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Emission Calculation Methodologies for CHP Plants

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Abstract

The paperdiscussesdifferent calculation methods to correctly express the emission level of air pollutants produced byCHP(CombinedHeatandPower) systems, in order to take into account the environmentalbenefitdueto cogeneration. New and established methods to estimate the emission saving due to cogeneration of heat and power are reviewed and compared, with reference to small scale CHP systems; the paper clarifies that a proper emission assessment of CHP systems should consider both the global and the local scales of environmental impact. In particular, the method of the "avoided heat generator" is proposed in this study, for a local-scale environmental impact evaluation. This approach calculates the reduction of emission due to CHP operation, in comparison with the non-CHP operation of the same machine, taking into account the amount of pollutant emitted by a heat generator which provides the same thermal power of the cogenerator. Moreover, it is shown in the paper that another method, based on the PSI (Pollutant Saving Index) value, is suitable to estimate the global-scale environmental impact.

The problem of the most representative unit of measure is also discussed, highlighting the advantages of an "output based" approach and providing easy-to-use formulas and graphs for the conversion of concentration values into output-based emission factors. Finally, a numerical evaluation of the CHP environmental benefit is provided for small electric power size CHP machines.

Keywords: Combined Heat and Power (CHP); pollutant emission; emission factor; micro gas turbine; reciprocating engine

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1. Introduction

Cogeneration is a sustainable, technically viable and economically convenient strategy to reduce the primary energy demand [1]: the energy saving due to CHP (Combined Heat and Power) systems leads to a lower dependency on fossil fuels, and to a reduction of the Green House Gas emissions.

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Many CHP systems based on internal reciprocating engines (ICEs), steam turbine cycles or combined cycles are currently installed for industrial applications, with electric power size in a range of medium values (1-20 MW); a market potential for ICEs, Micro Gas Turbines (MGTs), Stirling and ORC (Organic Rankine Cycles) systems can be also identified in the field of small power systems (5-100 kW) especially for domestic applications, in the framework of distributed energy generation; this is shown for example in [2] and [3], studies which highlight the micro-CHP systems convenience, taking into account the actual heat and power demand of residential buildings.

The CHP production is supported in many countries, taking into account the energy saving factor; among the different efficiency parameters, the PES (Primary Energy Saving) index [1] is the most significant to qualify a CHP plant; this index measures the amount of primary energy resource saved with CHP, in comparison with the Separated Production (SP) of heat and electric power (see, for example [4]). On the other side, a lack of dedicated regulation and guidelines for CHP emission specification can be observed; CHP systems are often constrained by the same environmental regulations and air pollution emission standards applied to non-CHP systems.Different contributions to the discussion on the issue of CHP emission can be found, e.g. [5-11]. Methodologies for quantifying the emission of CHP and SP are discussed in [9-12], mainly linking the environmental benefit of CHP to the reduction of primary energy [10] or to the exergy analysis [13].The aim of a CHP system should be to contextually minimize the environmental impact and the consumption of primary energy.

Nomenclature

Symbols

E	energy [kJ]
h	hours [h]
K	stoichiometric dry flue gas per unit of fuel [Nm^3/kg]
P	power [kW]
X	O_2 volume fraction [%]
x	element mass fraction [-]
γ	mass concentration [Nm^3/kg]
δ	output-based specific emission [mg/kWh_e]
λ	input-based specific emission [mg/kWh_{LHV}]
Λ	total mass of emitted air pollutant [mg]
η	efficiency [-]

Subscripts and superscripts

avd	avoided
conv	conversion
e	electrical
lim	limit value, electric or thermal produc.
min	minimum value
t	thermal
(‘)	of the reference SP

The present work provides a comprehensive overview on methods for the assessment of CHP emissions in comparison with SP; the key advantages and disadvantages of each method are highlighted, in order to perform a meaningful comparison. The aim of this study is to provide a criterion to better select the most appropriate method for emission saving estimation. The applied contribution of this paper is also to suggest strategies for the implementation of dedicated regulations for CHP emission, especially in the regional areas and in the applications sectors where these regulations are currently under discussion. The following aspects are clarified in the paper: i) The unit of measure to better indicate the amount of air pollutants released by a CHP system; ii) The emission standard values to comply with, when the energy system is operated in CHP mode, with reference to the existing emission standard for non-CHP systems; iii) The methods to assess the emission saving due to CHP operation of the plant in comparison with the SP.

1.1. Local/global environmental impact of CHP air pollutants

First of all, a distinction should be carried out between local and global impact of CHP, as suggested also in [9]. The chemical composition of flue gases and the quantity of air pollutants produced by CHP systems are strongly linked with the combustion process (premixor non-premix, stoichiometric or "lean burnt", continuous or cyclic, etc.), with the fuel composition (mostly NG, but also other fossil or renewable fuels) and with the kind of energy system (MGT, ICE, etc.), and finally with the technological level (state-of-the-art or old-generation). Species such as NO_X and CO are the predominant air pollutants emitted by CHP systems (especially the most diffused NG fuelled ICEs and MGTs), while other species emerge only in particular conditions (e.g. PM and VOC produced by ICE run on Diesel fuel).

Each pollutant is characterized by a distinctive spatial range of action, a key aspect to consider for CHP system; two opposite scales apply: i) global impact scale, related to air pollutants with a negative effect on the environment totally independent on the distance from the source (e.g, CO_2); ii) local impact scale, for pollutant with negative effects only around the source plant, depending on dispersion, extinction phenomena and residence time (see Fig. 1 showingspatial range of pollutants).

The involved area can be more or less critical for specific pollutants (e.g.PM in the urban areas). In case of small CHP, the local impact is a key aspect: the installation of the system in a given site, if it replaces a far centralized power production, is conditioned by a local impact assessment for the nearby users and hazardous species receptors. The CHP emission estimation is oriented toward a local or a global impact assessment, depending on the pollutant under investigation: a different philosophy should be used in the framework of the regulations.

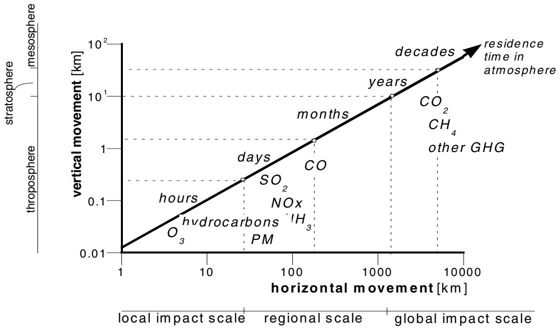

Fig. 1

2. Unit of measure for a correct indication of CHP emission

In many air pollution and control regulations (e.g., [14-16]) and technical documents, the air pollutant emissions of a prime mover are mainly indicated by means of vol. or mass concentration in the dry flue gases (in [ppm_{vd}] or [mg/Nm^3]). In case of CHP and especially if a comparison between different kind of energy systems is required, the use of concentration can be misleading. Indeed, the concentration values are conventionally referred to a prescribed O_2 content in the dry flue gas, which varies depending on the system type (15% for GT, 5% for ICE, 3% for boilers run on gas and liquid fuels). Moreover, the use of concentration unit provides indication neither on the flue gas mass flow nor on the system power size; both these aspect are important in the framework of an environmental assessment.

The concentration can be converted, for a given fuel, to the mass of pollutant per unit of fuel input energy, with reference to its LHV,λ (mg/kWh_{LHV}).This conversion requires to know the fuel composition: λ can be calculated as a function of the mass concentration γ_x (mg/Nm^3) with reference to a given O_2 volume fraction in the dry flue gas X %:

$$\lambda = 21/(21-X) \cdot \gamma_x \cdot (3600/LHV) \cdot K \qquad (1)$$

where the term21/(21-X)converts the flue gas composition to the stoichiometric condition; K(Nm^3/kg) represents the amount of stoichiometric dry flue gas per unit of fuel mass.

In the case of a fuel containing C, H, N, S and O, *K* can be obtainedby the stoichiometric reaction:

$$C_cH_hS_sN_nO_o+\left(c+\frac{h}{4}+s-\frac{o}{2}\right)\left(O_2+3.76N_2\right)\rightarrow cCO_2+\frac{h}{2}H_2O+sSO_2+\left[3.76\left(c+\frac{h}{4}+s-\frac{o}{2}\right)+\frac{n}{2}\right]N_2 \quad (2)$$

Then, the volume of dry flue gas per unit of fuel mass is given by:

$$K=22.414\left(4.76/12\cdot x_C+3.76/4\cdot x_H+4.76/32\cdot x_S-3.76/32\cdot x_O+1/28\cdot x_N\right) \quad (3)$$

where, x_C, x_H, x_N, x_S e x_O are the mass fractions of the fuel elements and the term under brackets represents the kmol of dry gasperkgof fuel. Calculated values of the *K* factor are in Table 1 for different fuels.

The definition of λ is based on an *input-based* approach i.e. the pollutants quantities are referred to the input fuel energy. Following this approach (used in [17]), it is possible to compare systems of different typology and size with equal fuel energy consumption. Nevertheless, this unit of measure, derived from γ_x, does not take into account the quality of the thermodynamic energy conversion.In order to overcome this limitation, emission can be indicated with reference to the system output production ([9,17,18]), represented by the electric energy production in case of a prime mover. In this case the specific emission, named in this paper asδ, is an *output-based* quantity (mass of pollutant species per unit of electric energy, (mg/kWh$_e$)). Instead, in the case of a heat generator, the *output-based* specific emission can be defined with reference to the produced thermal energy (mg/kWh$_t$).In general, the *output-based* specific emission is defined as:δ/η_{conv}, where η_{conv} is the conversion efficiency of the process transforming the fuel energy into "useful" energy (i.e., for an engine, this is the electric efficiency and for a heat generator it is the thermal efficiency).The *output-based* approach leads to the following advantages: (i) it is clear indicator of the ratio between environmental cost and energy benefit for the users; the value of δ depends also on η_{conv}, while λ does not; thus, the use of the *output-based* approach encourages the adoption of more efficient power plants. A synergic effect between the efficiency strategies and the pollution prevention policies can be pursued; (ii) suggests that increasing η_{conv} is a strategy to reduce emission of all the involved pollutants at the same time; (iii) the reduction of $\delta$by increasing η_{conv} is a strategy alternative to the adoption of complex and often not fully "clean" flue gas treatment systems[2]; in the framework of a *output-based* approach, the evolution towards more stringent emission standards requires less significant modifications in new efficient plants and stronger changes in old plants; thus, a rapid shift towards emerging technologies are encouraged by a *output-based* indication of emission.

Table 1: the *K* factor for different fuels

Fuel	**C**	**H**	**S**	**N**	**O**	***LHV***	***K***	**Fuel**	**C**	**H**	**S**	**N**	**O**	***LHV***	***K***
CO	42.9	0.0	0.0	0.0	57.1	10096	2.3	Ethanol	52.1	13.1	0.0	0.0	34.8	26400	6.5
Methanol	37.5	12.5	0.0	0.0	50.0	19700	4.6	Palm oil	76.4	11.7	0.0	0.0	11.5	36500	8.9
Methane	75.0	25.0	0.0	0.0	0.0	50140	11.9	Soybean oil	78.3	11.3	0.0	0.0	10.3	36800	9.1
LPG	82.4	17.7	0.0	0.0	0.0	46100	11.0	Coal	83.1	3.9	0.8	1.5	4.4	33500	8.1
Diesel	86.0	13.0	0.0	0.0	0.0	42860	10.4	Biogas	44.1	8.8	0.0	0.0	47.1	17699	4.5
Biodiesel	77.0	12.0	0.0	0.0	11.0	37100	9.1	Hydrogen	0.0	100	0.0	0.0	0.0	121000	21.0

Figure 2 presents a diagram useful to convert the concentration into *output-based* specific emission, provided the O_2 concentration and η_{conv} are known; in order to obtain λ and δvalues, the *K* of the fuel must be calculated with eq. (3). Both λ and δ do not provide complete information on the local impact, which can be measured in terms of the total amount of emitted pollutant (Λ) proportional to δ, to the power plant size *P* and to the number of equivalent hour *h*, according to: $\Lambda=\delta\,P\,h=\left(\lambda P\,h\right)/\eta_{conv}$.

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[2] For example, the ammonia slip phenomena emerge when aSCR is introduced for NOx emission abatement.

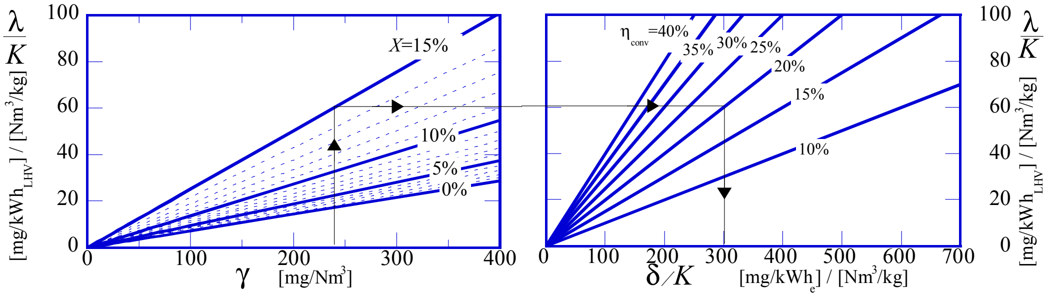

Fig. 2. conversion of air concentration into input-based and output-based specific emission.

3. Methods for CHP systems emission assessment

The assessment of CHP specific emissions should take into account that CHP provides a double output. Therefore, in the framework of a *output-based* approach, the specific emissions of the CHP plant could be calculated: i) by referring the emission to the thermal production, considering the CHP similar to a heat generator; i) by referring the emission to the electric production, considering the CHP similar to an electricity generator; iii) by introducing a new definition of specific emission, which takes into account both the outputs.[3]For each approach, it is necessary to define a criterion to quantify the convenience of the CHP system; the comparison should be respectively with a heat generator, with a non-CHP prime mover, or with the SP. Different calculation methods of the CHP emissions can be introduced.

3.1. Methods to express CHP emission with reference to the thermal energy

If the specific emission of a CHP plant is calculated with reference to the produced thermal energy, in order to comply with the heat generator environmental rules, the limiting condition in terms of *output-based* emission is:

$$(\lambda_{CHP}/\eta_t) < (\lambda_{\lim,t}/\eta'_t) \quad \text{METHOD OF THE EQUIVALENT HEAT GENERATOR} \qquad (4)$$

where λ_{CHP} is the emission of the cogenerator,$\lambda_{lim,t}$ is the limit value (the emission standard established by the local rules, expressed in terms of *input-based* specific emission) for the heat generator,$\eta_t$is the thermal efficiency of the CHP system and η'_t is the efficiency of a reference heat generator.

This criterion, named here as "method of the equivalent heat generator", tends to penalize the CHP systems; indeed, in general the inequality $\eta_t < \eta'_t$is valid, considering a CHP and a non-CHP system with the same thermal energy output; therefore, the amount of fuel and of emitted pollutants will be larger in the case of the CHP plant; but the CHP plant produces also electricity, not taken into account.

In order to recognize an environmental benefit of cogeneration due to the additional production of electric energy, it is possible to reduce the CHP system emissions subtracting the avoided emissions due to the electric energy production. In this case, the following expression applies:

$$\lambda_{CHP}/\eta_t - (\lambda'_e/\eta_e)\cdot(E_e/E_t) = ((\lambda_{CHP} - \lambda'_e)/\eta_t) < \lambda_{\lim,t}/\eta'_t \quad \text{METHOD OF AVOIDED ELECTRIC PRODUCTION} \qquad (5)$$

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[3] In the first case the emission standards are the ones valid for the heat generators; in the second the reference is the emission standard of the prime mover; in the last case new limitation should be introduced for CHP systems.

where E_t and E_e are the thermal and electric produced energies, η_e is the electric efficiency of the CHP and λ'_e is the *input-based* specific emission of a reference electricity generation system; the second left hand term represents the saved emission due to the avoided electricity production, equal to the emissions of a reference engine with electric power size equal to the CHP size. This approach, indicated here as “method of the avoided electric production”, requires the choice of a reference value for λ'_e.

The above introduced approaches consider the thermal production as the main useful effect of the CHP system; nevertheless, the most thermodynamically valued energy generated by the CHP system is the electric production.This is true especially in the “topping” CHP applications,where the heat discharged by the topper is recovered downstream,as a by-product of the main thermodynamic transform. In the less diffused case of bottoming CHP systems (e.g., ORC systems) instead, the electric energy is the by-productof the topping conversion process, aimed at producing heat as main output; in this case the method of avoided electric production seems more appropriate.

3.2. Methods to express CHP emission with reference to the electric energy

If the CHP system is considered as a prime mover, its specific emission can be referred to the produced electric energy, as mentioned before. The CHP actual emissions, indicated with δ_{CHP}, could be compared with a limit value $\delta_{lim,e}$ related with the emission standards imposed by the existing environmental regulation on prime movers; nevertheless this approach neglects the environmental benefit due to the heat recovery and considers the CHP system equal in terms of emission to the system without hear recovery.In order to quantify this environmental benefit of CHP, it is possible to estimate the avoided emission δ_{avd} which reduces the actual emission of the system, thanks to the heat production; the limit condition becomes: $\delta_{CHP}-\delta_{avd}<\delta_{lim,e}$. The δ_{avd} can be calculated with different approaches described below.

Method of the avoided heat generator: in this case δ_{avd} is calculated considering that, thanks to the heat recuperation, it is possible to avoid a heat generator and the related emission.The total avoided emission (Λ_{avd}), due to the elimination of heat generator with a thermal size equal to the CHP thermal power output, and the avoided specific emission are calculated as:

$$\Lambda_{avd} = \lambda'_t \cdot (E_t/\eta'_t) \qquad \delta_{avd} = (\lambda'_t/\eta'_t)\cdot(\eta_t/\eta_e) \text{ METHOD OF THE AVOIDED HEAT GENERATOR} \quad (6)$$

where λ'_t is the specific emission of the avoided heat generatorand E_t/η'_t its energy consumption. This method provides a measure of the environmental pressure affecting the receptors close to the CHP which receive the emission by the plant, but escapes the emission of the avoided heat generator.

Method of Ecabert:in this case, firstly, the reduction in fuel consumption of the prime mover is evaluated by subtracting from the fuel consumption of the CHP system the quantity E_t/η'_t, representing the amount of fuel energy of a reference heat generator with the same thermal production of the CHP [8]. Then, the following equationsareused to express the total and specific emission saving respectively:

$$\Lambda_{avd} = \lambda_{CHP}(E_t/\eta'_t) \qquad \delta_{avd} = \delta_{CHP}(\eta_t/\eta'_t) \text{ METHOD OF ECABERT} \quad (7)$$

Thus, it is not required to specify the environmental performance of the avoided heat generation.

Method based on *PES*: the environmental benefit of cogeneration is evaluated as a function of the fuel saving due to CHP, in comparison with the SP. The fuel saving is measured by means of *PES*, an indicator taking into account both electric and thermal production. The following expression apply:

$$\lambda_{CHP} - \lambda_{avd} = \lambda_{CHP}(E_{LHV}/E'_{LHV}) = \lambda_{CHP}(1-PES) \qquad (8)$$

where E_{LHV} and E'_{LHV} are the fuel energy consumption of the CHP and of the SP. The δ_{avd} becomes:

$$\delta_{avd} = \delta_{CHP}\ PES = \delta_{CHP} - \delta_{CHP} / \left((\eta_e / \eta'_e) + (\eta_t / \eta'_t) \right) \qquad \text{METHOD OF } PES \qquad (9)$$

As in the Ecabert, $\delta_{avd}$is proportional to the emission of the prime mover, and, in this case, to the CHP performance in terms of *PES*, which requires to define the reference efficiency values of the SP.

3.3. Method based on PSI

A different approach for assessing the environmental effect of CHP in terms of pollutant emissions consists in evaluating the difference between the total emission of the CHP system and the total emission of the SP. A new index is introduced,named Pollutant Saving Index (*PSI*), which quantifies the saving in pollutant emission, due to CHP:

$$PSI = \frac{\Lambda' - \Lambda}{\Lambda'} = 1 - \left(\delta_{CHP} E_e\right) \Big/ \left(\lambda'_e \frac{E_e}{\eta'_e} + \lambda'_t \frac{E_t}{\eta'_t} \right) = 1 - \delta_{CHP} \Big/ \left(\frac{\lambda'_e}{\eta'_e} + \frac{\lambda'_t}{\eta'_t} \frac{\eta_t}{\eta_e} \right) \qquad (10)$$

where Λ and Λ' are respectively the total emission of the CHP plant and of the reference SP. *PSI* is a function of many factors, including the reference efficiency and emission factorsvalues of SP.

According to the *PSI* approach, in order to provide a significant saving in pollutants, the following inequality must be verified:$PSI > PSI_{min}$, where PSI_{min} is a minimum standard of emission saving. Therefore, also a PSI_{min} value must be prescribed. The final condition to meet is:

$$\delta_{CHP} < \left(\lambda'_e / \eta'_e + (\lambda'_t / \eta'_t)(\eta_t / \eta_e) \right) \cdot \left(1 - PSI_{\min}\right) \qquad \text{METHOD OF } PSI \qquad (11)$$

This method is more apt to identify the global impact due to the replacement of the SP with the CHP, but the local impact is not clearly quantified, asthe emission saving is evaluated independently on the site of the CHP and of the SP.

4. Results for a small size CHP

The assessment of pollutant emissions due to CHP is currently under attention especially concerning small size systems (P_e<50 kW$_e$). These systems are typically nearby the users, connected to the electric grid at low voltage and used in CHP applications as alternative to the SP. In this study a preliminary calculation on two cases is carried out using the methods described above. Table 3 reports the energy and environmental performance of an ICE and a MGT in CHP application operated with NG.

Table 3. Energy and environmental performance of CHP ICE & MGT

	MGT	**ICE**
η_e - η_t	0.30 – 0.55	0.37 – 0.49
PES	0.176	0.224
NOx γ[mg/Nm^3]	50@15%O$_2$	250@5%O$_2$
NOx λ_{CHP} [mg/kWh$_{LHV}$]-δ_{CHP} [mg/kWh$_e$]	151 - 505	281 - 759
NOx δ_{avd} [mg/kWh$_e$](avd heat generator)	408	295
PSI (NOx)	0.407	-0.029
CO γ[mg/Nm^3]	50@15%O$_2$	300@5%O$_2$
CO λ_{CHP} [mg/kWh$_{LHV}$]-δ_{CHP} [mg/kWh$_e$]	151 - 505	337 - 911
CO δ_{avd} [mg/kWh$_e$](avd heat generator)	204	148
PSI (CO)	-0.024	-1.089
CO$_2$ δ_{CHP} [kg/kWh$_e$]	0.667	0.541
CO$_2$ δ_{avd} [kg/kWh$_e$] (avd heat generator)	0.407	0.294
PSI (CO$_2$)	0.754	0.792

Table 4. Reference values

Parameter	Value	Ref.
η'_t	0.90	[20]
η'_e	0.52	[20,21]
NOx λ'_t [mg/ kWh$_{LHV}$]	200	[22]
CO λ'_t [mg/ kWh$_{LHV}$]	100	[23]
CO$_2$: $\lambda'_t = \lambda_{CHP}$ [kg/kWh$_{LHV}$]	0.20	-
NOx λ'_e [mg/ kWh$_{LHV}$]	230	[24], [25]
CO λ'_e [mg/ kWh$_{LHV}$]	150	[25]
CO$_2$ λ'_e [kg/ kWh$_{LHV}$]	0.47	[24]

The emission values are calculated using the reference values in Table 4. The avoided heat generator method highlights an environmental convenience of CHP for both systems concerning NO_x, CO and CO_2; the calculated values of *PSI* are positive only for CO_2, become negative for ICE in case of NO_x and are negative for both systems in case of CO, showing that on a global environmental basis the use of these CHP systemscan be questionable.

5. Conclusion

This paper has shown the advantages of an output-based approach for the emission definition and a review of the methods to estimate the environmental benefit of cogeneration. In the frame work of all the presented methods, it is required to define some reference parameters of the electric and/or thermal power production and the chosen values can strongly affect the final numerical results. Moreover, in the specific case of small "topping" CHP systems it has been shown that the method of the avoided heat generator represents the best methods to estimate the local impact effect of distributed cogeneration.

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