Effect of Collector Tilt Angle on the Performance of a Residential Solar-Heating-and-Cooling System

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Abstract: A residential solar-heating-and-cooling (SHC) system is a possible alternative for the reduction of fossil fuel consumption to cover residential energy loads. These systems can cover all thermal loads, i.e. space heating, space cooling and domestic hot water preparation. Space cooling is fulfilled through a heat-activated (hot water), single-effect LiBr-water absorption chiller. Proper operation of such a system requires coupling of the solar collector array to a hot water storage tank with auxiliary heating. Auxiliary heating, in this case in the form of a diesel-fired boiler, is necessary to supplement heating in the storage tank when demand exceeds solar heating availability. In this study emphasis is given on the effect of the collector tilt angle (slope) on the performance of a SHC system. A constant slope throughout the year simplifies system configuration and maintenance, but on the other hand a variable slope improves performance, in terms of energy efficiency, and thereby lowers the operating cost of auxiliary heating. The results of the study show that it is economically beneficial to vary the slope throughout the year (on a monthly basis), since $233/year can be saved when a variable slope is used.

Keywords: Solar heating and cooling, Solar energy, Solar air conditioning, Absorption chiller, Cost analysis, Collector tilt.

1. INTRODUCTION

The high cost of electricity, when generated from fossil fuels, requires other alternatives to cover thermal loads in buildings. Dwellings in locations with prolonged summer-like weather conditions require space cooling, in addition to demand in space heating and domestic hot water. Currently, space cooling demand is primarily covered with electric vapor-compression heat pumps (split type air conditioning units), while space heating demand is covered with oil- or gas-fired boilers. Domestic hot water demand is typically covered fully or partly (depending on season) with flat-plate solar collectors. The latter application can be extended to cover the other two demands, space cooling and space heating, if more efficient, higher temperature and larger scale solar collectors are utilized [1,2]. A solar heating and cooling (SHC) system can provide all required thermal loads, although typically it must be assisted by auxiliary heating to maintain a reasonable size of solar collector array area. Solar collectors able to perform efficiently and reach high operating temperatures, namely evacuated tube collectors (ETC), are currently expensive in terms of capital cost. Therefore a compromise between capital cost and operating cost must be made, when designing a SHC system. Additionally absorption chiller units require a minimum generator temperature to allow proper and efficient operation of the refrigeration cycle. There are certain advantages in solar cooling air-conditioning, such as the good matching of high solar irradiation availability during peak demand of the space cooling load [3]. Also utilization of renewable energy sources eliminates greenhouse gas emissions, and therefore this technology is environmentally friendly, while onsite energy generation reduces grid transmission and distribution costs, especially when power plants are located far from the serviced household. Also congestion of the power grid during peak demand is largely reduced. Finally, compared to a district cooling/heating network, thermal losses from the pipelines are eliminated.

1.1. Literature Review

Available research work has concentrated on the study of solar cooling systems, while SHC systems, have received less attention. Ali et al. [3] simulated a system situated in Oberhausen, Germany, with the following characteristics: absorption chiller unit with a cooling capacity of 35 kW, 108 m^2 ETC solar array, 6.8 m^3 hot water storage tank, 1.5 m^3 chilled water storage tank, and 134 kW cooling tower. The coefficient of performance (COP) for the absorption chiller ranged between 0.37-0.81, while solar fraction ranged between 0.33 0.41 (on a daily basis). The average collector efficiency was 0.35-0.49 (on a monthly basis) for an average solar fraction between 34-42%. Calise et al. [1] developed a TRNSYS-based model of a SHC system, with three system configurations. A single-effect LiBr-water absorption chiller was coupled to an ETC array with a gas-fired boiler. In the first configuration the

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system was set for maximum cooling capacity and an electric chiller was used for additional cooling. In the second configuration the system was set to partly balance the maximum cooling load. In the last configuration no electric chiller was used and the boiler was also operated in the summer to add heat to the absorption chiller. A mixed heuristic-deterministic optimization methodology was used to determine the set of optimum variables for maximum energy efficiency. The results indicated that the total cost of the system was rather unfavorable, mainly because of the high capital cost. Florides et al. [2] simulated a TRNSYS-based solar air-conditioning system located in Nicosia, Cyprus. The system was optimized in terms of solar collector type, slope and area; storage tank capacity, and thermostat setting for the auxiliary boiler. The final optimum configuration included a 15 m^2 compound parabolic collector (30^o slope), a 600 L thermal storage tank, and a boiler temperature at 87^oC. Koroneos et al. [4] studied the performance of a solar cooling system for a medical center in Igoumenitsa, Greece. The system characteristics were: 70 kW absorption chiller and solar collector area of 291 m^2.

1.2. Research Objectives

This work extends research on SHC systems, with an emphasis on the effect of collector tilt angle (slope). For simplicity, slope angles are typically set at a constant (fixed) value for the entire year. However, the change of the azimuth angle throughout the different seasons suggests that the slope of the collector array must vary, to allow maximum utilization of available solar energy. In this study a parametric study is used to analyze and predict performance for different values of collector slope and its effect on operating cost for the whole year. For simplicity and practicality, slope is assumed to vary only on a monthly basis, without the need of using expensive sun-tracking or other similar equipment. Therefore the performance of a system at a range of constant values throughout the year is compared with a system with variable (on monthly basis) slope in terms of solar fraction and total cost. The main components of the SHC system are: a single-effect Li-Br absorption chiller activated via hot water, a solar collector array, a hot water storage tank with a cooling tower, and a diesel-fired boiler.

2. CONFIGURATION OF THE SHC SYSTEM

The working principle of the SHC system, shown in Figure **1**, is as follows: Heat from the hot water storage tank is circulated to cover the domestic hot water load. In the winter period, hot water is used for space heating, while in the summer period, hot water activates the absorption chiller for chilled water generation fulfilling the space cooling load. Heat rejection, from the condenser and absorber, is

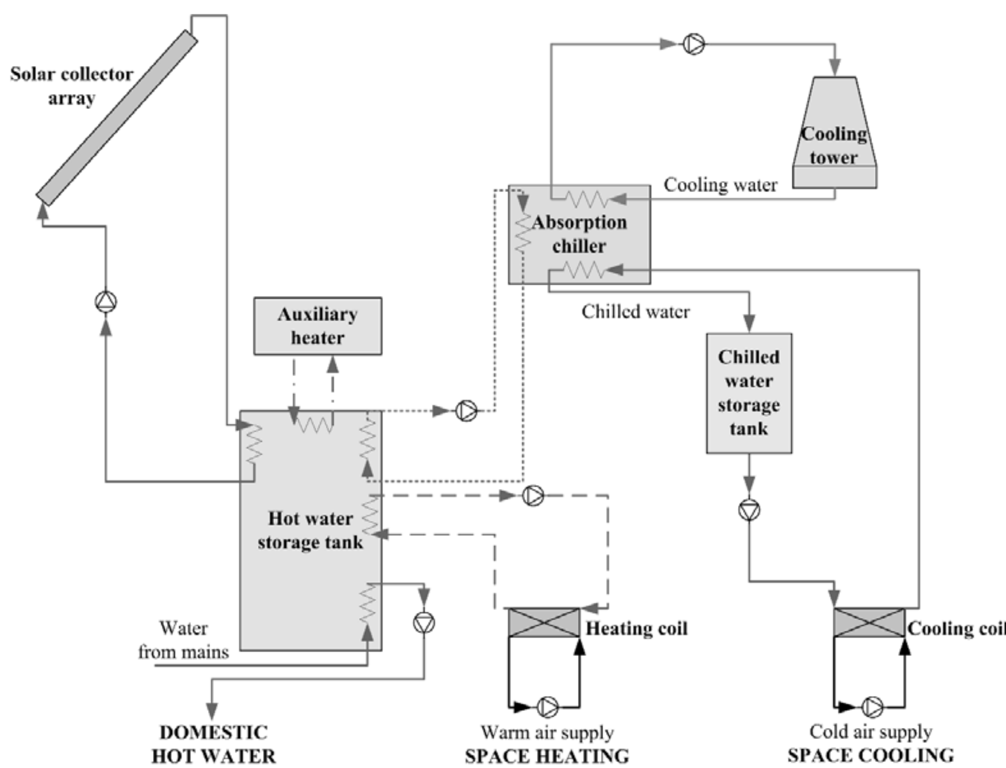

Figure 1: Schematic representation of the solar heating and cooling system.

Table 1: System Input Parameters

Parameter Description	Value
Area of solar collector array	50 m^2
Coefficient of performance for the absorption chiller	0.7
Collector tilt angle (slope)	5-85^o
Ground reflectance	0.2
Latitude of location (Nicosia, Cyprus)	35.2^o
Minimum operating temperature of absorption chiller	78^{o}C
Product of collector heat removal factor and collector overall heat loss coefficient	2.63 W/m^2-^{o}C
Product of collector heat removal factor and product of transmittance and absorptance	0.72
Volumetric capacity of hot water storage tank	2000 L

accomplished through circulation of cooling water from the cooling tower. Control of the different modes of system operation is accomplished via actuators (valves and pumps), as required by the fluctuating load profile of the household. The adopted load profile for this study is taken for a typical detached single-family household located in Nicosia, Cyprus, as given by Florides et al. in [2], with the following annual total loads: 6,012 MJ for domestic hot water preparation, 78,235 MJ for space cooling and 12,528 MJ for space heating. Average monthly demand is taken with meteorological data for the assumed location (heating degree days, cooling degree days, monthly average radiation on a horizontal surface, monthly average clearness index and monthly average ambient temperature), taken from [5]. Heat losses from the hot water storage tank are assumed at a constant rate of 7 W/^{o}C, as given in [6].

3. SYSTEM MODELING

The SHC system is modeled based on the combined $\bar{\phi}, f$ -chart method, which is described in detail in [6]. Solar fraction is the heat harnessed through solar energy to total thermal load. Table **1** includes the input parameters used in the system model. The area of the solar collector is set at 50 m^2, while the volume of the hot water storage tank is set at 2000 L. The collector tilt angle is varied in the range 5-85^o. The minimum operating temperature for the absorption chiller is set at 78^{o}C. The values of the remaining parameters are as set in [6]. To reduce thermal losses from the hot water storage tank, it is assumed that the tank is placed externally to the household. The total heat that must be delivered by the hot water storage tank is the sum of the heat needed to cover the total heating demand and the heat delivered to the generator of the absorption chiller to generate enough cooling to satisfy space cooling demand.

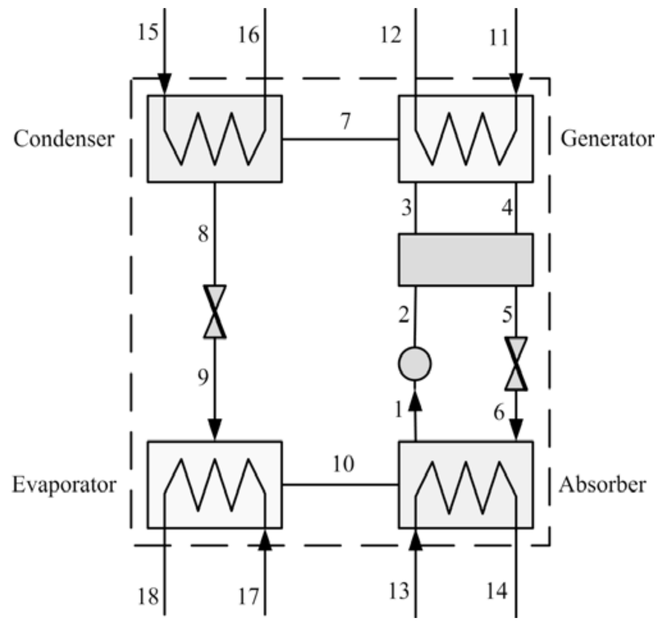

Figure 2: Working principle of the absorption chiller unit, including external heat transfer flows.

The absorption chiller unit in Figure **2** shows the refrigeration cycle and the external heat transfer flows, which activate and maintain the operation of the unit [7]. The component is modeled by individual mass and energy balances within the four main parts, namely absorber, generator, condenser and evaporator [8], calculating specific enthalpy, mass flow rate, pressure, temperature, vapor quality fraction and refrigerant percentage in the mixture (% LiBr) for all state points shown in Figure **2**. The cooling capacity of the absorption chiller is set at 20 kW, which is assumed to be the rated cooling capacity of the household.

Table 2: Cost Model Including Component Cost, Auxiliary Heating Cost and Total Annualized Cost

Cost parameter description	Cost value/function
Cost of solar collector array	$Z_c = 25,000$
Cost of diesel-fired boiler (auxiliary heating)	$Z_{ah} = 1,200$
Cost of absorption chiller unit	$Z_{ach} = 6,000$
Cost of hot water storage tank	$Z_{hwtk} = 1,000$
Cost of chilled water storage tank	$Z_{cwtk} = 200$
Cost of auxiliary equipment (pumps, fans, piping, etc.)	$Z_{aux} = 500$
Annual cost of auxiliary heating	$C_{ah} = \frac{Q_{ah} c_{diesel}}{\eta_{ah} LHV_{diesel}}$
Total annualized cost of the SHC system	$C_{tot} = \frac{\sum_i Z_i}{f_a} + C_{ah} + C_{el}$

4. COST ANALYSIS

For a proper estimation and analysis of all necessary costs for the modeled SHC system, a cost model is constructed. The cost model, shown in Table **2**, calculates component costs, capital cost, running cost and total annualized cost, with all given values in USD ($).The unit cost of solar collectors is set at $500/m^2 [2], while the cost of the diesel-fired boiler is set at $1,200 [9]. The unit cost of the absorption chiller unit (incl. cooling tower and cooling water pump) is set at $300/kW, which is roughly the average of the range given in [10]. The unit cost of the thermally-insulated hot water storage tank is taken to be $500/m^3 [11]. The cost of the chilled water storage tank is assumed to be $200 [2]. The cost of auxiliary equipment (incl. pumps, fittings, piping, insulation, etc.) is assumed to be $500 [2]. The unit cost of diesel $\left(c_{diesel}\right)$ is assumed to be $1,252/m^3 [12]. The efficiency of the auxiliary heater $\left(\eta_{ah}\right)$ is assumed to be 0.95. The lower heating value of diesel $\left(LHV_{diesel}\right)$ is assumed to be 36.4 GJ/m^3. The total annualized cost [9] for the proposed SHC system is the sum of the equipment cost divided by an annuity factor $\left(f_a\right)$, the cost of thermal energy supplied by the auxiliary heater, and the cost of the electricity supplied to the system to various electric equipment (fans for cooling tower, pumps, controllers, etc.). The latter cost parameter $\left(C_{el}\right)$ is based on [10]. The total

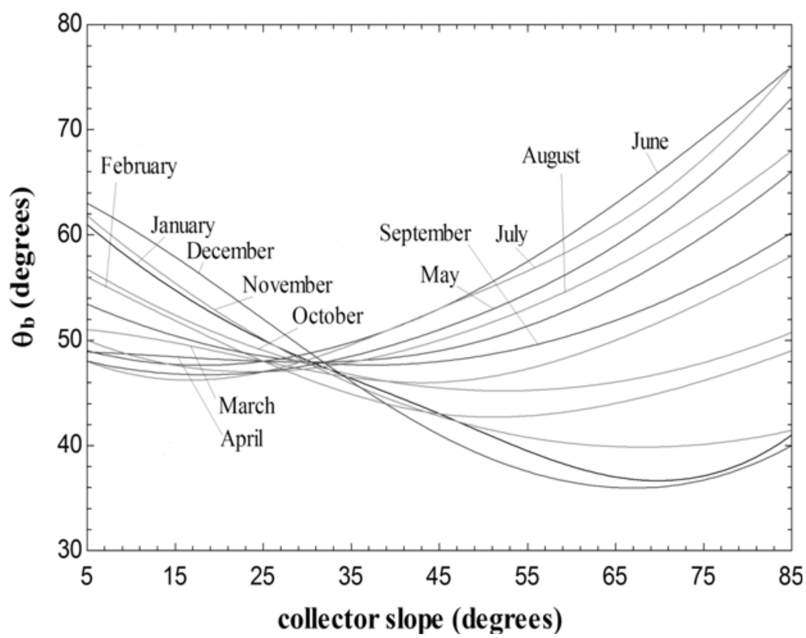

Figure 3: Average beam incidence angle for Nicosia, Cyprus for different collector slopes per month.

heat supplied by the auxiliary heater $\left(Q_{ah}\right)$ is the sum of every monthly addition to the heat generated by solar collectors, necessary to fulfill the total load. f_a is assumed to be 12.5 years, based on [9]. The unit cost of electricity is assumed to be $0.34/kWh [13].

5. RESULTS AND DISCUSSION

The choice of the value for the collector slope is based on the latitude of the selected location. The optimum values of the slope for each month, resulting in the maximum possible solar fraction values, are selected based on interpolation of the data for the plots at latitudes at 30^o and 40^o given for the selected latitude in [6]. The resulting plot for the selected location's latitude is shown in Figure **3**, where the monthly average beam incidence angle $\bar{\theta}_b$ is plotted for each month of the year for different slope values.

Optimum monthly collector slopes are shown in Figure **4**. The trend showed suggests that low collector slope values are required in the summer period, due to the small solar zenith angles during that period, while the opposite pattern is evident in the winter period.

The performance of the SHC system in terms of annual average solar fraction is shown in Figure **5**. It is evident that if the tilt angle is varied throughout the year, a higher average solar fraction will be accomplished. However the space cooling load is by far larger than the other two loads. This means that the collector slope will be more influential during the summer, when the system operates in space cooling mode. Therefore smaller slope values are favored if a constant value must be chosen for the whole year. In this case, the optimum angle is 35^o, for which the SHC system performs at an annual average solar fraction of

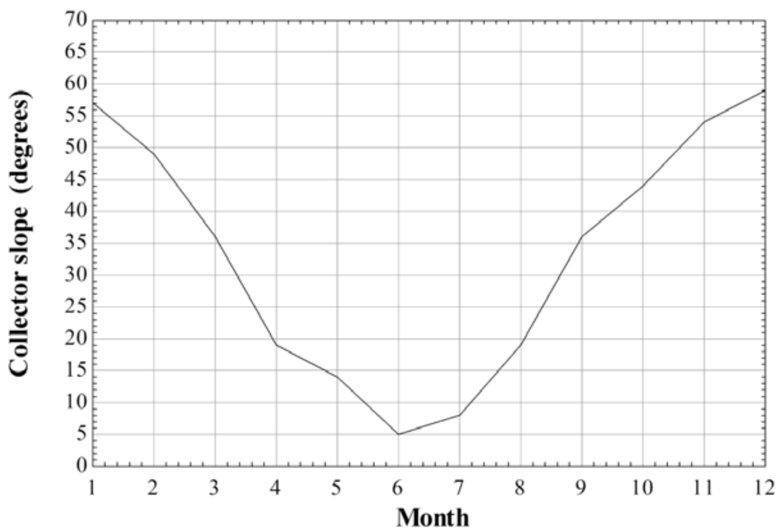

Figure 4: Optimum monthly collector slope values.

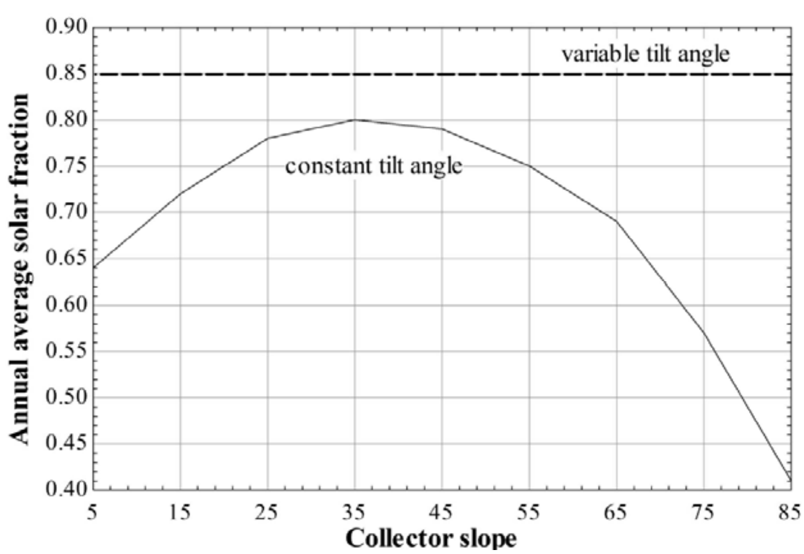

Figure 5: Collector slope (fixed and variable) vs. annual average solar fraction.

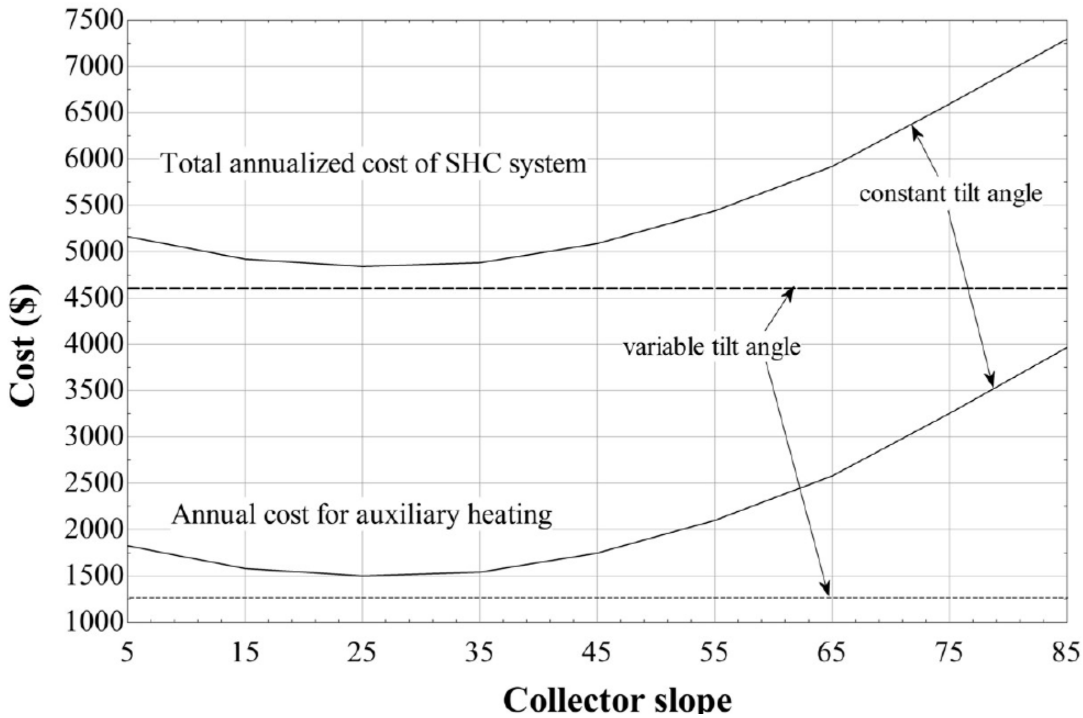

Figure 6: Collector slope (fixed and variable) vs. total annualized cost of SHC system and annual cost for auxiliary heating.

0.80, compared to 0.85 for a variable tilt angle. The performance of the SHC system in terms of total annualized cost of SHC system and annual cost for auxiliary heating is shown in Figure **6**. Smaller collector slope values are favored for the reason stated for the previous plot, but in this case a fixed collector slope at 25^o is more economically beneficial. This is due to the fact that more solar energy is harnessed during the summer months at 25^o rather than 35^o, where demand is much higher compared to the overall annual demand. The total annualized cost of the SHC system for a fixed slope at 25^o and a variable slope is 4840 and 4607, respectively. The annual cost for auxiliary heating for a fixed slope at 25^o and a variable slope is 1500 and 1267, respectively.

6. CONCLUSIONS

In this research work the effect of a constant and a variable collector tilt angle is analyzed for a residential SHC system. The system includes a hot water storage tank to allow storing of harnessed solar energy and flexibility in the fulfillment of thermal demands (domestic hot water, space heating and space cooling). A single-effect absorption chiller of the LiBr-water type is coupled to the system to generate cooling energy to fulfill space cooling demand. The system is modeled using the combined $\bar{\phi}, f$ -chart method, which allows a practical simulation of the system and prediction of performance on a monthly basis for the whole year. A cost model is also constructed to allow calculation of capital cost, auxiliary heating cost, and total annualized cost of the SHC system. The results suggest that a variable collector slope (varied on a monthly basis) can contribute to a better energy performance of the system, in terms of solar fraction (0.85 for a variable slope compared to 0.80 for a fixed slope). It is also more economically beneficial to vary the slope throughout the year, since $233/year can be saved when the collector slope is varied.

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