Analysis of changes in the maximum allowable capacity of heat pumps at thermal power plants

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Abstract. This article is devoted to the assessment of the maximum allowable capacity of a heat pump unit (HPU), which can be integrated in a technological scheme, conditional upon a break-even operation in the electricity market for a number of existing thermal power plants (TPP) of Territorial Generating Company No. 1 (TGC-1). For the considered power plants, values of the maximum allowable capacity of a HPU were calculated for a period of 1 month. The most beneficial combine heat power plants (CHPPs) in terms of the methodology used in the study were the CHPP-22 and the CHPP-5. With a HPU's energy conversion coefficient (ECC) equal to 5, the average maximum allowable capacity for the CHPP-22 was 689.1 MW, and for the CHPP-5 – 711.6 MW. An assessment is given and the influence of the technical and economic indicators of stations on the formation of the final value of a heat pump's capacity is illustrated by the example of the CHPP-5. It is shown that when assessing and choosing the capacity of a heat pump for a real thermal power plant, it is necessary to take into account the complex of such technical and economic indicators of the operation of this station as: the amount of electricity supplied, the wholesale electricity market (WEM) weighted average cost of electricity supplied and the specific consumption of the reference fuel for electricity supply.

Keywords: thermal power plants; heat supply; heat pumps; electricity market; energetics

Introduction

Working within the tough framework of economic competition forces generating companies to take actions to reduce the consumption of primary energy resources. For thermal power plants, this is expressed in a decrease in the consumption of natural fuel for the production

of heat and electric energy. One of the promising directions indicated in the energy strategy of the Russian Federation until 2035 [1] for energy and resources conservation at TPPs is the use of heat pump units in technological schemes of TPPs for additional heat production at stations or optimization of operating modes. In this area, studies are being carried out in which the possibility of heat pumps' integration into schemes of power plants of various types is considered: basic cogeneration steam turbine units [2], condensing steam turbine units of nuclear power plants [3], and the increasingly popular combined cycle gas turbine units [4].

For a heat pump unit, it is important to determine its boundary conditions of operation (the maximum capacity), at which it ceases to be economically efficient in the wholesale electricity market. These boundaries are determined by the condition of a break-even operation in the electricity market: there is a full compensation of fuel costs by revenues from supplies to the electricity market [5]. Thus, for one generating company with several TPPs, the maximum capacity of a HPU can vary widely and depends on many factors that are determined by the characteristics of a particular station's production and marketing activities.

The purpose of this work is to determine the maximum capacity of heat pumps at a CHPP in a break-even operation on the electricity market, using the example of a generating company in the Russian Federation, and analyze factors, that affect on the capacity.

Materials and methods

All calculations were made for the generating company TGC-1 using data on the actual operating modes of its stations and data on the specifics of its' work in the wholesale electricity market. Ten CHPPs of TGC-1 were considered: Central CHPP (C-CHPP), Pravoberezhnaya CHPP-5, Vasileostrovskaya CHPP-7, Pervomayskaya CHPP-14, Avtovskaya CHPP-15, Vyborgskaya CHPP-17, Severnaya CHPP- 21, Yuzhnaya CHPP-22, Petrozavodskaya CHPP (P-CHPP) and Apatitskaya CHPP (A-CHPP). February 2021 was selected as the calculation period.

The method for finding the value of the maximum allowable capacity of a HPU is based on limiting the maximum capacity of a heat pump unit by the condition of a break-even operation in the electricity market (the should be a full compensation of fuel costs associated with electricity production by income from supplies to the electricity market) [5]:

$$Q_{HPU}^{\max} = W_{e/e} \times \left(1 - w_{TPP}^{ON}\right) \times \left(1 - b_{e/e} \times 10^{-3} \times \frac{P_{nf}^{act}}{C_{e/e}} \times \frac{29300}{Q_a^c}\right) \times \varphi, \quad (1)$$

where $W_{e/e}$ – hourly output of electricity from a TPP, MW;

w_{TPP}^{ON} – share of electricity for own needs;

$b_{e/e}$ – specific consumption of the reference fuel (r.f.) for electricity supply, kg r.f./(MW·h);

P_{nf}^{act} – natural fuel price, rubles/thousand m^3 (rubles/t);

$C_{e/e}$ – the WEM weighted average cost of released electricity, rubles/(MW·h);

29300 kJ/kg r.f. – the calorific value of the reference fuel;

Q_a^c – actual heat of natural fuel combustion, kJ/nm^3;

$\varphi=3\div5$ – HPU's energy conversion coefficient.

On the wholesale electricity market, power plants sell electricity simultaneously in several sectors. For TGC-1, two sectors are decisive: the day-ahead market (DAM) and the regulated contracts (RC). The WEM weighted average cost of electricity supplied, rubles/(MW·h):

$$C_{e/e} = \frac{W_{e/e.DAM} \cdot C_{DAM} + W_{e/e.RC} \cdot C_{RC}}{W_{e/e.DAM} + W_{e/e.RC}}, \quad (2)$$

where $W_{e/e.DAM}$ – electricity supply to the day-ahead market, MW·h;

C_{DAM} – the day-ahead market electricity cost, rubles/(MW·h);

$W_{e/e.RC}$ – electricity supply under the regulated contracts, MW·h;

C_{RC} – the regulated contracts electricity cost, rubles/(MW·h);

Results and discussion

For every day of the considered period the values of the maximum allowable capacity of a heat pump were found, using equation (1). Figures 1-3 show the values of the maximum, the minimum, and the average values of the allowable capacity of a heat pump unit for the above-mentioned TTPs with different values of HPUs' energy conversion factor.

The results show that the CHPP-5 and the CHPP-22 have the maximum allowable capacity of a HPU.

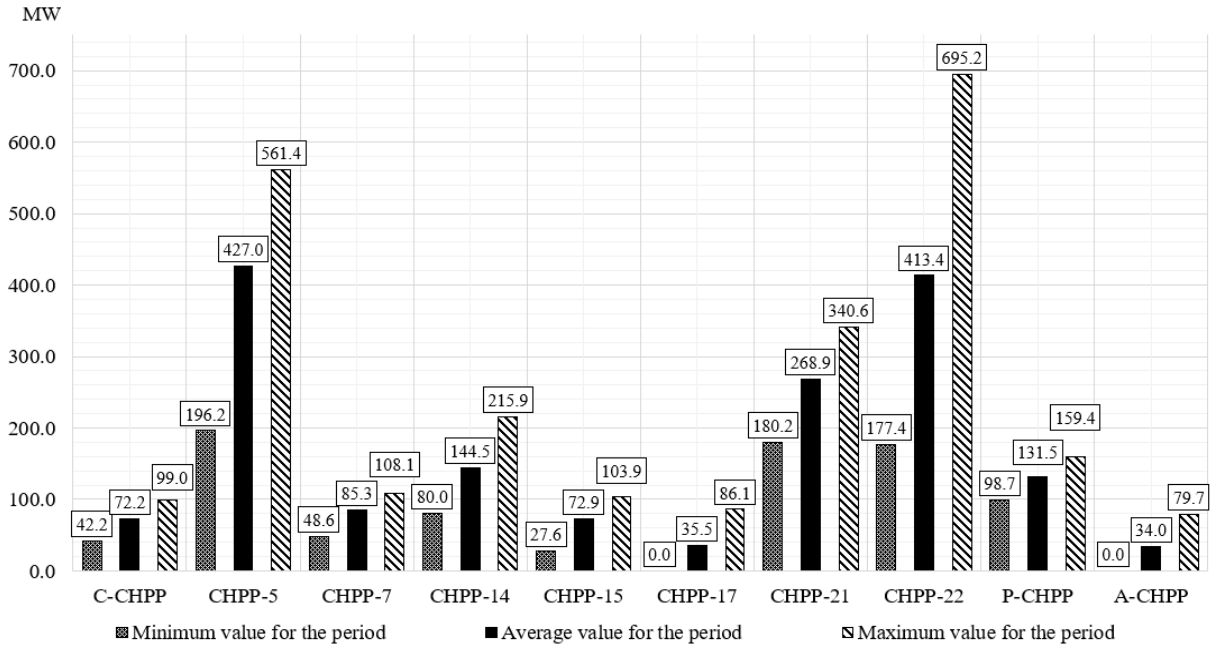

Figure 1. Maximum allowable capacity of a HPU for real CHPPs at φ=3

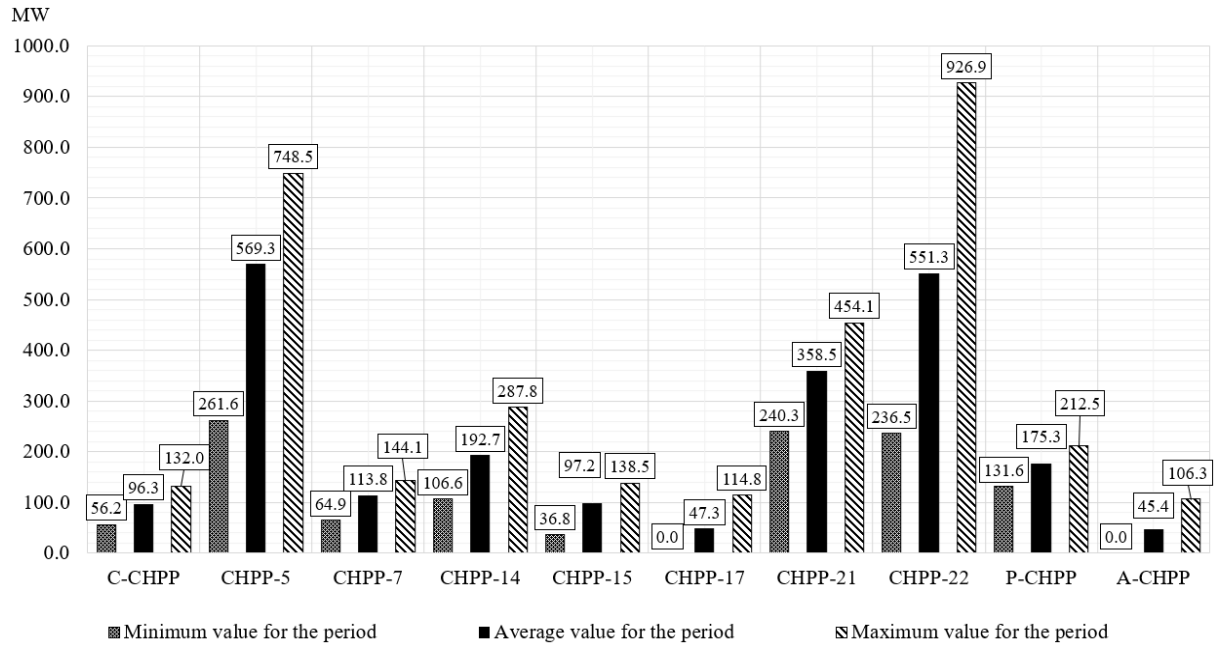

Figure 2. Maximum allowable capacity of a HPU for real CHPPs at φ=4

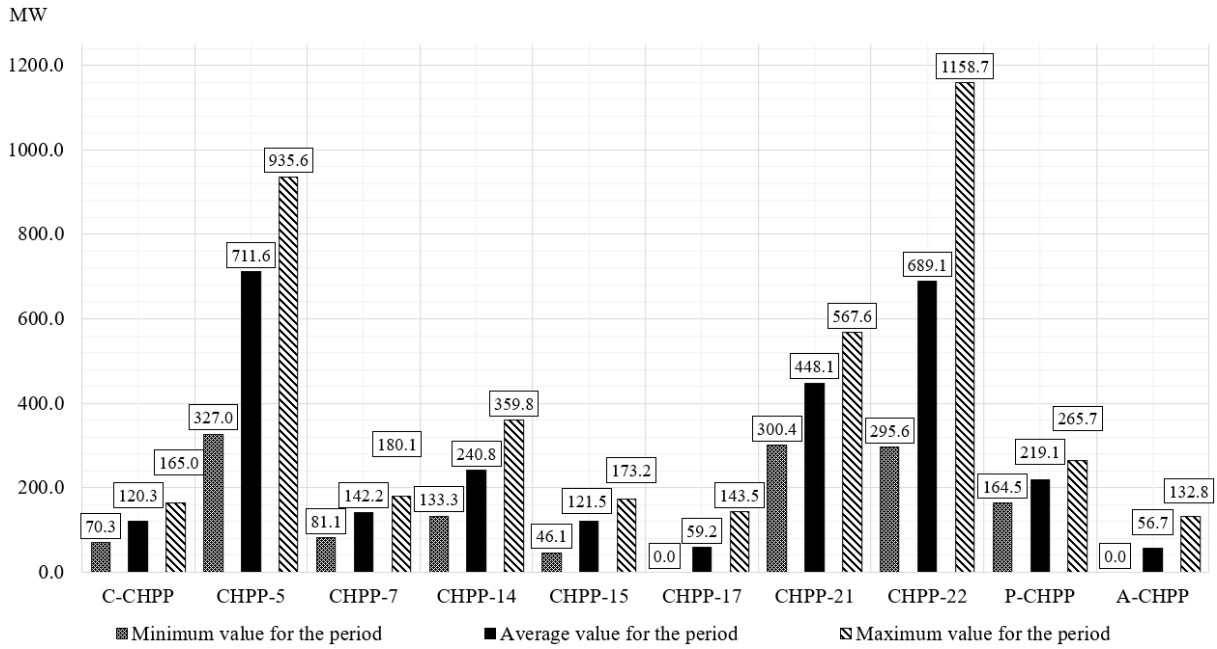

Figure 3. Maximum allowable capacity of a HPU for real CHPPs at φ=5

For the Pravoberezhnaya CHPP-5, the change in the allowable capacity of a HPU and the effect on its value of the parameters included in formula (1) during the considered calculation period are analyzed below.

Figure 4 shows the dynamics of the maximum allowable capacity changes. Figure 5 illustrates the hourly electricity supply, as well as the daily sales value of the electricity supplied. Figure 6 shows changes in the specific consumption of the reference fuel for electricity supply, as well as fluctuations in the cost of fuel (the cost of natural fuel is recalculated to the cost of the reference fuel).

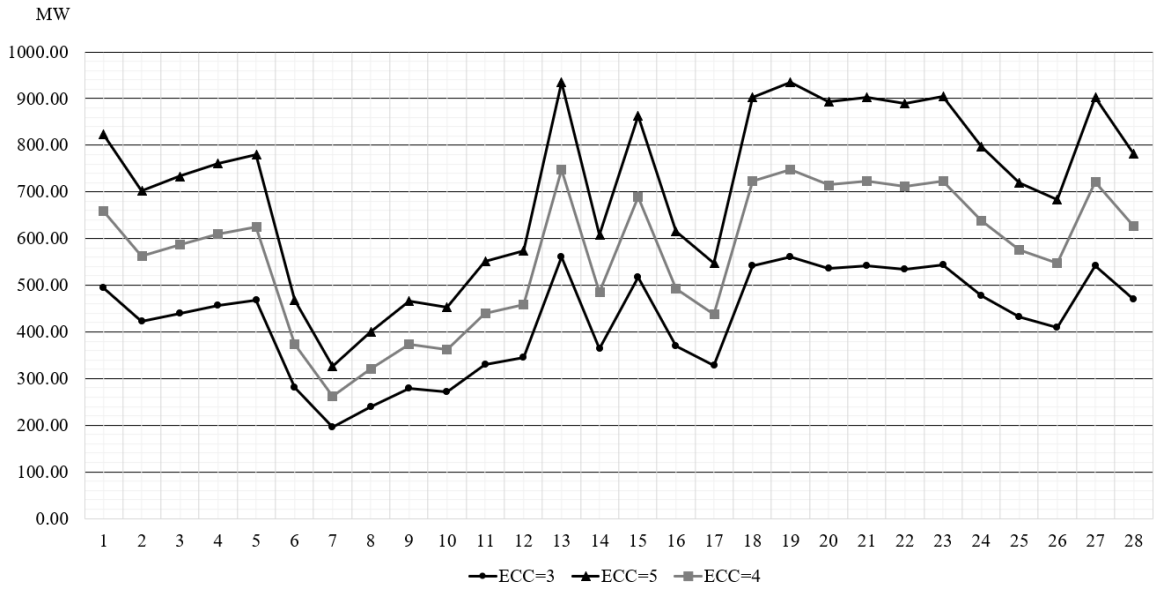

Figure 4. Changes in the maximum allowable capacity of a HPU at the CHPP-

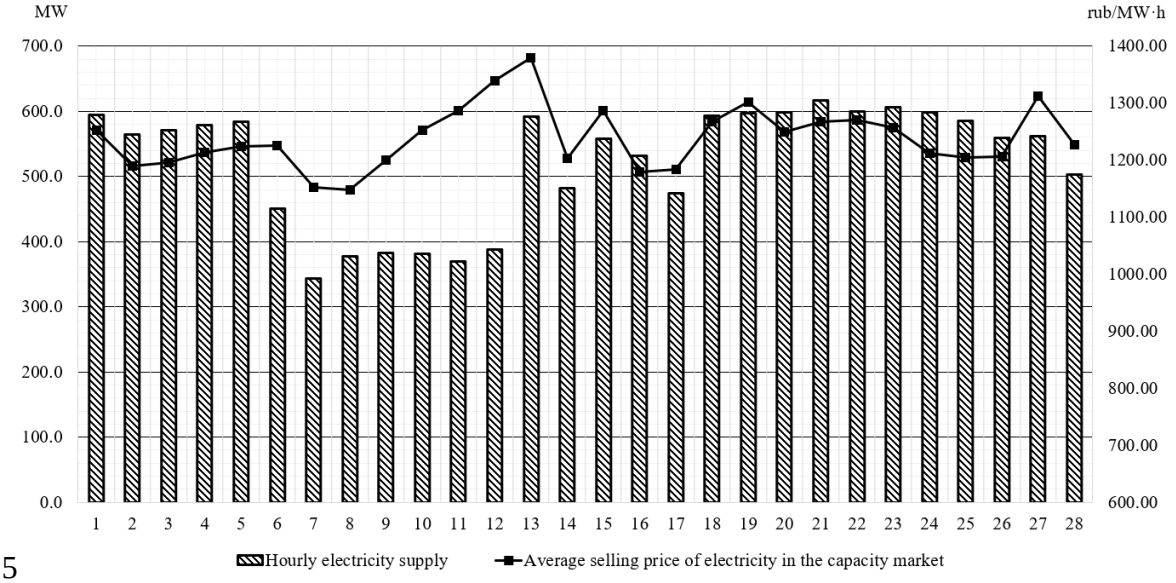

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Figure 5. Changes in the hourly electricity supply and the average cost of electricity sales

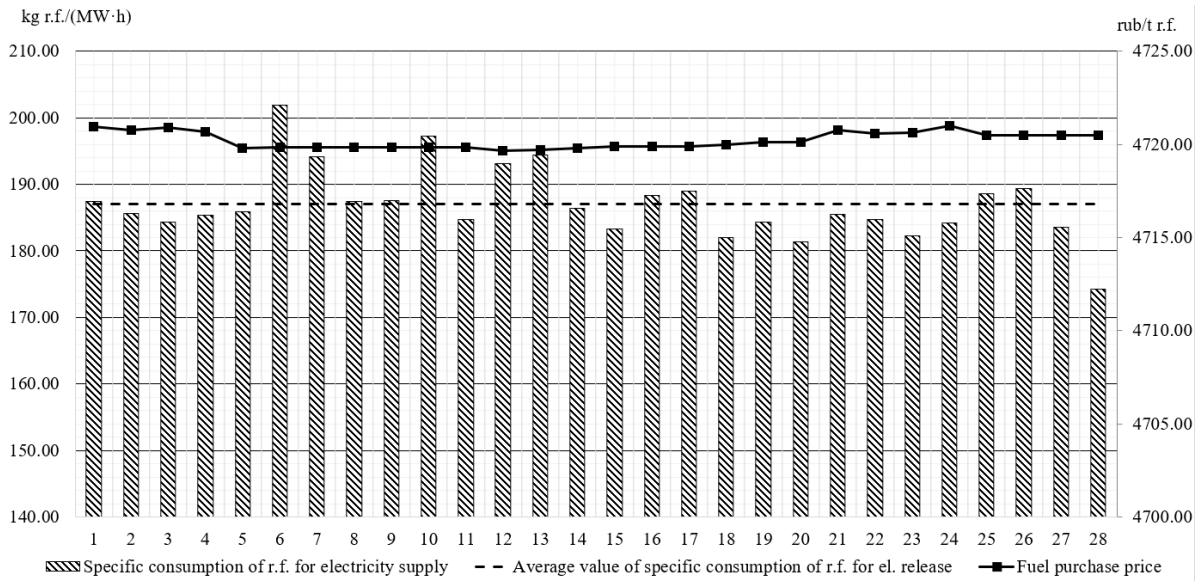

Figure 6. Changes in the specific consumption of the for electricity supply and the cost of fuel

Figure 4 shows that in the period, the cost of purchasing fuel by the station can be considered constant: actually, the changes in the cost values do not exceed 1 rubles/t r.f. and fluctuate around 4,720 rubles/t r.f. Thus, the cost of fuel practically does not affect the value of the maximum allowable capacity of a heat pump.

If to consider the periods from February 1 to February 5, as well as from February 13 to February 28 in Figures 4 and 5, it can be seen that the profiles of the graphs of changes in the allowable HPU's capacity and changes in prices for electricity supply look the same. This is especially noticeable on the days of peak values of a HPU's allowable capacity: February 13, 15, 19 and 27.

In the period from February 5 to 13, a significant decrease in the value of the maximum allowable capacity of a heat pump is observed. Despite the fact that the minimum value of the electricity supply price is on February 8 (1147.73 rubles/(MW·h)), the minimum value of a HPU's allowable capacity is on February 7. This is due to the influence of the hourly supply of electricity from the CHPP-5.

It can be assumed that of the three considered parameters, the change in the specific consumption of the reference fuel for electricity supply has the weakest effect on the value of the maximum allowable capacity of a HPP. This is clearly seen in Figures 4 and 6. For example, with the highest specific consumption of the reference for electricity supply on February 6 (201.91 kg r.f./(MW·h)), the value of the HPU's allowable capacity (467.43 MW at $\varphi = 5$) is far from the lowest in Figure 4 with $\varphi = 5$.

On the example of CHPP-5, it can be seen that when analyzing the maximum allowable capacity of a heat pump according to the method [5], resulting in equation (1), it is important to take into account a combination of factors (the hourly electricity supply, the weighted average price of electricity supply to the wholesale electricity market and the specific consumption of the reference fuel consumption for electricity supply). This goes from the fact that the prevailing factor changes in different periods of operation of the thermal power plant, which is studied.

Conclusions

The maximum allowable capacities of heat pumps at ten CHPPs of TGC-1 in conditions of break-even operation on the electricity market were determined for the calculation period of February 2021. The Pravoberezhnaya CHPP-5 and the Yuzhnaya CHPP-22 have the maximum values of the allowable capacity of a HPU.

For the CHPP-5, changes in HPU's capacity and factors determining it were shown. During analysis, it was revealed that the determining factors are the amount of electricity supplied, the weighted average selling price of electricity on the wholesale electricity market,

and the specific consumption of the reference fuel for electricity supply, which affects to a lesser extent. It was clearly shown that when determining the capacity of a heat pump, there is a combination of the listed factors that should be taken into account.

Nomenclature

Abbreviations

A-CHPP	Apatity combined heat and power plant
C-CHPP	Central combined heat and power plant
CHPP	combined heat and power plant
DAM	day-ahead market
ECC	energy conversion coefficient
HPU	heat pump unit
P-CHPP	Petrozavodsk combined heat and power plant
r.f.	reference fuel
RC	regulated contracts
TPP	thermal power plant
WEM	wholesale electricity market

Variables and coefficients

$b_{e/e}$	specific consumption of the reference fuel for electricity supply, kg r.f./(MW·h)
C_{DAM}	the day-ahead market electricity cost, rubles/(MW·h)
$C_{e/e}$	the WEM weighted average cost of electricity supply, rubles/(MW·h)
C_{RC}	regulated contracts electricity cost, rubles/(MW·h)
P_{nf}^{act}	natural fuel price, rubles/thousand nm^3 (rubles/t);
Q_a^c	actual heat of natural fuel combustion, kcal/nm^3
Q_{HPU}^{max}	maximum allowable power of a heat pump unit, MW
$W_{e/e}$	hourly output of electricity from a TPP, MW
$W_{e/e.DAM}$	electricity supply to the day-ahead market, MW·h
$W_{e/e.RC}$	electricity supply under regulated contracts, MW·h
w_{TPP}^{ON}	share of electricity for own needs
$\varphi=3\div5$	HPU's energy conversion coefficient
29300	calorific value of the reference fuel, kJ/kg r.f.

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