Quantification of Capacity Credit of Additional Photovoltaics Installations on the Island of Crete

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Abstract— **Renewable Energy Sources have significantly helped in meeting the electricity production of Crete, with their share in the energy balance to account for about 25% of the annual electricity production for the recent 5 years. Contribution of PVs in the energy balance, especially during summer time, has been also significant.**

This paper investigates what the capacity credit would be, i.e. up to what extent additional PV capacity of about 20% can be considered as certain, to avoid installing thermal power units. In order to do so, probabilistic techniques are applied to quantify the load that the installed thermal units in the Cretan power system should be able to meet at any time. In addition, the effect of the additional PV capacity to power system's reliability is evaluated taking into account actual data regarding the planned and unplanned thermal units' maintenance. Two scenarios have been examined using actual hourly data for load demand, PV and wind production from the island power system of Crete. In the first scenario, the calculations were carried out considering the operation of the Cretan power system in its current state, while in the second scenario it was assumed that the PV production has been increased by 20%.

Index terms – Photovoltaics, Probabilistic analysis, Capacity credit, Reliability, Island power systems

I. INTRODUCTION

Photovoltaics (PVs) have now a major role in meeting the electricity demand. According to [1], 99.1 GW of grid-connected PV capacity was installed only during 2017, as much PV capacity as the world had been cumulatively installed by the end of 2012 (100.9 GW). There have been numerous studies regarding the potential benefits of PVs already by 90's [3], [4], [5], [4], without mentioning their contribution to rural electrification.

In the island power system of Crete, the installed capacity has already reached 98.67 MW [2]. It has been noted that about 10% of the peak demand at the summer period, is met by PVs. In view of the increase of the installed capacity of PVs at about 20% of the currently installed capacity via the legislative framework of "Net Metering" and "Virtual Net Metering", with the active participation of the Public Authorities of the islands, it would be interesting to investigate up to what extent this additional capacity of PVs could replace firm capacity from thermal units. Such an investigation has been proposed both for microgrids [7] and large power systems for wind power [8] as well.

Additionally, the impact of PV generation on various reliability indices for the power system of Crete, such as Expected Energy Not Supplied (EENS), Loss of Load Probability (LOLP) will be investigated to show the potential impact of PVs on the generation adequacy of the power system of Crete. Additionally, the methodology applied cannot only quantify the additional firm capacity that is required for obtaining 99.9999% generation adequacy for the island of Crete but identify the situations that this may be required. Such information can be very useful for the operator of a power system in order to perhaps rent generation capacity or apply Demand Side Management (DSM) measures.

The methodology followed has been based on probabilistic techniques and actual data from the island power system of Crete. Demand and Renewable Energy Sources (RES) generation have been modeled as random variables while well-known generation adequacy assessment techniques, based on Forced Outage Rate (FOR) have been applied. This methodology applies per group of hours and months to account for the inherent seasonal and daily variability of PV generation based also on similar approach, presented by some of the authors [9]. More details on this methodology have been described in section II. More details on the power system of Crete are provided in section III and results from this analysis are provided in section IV either with or without considering installation of the additional PV capacity. Finally conclusions are drawn in section V.

II. METHODOLOGY

This section describes the methodology followed for the estimation of the capacity credit of the additional PV capacity along with their contribution in reducing EENS and improving other reliability indices, as far as generation adequacy is concerned. In order to evaluate all these parameters, probabilistic techniques have been used. The analysis has been made by grouping actual hourly data for load demand, PV and wind power production from the island power system of Crete for the last three years (2016, 2017, 2018), per month (mo) and per hour type (hr) in order to derive corresponding random variables probability density functions (pdf). The proposed methodology consists of the two following steps.

A. Derivation of the expected thermal generation probability density function (pdf)

In Crete, as in most island power systems single buyer model and feed-in tariff schemes apply. In such a case, the load to be distributed to the thermal units of the power system under study is provided by (1)

$$P_{Th\_units} = P_{Load} - P_{Wind} - P_{PV} \tag{1}$$

where P_{Load} is the actual demand while P_{Wind}, P_{PV} are the wind parks and PVs production. The load that the installed thermal units in the Cretan power system should be able to meet at any time varies due to various factors. The season, or more specifically the month of the year, as well as the type of the day are two important factors that cause significant fluctuations in hourly load demand and RES production. Therefore, this is why the data and hence the results are classified per month and per hour. However, the load to be distributed to the thermal units cannot be accurately estimated, as load demand varies considerably over time and weather conditions are clearly unstable.

In this study, the estimation of the random variable representing the load to be served by the conventional units P_{Th_units}, is obtained, as described in (2), as a result of the convolution of the independent pdfs $P_{Load}(mo,hr)$, $P_{Wind}(mo,hr)$ and $P_{PV}(mo,hr)$

$$P_{Th\_units}(mo,hr) = P_{Load}(mo,hr) - P_{Wind}(mo,hr) - P_{PV}(mo,hr) \tag{2}$$

These pdfs have been extracted from hourly data of these three years, defining discrete steps of demand or production for each month and hourly type. The steps for the purposes of this paper are defined as:

- 10 MW for $P_{Load}(mo,hr)$
- 5 MW for $P_{Wind}(mo,hr)$
- 2.5 MW for $P_{PV}(mo,hr)$

The frequency bins for equation (2) are provided by equation (3).

$$f_{Th\_units}(mo,hr) = f_{Load}(mo,hr) \cdot f_{Wind}(mo,hr) \cdot f_{PV}(mo,hr) \tag{3}$$

A typical graph for the final $P_{Th\_units}(mo,hr)$ pdf is shown in Figure 1. A similar approach had been used for evaluation PV value on the island power system of Crete in [9].

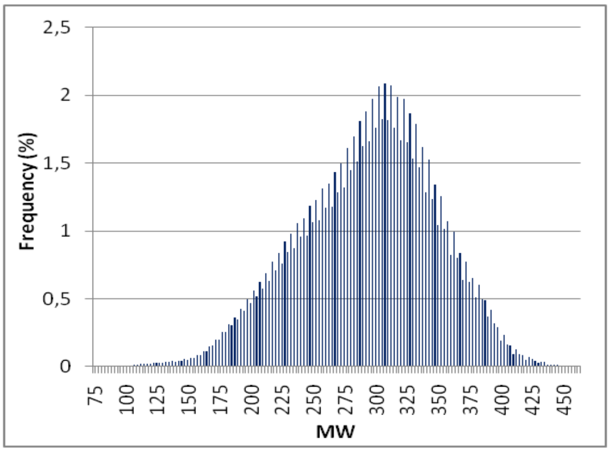

Figure 1. $P_{Th\_units}(mo,hr)$ for 12:00 and May for the Cretan power system

B. Reliability and Forced Outage Rate

All conventional units of any power system are subject to several random unplanned outages. Generation adequacy of a power system is the assessment of the ability of the conventional units to meet the consumption of the power system, based on reliability indices. The simplest stochastic method for considering the reliability of a production unit is the two-state model, provided by (4). This model defines two possible states for each unit. Each generation unit may be either capable of producing at its rated power or not available due to a failure, each case with a corresponding probability. The probability of the unit being available is p_i, while the probability of being unavailable is q_i which is called "Forced Outage Rate" (FOR):

$$p_i + q_i = 1 \tag{4}$$

Therefore, taking into account FOR and $P_{Th\_units}(mo,hr)$, a new pdf $P_{Load\_loss}(mo,hr)$, related to the load that available units cannot meet, is calculated by an iterative algorithm.

The system reliability based on generation adequacy can be evaluated, examining this new pdf. EENS, Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE) [10] represent reliability indices. EENS defined by (5), is a measure of the amount of energy demand, which is expected not to be met by thermal units during a specified time period.

$$EENS = \int_0^n P_{Load\_loss}(t)\,dt \tag{5}$$

LOLP expresses the case when the available generating capacity exceeds the expected demand. It is a projected value of how high is the probability, in the long run, of the load of a power system is expected to exceed the capacity of the available generating resources. LOLE defines the time for which the load demand is expected to exceed the available capacity within a specified time period (T) and is given by (6).

$$LOLE(mo,hr) = LOLP(mo,hr) \cdot T \tag{6}$$

Moreover, a new index (LWLOLE) is defined by (7), which represents the load no to be supplied for duration bigger than 0.1sec, corresponding to 99.9999% of the period studied. This will show how easy it is for the generation system to adapt to the generation shortage, e.g. by renting gen-sets or by demand reduction.

$$LWLOLE\left(mo,hr\right)=LOLE\left(mo,hr\right)>0.1sec \qquad (7)$$

III. POWER SYSTEM OF CRETE

Crete is the largest Greek island, and the fifth-largest island in the Mediterranean Sea. Crete has population of 623,065 [11]. The population is significantly increased during the summer period due to tourists influencing the peak demand.

The island of Crete has the largest autonomous power system in Greece with instantaneous peak demand that has reached 707 MW and annual energy demand of 3.2 TWh [2].

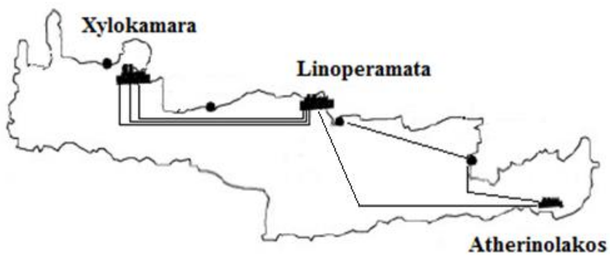

Figure 2. Power stations location

A large number of conventional units with different technologies and response characteristics (steam turbines, Internal Combustion Engines (ICE), Open Cycle Gas Turbines (OCGT), and one combined cycle (CC) unit with total capacity of 824.8 MW have been installed in three power stations, namely Xylokamara, Linoperamata and Atherinolakos, on the island as is depicted in Figure 2 . In Table I, the capacity per unit type and power station is provided [12].

Table I. Installed capacity (in MW) per unit type and power station

Power station	Steam	ICE	OCGT	CC	Total
Linoperamata	111.3	49.2	118.6	-	279.1
Xylokamara	-	-	202.2	132.3	334.5
Atherinolakos	93	118.2	-		211.2
Total capacity	204.3	167.4	320.8	132.3	824.8

Crete has one of the highest solar potentials in whole Europe, reaching up to 2100 kWh/m^2/yr, and also high average wind speed that in many locations exceeds 8.5m/sec. These characteristics make the island an ideal place for the installation of wind and solar technologies [13]. There are more than 1000 small PV parks (mainly of 80 kW each) and 1800 roof PVs (≤ 10 kW, of about 17 MW) installed. Only 5 PV parks have capacity higher than 100 kW with total capacity about 0.9 MW. The largest has capacity 0.3 MW [14]. There are also 38 wind parks with total installed capacity about 200 MW. Currently, the total installed capacity of the RES stations amounts to 296 MW and it is also estimated the development of new RES stations such as hybrid stations, solar thermal stations, geothermal stations and biomass stations. In 2016 the total yearly RES generation amounted to 696.9GWh, while in 2017 to 652.9GWh, presenting in this way a decrease of 6.31 %.

The energy production balance of Crete is as shown in Figure 3 [2]. More details about the distribution of demand in each one of the four prefectures of the island can be found in [15].

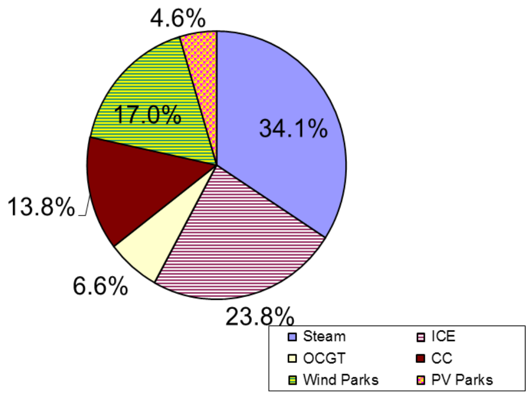

Figure 3. Power Generation Breakdown in 2017

The latest overview of the autonomous power system of Crete is based on actual operational data from the SCADA system of HEDNO SA. Only for 46 hours load demand exceeded 600 MW, while for 942 hours the load exceeded 500MW. In Figure 4 the load duration curve for P_{Th_units} of the Cretan Power System for the year 2018 is presented showing that only for 90 hours, 520MW of thermal capacity would be necessary to operate. However, the maximum actual demand to be served by the thermal units, as derived by (2) has little but not negligible possibility to be as high as 630MW.

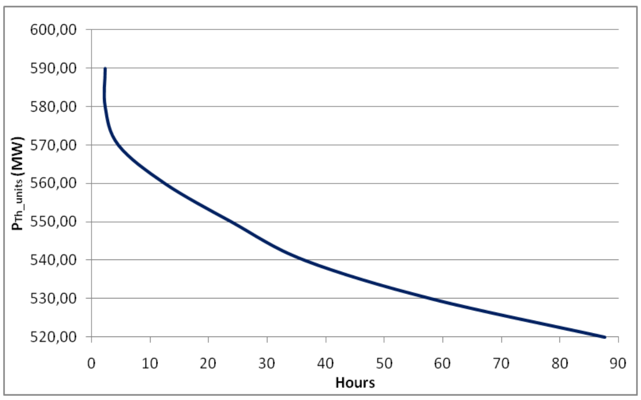

Figure 4. Actual demand to be served by the thermal units (HEDNO 2018)

IV. RESULTS

A. *Capacity Credit Estimation*

Examining the results from applying the first part of the methodology (A), the effect of 20 MW additional capacity, which is the limit for PV provided by the Regulatory Authority of Energy of Greece, is evaluated. This additional capacity decreases the load that the thermal units have to meet for some hours of the day, as well as manages to decrease the maximum monthly capacity required especially during the summer months. Figure 5 depicts the probability that the demand to be met by thermal units is expected to be higher than 600MW, considering the additional installation of PVs. July is the month with the highest reduction (-24.23%) regarding this criterion, while in June the difference between the two states is almost negligible. In June, in particular in the second half of June, values of load demand greater than 600 MW have been observed, during 20:00-22:00, which is a time period that the solar PV plants cannot marginally contribute to the total generation.

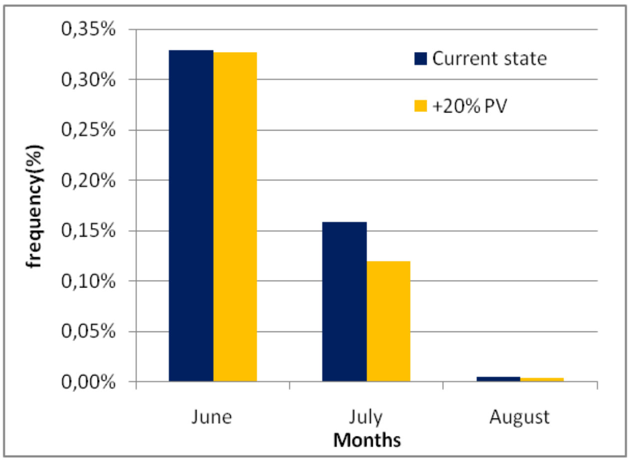

Figure 5. Expectation of the demand to be met by thermal units to exceed 600MW

According to the Table II, the maximum load that thermal units have to meet is by 7.5MW lower than the respective in the current state of Cretan power system. This load corresponds to the peak demand that the thermal units of the system are expected to meet, thus is estimated that 7.5 MW capacity of firm thermal units could be replaced, because of the additional capacity of PVs.

Table II. Maximum load to be met by thermal units (MW)

Months	Current state	+20% PV	Hour
June	610	610	20:00-22:00
July	630	622,5	14:00-15:00
August	610	602,5	13:00-14:00

B. Reliability Evaluation

Thermal units of the island power system of Crete need to be maintained for some time periods during a year. This requirement, leads each unit to scheduled outages which are determined by the administrator of the power system (HEDNO), usually in specific time periods. Autumn and spring are the most appropriate seasons for such maintenance, due to low load demand. In such a case it is assumed that the steam turbines are committed to service for a long time (month), contrary to diesel and gas turbines whose maintenance lasts less (one or two weeks). In order to take into account this necessity, for any unit which is under scheduled maintenance, FOR has been sent to 1.

In this section, reliability indices of the Cretan power system are evaluated from the generation adequacy of thermal units' perspective, examining two different scenarios. The results are provided comparing the reliability indices of the system in its current state and with the assumption that the PV production has been increased by 20%. Figure 6 shows the EENS for five examined months. February and November are two months with low values of load demand. The EENS in the former case is 0.22 MWh while in the latter case was calculated as 1.54 MWh. This significant difference is because of the units which are maintained in each case. It was assumed that in February those units could be a diesel unit of the power station of Linoperamata (10MW) and a gas turbine (27MW), while in November a part of the Combined Cycled (52MW) unit could be out for service in addition to the Steam turbines 4, 5 (24MW each) of the power station of Linoperamata. Lower capacity of the available units during November justifies higher EENS values compared to February. During summer, although FOR is the only probability that was included for generation outages, high load demand leads to high EENS values.

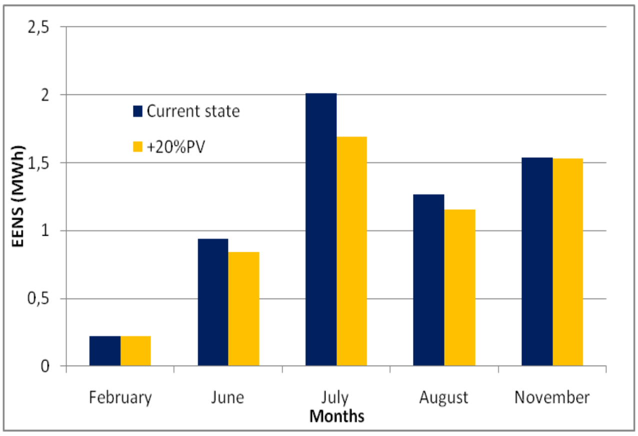

Figure 6. Expected Energy Not Supplied for five representative months

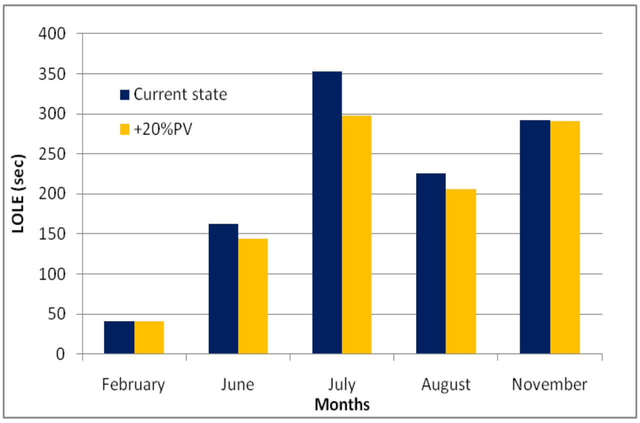

Figure 7. Sum of Loss of Load Expectation for each representative month

Similar results are obtained for LOLE as is depicted in Figure 7. In July 20% of additional PV generation could decrease the EENS by 15.93% and the LOLE by 15.71% for the whole month, while in November 0.19% for EENS and 0.25% for LOLE. It is interesting to examine the change in LOLE during daytime. Figure 8 presents LOLE for July, grouped by hour type. Cleary high reduction of LOLE, exceeding 45% during hours 12:00-15:00 can be achieved. That proves the great impact of PV generation on system's reliability for periods with high solar irradiation. Nevertheless the maximum LOLE which is summarized for each month in Table III, cannot be decreased by this additional PV capacity. For all months except February, this maximum value is observed, during the first night hour, when the solar PV cannot produce.

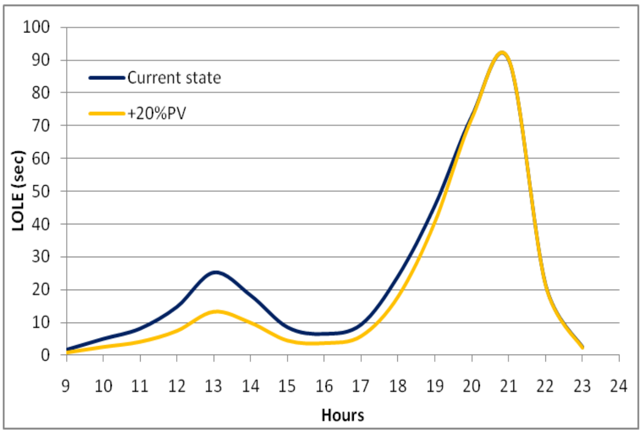

Figure 8. Loss of Load Expectation for each hour in July

Table III. Maximum Loss of Load Expectation for each month and hour type

Months	Max LOLE (sec)	Hour
February	16,65	19:00-20:00
June	47,21	21:00-22:00
July	90,04	21:00-22:00
August	88,40	20:00-21:00
November	99,25	18:00-19:00

Figure 9 shows the value of LWLOLE in July for each hour type. The effect of additional PV capacity is observed during the daytime with the highest reduction in LWLOLE being achieved at 13:00-14:00 by 15 MW (-14.3%), while 22.2% (-10MW) reduction in LWLOLE at 09:00-10:00 can be also achieved.

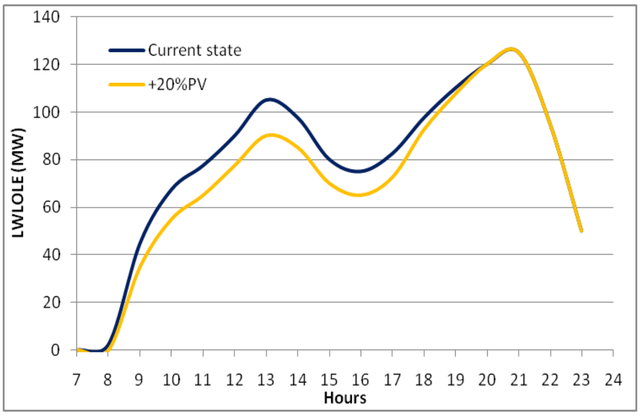

Figure 9. Load with Loss of Load Expectation > 0.1sec for each hour in July

However, this effect cannot decrease the additional firm capacity that is required for obtaining 99.9999% generation adequacy, due to the maximum LWLOLE which appears at night hours as confirmed by Table IV.

Table IV. Maximum Load with Loss of Load Expectation > 0.1sec for each month

Months	Max LWLOLE (MW)	Hour
February	90	19:00-20:00
June	115	20:00-22:00
July	125	21:00-22:00
August	125	20:00-21:00
November	110	18:00-19:00

V. CONCLUSIONS

One of the questions that the operators of autonomous power systems have to address for the planning studies of their systems is whether volatile RES, such as PVs, can provide any capacity credit to the power system they manage. This paper proposes a methodology not only to assess the potential impact of PVs on capacity credit, but also to give further insight on various reliability indices for the generation system and the additional PV capacity indices on them.

The example case study was the largest autonomous power system in Greece, the island power of Crete, an island with already significant PV capacity reaching 100MW. For this power system the additional capacity limit for PV is considered by the Regulatory Authority of Energy of Greece equal to 20MW corresponding to increase by 20% of the currently existing PV capacity. The legislative framework of "Net Metering" and "Virtual Net Metering" makes such an assumption rather reasonable in the forthcoming years.

Utilizing probabilistic techniques, MATLAB software and actual hourly data for load demand, PV and wind power production from the island power system of Crete for the last three years, the capacity credit of 20MW additional capacity of PVs on the island was examined. The obtained results showed that 20MW of PVs can offer 7.5 MW capacity credit, or can reduce by 1.2% the maximum probable thermal units loading expected to appear during early afternoon hours of July.

The impact of the additional PV capacity on other reliability indices was then evaluated taking into account actual data on FOR and the typical maintenance schedule. Clearly, reduction in EENS and LOLE for summer months like July can exceed 15.5%. However, this reduction is mainly expected during periods when solar irradiation is apparent and unfortunately EENS and LOLE which are rather high during the first hour of the night hours are not influenced.

In this paper also, an index in Capacity terms (MW), LWLOLE, is introduced, to reflect the possibility of having inadequate capacity with expected disconnection time higher than 0.1sec. This may show the magnitude of required firm capacity for the power system. This index can be also introduced for variable values of time shortage. PVs can decrease significantly this index by up to 15MW during July but unfortunately can provide no aid in the generic reduction of this index for each month.

Moreover, this methodology shows clearly that decommissioning of units deteriorates the reliability indices even during periods of low demand, to comparable values to the summer period when no scheduled maintenance take place but the demand is much higher.

The methodology applied can be replicated to other power systems utilizing data that are usually available to the operators of power systems. It can be estimated that if the evening demand is high, then the PV capacity credit might be even lower than the case of Crete. Moreover, if reliability indices of Crete are to be improved there is clearly the need of using stored energy during the first couple of nighttime hours.

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