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Techno-economic evaluation of different technologies to produce steam at 150 ºC in the Spanish industry

Jorge Payá[1*], Antonio Cazorla-Marín[1], Abdelrahman H. Hassan[1,2], Cordin Arpagaus[3]

[1] Instituto Universitario de Investigación en Ingeniería Energética, Universitat Politècnica de València,

Camino de Vera s/n Edificio 8E semisótano frente acceso J, 46022 Valencia, Spain; e-mail: jorge.paya@iie.upv.es*

[2] Mechanical Power Engineering Department, Faculty of Engineering, Zagazig University,

Zagazig 44519, Egypt

[3] Eastern Switzerland University of Applied Sciences, Institute for Energy Systems, Werdenbergstrasse 4, CH-9471 Buchs, Switzerland

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1. Introduction

Global warming is one of the significant challenges for the upcoming years and faces different energy policies. To reach the EU 2030 objectives, it is essential to improve the efficiency of the current energy systems and to increase the share of renewable energies.

One of the key sectors which should be tackled is the industry, which in Europe is responsible for 21% of the total CO_2 emissions [1]. In the range from 100 to 200 ºC, the heat is generally produced with a natural gas boiler. This system implies significant CO_2 emissions and a great dependency on the price of gas, which is continuously fluctuating.

This paper deals with two potential alternatives which are already feasible with the current state-of-the-art. Based on vapor-compression cycles, heat pump technologies are well known as effective technology for space heating or domestic hot water generation. Very recently, some manufacturers are starting to offer high-temperature heat pumps (HTHPs) capable of generating process heat for 120 to 150 ºC [2-5]. To reach a sufficiently good performance and economic feasibility, a key point is to recover and upgrade waste heat of 30 to 90 ºC (e.g., condenser cooling water, process water, solar or low-grade geothermal heat). Otherwise, if the heat source of the heat pump is at ambient temperature, the pressure ratio can be too high, as well as the electric power consumption.

Another alternative is solar heat for industrial processes (SHIP), attracting increasing interest. However, SHIP is currently in the early stages of development. Despite the technical potential and the potential economic benefits of using solar heat in industry, actual deployment levels remain relatively low [5]. According to the International Renewable Energy Agency (IRENA), one of the key challenges for solar thermal heat in industrial applications is to reach the short expected payback period of less than 3 years.

The main objective of this study is to carry out a techno-economic comparison of HTHPs, SHIP systems, and gas boilers, as a reference, for industrial heat production at 150 ºC.

2. Methodology

2.1. Description of the model

The present case study has been applied for a demand of steam of 500 kW, 24 h per day, 5 days/week. Given the supply temperature of 150 ºC, the HTHP requires waste heat injection in the evaporator. The present study assumes that waste heat is available at 40 ºC, 60 ºC, or 80 ºC. Otherwise, the pressure ratio would be too high for the available compressors. Thus,. Of course, depending on the industry and the different manufacturing processes, this heat may not always be available, so the replicability of HTHPs is limited depending on the availability of waste heat.

The present study is based on an analytical model solved explicitly with a time step of one hour. Several inputs are time-dependent and refer mainly to ambient conditions, such as the hourly ambient temperature or the mean hourly global irradiance on a horizontal surface. Almería is the chosen location for the installation and has an annual direct normal irradiation (DNI) of 1991.6 kWh/m^2.

The annual gas or electricity consumption of the different scenarios are calculated by Eqs. (1) and (2) given the efficiency of the gas boiler (η_{gas_boiler} = 0.9 (Dengler et al., 2016)) or the coefficient of performance (COP) of the HTHP (Arpagaus, Bless, Uhlmann, Schiffmann, & Bertsch, 2018).

$$W_{annual\_gas} = \frac{Q_{annual\ demand}}{\eta_{gas\_boiler}} = \frac{\int_0^{1\ year} Q_{demand}(t)dt}{\eta_{gas\_boiler}}$$

$$W_{annual\_elec} = \frac{Q_{annual\ demand}}{COP(T_{source,in})} = \frac{\int_0^{1\ year} Q_{demand}(t)dt}{68.455 \cdot (\mathrm{T_{sink,out}} - \mathrm{T_{source,in}})^{-0.76}}$$

In all cases, $T_{sink,out}$ = 150 °C. Therefore, depending on the available waste heat temperature ($T_{source,in}$), the COP of the HTHP is 1.92, 2.24, and 2.71 for the three assessed waste heat temperatures $T_{source,in}$ of 40 °C (ΔT_{lift} = 110 K), 60 °C (ΔT_{lift} = 90 K) and 80 °C (ΔT_{lift} = 70 K) respectively.

In the SHIP system, part of the demand is covered by the solar installation, and part is fulfilled with a conventional (back-up) gas boiler. In this case, Eq. (3) is employed to obtain the annual gas consumption. The net heat provided by the solar installation ($Q_{net\_solar\_heat}$) is provided by the SHIPCAL model (Frasquet, 2022)(Frasquet, 2016).

$$W_{annual\_gas} = \frac{Q_{annual\_demand} - Q_{net\_solar\_heat}}{\eta_{gas\_boiler}} \tag{3}$$

The total annual costs (Table 1) are the sum of the operating & maintenance (O&M) costs, the cost of the CO_2 emissions (r_{gas_CO2} = 0.234 kg / kWh [27], c_{CO2}=14.63 €/ton ('Tax Foundation', 2022), and the cost of the energy consumption. Table 1 shows the equations which have been employed, depending on the energy consumption (gas and/or electricity). The energy costs depend on the total power of the industry and on the negotiated tariffs, and they have been assumed to be c_{gas}= 5.5 c€/kWh and c_{elec}= 11.2 c€/kWh, in agreement with recent literature (Instituto para la Diversificación y el Ahorro de Energía, 2021).

The annual costs in Table 1 are indicated for year 1. For the remaining years (analysis period 20 years), an annual inflation rate of 3% has been assumed both for gas and electricity. In addition, a discount rate of 5% has also been employed to consider the discounted cash flow.

Table 1. Annual cost of each scenario for year 1

Scenario	$C_{O\&M,Y1}$	$C_{CO2emissions,Y1}$	$C_{energy,Y1}$
Gas boiler only (reference)	$0.02 \times CAPEX_{scenario}$	$W_{annual\_gas} \times r_{gas\_CO2} \times c_{CO2}$	$W_{annual\_gas} \times c_{gas}$
Solar + gas boiler			
HTHP 40ºC		$W_{annual\_elec} \times r_{elec\_CO2} \times c_{CO2}$	$W_{annual\_elec} \times c_{elec}$
HTHP 60ºC			
HTHP 80ºC			

For each technology, the capital expenditures (CAPEX) assume the following specific costs, which include commissioning: 70 €/kW (Commission & Centre, 2017) for the gas boiler, 700 €/kW for the HTHP (Arpagaus & Bless, 2022; Arpagaus, Bless, & Bertsch, 2022), and 320 €/m^2 (Stryi-Hipp, Dias, Ivancic, Mugnier, & Weiss, 2014) for the solar system.

2.2. Key Performance Indicators

Several key performance indicators (KPIs) are used to compare the different scenarios. For each scenario, two indicators reflect the cost of heat production. The net present value (NPV) of all of the project costs (Eq. (6)) represents the total money paid, either for the initial CAPEX or for the annual expenses during the entire service life of the installation. The levelised cost of heat (LCOH, Eq. (7)) indicates the total cost in €/kWh for the entire service life of the installation. Basically, both indicators reflect the individual cost of each scenario, although the LCOH relates this cost to the accumulated heat production.

$$NPV_{all\_costs\_scenario} = CAPEX_{scenario} + \sum_{n=1}^{n=20\,years} C_{Yn} \tag{6}$$

$$LCOH_{scenario} = \frac{CAPEX_{scenario} + \sum_{n=1}^{n=20\,years} C_{Yn}}{\sum_{n=1}^{n=20\,years} \frac{Q_{annual\_demand}}{(1+d)^n}} \tag{7}$$

The LCOH or the $NPV_{all\_costs\_scenario}$ provides valuable information to know which technology is less expensive given all the underlying costs. Nevertheless, the industry will not likely replace its current gas boilers unless payback periods below 3 to 4 years are obtained.
Thus, some additional indicators have been calculated to study if replacing the current industrial gas boilers is economically feasible.

$$NPV_{replace\_scenario}(n) = -CAPEX_{scenario} + \sum_{n=1}^{n} (C_{Yn,ref} - C_{Yn,scenario}) \tag{8}$$

Eq. (8) can be represented graphically as a function of time, as shown in the results and discussion section. By definition, the discounted payback period (DPB) is the number of years "n" necessary to obtain $NPV_{replace\_scenario}(n = DPB) = 0$.

For economic feasibility, the DPB should be lower than the service life of the installation (20 years). In such cases, profitability can be assessed by calculating / and the internal rate of return (IRR), which is the market discount rate (d) that yields $NPV_{replace\_scenario}(n = 20\ years) = 0$.

The model has been programmed in Excel / Microsoft Office Professional Plus 2016. Most of the underlying equations are solved directly, whereas two specific indicators, such as the DPB or the IRR have been obtained iteratively with the Excel's solver tool (GRG Non-Linear resolution option).

3. Results and discussion

The following section discusses the results obtained for the location of Almería (South of Spain).

Figure 1 shows the monthly thermal demand (left y-axis, grey histogram). The demand is practically the same every month, given that the profile is constant and that the only monthly difference is the number of days per month. The net solar heat (left y-axis, red histogram) reaches its maximum in summer, corresponding to the maximum in the DNI (right y-axis, orange curve).

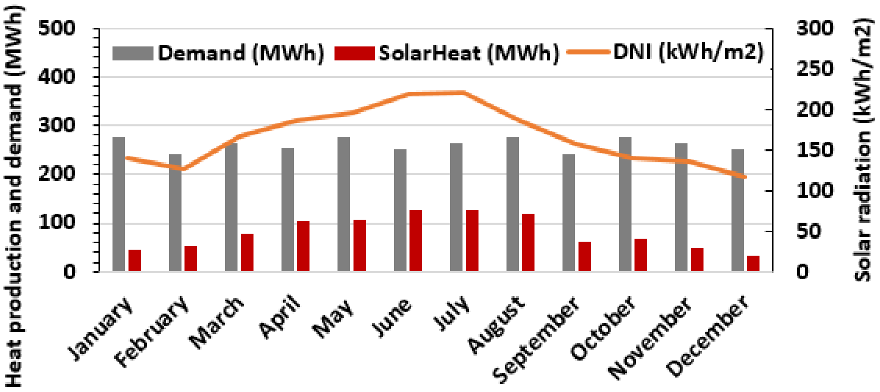

Figure 1. Monthly thermal demand, solar radiation, and net solar heat production for the location of Almería (South of Spain).

Figure 2 represents the hourly solar fraction for several days of the year. The solar fraction is the relationship between the net solar heat and the thermal demand. For especially cloudy days, such as on the 1st of January, a maximum hourly solar fraction of 70% is reached close to the solar mid-day. In clear day skies, such as on the 2nd of July, 2nd of April or the 1st of October, solar fractions of 100% can be reached in the central part of the day. However, on an annual basis, the mean solar fraction is only 31%, given that there are many hours of thermal demand at night with no solar radiation. For example, the maximum monthly solar fraction is 49.5% in June, and the minimum monthly solar fraction is 12.9% in December.

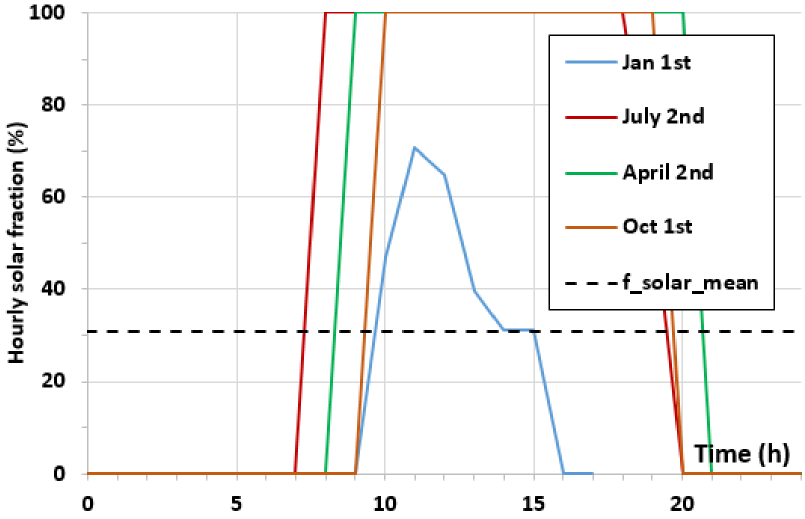

Figure 2. Hourly solar fraction for several days of the year in Almería.

Figure 3 illustrates the avoided annual CO_2 emissions compared to the gas boiler scenario, which emits 814 tons/year. The HTHP involves higher CO_2 emission savings assuming that a significant proportion of the Spanish electricity mix comes from renewable energies (1.56 10^{-4} ton/kWhe). The higher the waste heat temperature, the higher the COP and the higher the avoided CO_2 emissions with the HTHP (maximum 634 tons/year avoided for a waste heat temperature of 80 ºC). The solar alternative has lower avoided CO_2 emissions, given that the annual solar fraction is only 31%, which means that most of the demand is covered with a gas boiler. The SHIP system could be eventually sized with more collectors, but in that case, the dumped energy would be bigger since the solar heat production could be larger than the demand in many hours of summer. For this reason, SHIP systems are often designed, as in the present case study, with annual solar fractions of around 30% (De Santos López, 2021) .

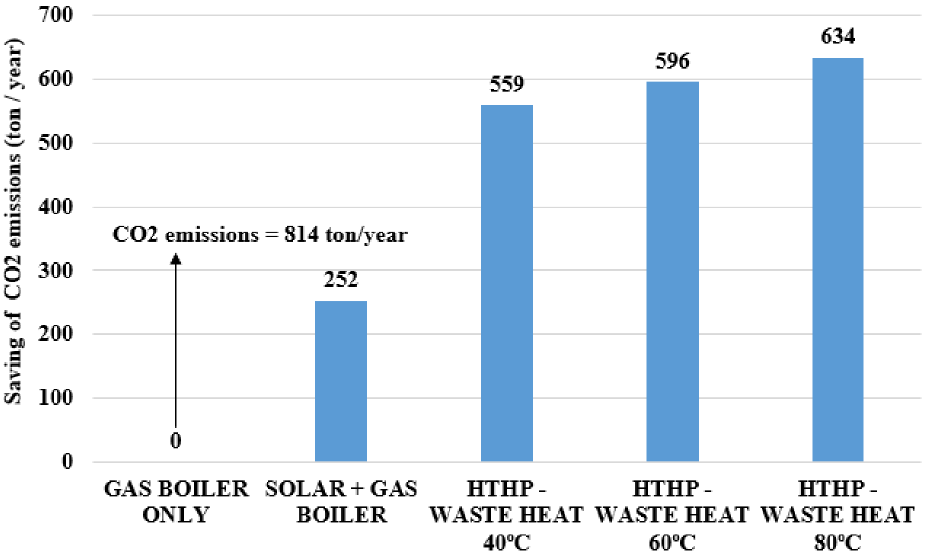

Figure 3. Annual CO_2 emission savings by different technologies with respect to the gas boiler scenario.

Figure 4 shows the NPV of the individual technologies. After 20 years, the less expensive scenario is the HTHP working with waste heat at 80 ºC, followed by the HTHP with waste heat at 60ºC or the solar option, which provide similar values after 20 years (despite a bigger initial investment with the solar option).

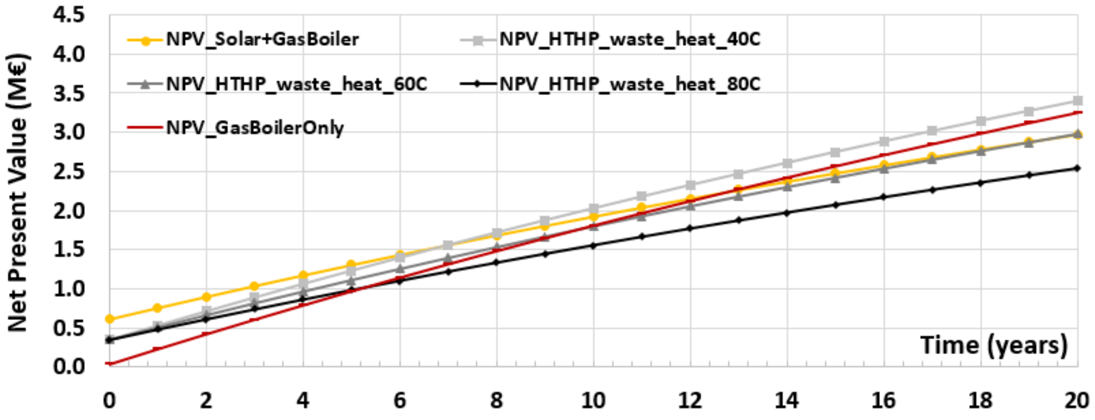

Figure 4. NPV of the individual technologies, calculated with Eq. (6).

From the LCOH point of view, Figure 5 compares each scenario with the gas boiler system, which has an LCOH of 8.3 c€/kWh. As observed before, the HTHP has the highest performance (21.9% lower LCOH). The solar+gas boiler option, or the HTHP with waste heat at 60 ºC, reduce the LCOH by around 8%.

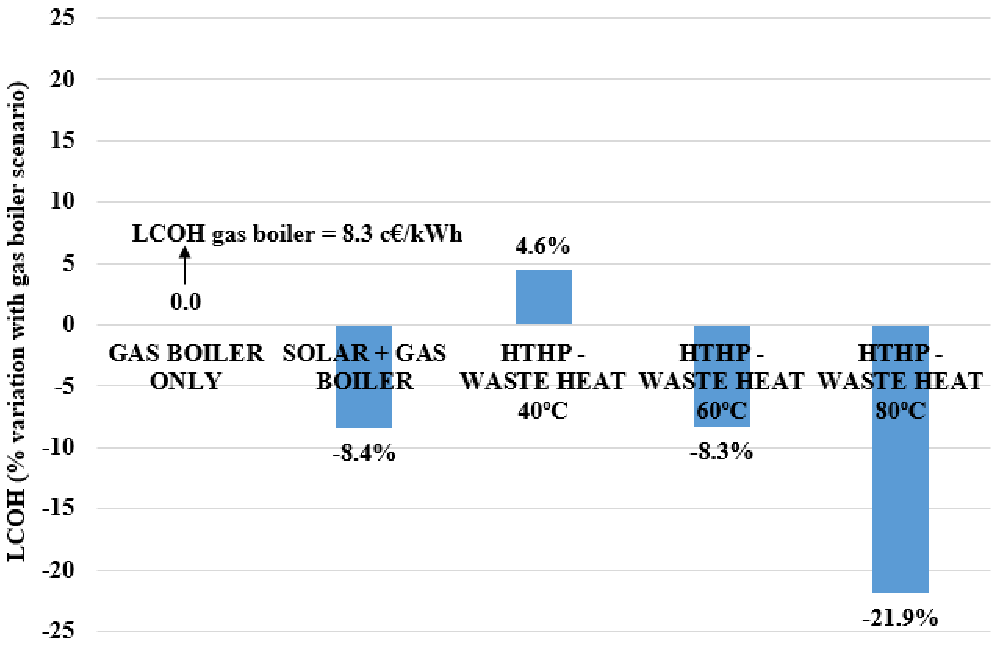

Figure 5. Levelised Cost of Heat (LCOH) for the individual technologies obtained with Eq. (7).

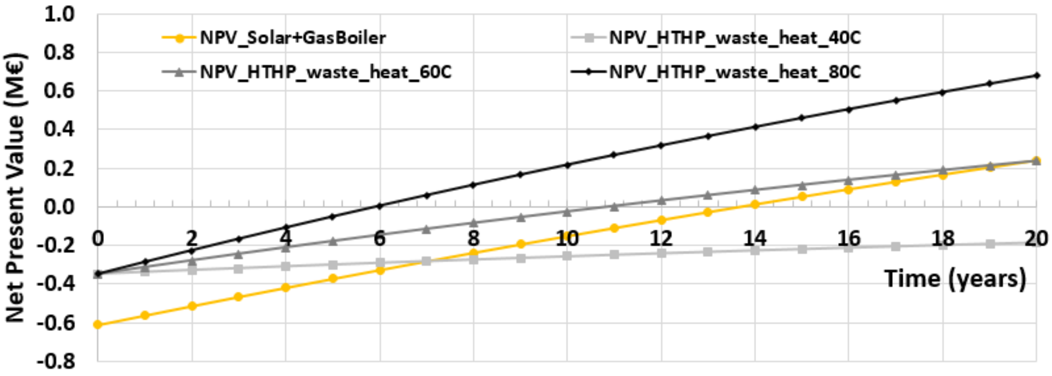

Figure 6. NPV of the individual technologies, calculated with Eq. (8).

Figure 6 provides useful information to determine replacing the current industrial gas boilers with other technologies is economically feasible. After 20 years, all the scenarios are economically feasible except for the scenario with HTHP and waste heat at 40 ºC. Here, the high temperature lift of 110 K leads to low COP. If a current gas boiler has to be replaced, the best option is to use a HTHP with waste heat at 80 ºC, and if this is not possible, HTHP with waste heat at 60 ºC or a solar+gas boiler system provides in overall a similar benefit.

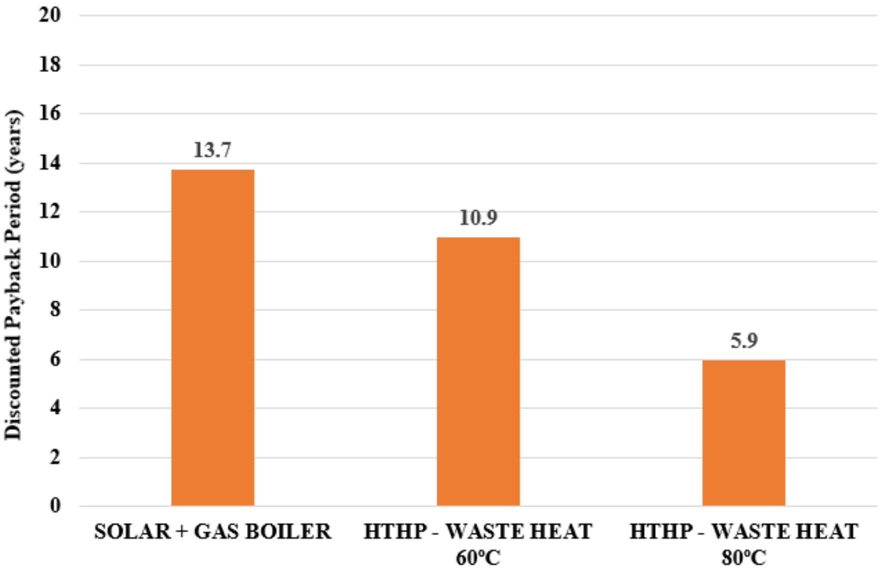

Figure 7. DPB for replacing the current gas boilers by the economically-feasible scenarios

Finally, Figure 7 provides the DPB for replacing the current industrial gas boilers. The solar+gas boiler option is a mid to long-term investment, but if the CAPEX drops down in the next years or the gas price continues to increase, the paybacks will also decrease. The scenario with HTHP and waste heat at 40 ºC has not been represented, since the payback is higher than the assumed service life of the installation (20 years).

The most interesting scenario from the DPB point of view is the HTHP with waste heat recovery at 80 ºC. The payback is 5.9 years, which can be considered a short to mid-term investment.

4. Conclusions

The present work compares the techno-economic performance of different technologies (Solar+gas boiler, HTHP+waste heat at 40 ºC, 60 ºC, and 80 °C), potentially replacing industrial gas boilers for steam generation at 150 ºC.

The analysis has been carried out with the current energy prices in Spain. Overall, the most beneficial alternative is the HTHP upgrading waste heat of 80 ºC. This is in principle possible in some processes, such as in the dairy pasteurization processes of the food industry. The discounted payback, in this case, is of 5.9 years. However, waste heat temperatures at around 80 ºC are not too frequent in the industry.

The second economic options are the solar+gas boiler, or the HTHP with waste heat at 60 ºC. However, their payback periods are above 10 years and can be considered a mid to long-term investment.

From an environmental point of view, the HTHP scenarios avoid more CO_2 emissions, given the good efficiency of the heat pumps and considering the current energy mix in Spain, which has a non-negligible contribution of renewable energies.

In future work, this study will be extended to a European level to detect which countries are more interesting for one technology or another depending on the available solar radiation, the energy prices, or the CO_2 taxes.

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