ISSN: 2350-0328

International Journal of AdvancedResearch in Science, Engineering and Technology

Vol. 5, Issue 6 , June 2018

Analysis of Three Types of Solar Systems: PV, Flat Plate Thermal, and Hybrid PV-T Using TRNSYS Model

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ABSTRACT: The upcoming years for India are not only important for the development of the country but also creating opportunities and awareness within the society. Most of our industrial processes and buildings need energy including both heat and electricity, and both of them can be provided using hybrid solar photovoltaic/thermal system. Solar thermal and photovoltaic systems absorb energy from solar radiation, but due to limited availability of area, installing separate system is expensive and land consuming. Hence a combined system for improved utilisation of solar radiation is suitable, less expensive and consumes less area for installation. In this paper, simulation models of the solar thermal collector, photovoltaic system and photovoltaic thermal system are presented.

I. INTRODUCTION

The most important development of solar technology is a photovoltaic: a solar energy utilising system that uses semi-conductors for direct conversion of solar radiation into electricity. Photovoltaic (PV) systems are made up of a large number of cells, generally made of crystalline silicon. They are connected in series or parallel to form a metal frame which is known as a module. The module is further connected in series and parallel combination as per the requirement. When solar radiation falls on the module, a small current of electricity is produced.

Flat plate thermal collector harnesses the energy provided by the sun for heating the water. The hot water produced by the solar heating system is stored and can be used to supplement domestic hot water requirement, larger stores of water (like swimming pools), under-floor heating, and for space heating/cooling.

Photovoltaic thermal hybrid solar collector (PV-T) converts the solar radiation into thermal and electrical energy. This system consists of solar cells which are directly pasted over a thermal collector. The hybrid system produces electricity and process heat from sun's radiation. It is highly recommended for industries which demand high process heat and electricity.

These three systems are base of solar energy; hence a comparative study is to be done between the systems for choosing the most reliable system for a particular situation. Using TRNSYS simulation tool, these systems are modelled and executed and the results are compared.

II. MATHEMATICAL MODELLING

A. Photovoltaic (PV) System

A photovoltaic component (Type94) is used for simulating the electrical performance, storage, utility grid, the area required etc. for aPV module. The I-V characteristics of a single module are predicted by an empirical equivalent circuit model (Type94) using mathematical equations governing it. The slope of the IV curve at short-circuit conditions is assumed to be zero. The four-parameter equivalent circuit was developed by Townsend in 1989 [1] and further detailing was done by Duffie and Beckam in 1991 [2]. The model was further added in TRNSYS by Eckstein [1990].
The "four parameters" in the model are $I_{L,ref}$, $I_{o,ref}$, γ, andR_s.

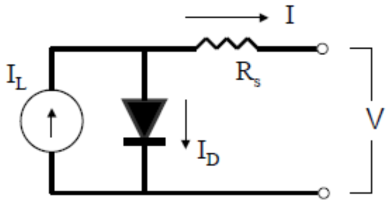

Figure 2.1: Four Parameter Model

where, $I_{L,ref}$= module photocurrent at reference condition, I_o = Diode reverse saturation current, γ= empirical PV curve-fitting parameter, R_s = Module series resistance

B.Performance under operating conditions

The IV characteristics of a PV change with both insolation and temperature. For every time step, the PV model employs environmental condition like insolation and temperature, and the four constants $I_{L,ref}$, $I_{o,ref}$, γ, and R_s. The equation of circuit shown in fig. 2.1 is as follows,

$$I = I_L - I_o\left[\exp\left(\frac{q}{\gamma k T_c}(V + IR_s)\right) - 1\right] \qquad (2.1.1)$$

where,
q = Electron charge constant
k = Boltzmann constant 1.38 x 10^{-23} (kg.m^2.s^{-2}.K^{-1})
T_c= Module temperature (K)
I_L = Photo-current and depends linearly on incident radiation.

C. Calculating $I_{L,ref}$, $I_{o,ref}$, γ, and R_s

To calculate $I_{L,ref}$, $I_{o,ref}$, γ, andR_s, certain parameters are required Type94 component. The first step is to substitute the current and voltage into eq. (2.1.1) at the open-circuit, short circuit and maximum power conditions and neglecting the negative term for simplifying the algebra because I_o is very small, generally of order 10^{-6} A.Hence after rearrangement,

$$I_{L,ref} \approx I_{sc,ref} \qquad (2.1.2)$$

$$\gamma = \frac{q\left(V_{mp,ref} - V_{oc,ref} + I_{mp,ref} R_s\right)}{kT_{c,ref}\ ln\left(1 - \frac{I_{mp,ref}}{I_{sc,ref}}\right)} \qquad (2.1.3)$$

$$I_{o,ref} = \frac{I_{sc,ref}}{exp\left(qV_{oc,ref} / \gamma k T_{c,ref}\right)} \qquad (2.1.4)$$

$$\frac{\partial V_{oc}}{\partial T_c} = \mu_{voc} = \frac{\gamma k}{q}\left(ln\left(\frac{I_{sc,ref}}{I_{o,ref}}\right) + \frac{T_c \mu_{isc}}{I_{sc,ref}} - \left(3 + \frac{q\varepsilon}{AkT_{c,ref}}\right)\right) \qquad (2.1.5)$$

where, $A = {}^{\gamma}/_{N_s}$
$V_{oc,ref}$= Open circuit voltage at reference condition (K)
$V_{mp,ref}$ = Voltage at maximum power point along IV curve, reference condition
$I_{sc,ref}$ = Short circuit current at reference condition
$I_{mp,ref}$ = Current at maximum power point along IV curve, reference condition
$I_{o,ref}$ = Diode saturation current at reference condition
μ_{voc} = temperature coefficient of open-circuit voltage (V/K)
μ_{voc}= temperature coefficient of short-circuit current (A/K)
N_s = Number of individual cells

One additional equation is required in order to calculate the last unknown parameterR_s. To derive the fourth equation, analytic derivative of voltage with respect to temperature for open-circuit condition is taken (2.1.5). Circuit characteristics are calculated by these 4 equations using iterative method.

D. Solar Thermal Collector System

Evaluation of flat plate solar collector performance was done by H. C. Hottel and A. Willier in 1958 at University of Arizona[3]. The collector efficiency of a flat-plate solar collector is defined as the ratio of useful heat gain to the solar radiation incident on the collector. At any instant mathematically,

$\eta = \frac{q_u}{AI}$ (2.2.1)

where,

q_u = Useful Heat Gain (rate of heat transferred to the working fluid (kJ/hour)

A = Area of Absorbing Plate (m^2)

I = Instantaneous Radiation Energy (kJ/m^2.hour)

Energy balance for absorbing plate,$q_u = AS - q_L$ (2.2.2)

$q_L = U_L A(T_{mp} - T_a)$ (2.2.3)

$q_u = AS - U_L A(T_{mp} - T_a)$ (2.2.4)

where,

S = Incident Solar Flux absorbed by the collector plate

q_L = Rate at which Energy is lost

T_{mp}= mean plate temperature of absorber plate

T_a = ambient temperature

A modified equation is also employed, if T_{mp} is replaced with temperature of fluid flowing in the pipe also called local fluid temperature (T_f).

$q_u = F'[AS - U_L A(T_f - T_a)]$ (2.2.5)

where, F' is the collector efficiency factor and it is defined as the ratio of actual useful heat collection rate to the useful heat collection rate, if mean plate temperature is at local fluid temperature. Since, it is difficult to find local fluid temperature or mean plate temperature. Hence equation was further modified on the basis on inlet fluid temperature,

$q_u = F_R A[S - U_L(T_{in} - T_a)]$ (2.2.6)

Where F_R is called the collector heat-removal factor. It is the ratio of actual useful heat collection rate to the useful heat collection rate, if mean plate temperature is at inlet fluid temperature.

$F_R = \frac{\dot{m}C_p}{U_L A}\left[1 - exp\left(-\frac{F' U_L A}{\dot{m}C_p}\right)\right]$ (2.2.7)

This equation (2.2.7) is also known as Hottel – Whillier – Bliss Equation.

E. Photovoltaic Thermal (PV-T) System

L.W. Florschuetz [1979] extended the work of Hottel-Whillier model and performed the analysis of combined photovoltaic/thermal (PV/T) flat plate collectors [4]. The temperature gradients in the absorber, transverse to the direction of flow field were treated independently of those parallel to the flow direction. Also, the temperature gradient across the absorber thickness was neglected and the cell efficiency was represented as a linearly decreasing function of cell temperature.

The modified overall loss heat transfer coefficient ($\bar{U}_L$)

$\bar{U}_L = U_L – (S/\alpha).\eta_r.\beta_r = U_L – \tau.H_T .\eta_r.\beta_r$ (2.3.1)

$\bar{S} = S (1 – \eta_a/\alpha)$ (2.3.2)

where,

U_L = overall loss heat transfer coefficient for flat plate collector (W/m^2.K)

S = solar radiation per unit area absorbed at absorber surface and $\bar{S}$ modified value

α = effective absorptance of collector absorber

η= cell array efficiency (η_r refers to value evaluated at reference temperature)

β_r = temperature coefficient of solar cell efficiency (1/K)

τ = transmittance of collector cover system

H_T = solar radiation per unit area incident on collector (W/m^2)

k = thermal conductivity (W/m.K)
t = thickness of absorber (mm)

Collector efficiency factor and collector heat removal factor were also modified by Florschuetz which were originally given by Hottel and Whiller.

Modified collector efficiency factor ($\bar{F}'$) = $\frac{1}{{}^{1}/_{F_{WD}} + {}^{\bar{U}_L}/_{U_f}}$ (2.3.3)

where $F_{WD} = \left(1 - \frac{D}{W}\right) F + \frac{D}{W}$ (2.3.4)

with $F = \frac{\tan h[m(W-D)/2]}{m(W-D)/2}$ and $m = \bar{U}_L/kt$ (2.3.5)

Finally modified useful energy ($\bar{Q}_u$) = $A_c.\overline{F}_R$. [$\bar{S}$ - $\bar{U}_L$ ($T_{f,i} - T_a$) (2.3.6)

where, the modified collector heat removal factor, $\overline{F}_R$ is given by,

$\overline{F}_R = \frac{G.C_p}{\overline{U}_L}[1 - exp(-\overline{U}_L.\overline{F'}/GC_p)]$ (2.3.7)

Using energy balance electrical output (Q_e) = $S.A_c - \bar{Q}_u - Q_L$ (2.3.8)

Therefore, $Q_e = \frac{A_c.\eta_a.S}{\alpha}\{1 - \frac{\eta_r.\beta_r}{\eta_a}[\bar{F}_R(T_{f,i} - T_a) + \frac{\bar{S}}{\bar{U}_L}(1 - \bar{F}_R)]\}$ (2.3.9)

where,
F_R = Collector heat removal factor ($\overline{F}_R$ is modified collector heat removal factor for cell/plate collector)
G = collector fluid mass flow rate per unit collector area (kg/sec.m^2)
C_p = specific heat of collector fluid (kJ/kg.K)
t = thickness of plate (mm)
A_c =collector area (m^2)
T_a = Ambient temperature (K)
$T_{f.i}$ = Inlet fluid temperature (K)

His results showed that $\overline{F}_R$ and $\bar{F}'$differ from $F_R$and F' respectively because of the modified value of U_L. No more than about 1% of $\overline{F}_R$ and $\bar{F}'$differ from F_R and F' respectively for any thermal design. Hence it was concluded that for practical purposes $F_R$and F' can be used instead of $\overline{F}_R$ and $\bar{F}'$ respectively.

III. SIMULATION MODEL

Project models made on TRNSYS are set up by connecting various components together and outputs are graphically displayed on a different window. Each component described by TRNSYS is mathematically modelled with proper units.

A. Load profile

Time dependent forcing function is used for creating a load profile. An average value of the function is multiplied with a common magnitude which produces a load profile for a given time step. A time step of 0.25 hour is considered. A load profile for a load of 6 kWh or 21,600 kJ is created using the time dependent forcing function, i.e. the area under the load profile is 21,600. The electrical load or the demand per day is assumed constant throughout the year. Figure 3.1shows the load profile of 6kWh per day.

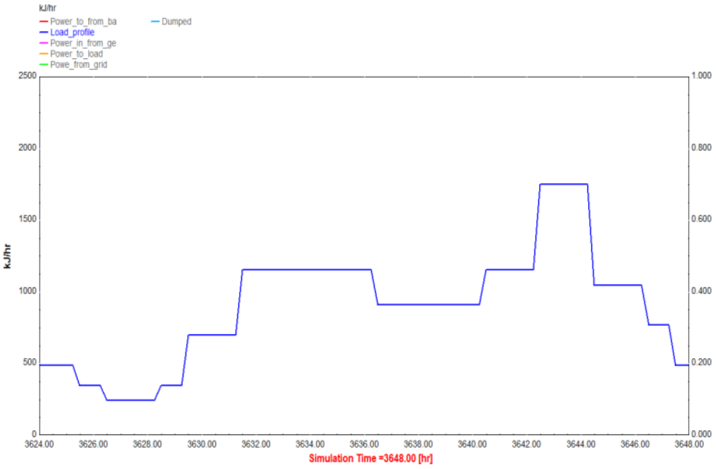

Figure 3.1: Load profile per day.

B. Photovoltaic (PV) model

For modelling PV system, module's details are taken from Vikram Solar panel, model number: ELDORA 300P. Details of the module are given in table 3.1. Standard test conditions for the module are 1000 W/m^2 of solar insolation, AM 1.5 and 25^{o}C cell temperature. The incident angle on the title surface is 45^o.

Table 3.1: Vikram Solar ELDORA 300P specifications

Sno.		
1	Rated Peak Power (P_{mpp})	300W
2	Open Circuit Voltage (V_{oc})	45.1V
3	Short Circuit Current (I_{sc})	8.74A
4	Rated Voltage (V_{mpp})	37.28V
5	Rated Current (I_{mpp})	8.05A
6	Fill Factor (FF)	76.31%
7	Efficiency	15.63%
8	Module Temperature at NOCT	45^{o}C
9	Dimensions	1955x982x36 mm
10	Temperature coefficient at I_{sc}	0.052
11	Temperature coefficient at V_{oc}	-0.310
12	Number of cell wired in series	72
13	Insolation at NOCT	800 W/m^2

Connections are made in such a way that power generated by the PV array is provided to the electrical load first. If the demand of load is fully filled, then power produced by the PV array is transferred to the battery for storage. Also, power from the battery will be withdrawn if the required power is not provided to the load. During low power generation, the grid is connected to supply the power. Specification for inverter/regulator and battery are shown in table 3.2.

Table 3.2: Inverter/regulator and Battery PARAMETERS

Sno.		
1	Regulator efficiency	0.78
2	Inverter Efficiency	0.96
3	High limit on fractional state of charge (FSOC)	0.95
4	Low limit on FSOC	0.1
5	Charge to discharge limit on FSOC	0

6	Cell energy capacity	300Wh
8	Cell in series and parallel	12, 1 resp.
9	Charging Efficiency	0.9

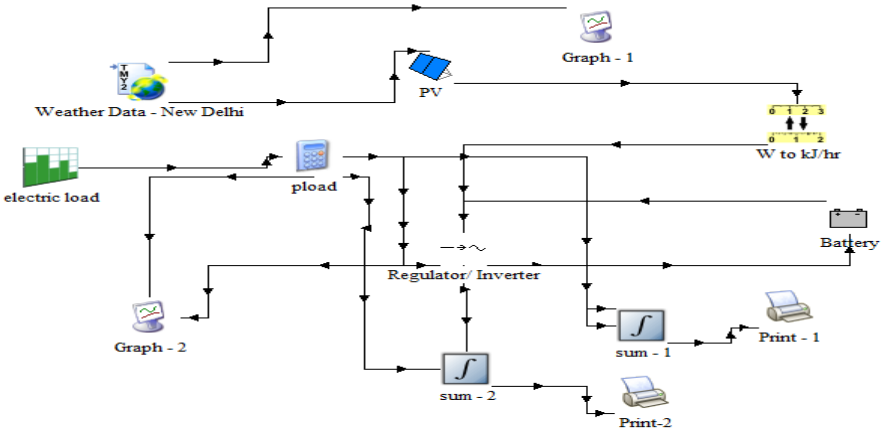

Figure 3.3: PV model.

C. Photovoltaic Thermal (PV/T) model

For modelling PV/T system, work of Florschuetz for the flat plate collector operating at peak power is employed. PV cells are directly pasted over the collector and it is assumed that the cell temperature is equal to collector temperature. PARAMETER details for PV-Thermal collector Type50 are shown in table 3.3.

Table 3.3: PV-Thermal collector (type50) PARAMETER details.

Sno.		
1	Collector Area	10m^2
2	Collector Efficiency Factor	0.7
3	Fluid thermal Capacity	4.19 kJ/kg.K
4	Collector plate absorptance	0.7
5	Number of glass cover	1
6	Collector plate emittance	0.9
7	Loss coefficient	20 kJ/hr.m^2.K
8	Collector Slope	45^o
9	Extinction Coefficient Thickness Product	0.03
10	Temperature Coefficient of PV cell efficiency	-0.0041 1/K
11	Temperature at cell reference efficiency	25^{0}C
12	Packing factor	1
13	Cell Efficiency	15.63%

Water is pump below the PV-T collector from 8 hour to 18 hour with a mass flow rate of 50kg/hour. Other parameters like collector plate absorbtance, emittance, and the loss coefficient are taken from the work done by Ram Kumar Agarwal and H. P. Garg [1994] [6] Packing factor is the ratio of PV cell area to absorber area with a default value of 1. A similar approach is also considered for the electrical part of the PV-T system, i.e. regulator/inverter compares the electrical load and the power produced by the PV array as explained in section 3.2. Parameters for regulator/inverter and battery are given in table 3.2.

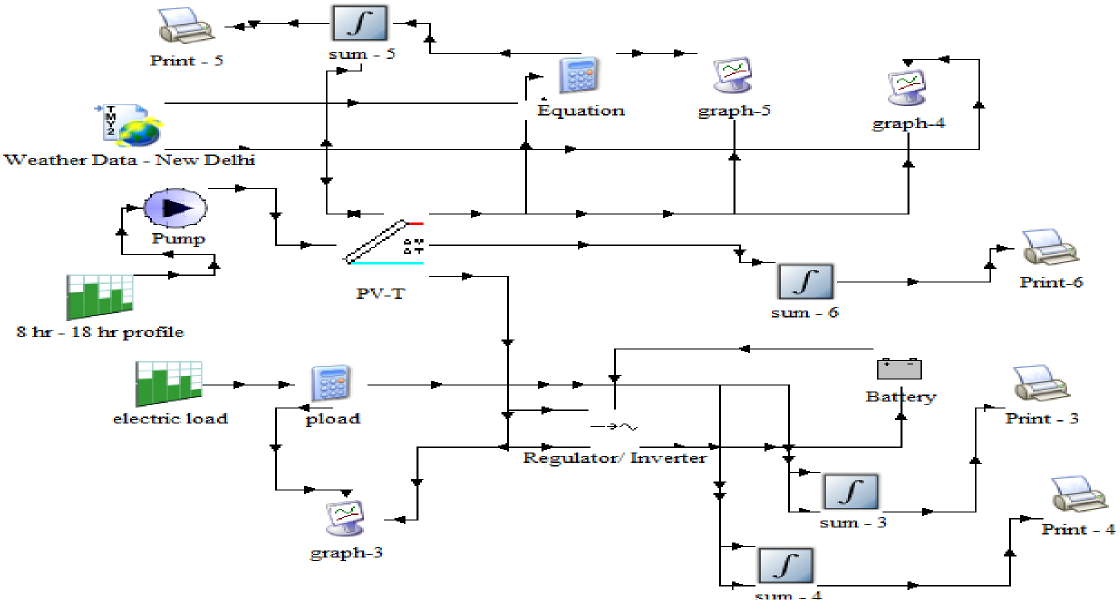

Figure 3.4: PV-T model

D. Flat plate solar thermal collector model

For modelling solar thermal collector, work done by H. C. Hottel and A. Willier in 1958 at University of Arizona for evaluating the performance of flat plate collector is employed. TRNSYS describes the work done by H. C. Hottel and A. Willier using a Type73 component.

Table 4.5: PARAMETER details for thermal collector.

Sno.	Parameter	
1	Number in series	1
2	Collector Area	10m^2
3	Fluid Specific heat	4.190 kJ/kg.k
4	Collector fin efficiency	0.7
5	Bottom, Edge loss coefficient	20 kJ/hr.m2.K
6	Absorber plate emittance	0.9
7	Absorptance of absorber plate	0.9
8	Number of covers	1
9	Extinction coeff. thickness product	0.03

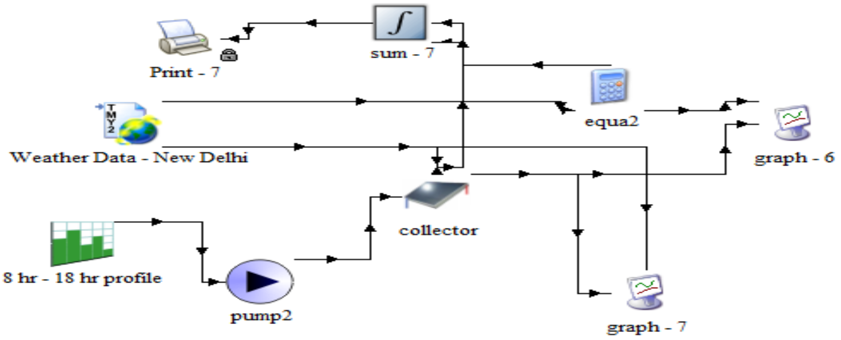

Figure 4.13: Flat plate solar thermal collector model.

IV. SIMULATION AND RESULTS

A. PV model

Table 4.1: Total energy provided to load from PV and grid annually for PV model.

	Time (hour)	Total Radiation (MJ)	Electrical Output (kJ)	Load (MJ)	Energy to Load (PV) (MJ)	Energy from Grid (MJ)
Total	8760	7591.95	1199.72	790.77	721.55	69.21

For an annual electric load of 790.77 MJ, 721.55 MJ of energy is supplied by PV array and the rest 69.21 MJ of energy is supplied from grid. Annually the efficiency of PV model is around 15.80%.

B. PV-T model

Table 4.2: Total energy provided to load from PV and grid annually for PV-T model.

	Time (hour)	Total Radiation (MJ)	Electrical Output (MJ)	Load (MJ)	Energy to Load (PV) (MJ)	Energy from Grid (MJ)
Total	8760	7591.95	1103.26	790.77	692.033	98.74

Table 4.3: Total energy obtained annually for PV-T model.

	Time (hour)	TotalRadiation for 10 m^2 area (MJ)	Total Energy gained (electrical + thermal) (MJ)	Electrical Energy obtained (MJ)	Thermal Energy obtained (MJ)
Total	8760	7591.95	3147.30	1103.27	2044.03

The total radiation falling on PV-T model of area 10 m^2 annually is 7591.95 MJ out of which 1103.27 MJ of energy is converted to electricity and 2044.03 MJ of energy is utilised as thermal energy. Electrical efficiency is 14.53% and thermal efficiency is around 26.92%. The total efficiency of PV-T model is the sum of respective efficiency, (i.e. electrical plus thermal efficiencies) = 41.45% annually.

C. Flat Plate Solar Thermal collector model

Table 4.4: Total Radiation and useful energy gained annually.

Time (hours)	Total Radiation (MJ)	Useful energy gained (MJ)
8760	7591.95	2543.7904

The useful energy obtained for a flat plate solar thermal collector is 2543.79 MJ with an efficiency of 33.50%.

V. CONCLUSION

From table 5.1 it is clear that in their respective fields the efficiencies of PV and flat plate solar thermal models are more than PV-T model but overall efficiency of the PV-T model is more than other two models. Also the electrical efficiency of PV-T model is 91.96% to the electrical efficiency of PV model and thermal efficiency is around 80.35% to thermal efficiency of solar thermal collector model annually.

Most of our industrial processes and buildings need energy including both heat and electricity, and both of them can be provided using hybrid solar photovoltaic/thermal system. Solar thermal and photovoltaic systems absorb energy from solar radiation but due to limited availability of area, installing separate system is expensive and land consuming. Hence the combined system for improved utilisation of solar radiation is suitable, less expensive and consumes less area for installation.

Table 5.1: Efficiency comparison between PV-T, PV, and flat plate collector model.

		Photovoltaic (PV) Model	Photovoltaic Thermal (PV-T) Model	Flat Plate Thermal Collector
Annually	Electrical Efficiency	15.8%	14.53%	--
	Thermal Efficiency	--	26.92%	33.50%
	% of energy to electric load from PV array	91.24%	87.5%	--
	% of energy to electric load from Grid	8.76%	12.5%	--

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