ENERGY RATING BASED ON THERMAL MODELLING OF FIVE DIFFERENT PV TECHNOLOGIES

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ABSTRACT: Minute by minute outdoor measurements of five commercial PV modules including multi c-Si, HIT, a-Si/µc-Si, CIS, CdTe over one year were used to develop a model for predicting the individual module temperatures. The simulated module temperatures over a whole year in minute interval correspond to the outdoor measured values within a RMSE of 1.5°C. Input of the model includes irradiance measurements, which are extracted from the measured short circuit current I_{SC}, the measured wind speed and the ambient temperature. The measured energy weighted module temperature for Zurich was found to be between 33.3°C and 38.0°C for the different module types with a maximum difference of 0.8°C relative to the simulated average module temperature. Due to the high module temperature, the annual average efficiency was reduced relative to the STC values by only 2.6% (HIT) and 5.6% (CIS). Another reduction of the STC efficiency could clearly be attributed to the efficiency at low I_{SC} values which classify low irradiance values. The value is a decrease of the annual energy output of 4.7% and an increase of 1.1%. A further loss analysis was performed to separate spectrum related losses resulting in a relative difference of 2% for the tandem compared to the multi c-Si module.
Keywords: Energy Rating, Loss Factors, Performance Ratio, Thermal Modelling

1 INTRODUCTION

There are various approaches and models, with which one can perform energy rating analysis of outdoor installed PV modules [1-3]. Less literature data are found to quantify the different loss mechanism of different PV technology and types of PV module production technology [2-4]. This paper focuses on the thermal model of five commercial PV module technologies, which describes the surface module temperature based on accurate measured environmental input data like irradiance, ambient temperature and wind speed. The reason for developing such a model lies in the long term goal of high accurate PV plant monitoring. For such monitoring systems, it's important to relay on a model depending only on environmental input data. A high accurate estimation of the electrical model output allows reducing the tolerance band for the comparison with measured electrical output. The same model is applied to forecast the day-ahead PV production in future PV grid integration systems including storages. The second part of the investigation is a precise evaluation of four loss factors including thermal losses, losses due to efficiency reduction at low I_{SC}, spectral and angular losses, and losses as a result of module degradation, during outdoor measurements of single module. Such a classification of the different loss mechanism allows a transparent comparison of module technologies based on specified indoor and outdoor measurements on the device under test. These losses are strongly correlated in typical outdoor application but have to be separated for the detailed analysis [2]. Furthermore, the different types of measurement of the module temperatures and the temperature coefficients (TC) have to be taken into account [5, 6]. The focus lies on the used measurement equipment and the applied methods for the data based analyses due to the model development.

The presented work is carried out under a multiple-year joint research project, whose member includes the electric utility EKZ, TEL Solar who is thin film photovoltaic production solutions provider, and the Zurich University of Applied Science.

2 APPROACH

Two wafer based silicon module technologies and three thin film module technologies are installed for long term outdoor monitoring at the location Dietikon, Zurich. One group includes the multi c-Si and the HIT modules and the other consists of a-Si/µc-Si, CIS and CdTe modules. The CdTe module from First Solar was part of a batch with product faults which leads to high module instability. Details of the examined technologies are listed in Table I [7, 8].

The analyses are based on minute by minute instantaneous outdoor measurements conducted from December 1st, 2011 to November 31st, 2012. All modules are 30° south oriented, and annual STC flasher measurements conducted with the Swiss Mobile Flasher Bus (SMFB) [9] are used.

Table I: Manufacturer data of the analysed PV modules mounted with a 30° inclination towards the south in Dietikon, Zurich. The TC values are relative to STC.

	Installed modules at the EKZ referenceplant in Zurich				
Manufacturer	Sunways	Sanyo	TEL Solar	Avancis	First Solar
Model	SM210 UA65	HIP-215 NKHE	micromorph	PowerMax 110	FS275
Technology	multi c-Si	mono c-Si HIT	a-Si/µc-Si TF	CIS TF	CdTe TF
Module efficiency	14%	17%	8%	10%	10%
P_n STC [W]	230	215	110	110	75
U_{MP} STC [V]	29.3	42.0	94.0	45.8	69.4
I_{MP} STC [A]	7.86	5.13	1.20	2.40	0.85
U_{OC} STC [V]	36.9	51.6	129.0	57.9	92.0
I_{SC} STC [A]	8.34	5.61	1.40	3.15	1.20
TC P_{MP} [%/°C]	-0.43	-0.30	-0.35	-0.45	-0.25
TC U_{OC} [%/°C]	-0.36	-0.25	-0.40	-0.35	-0.25
TC I_{SC} [%/°C]	0.06	0.03	0.07	0.00	0.04
Length [m]	1.68	1.58	1.30	1.60	1.20
Width [m]	0.99	0.80	1.10	0.69	0.60
Area [m²]	1.66	1.26	1.43	1.09	0.72
Weight [kg]	24	15	25	22	12

The test field is equipped with a single module measurement system, which uses four terminal sensing. The monitoring is performed with precise measurement devices as shown in Table II. The PT100 temperature sensors are mounted on the backside of the module with a thermal conductance paste and a Kapton tape [1]. The ambient temperature and the wind sensor are located at a height of 4.5m above the flat surface in the centre.

Table II: The uncertainty calculation (k=2) for the wind speed measurement is done for 10m/s and the uncertainties for all other parameters are determined for STC condition [1]. The uncertainty of the SMFB regards to c-Si module measurements (*).

Parameter	Measurement device	Uncertainty k=2
Irradiance	Kipp&Zonen CMP21	12W/m^2
P_{MPP} outdoor	Agilent N3303A	2.6W-2.9W
I_{SC} outdoor	Agilent N3303A	11mA-18mA
Wind speed	Kroneis 263AA	0.6m/s
Ambient temp.	PT100	0.4K
Module temp.	PT100	0.4K
P_{MPP} Flash (*)	SMFB	2.5%

A lot of time is spent in O&M effort for sensor cleaning, yearly flasher measurements, server administration etc., in order to meet high scientific standards.

3 THERMAL MODELLING

The developed thermal model simulates the module temperature based on three environmental input parameters including irradiance, ambient temperature, and wind. For the model the irradiance dependent efficiency, the convective heat transfer coefficient, and the module heat capacity should be determined to fulfil the requirement of the differential equation based on the conservation of energy among irradiation $\dot{Q}_S$, electric energy $\dot{W}_{PV}$, convective heat transfer $\dot{Q}_C$ and the internal energy.

$$C_m \cdot \frac{dT_m}{dt} = \dot{Q}_S - \dot{W}_{PV} - \dot{Q}_C \quad (1)$$

$$\dot{Q}_S = A_m \cdot G_{POA} \cdot \alpha \quad (2)$$

$$\dot{W}_{PV} = \dot{Q}_S \cdot \eta(G_{POA}) \cdot \left(1 + \delta(T_m - T_{STC})\right) \quad (3)$$

$$\dot{Q}_C = A_m \cdot U(v_W) \cdot (T_m - T_a) \quad (4)$$

where C_m is the heat capacity, T_m and T_a correspond to the module and the ambient temperature, A_m is the module area, α and δ are the absorption and the power temperature coefficient, η is the efficiency depending on irradiance G_{POA} in the module plane and U stands for the convective heat transfer coefficient which depends on the wind speed v_w.

This chapter is elaborated from the project work that resulted in a Master's programme by one of the authors of this paper [10].

3.1 Efficiency at low short circuit current

The I_{SC} values were used as a quantity for irradiance to eliminate the influence of the angular dependency and the difference of spectral behaviour to the irradiance sensor (reference cell or pyranometer) [9]. The disadvantage is that the infrared light will affect the module temperature but not the I_{SC}. But on the other hand, spectral influences are excluded from the thermal model.

$$G_{POA} \cdot \alpha = \frac{I_{SC} \cdot 1000W}{I_{SC,STC} \cdot \left(1 + TC_{Isc} \cdot (T_m - T_{STC})\right)} \quad (5)$$

Equation 5 describes this proportionality using the STC I_{SC} determined by the flasher measurements from April 2012 and the manufacturer's temperature coefficients (Table III). With the method, the absorption coefficient is already taken into consideration.

Table III: The short circuit currents measured with the SMFB [9] in April 2012 and the manufacturer's temperature coefficients.

Technology	$I_{SC,STC}$ [A]	TC_{Isc} [%/°C]
multi c-Si	8.30	0.06
HIT	5.53	0.03
a-Si/µc-Si	1.44	0.07
CIS	3.10	0.00
CdTe	1.21	0.04

First, the irradiance data is binned into 22 intervals (±25W/m^2) between 50W/m^2 and 1100W/m^2. The measured data has to meet two stability criteria in order to eliminate transient effects. Two consecutive temperature or irradiance measurements should not differ by more than 1°C or 0.5%, respectively. Second, the outdoor module power at 25°C is calculated by a robust linear regression. This so called bisquare weights method, which is one of the robust linear regression methods, minimises the sum of all weighted and squared residues according to their distance to the regression line and is therefore less sensitive to outliers [11]. Thus, the efficiencies for each irradiance interval and their exponential fits are computed.

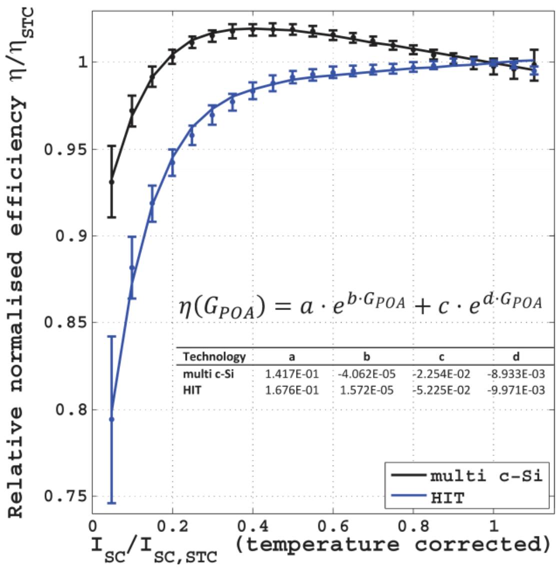

Figure 1: Relative normalised efficiency behaviour of the 30° south oriented multi c-Si and HIT module during single module observation over one year in Dietikon, Zurich. Additionally, the corresponding standard deviations in the 50W/m^2 intervals are shown. The short circuit current is roughly proportional to the spectral corrected solar irradiance measurements.

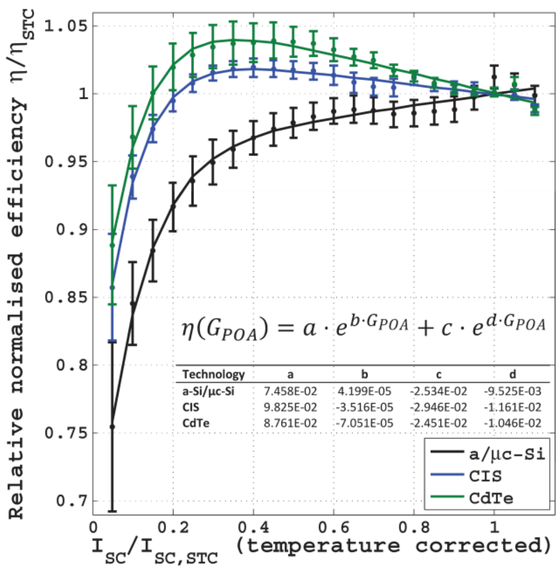

Figure 2: Relative normalised efficiency behaviour of the 30° south oriented thin film modules during single module observation over one year in Dietikon, Zurich. Additionally, the corresponding standard deviations in the 50W/m^2 intervals are shown.

In Figure 1, the discrete efficiencies and the exponential fits of the installed crystalline module technologies are illustrated. The efficiency of the multi c-Si module at 400W/m^2 is about 2% higher than the efficiency of the STC. The behaviour of the HIT module is monotonically decreasing. For the thin film modules, the same analysis is shown in Figure 2. Therefore, the analysed CdTe module has the highest low I_{SC} efficiency behaviour relative to the STC. The fact is attributed to a high serial resistance with a relative low STC efficiency.

3.2 Convective heat transfer coefficient

The heat transfer coefficients depend on material and geometrical and flow properties, and the Reynolds number, Prandtl number and Nusselt number have to be assigned to these properties [12, 13]. Therefore, the specific wind speed on the individual module surfaces should be known. But this is not possible with the used measurement setup in order that another approach is considered.

In the model, only the centralised wind measurement was taken into account. An empirical approach is taken assuming that the wind speed affects linearly the heat transfer coefficient $U(v_W)$ [14]. Equation 6 shows this assumption in case of stationary of the differential Equation 1 with Equation 2 and 4.

$$T_m = \frac{A_m \cdot G_{POA} \cdot \alpha - P_{MPP}}{A_m \cdot (U_0 + U_1 \cdot v)} + T_a \qquad (6)$$

All minute by minute instantaneous measurement data are averaged over 10 minutes due to the quasi-stationary assumption. The coefficients are calculated with the same robust linear regression method as described in chapter 3.1 within the same intervals. The computed factors show that the lower the irradiance interval is the higher the RMSE is and the less representative it is. Thus, the mean of the coefficient with an RMSE less than 4W/m^{2}K is taken into account as listed in Table IV. The tandem module (glass-glass module) has the best behaviour with respect to heat dissipation. The heat transfer coefficient $U(v_W)$ increases linearly from U_0 = 24.6W/m^{2}K with the wind speed by a factor of U_1 = 5.3Ws/m^{3}K. The other two glass-glass modules CIS and CdTe show lower heat transfer coefficients, revealing in higher average module temperature (see Table V).

3.3 Module heat capacity

The module heat capacity is determined by minimising the RMSE between the measured and simulated module temperatures [15]. The simulation is performed according to the Heun's method. The initial value of the module temperature is set to the ambient temperature for each simulation at the start in the morning. The heat capacities for the installed module technologies are shown in Table IV. The micromorph module has the highest heat capacity of 29.3kJ/K and the CdTe has the lowest capacity of 11.7kJ/K.

Table IV: The convective heat transfer coefficient U_0 describes the behaviour without any wind, and the coefficients U_1 assumes the wind as linear. The values are extracted from the linear regression of the Equation 6 based on 10 minute measurement values.

Technology	U_0 W/m^{2}K	U_1 Ws/m^{3}K	C_m kJ/K	RMSE K
multi c-Si	23.58	4.52	23.5	1.49
HIT	22.91	4.65	21.2	1.61
a-Si/μc-Si	24.61	5.30	29.3	1.47
CIS	19.63	3.68	17.1	1.54
CdTe	21.68	3.27	11.7	1.49

3.4 Validation

The minute by minute module temperature simulation of each module technology shows a good match with the measured temperatures. The RMSE determined over one year is about 1.5°C for all the module technologies. Two of these simulated days are shown in Figure 3 and Figure 4 One of these days shows high fluctuating irradiance and strong winds and the other day clear sky condition and marginal wind.

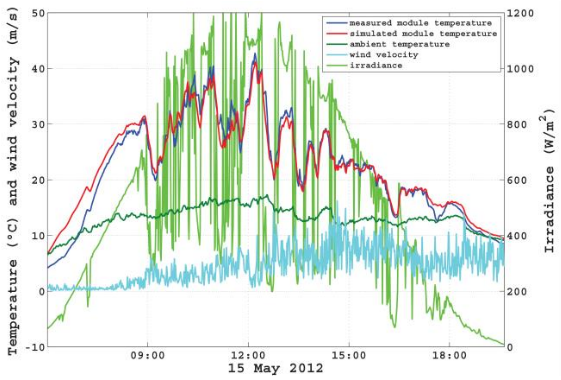

Figure 3: Simulated and measured module temperatures of the HIT module on May 15th, 2012 in Dietikon, Zurich, Switzerland. It shows high fluctuating irradiance as well as wind up to 16m/s in the afternoon. The root mean square error over the day corresponds to 2.0°C. This is mainly driven by a higher simulated temperature in the morning. The RMSE calculated between 09:00 and 15:00 is 1.6°C.

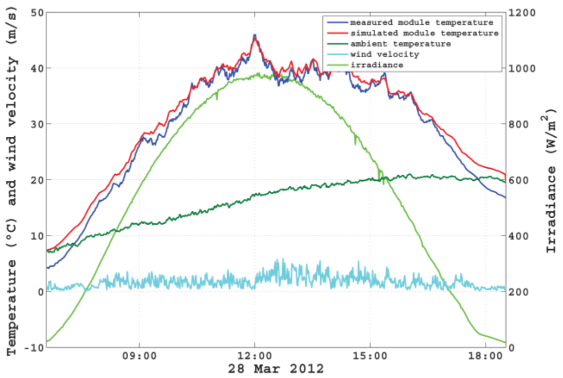

Figure 4: Simulated and measured module temperatures of the a-Si/µc-Si module on March 28th, 2012 in Dietikon, Zurich, Switzerland. This day has nearly a clear sky and low wind. The root mean square error of the simulated module temperature over the day corresponds to 1.8°C. The simulated temperatures in the morning and in the evening are much higher than the measurements. This effect was already shown in Figure 3. The RMSE calculated between 09:00 and 15:00 is 1.2°C.

The highly fluctuating measured module temperature was indicated by the transient thermal model within a deviation of about 2°C (Figure 3). These values are higher in the morning when the module temperature is up to 3°C lower compared to the ambient temperature measured at 4.5m above the roof.

Table V shows the results of the average module temperature and the NOCT. The measured energy weighted module temperatures [16] vary between 33.3°C (HIT) and 38.0 °C (CIS) for the different module types at the location Dietikon. The corresponding simulated temperatures based on the weather input data are within a maximum temperature deviation of 0.8°C. The measured module temperatures under NOCT condition were found between 43.1°C (HIT) and 49.67°C (CIS) with a maximum deviation of 1.2°C relative to the simulated temperatures. The manufacturer NOCT values are only available for the multi c-Si, a-Si/µc-Si and the CIS module. Only the manufacturer NOCT value of the CIS module diverges significantly up to 6.3°C from the measured value. The NOCT is analysed using selected module measurement data for the meteo condition 800W/m^2 ± 50W/m^2 irradiance, 20°C ± 2°C ambient temperature and 1m/s ± 0.3m/s wind speed.

Table V: Measured energy weighted average (WA) module temperatures as well as the examination of NOCT condition for different module types versus simulated values on the base of measured weather data.

Parameter	multi c-Si	HIT	a-Si/ µc-Si	CIS	CdTe
Meas. WA. T_m [°C]	33.76	33.25	33.76	38.02	37.06
Sim. WA. T_m [°C]	33.15	32.75	33.29	37.30	36.27
Measured NOCT [°C]	43.97	43.14	43.34	49.67	48.46
Simulated NOCT [°C]	44.13	43.73	44.51	50.61	49.12
Manufact. NOCT [°C]	45	-	45	56.9	-

4 ENERGY RATING

This chapter considers the energy rating of the five PV technologies according to the selected performance factors. Therefore, the DC performance ratio is calculated:

$$PR_{DC} = \frac{W_{DC}}{E_{POA} \cdot A \cdot \eta_{STC}} = k_T \cdot k_{lowIsc} \cdot k_\lambda \cdot k_D \quad (7)$$

The first performance factor k_T considers thermal losses. The second factor k_{lowIsc} corresponds to the efficiency reduction at lower I_{SC} compared to STC efficiency. Spectral mismatch and other losses (IAM, AOI) are included in k_λ. The last factor k_D is attributed to the module degradation. String losses and ohmic losses are disregarded because it is a single module analysis with the four terminal electrical sensing. Table VI shows additional data used in this analysis.

Table VI: Temperature coefficient of P_{MPP}, nominal outdoor power, nominal outdoor module efficiency and weighted annual mean module efficiency are analysed for annual observation period in 2012.

Technology	TC_{Pmpp} %/°C	P_{MPP} W	$\eta_{Outdoor}$ %	$\eta_{weighted}$ %
multi c-Si	-0.46	225.83	13.58	13.67
HIT	-0.32	214.66	17.03	16.65
a-Si/µc-Si	-0.34	112.64	7.88	7.51
CIS	-0.43	103.98	9.50	9.49
CdTe	-0.38	58.83	8.17	8.26

The thermal loss factor is defined as the yearly losses which occur due to module temperatures above the STC temperature of 25°C. The outdoor temperature coefficient of P_{MPP} and the measured average module temperature control the loss parameter k_T.

The results from chapter 3.1, which describes the efficiency at lower I_{SC}, are used to calculate k_{lowIsc}. The concept is the same as the method of calculating the euro efficiency for the PV inverters [17]. The computation is carried out by weighting the irradiance dependent efficiency with the percentiles irradiation distribution (interval of 50W/m^2). The availability of the irradiation is not 100%. However, the comparison to the distribution based on 10 minutes data from IDAWEB (MeteoSwiss) [18] showed still a good match within 0.28%.

The spectral and angular loss factor is determined by the ratio of the yearly irradiation regarding I_{SC} and the yearly irradiation measured with the pyranometer sensor.

For the degradation factor, the effective nominal outdoor power at 25°C STC has to be known. It is normalised to manufacturer's nominal power rating.

The combined results of this analysis are shown in Table VII and Figure 5. Due to the higher effective module temperatures relative to the STC power output, the reduction of PR is between 2.6% (HIT) and 5.6% (CIS). The corresponding outdoor TCs are -0.32%/°C and -0.43%/°C, respectively. For the multi crystalline and the CdTe module, an increase in the energy output of 0.7% and 1.1% respectively can be attributed to the efficiency at low I_{SC} values. The other module technologies have a decrease of at most 4.7% at low I_{SC}. Comparing the multi c-Si with the tandem module, a difference of 2% can be found with respect to the spectral related losses. The spectral and the degradation losses are very high for the CdTe module due to high instability described in Table VII. The micromorph module shows a high factor for module degradation (1.023) because of the light induced degradation which was not yet completed in 2012 but nearly finalised in 2014.

The deviations from measured to calculated PR_{DC} on the base of weather data are between -0.37% and 0.31%. The total PR_{DC} of the multi c-Si and the HIT module are close together at 0.930 and 0.926, respectively. The CIS module has the worst temperature behaviour of the five analysed module types quantified by a factor of 0.944. The PR_{DC} of that CIS module resulted at 0.859.

Table VII: The performance factors as well as the calculated and measured PR_{DC} are shown for each examined technology. The spectral and the degradation losses are very high for the CdTe module because it was part of a batch with product faults which leads to a high module instability (*). (Definition of the PR_{DC} in Equation 7)

Para-meter	multi c-Si	HIT	a-Si/ µc-Si	CIS	CdTe
k_T	0.960	0.974	0.970	0.944	0.954
k_{lowIsc}	1.007	0.978	0.953	0.999	1.011
k_λ	0.981	0.974	0.962	0.964	0.906*
k_D	0.982	0.999	1.024	0.946	0.784*
Calc. PR_{DC}	0.930	0.926	0.911	0.859	0.686
Meas. PR_{DC}	0.928	0.923	0.915	0.861	0.686

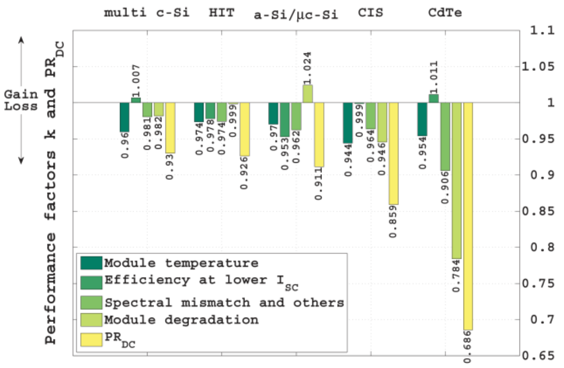

Figure 5: Graphical illustration of the analysed performance factors. The CdTe module has a very low PR_{DC} due to high instability shown in detail in Table VII.

5 CONCLUSION

The thermal model developed to simulate the PV module temperature uses the three environmental input parameters including irradiance, ambient temperature and wind. The model is based on the conservation of energy among irradiation, electric energy, convective heat transfer and the internal energy. The module temperature simulation of each technology shows a good match with the PT100 temperature measurements. The RMSE determined over one year is about 1.5°C for all the technologies. The measured energy weighted module temperatures differ from the simulated temperature by at least 0.50°C (HIT) and by at most 0.79°C (CdTe).

The PR_{DC} could be split up into four performance factors which lead to values between 0.686 for the CdTe and 0.930 for multi c-Si module. Only in the HIT technology, the individual effect of efficiency reduction by the temperature coefficient, the low ISC effect, and the spectral behaviour relative to the pyrometer are very similar. This results in a reduced PR_{DC} from 1 to the value of 0.923. The poly c-Si technology produces about the same final PR_{DC} yet with higher values of the temperature losses and lower losses due to low I_{SC}.

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