be performed using a **Continuous Emissions Monitoring System**.

The calculation of CO_2 emissions using the fuel analysis method involves determining a carbon content in combusted fuel;

An **emission factor** is defined as the average emission rate of a given GHG for a given source, relative to units of activity (typically the amounts of fuels combusted, or kWh of electricity used, etc.).

CO2
CO
CH4
N2O
Nox
SO2

Emission Factor

GHG emission of various fuels

There are 3 standard equations that describe CO_2 emissions for each type of combusted fuel:

GHG emissions = Fuel * EF1 (1)

GHG emissions = Amount of CO_2, CH_4 or N_2O emitted, ***Fuel*** = mass or volume of fuel combusted,
EF1 = CO_2, CH_4 or N_2O **emission factor** per mass or volume unit,

GHG Emissions = Fuel * HHV* EF2 (2)

EPA Greenhouse Gas Inventory Guidance, *Direct Emissions from Stationary Combustion Sources*, 2016;
HHV = Fuel heat content (higher heating value), in units of energy per mass or volume of fuel ;
EF2 = CO_2, CH_4, or N_2O emission factor per energy unit

GHG Emissions = Fuel * CC * 44/12 (3)

CC = Fuel carbon content in units of mass of carbon per mass or volume of fuel,
44/12 = ratio of molecular weights of CO_2 and carbon.

Primary energy and primary energy factor

Primary energy (PE)
means energy from renewable and non-renewable sources which has not undergone any conversion or transformation.

PE may be fossil or renewable or a combination of both. It can be converted and delivered to end users as final energy, e.g. electricity or heat. PE inputs generally include the upstream activities and processes in supply chain (i.e. extraction, transport and preparation of input fuels).

Primary Energy Factor (PEF)
connects primary and final energy - shows how much PE is used to generate a unit of electricity or a unit of useable thermal energy

Primary energy * System efficiency = final energy

Primary energy factor = Primary energy/final energy

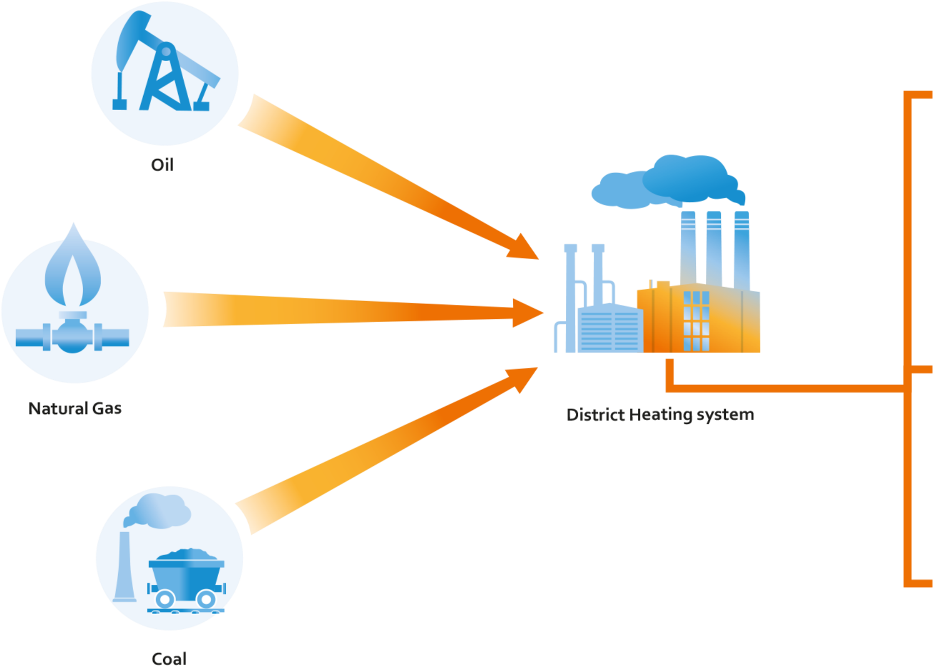

Figure 3: Conventional district heating. Source: Original LowTEMP illustration by Peter Abrahamsson, AliasDesign, for Sustainable Business Hub

Primary energy factor $f_{P,DH}$ of the district heating system

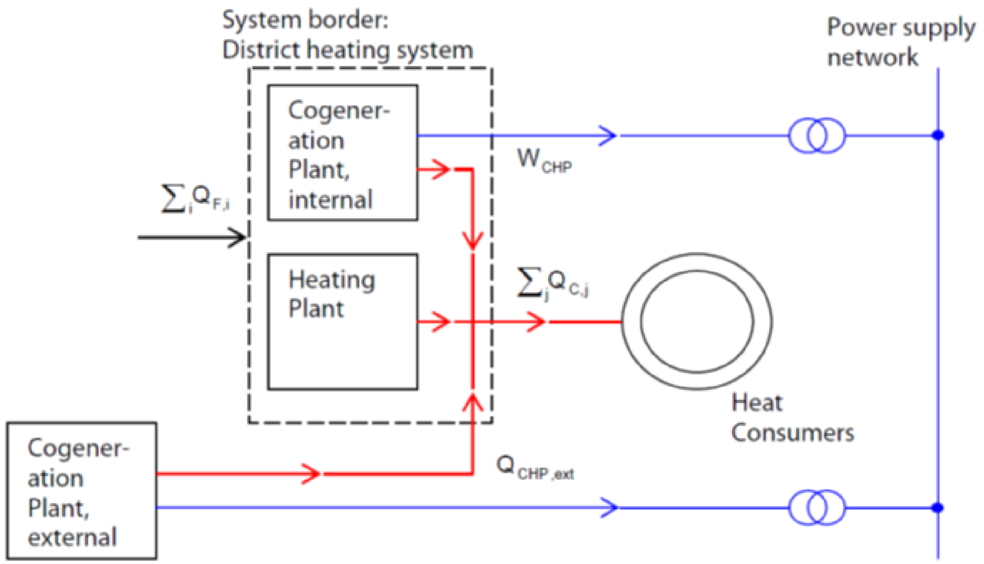

Figure 4. Scheme of district heating grid. Source: A. Wallisch, [1]

$$f_{P,DH} = \frac{\sum_i Q_{F,i} \cdot f_{P,F,i} - W_{CHP} \cdot f_{P,elt}}{\sum_j Q_{C,i}}$$

$Q_{F,i}$ – fuel (final energy) input to the heating plants and to the cogeneration plants within the considered system within the considered period (usually one year) - measured at the point of delivery;

W_{CHP} – electricity production of the cogeneration plants of the considered system;

$Q_{C,j}$ – heat energy consumption measured at the primary side of customer's substations within the *considered time (usually one year);*

$Q_{CHP,ext}$ – heat delivery to the considered system from external cogeneration power plants

$f_{P,F,i}$ – primary energy/resource factor of fuel (final energy inputs);

$f_{P,elt}$ – primary energy/resource factor of electrical power.

CO_2 emissions from a district heating system

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$$K_{dh} = \frac{\sum_{i=1}^{n} Q_{F(i)} * K_{F,tot(i)} - \sum_{i=1}^{n} \frac{W_{chp(i)} * K_{F,chp(i)}}{\eta_{el,(i)}}}{\sum_{j=1}^{n} Q_{C(j)}}$$

K_{dh} – carbon dioxide emission-factor for heat delivered to the building in $kgCO_2$/MWh,
$Q_{F(i)}$ – net energy content of fuel '*i*' delivered to the gate where it is finally converted to heat {MWh] (using lower heating value),
$K_{F,tot(i)}$ – carbon dioxide emission factor for fuel '*i*' in kg CO_2/MWh_{fuel},
$W_{chp(i)}$ – net produced electricity in co-generation plant from fuel '*i*' (produced electricity minus auxiliary electricity use),
$K_{F,\ chp(i)}$ – total greenhouse gas emission factor for electricity produced in CHP plant in kg CO_2/MWh,
$\eta_{el,(i)}$ – default electrical efficiency condensing for a conventional thermal power plant set to 40%,
$Q_{C(j)}$ – delivered heat to the building '*j*' at system boundary.

Allocation of CO_2 emissions to electricity and heat produced by CHP installations

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The allocation of CO2 emission to the CHP energy outputs is required especially in the case when produced heat and electricity are consumed by different customers and when a comparison needs to be made with other means of supplying heat.

In CHP plants when heat and electricity are generated simultaneously it is difficult/debatable how to precisely allocate the primary energy input, emissions or operating costs to either of these energy outputs.

Figure 5. The 50 kW cogeneration unit; source: A.Cenian, IMP PAN

CO_2 allocation methods

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The following (most popular in EU) methods were assessed in LowTemp project

Energy method,
Alternative generation method,
Power bonus method,
Exergy method,
200% method,
Pas 2050,
Dresden method.

There are other methods

Work method
Finnish method
All savings allocated to electricity
All savings allocated to heat
50%-50% sharing of savings between heat an electricity
Primary energy content of heat and electricity.

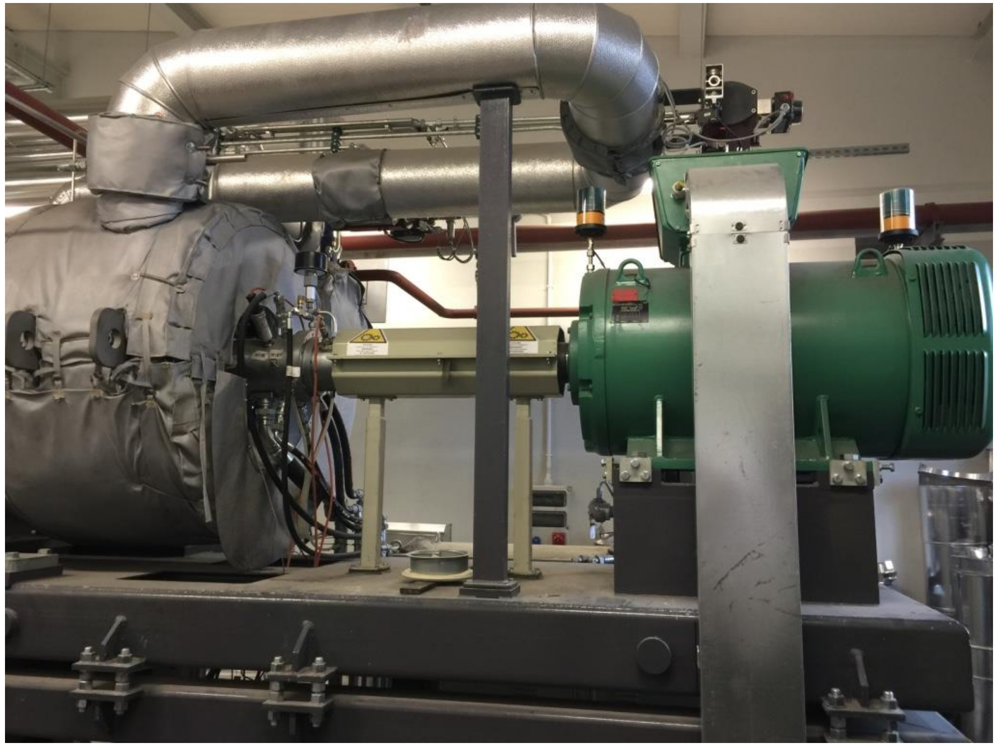


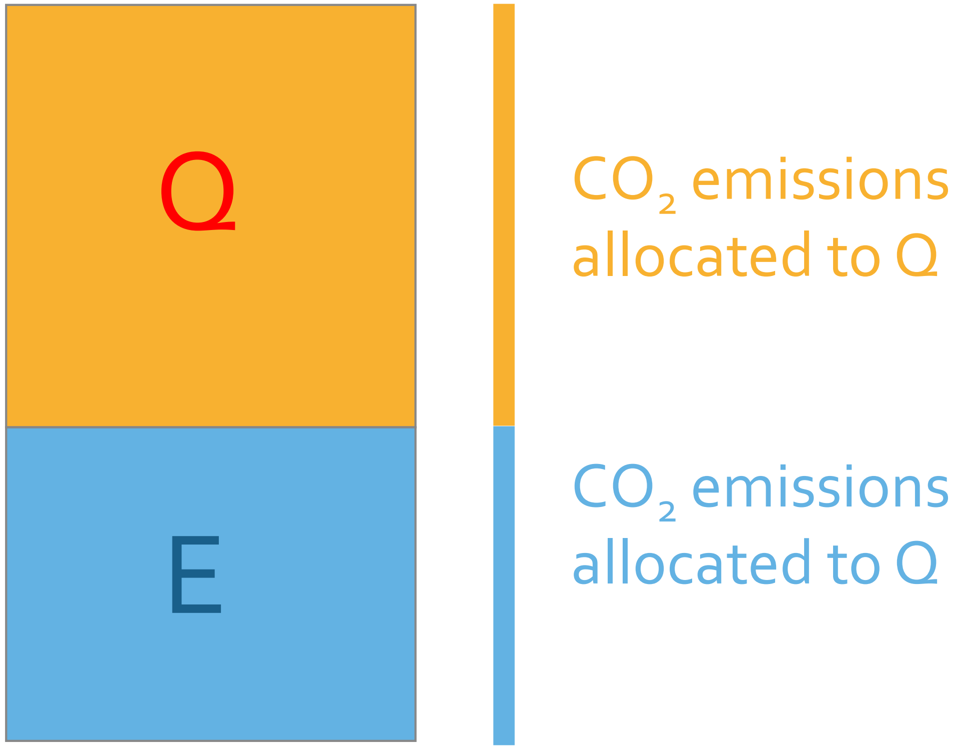
Figure 6. The 120 kW ORC CHO turbine; source: A. Cenian, IMP PAN

The Energy Method

The Energy Method - fuel input or CO_2 emissions are allocated to the produced heat and electricity based on the energy content of the produced products. The advantage of this method is that it is very simple and transparent. The disadvantage is that the energy content of the products does not distinguish energy products, i.e. does not take into account their qualities (electricity can be easier transformed to heat than opposite).

CO2 allocation factor for heat production:

$$f_Q = Q / (Q + E)$$

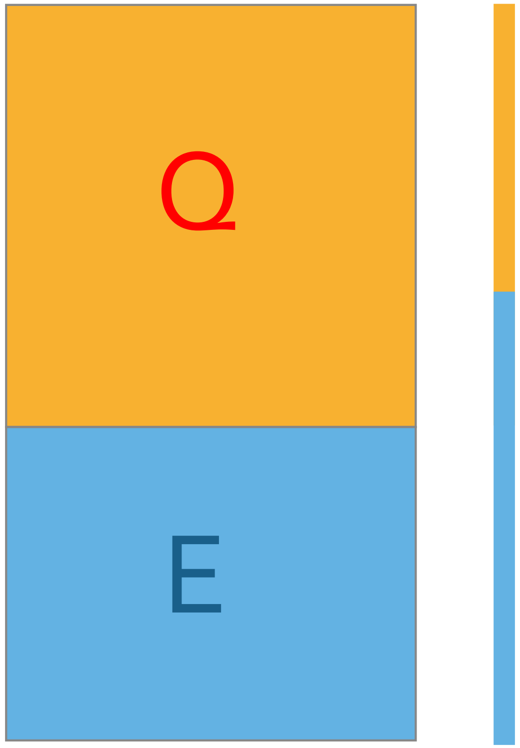


Produced heat nad power

The Alternative Generation method

The Alternative Generation method also known as the Efficiency Method or the Benefit Sharing Method (BSM) has been developed by The Finnish District Heating Association. The method allocates CO_2 emissions and resources to the heat and power production in proportion to the fuel needed to produce the same amount of heat or power in separate plants. Alternative production in two separate plants, will depend on their efficiencies η_{heat} and η_{elec} respectively.

$$f_Q = (Q/\eta_{alt\_heat}) / (Q/\eta_{alt\_heat} + E/\eta_{alt\_elec})$$



CO_2 emissions allocated to Q

$f_Q = (Q/\eta_{alt\_heat}) / (Q/\eta_{alt\_heat} + E/\eta_{alt\_elec})$

CO_2 emissions allocated to Q

$f_E = 1 - f_Q$

Produced heat nad power

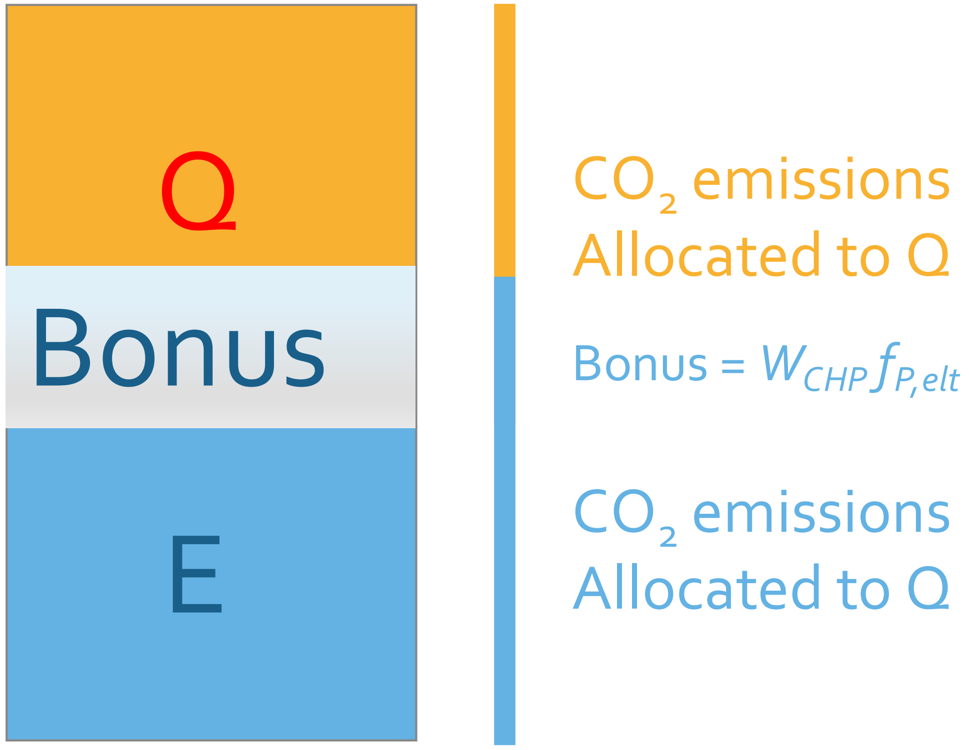
The Power Bonus Method

The Power Bonus Method is often used for allocation of CO_2 emissions between heat and power production in the European Union.

In this method the heat is the main product, while power produced during the process is considered as a bonus.

The primary energy is allocated first to the electricity produced in the CHP plant, which is later subtracted from primary energy input.

$$f_Q = (E_{P,in} - W_{CHP} f_{P,elt}) / (Q_{del} + E_{del})$$



Produced heat nad power

The Exergy Method

The Exergy Method (physically correct method) - fuel use or CO_2 emissions are allocated to the produced heat and electricity based on the exergy content of the products. The exergy content of a product is a measure for the maximum useful work that can be performed by the product. The ratio between the energy and exergy content is referred to as the quality factor.

From the thermodynamic point of view, electricity generated during cogeneration is rated with an exergy factor of 1, so the exergy of electricity is defined as $\boldsymbol{Ex_E = E}$. This means that 100% of electricity can be converted to any form of energy. Heat can be converted to power or any other form of energy only to some extent, so the heat exergy can be calculated

$$Ex_Q = (1 - T_o/T)\,Q$$

where T_o – is the average ambient temperature during the heating period and T – is DH thermodynamic mean temperature

$$T = (T_s - T_r) / \ln (T_s/T_r)$$

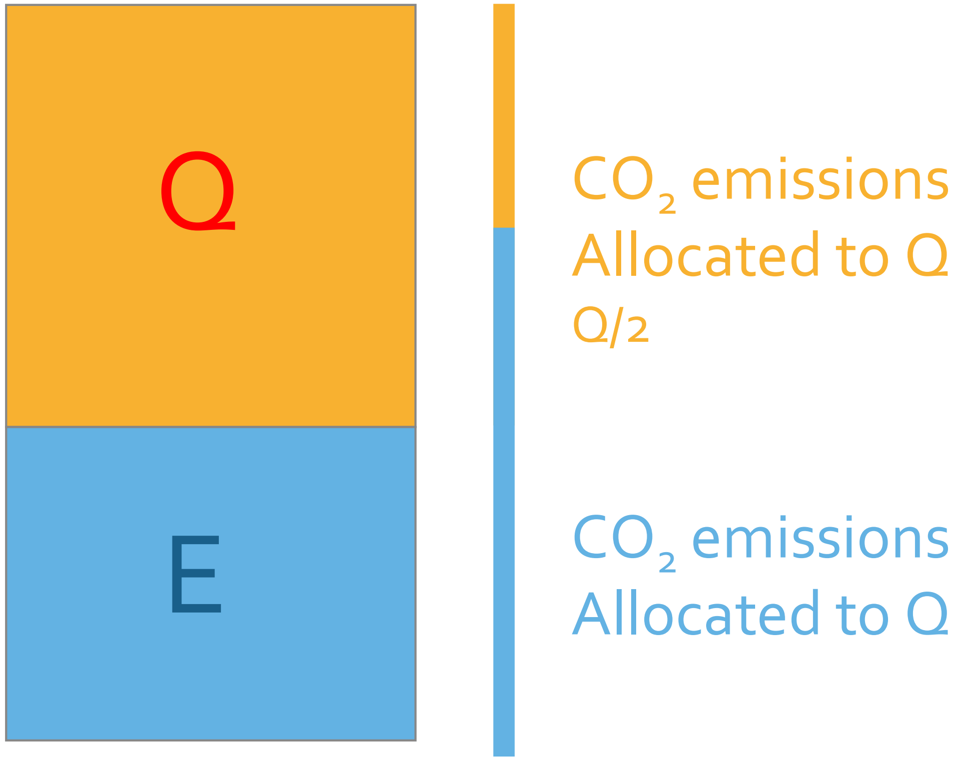
$$\boldsymbol{f_Q = Ex_Q / (Ex_Q + Ex_E)}$$

The 200% method

The 200% method – assumes 200% efficiency for heat production. This means that, in order to produce 1 unit of heat, 0.5 unit of fuel has to be used and the other 0.5 unit will be recovered from the turbine condenser. This means that half of emissions related to heat production can be associated with power generation.

This method, introduced by the Danish Energy Agency, can be used when allocating the fuel costs of the CHP to the heat production in the energy and emission statistics.

$$f_Q = Q \,/\, 2\, Fuel_{in}$$



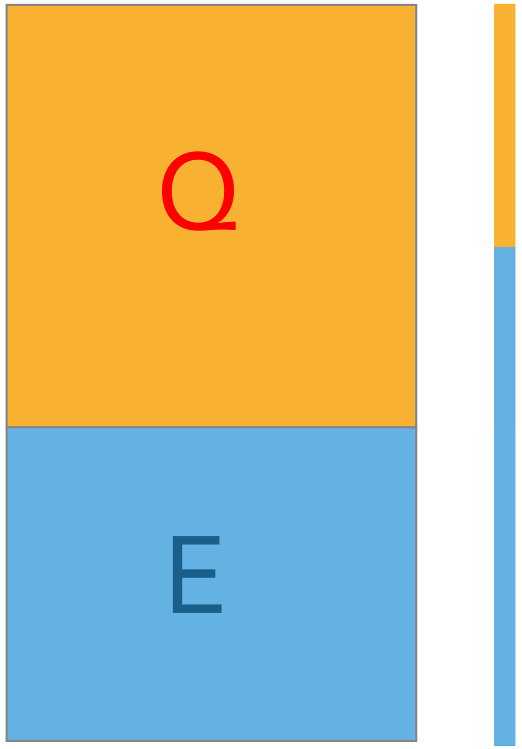
Produced heat nad power

PAS 2050 method

PAS 2050 method is the British standard, which explains the calculation of GHG emissions for production of goods and services. Allocating the emissions from CHP system to the heat and power produced, the special 'intensity' coefficient *'n'* is used, which specifies the emissions released during fuel combustion

$$f_Q = Q / (Q + n E)$$

The allocation of emissions to heat and electricity relies on the process-specific ratio of heat to electricity from each CHP system. For boiler-based CHP systems (coal, wood, solid fuel), the coefficient *n is 2.5*, while for turbine-based CHP systems (natural gas, landfill gas) *n = 2.0*.



CO_2 emissions Allocated to Q

$f_Q = Q / (Q + n E)$

CO_2 emissions Allocated to Q

$f_E = 1 - f_Q$

Produced heat nad power

The Dresden method

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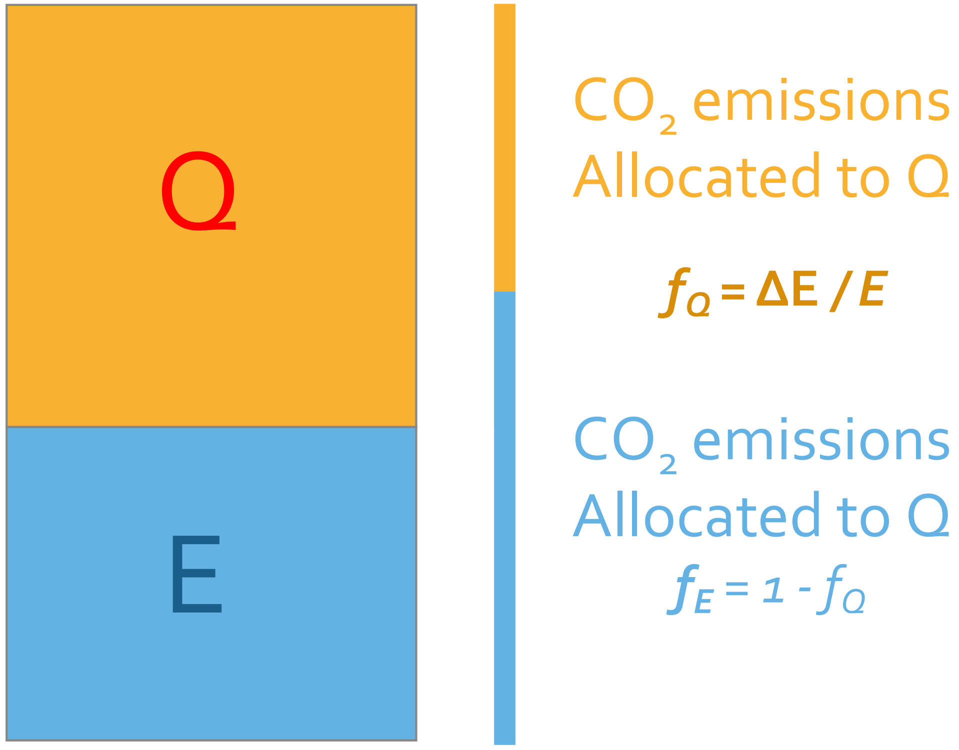
The Dresden method is based on exergy assessment. In power plants all primary energy is related to electricity production. At the same time in the CHP plants, one part of primary energy is consumed for thermal energy production. The *Dresden method* describes how to evaluate the electricity loss caused by the heat extraction (water steam condensation) in the CHP plant

$$\Delta E = Q\ \eta_c\ \nu_p ,$$

where η_c is Carnot efficiency and ν_p is degree of process quality.

$$f_Q = \Delta E / E$$



Produced heat nad power

CO_2 allocation factors CO2 for heat production

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Allocation factor for CHP system with annual heat load 27 GWh and maximum heat requirement 14 MW

Method	**Allocation factor of heat production, f_Q**	***E.g. f_Q value***
Energy method	$Q / (Q + E)$	0,2162
Alternative generation meth.	$(Q/\eta_{alt\_heat}) / (Q/\eta_{alt\_heat} + E/\eta_{alt\_elec})$	0,3830
Power bonus method	$(E_{P,in} - W_{CHP}\, f_{P,elt}) / (Q_{del} + E_{del})$	0,2226
Exergy method	$Ex_Q / (Ex_Q + Ex_E)$	0,1507
200% method	$Q / 2\, Fuel_{in}$	0,0608
PAS 2050	$Q / (Q + n\, E)$	0,1212
Dresden method	$\Delta E / E$	0,0834

Source: T. Tereshenko, [2]

Sensitivity of CO_2 allocation methods

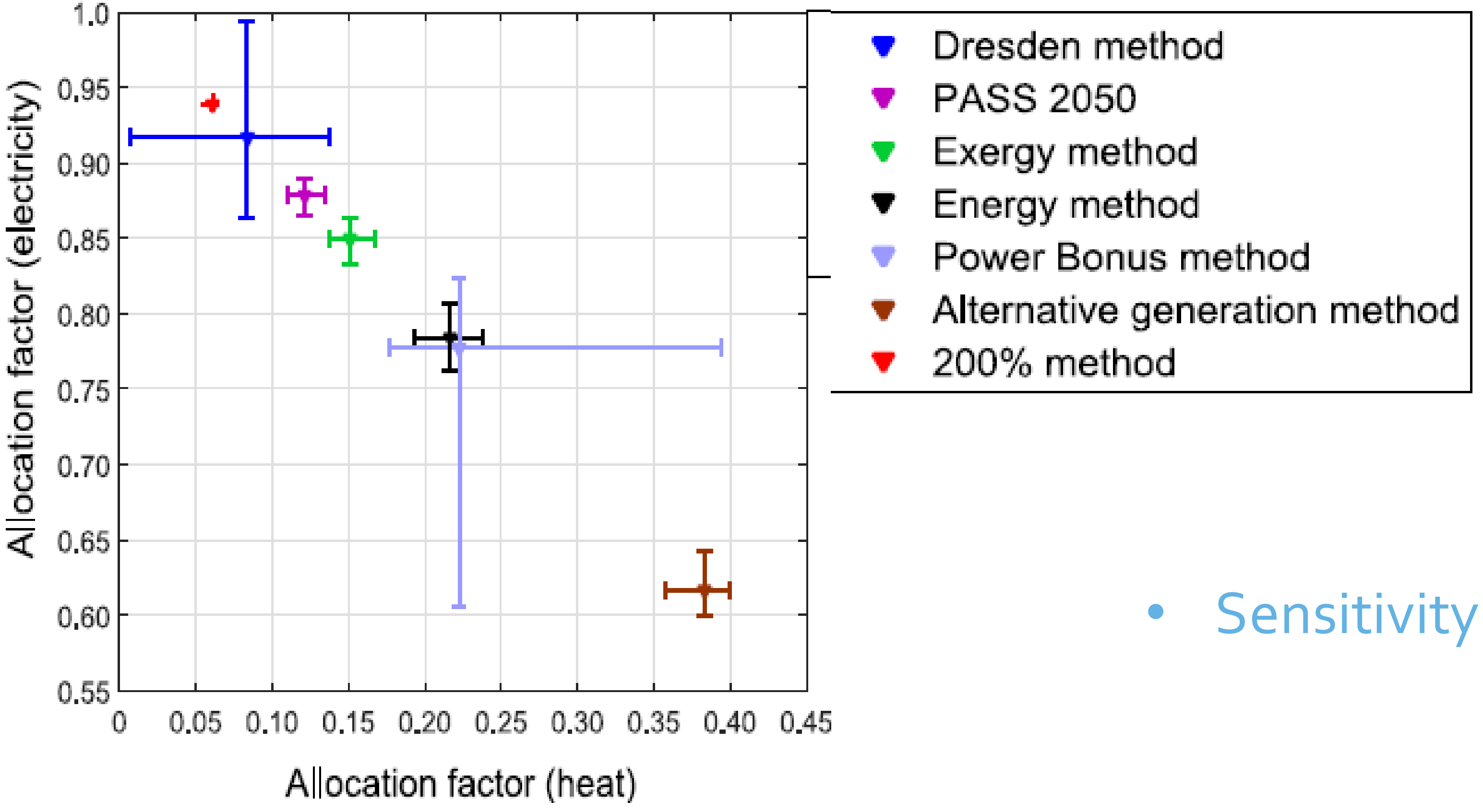

Figure 7. Sensitivity of CO2 allocation methods; source: T.Tereshenko et al.[2]

- Sensitivity depends on a system

LTDH project assessment of CO_2 allocation methods

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Project LowTEMP evaluated **CO_2 allocation methods** using Multi-criteria decision analysis and nine criteria belonging to four groups:
popularity (**Simplicity of the method**, **Area of application**, and **Method recognized and proven**), thermodynamic aspects (**Appropriate for allocating CO_2 emissions**, **Thermodynamical plausibility**, **Inclusion of CHP efficiency**, **Exergy**), availability of data and sensitivity.

The criteria and later methods have been evaluated by 7 partners of the BSR LowTEMP project: AGFW, ZEBAU, BTU, RTU, IMP PAN, Thermopolis, and HEM from 5 BSR countries (Germany, Finland, Latvia, Poland, and Sweden).

MCDA criteria

- **Simplicity of the method,**
- **Area of application,**
- **Method recognized and proven**
- **Appropriate for allocating CO_2 emissions,**
- **Thermodynamical plausibility,**
- **Inclusion of CHP efficiency,**
- **Exergy**
- **Availability of data**
- **Sensitivity**.

LTDH project assessment of CO_2 allocation methods

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Table 4.1. Weights proposed by Partners and their aggregations (arithmetic means – eq. (4.3)).

LowTEMP Partner	Simplicity of the me-thod	Area of ap-plication	Method recognized and proven	Appropriate for allocating CO2 emissions	Thermodynami-cal plausibility	Inclusion of CHP efficiency	Exergy	Accessibility of data	Sensitivity
AGFW	1	5	2	5	5	5	4	2	4
ZEBAU	1	5	2	5	5	5	3	2	3
BTU	2	3	3	4	5	4	4	3	4
RTU	3	3	3	3	3	3	3	3	3
IMP PAN	3	3	4	3	5	3	4	4	3
Thermopolis	4	4	4	4	3	2	1	4	4
HEM	5	4	3	5	3	3	2	5	4
Average	2.714	3.857	3.000	4.143	4.143	3.571	3.000	3.286	3.571

Source: Own calculations based on MCDA

LTDH project assessment of CO_2 allocation methods

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Table 4.2. Scores for the chosen method in MCDA analysis.

Method	AGFW	ZEBAU	BTU	RTU	IMP PAN	Thermopolis	HEM	SUM	Ranking	Variation
Energy method	52.000	52.000	49.857	52.286	53.143	**59.143**	53.143	**371.57**	**5**	**5.0%**
Alternative generation method	43.286	53.286	46.429	52.714	45.857	36.429	40.571	**318.57**	**7**	**12.5%**
Power bonus method	48.286	48.286	41.286	52.143	**55.429**	44.571	39.857	**329.86**	**6**	**11.1%**
Exergy method	**71.000**	**71.000**	**70.714**	**60.714**	**60.571**	**59.429**	**57.000**	**450.43**	**1**	**9.0%**
200% method	**60.286**	56.857	**59.143**	56.143	53.143	44.571	**66.000**	**396.14**	**3**	**10.9%**
PAS 2050	57.571	**57.000**	**59.429**	**63.857**	**57.286**	44.571	**58.571**	**398.29**	**2**	**9.6%**
Dresden Method	**63.857**	**63.857**	45.714	**60.143**	46.286	44.571	50.429	**374.86**	**4**	**15.1%**
	15.5%	**12.4%**	**17.9%**	**7.7%**	**9.5%**	**16.5%**	**16.9%**			

LowTemp recommendations

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The Partners have pointed **Exergy (Carnot) method** as the best evailable method (above 450 points) for CO_2 allocation at least among the considered. Two other methods: **PAS 2050** and **200%** should be considered as possible alternative – they have received similar score i.e. almost 400 points.

The most appropriate from a thermodynamic point of view – the **Exergy method** – includes more extensively energy quality and maps a physical upper limit for the CO_2 allocation to heat as a by-product. There is a variant of the Exergy method – **Dresden**, but it requires more data availability and more extensive calculations.

The **Alternative generation** and **Power bonus method** have been found as least useful ones by project Partnership.

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