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Suneet Singh
Venkatasailanathan Ramadesigan *Editors*

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Editors
Suneet Singh
Department of Energy Science
and Engineering
Indian Institute of Technology Bombay
Mumbai, Maharashtra, India

Venkatasailanathan Ramadesigan
Department of Energy Science
and Engineering
Indian Institute of Technology Bombay
Mumbai, Maharashtra, India

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Chapter 6
Agri-Voltaic System for Crop Production and Electricity Generation from a Single Land Unit

Priyabrata Santra, R. K. Singh, H. M. Meena, R. N. Kumawat, Dhananjay Mishra, D. Machiwal, Devi Dayal, D. Jain and O. P. Yadav

Abstract Renewable energy generation has gained much more importance in India than ever before. Photovoltaic (PV)-based electricity generation shares a major portion of renewable energy generation in India. PV-based electricity generation requires land of about 2 ha per MW of installation. Since both food and energy are required for human civilization to progress, here a concept of integrating PV-based electricity generation and crop production from a single land unit is designed and developed, which is known as agri-voltaic system. Such systems of 105 and 25 kW have been established at ICAR-Central Arid Zone Research Institute, Jodhpur, and its regional station at Bhuj, respectively, with a land requirement of 29 m^2 per kW. Rainwater harvesting system from top surface of PV module has been designed and developed. The harvested water is expected to provide supplemental irrigation of 43 mm in 0.76 acre land on which 105 kW system has been established. Suitable crops for agri-voltaic system have been identified, which generally does not attain height not more than 50 cm during its crop growth period. Few of the selected crops are *Vigna radiata* (moong bean), *Vigna aconitifolia* (moth bean), *Plantago ovata* (isabgool), *cuminum cyminum* (cumin), etc.

Keywords Agri-voltaic system · Solar farming · Water harvesting · PV modules · Crop production · Shade-tolerant crops

6.1 Introduction

Energy and food are the two main requisites for human civilization to progress. However, the demands for these two resources have been increasing at a fast rate. Fossil fuels, the major source of energy, have been exhausted rapidly, and therefore, energy from biomass has been claimed to be a possible substitutes of it during recent times. However, the amount of land required for growing bioenergy crops

P. Santra (✉) · R. K. Singh · H. M. Meena · R. N. Kumawat · D. Mishra · D. Jain · O. P. Yadav
ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan, India
e-mail: priyabrata.santra@icar.gov.in

D. Machiwal · D. Dayal
ICAR-Central Arid Zone Research Institute, Regional Research Station, Bhuj, Gujarat, India

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in order to replace fossil fuels with biofuels largely exceeds the present cropland area in the world. Biofuels from cereals or oil crops are generally produced through ethanol pathway or trans-esterification pathway. It has been estimated that growing cereals in a hectare will be sufficient to produce bioenergy which will allow running a car for about 18,000 km, and it will be about 22,000 km if most efficient trans-esterification pathway is adopted. The low efficiency of the photosynthetic process of most bioenergy crops which is about 3–5% will not be able to cope up with increasing energy demand of the world [1]. In contrast, commercially available photovoltaic modules have an efficiency of 12–15% for converting solar energy to electricity through photovoltaic process and thus can supply the future energy needs. Therefore, solar PV-based power plants are envisaged to compete with agriculture for land. Therefore, the issue of competition for land by future agriculture production system and energy sectors is discussed recently in several literatures [2–6]. In view of this, agri-voltaic system (AVS) has been proposed as a mixed systems associating solar PV modules and crops on the same land area [7, 8]. Keeping in mind the potential of AVS in future, 105 and 25 kW capacity of such system have been designed and installed at ICAR-Central Arid Zone Research Institute (ICAR-CAZRI), Jodhpur, and its regional research station at Bhuj, respectively. In this manuscript, design of installed agri-voltaic system and its performance has been discussed in brief.

6.2 Study Area

Arid western India mainly comprises the western part of Rajasthan and north-western part of Gujarat with some parts of Haryana and Punjab at its North East and East, respectively. It lies between 21°17′–31°12′N and 68°8′–76°20′E covering an area of 32 million ha. The arid part of the country receives much more radiation as compared to the rest of the country. The average irradiance on horizontal surface in India is 5.6 kWh m^{-2} day^{-1}, whereas at Jodhpur, which lies at the arid part of the country, it is 6.11 kWh m^{-2} day^{-1}. The solar resource map of western Rajasthan shows that western India receives maximum amount of solar irradiation, whereas major portion of India (~140 million ha) is receiving solar irradiation of 5–5.5 kWh m^{-2} day^{-1} (Fig. 6.1). At Jodhpur, the highest amount of irradiation is received during April (7.17 kWh m^{-2} day^{-1}), whereas the lowest amount of irradiation is received during December (5.12 kWh m^{-2} day^{-1}). In total, 6390 kWh of solar energy is available during a year at Jodhpur. Moreover, most of the days in a year at Jodhpur are cloud free which has been measured and reported in several literatures as 300 days clear sunny days in a year.

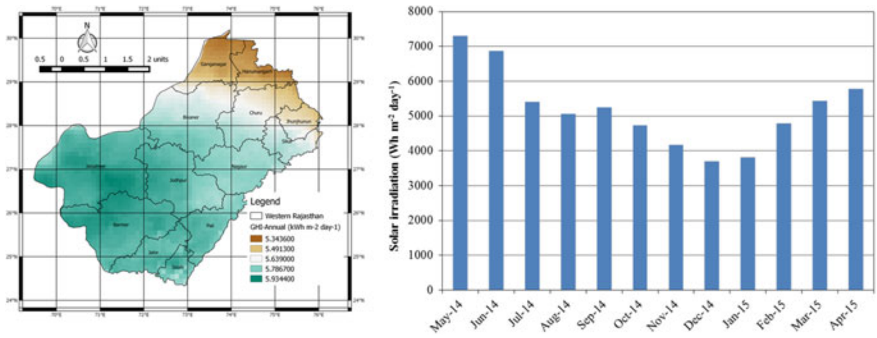

Fig. 6.1 Availability of solar irradiation in western Rajasthan and at Jodhpur

6.3 Design of Agri-Voltaic System

6.3.1 PV Module Installation

At Jodhpur, PV installation system consists of three experimental designs in three separate blocks, each of 36 m × 36 m area. These are (i) PV arrays of one row PV module and 3 m interspaces between arrays (ii) PV arrays of two row PV modules and 6 m interspaces between arrays and (iii) PV arrays of three row PV modules and 9 m interspaces between arrays (Fig. 6.2).

In all these three blocks, two different designs were followed: few arrays with gap in between PV modules and few arrays covered fully with PV module which allows receiving different amount of intercepted solar irradiation on ground surface, which is required for crop cultivation in between PV arrays and also below PV panel areas. At Bhuj, 25 kW capacity PV installation was done in 15 m × 34 m area with the two row PV array design however with two different PV module coverages: (i) full coverage of array with PV modules and (ii) half coverage of array with PV modules. Installation of PV modules as per the above-mentioned design is depicted in Figs. 6.3 and 6.4. Solar PV modules were installed on fixed MS iron angle structure facing perpendicular to south and inclination of 26° at both the sites.

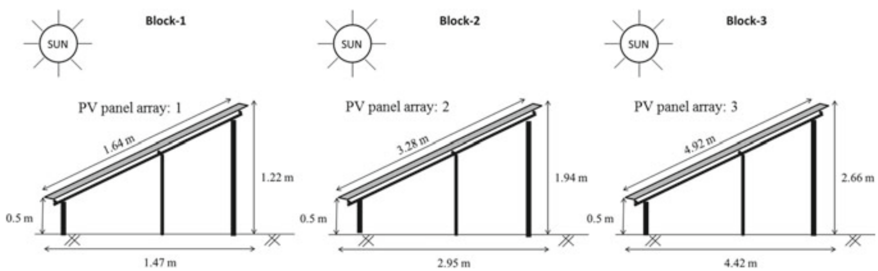

Fig. 6.2 Schematic design of PV module installations for agri-voltaic system

Fig. 6.3 Installed agri-voltaic system at ICAR-Central Arid Zone Research Institute, Jodhpur

Fig. 6.4 Installed agri-voltaic system at regional research station Bhuj of ICAR-Central Arid Zone Research Institute

6.3.2 Cropping Options

Plan has been formulated to grow crops in between PV arrays and also below PV module area. Generally, PV modules installed at an inclination create shades in the leeward side on ground surface as per the zenith and azimuth movement of the sun. Available amount of solar irradiation both under direct (open sun) and diffused conditions governs plant growth because the amount of photosynthetically active radiation (PAR) is different under both these conditions. Height of crops is a key parameter for selection of crops for agri-voltaic system because high crops may create shade on PV modules and thus reduce the PV generation. Therefore, crops with low height preferably less than 50 cm and which tolerate certain degree of shade and require less amount of water are most suitable for agri-voltaic system. Following crops are initially chosen to grow in agri-voltaic system. Under rainfed situation, *Vigna radiata* (moong bean), *Vigna aconitifolia* (moth bean) and *Cyamopsis tetragonoloba* (clusterbean) have been selected as arable crop, whereas under irrigated situation during rabi season *Plantago ovata* (isabgool), *Cuminum cyminum* (cumin), *Eruca sativa* (taramira) and *Cicer arietinum* (chickpea) have been selected. Apart from these arable crops, few medicinal plants have also been selected as perennial, e.g. *Aloe vera* (gwarpatha), *Cassia angustifolia* (sonamukhi) and *Convolvulus pluricaulis* (sankpuspi). For cultivation in areas below PV modules, few vegetable crops, e.g. *Capsicum annum* (chilli), *Brassica oleracea* var. capitate (cabbage), *Allium cepa* Linn. (onion), *Allium sativum* (garlic), *Vigna unguiculata* (Linn.) Walp. (cowpea), *Citrullus lanatus* (Thunb.) Matsumara & Nakai ('matira'), Cucurbita pepo Linn. ('kakri'), *Cucumis callosus* (Rottl.) Cong. ('kachri'), etc., have been selected. These crops are expected to modify the microclimates below PV modules and thus help in optimum PV generation in arid ecosystem. Moreover, the coverage of crops on soil surface in between PV arrays will also check the erosion of soil by wind action and thus will reduce the dust load on PV module.

6.3.3 Water Harvesting System

Water harvesting system to collect rainwater from top surface of PV module and to store it in an underground water storage tank has also been designed and developed with 105 kW agri-voltaic system. Rectangular-shaped water collector channels made of MS sheet have been fixed with about 2° slope at the edge of each PV array, which were connected to underground conveying PVC pipes of 4″ diameter. Collected water is stored in an underground water storage tank of 1 lakh litre capacity. The stored water is to be used for washing PV panels and to provide supplemental irrigation the crops to be grown in the agri-voltaic system.

6.4 Potential Benefits of Agri-Voltaic System

6.4.1 Availability of PAR Under Shade of PV Module

Net radiation (NR) and photosynthetically active radiation (PAR) were measured in shaded areas under solar PV modules and at open sun condition in the agri-voltaic system. Both NR and PAR were measured at one hour interval from morning to evening during clear winter days. NR was measured by net radiometer, whereas

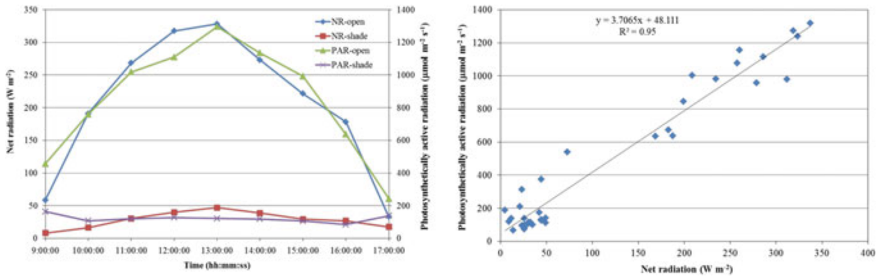

Fig. 6.5 Net radiation and photosynthetically active radiation in open sun and shade under PV modules during clear winter days at Jodhpur

PAR was measured by line quantum sensor. Measured variations of NR and PAR are presented in Fig. 6.5. Net radiation varied from 32.8 to 328 W m^{-2} under open sun condition, whereas under shade, it was 8.2–46.9 W m^{-2}, which shows that the shade created by PV modules significantly reduced the available net radiation (Fig. 6.5). However, the shade is dynamic following the sun's movement, and thus, the shaded portion on ground surface does not remain static but changes with time. Available photosynthetically active radiation (PAR) on shaded ground surface was also found significantly lower than open sun condition (Fig. 6.5). Available PAR on ground surface under open sun condition was 243–1296 µmol m^{-2} s^{-1}, whereas on shaded portion, it was 84.5–127 µmol m^{-2} s^{-1}. Significant relationship between net radiation and PAR was also observed (Fig. 6.5), which may be used to calculate PAR if only net radiation data are available. Available net radiation and PAR on shaded portion are very important parameters to screen the shade-tolerant crops suitable for solar farming.

6.4.2 *Potential PV Generation*

At Jodhpur, effective solar irradiation to generate electricity is available for an average of 4–5 h in a day. Therefore, 1 kW$_p$ PV system is expected to generate 4–5 kWh unit of electricity per day. Thus, 105 kW agri-voltaic system in Jodhpur will generate at least 420 kWh unit of electricity in a clear sunny day. Similarly, 25 kW agri-voltaic system at Bhuj will generate at least 100 kWh unit of electricity. The installed agri-voltaic system has been connected to local electricity grid through net metering system. Therefore, the generated electricity is directly sold to state electricity board at a fixed tariff which varies in different states of India. The average tariff rate of Rs 5 per kWh may be considered to calculate the income from PV-generated electricity.

6.4.3 Potential Crop Production

Crops can be cultivated in agri-voltaic system at interspace areas between PV arrays and at areas below the PV arrays. Area available for cropping purpose changes as per design of the installation. In our study, PV modules were installed in three different designs however with similar capacity and same size of land area, e.g. 35 kW_p capacity in an area of 32 m × 32 m area. Thus, the land requirement for installation was maintained 34 W m^{-2} for all three separate blocks. Thus, in 1 ha land area, 340 kW capacity agri-voltaic system can be installed, or in 1 acre of land, 136 kW can be installed. The interspace areas and below PV module areas available for cultivation of crops were 49 and 24% of the total block area, respectively. Rest areas of the blocks are left as roads for movement of implements and other purposes. The interspace areas are planned to be used to grow major arable crops suitable for agri-voltaic system. Potential yield and market price of the selected crops in western Rajasthan are given in Tables 6.1 and 6.2.

Field experiments on crop production in agri-voltaic system during kharif season of 2017 showed the trend effect of shading on crop yield. For example, the yield of moong bean (*Vigna radiata*) was 897 kg ha^{-1} in control plot, whereas the average yield in interspace areas of PV arrays was 735 kg ha^{-1}. In interspace areas, the yield of moong bean near to PV array structure was 704 kg ha^{-1}, whereas the yield away from the PV array structure was 933 kg ha^{-1}. Similar trend effect of shade on crop yield was also observed in moth bean (*Vigna aconitifolia*) and clusterbean (*Cyamopsis tetragonoloba*). For example, the yield of moth bean near PV array structure was 138 kg ha^{-1}, whereas the yield away from the PV array structure was 269 kg ha^{-1}. Yield of clusterbean near PV array structure was 238 kg ha^{-1}, whereas the yield away from the PV array structure was 349 kg ha^{-1}. Vegetative growth of medicinal crops, e.g. sonamukhi (*Cassia angustifolia*), gwarpatha (*Aloe vera*), sankpuspi (*Convolvulus pluricauli*), was also significantly affected by the shade of PV modules. Field view of different crops grown in the agri-voltaic system is shown in Fig. 6.6.

6.4.4 Potential Rainwater Harvesting

Surface area of a solar PV module of 260 W_p capacity is 1.64 m × 0.992 m. Thus, total surface area of 105 kW capacity agri-voltaic system is about 651 m^2. Average annual rainfall at Jodhpur is about 384 mm which is measured by rain gauge installed at meteorological observatory of ICAR-Central Arid Zone Research Institute, Jodhpur (Fig. 6.7). Out of this total annual rainfall, each rain event and all raindrops cannot be harvested from PV module surface because of splash loss, evaporation loss, etc. Therefore, a factor of 0.8 may be considered to estimate the total harvested water from rainfall amount. Again, 10% conveyance loss of the collected water to rainwater storage reservoir needs to be considered. Therefore, about 72% of annual rainfall is

Table 6.1 Average productivity (over the period from 2000–2001 to 2014–2015) of arable crops selected for agri-voltaic system in western Rajasthan

District	Average productivity (kg ha^{-1})					
	Moong bean (*Vigna radiata*)	Moth bean (*Vigna aconitifolia*)	Clusterbean (*Cyamopsis tetragonoloba*)	Isabgool (*Plantago ovata*)	Cumin (*Cuminum cyminum*)	Taramira (*Eruca sativa*)
Barmer	191	279	159	431	314	385
Bikaner	467	225	306	453	301	388
Churu	369	224	209	566	276	302
Ganaganagar	591	381	682	235	315	334
Hanuman	221	368	658	147	–	285
Jaisalmer	251	235	108	303	303	334
Jalore	325	413	401	554	370	523
Jhunjhunu	351	216	527	284	280	420
Jodhpur	327	251	318	528	397	463
Nagaur	364	247	347	598	363	558
Pali	299	182	440	553	328	423
Sikar	335	208	479	490	354	413
Sirohi	373	414	525	482	354	393
Average	343	280	397	433	330	402

Table 6.2 Trend of market price of selected crops for agri-voltaic system during the period from 2014–2015 to 2016–2017

Parameters	Price (Rs kg^{-1})					
	Moong bean (*Vigna radiata*)	Moth bean (*Vigna aconitifolia*)	Cluster bean (*Cyamopsis tetragonoloba*)	Isabgool (*Plantago ovata*)	Cumin (*Cuminum cyminum*)	Taramira (*Eruca sativa*)
Minimum	46	31	29	100	120	65
Maximum	52.5	35	32	120	150	70
Average	49	33	30.5	110	135	67.5

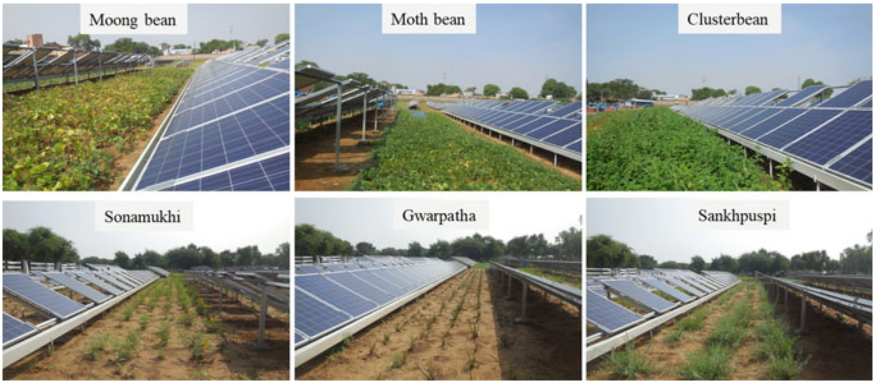

Fig. 6.6 Field view of crops grown in agri-voltaic system at ICAR-Central Arid Zone Research Institute, Jodhpur

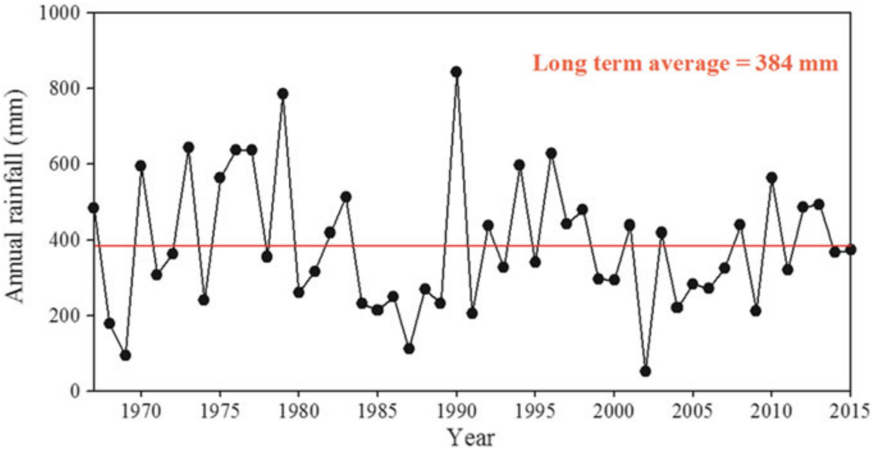

Fig. 6.7 Annual rainfall pattern in Jodhpur during 1967–2015

expected to be collected in water reservoir. Thus, about 180,000 litre of water can be harvested from 105 kW agri-voltaic system. However, initial observations during monsoon season of 2017 revealed an efficiency of 59% to harvest rainfall of 81 mm occurred during 14–25 July 2017. The stored water in water reservoir can be used for supplemental irrigation to crops and has potential to provide 48 mm irrigation over an area of 0.76 acre.

6.4.5 Economics of Agri-Voltaic System

PV modules of agri-voltaic system have been installed at a price rate of Rs 49.84 per W_p, and thus, a cost of Rs 5,233,200 and Rs 1,246,000/- has been incurred to install 105 and 25 kW capacity agri-voltaic system, respectively, at Jodhpur and Bhuj. The income from selling of PV-generated electricity will be about Rs 630,000/- per year and Rs 30,000/- per year from 125 to 25 kW agri-voltaic system at Jodhpur and Bhuj, respectively, considering a minimum generation of 4 kWh unit of electricity per kW system per day and for 300 clear sunny days in a year, while average selling price of PV-generated electricity is considered as Rs 5 per kWh. From agricultural activity within the agri-voltaic system, an income of Rs 8235/- from *Vigna radiata* (moong bean) during *kharif* season and Rs 23,339/- from *Plantago ovata* (isabgool) during *rabi* season can be generated if moong bean-isabgool crop rotation is followed. Similarly, income from other crop rotations can be calculated from Tables 6.1 and 6.2 using the interspace area of 49% of the total area of PV installation. As compared to the income from PV-generated electricity, income from agricultural activity is quite less, but it has several environmental and societal benefit. Few examples of environmental benefit due to agricultural activity in agri-voltaic system are: (i) it will judiciously use the scarce rainwater of arid region, (ii) it will control soil erosion through wind action and thus reduce the dust load on PV modules, (iii) it will improve microclimate surrounding the PV module and thus helps in optimum generation of electricity from PV module, (iv) it will improve land equivalent ratio (LER) etc. The breakeven period of agri-voltaic system is roughly calculated as 9–10 years, whereas the life cycle period of PV module is 25 years with efficiency of not less than 90% at the end of ten years, not less than 80% at the end of 20 years and not less than 75% at the end of life cycle. Therefore, installation of agri-voltaic system may be viable option for future specifically in arid regions of the country.

6.5 Conclusion

Agri-voltaic system is designed and developed at ICAR-Central Arid Zone Research Institute, Jodhpur, through which both electricity can be generated as well as food can be produced from a single piece of land. In the present study, feasibility of cropping activity with harvested rainwater in land-based solar PV installation has been discussed. It has been observed that 49% land area of a solar PV installation system can be used to cultivate crops, which is otherwise left as fallow. Crops which can be grown in interspace areas between PV arrays are *Vigna radiata* (moong bean), *Vigna aconitifolia* (moth bean), *Cyamopsis tetragonoloba* (clusterbean), *Plantago ovata* (isabgool), *Cuminum cyminum* (cumin), *Eruca sativa* (taramira), *Cicer arietinum* (chickpea), etc. Apart from these, medicinal plants, e.g. *Aloe vera* (gwarpatha), *Cassia angustifolia* (sonamukhi), *Convolvulus pluricaulis* (sankpuspi), etc., can be grown. All these crops are generally low height crops and require less amount of water and thus are suitable for agri-voltaic system. Apart from PV generation and crop production, water harvesting system from top surface of PV module has also been designed and developed to optimally use the scarce water resources. It has been found that 1400 litre of rainwater can be harvested per kW of agri-voltaic system. The stored water can be used as supplemental irrigation to crops during rabi season. Annual income from PV-generated electricity has been estimated as Rs 6000/- per kW installation, whereas cost involved for installation of such system is Rs 49,840/-, and thus, the breakeven period of the system is about 9–10 years.

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