

The state of solar PV and performance analysis of different PV technologies grid-connected installations in Hungary

Divine Atsu^{a,c}, Istvan Seres^b, Istvan Farkas^{b,*}

^a Doctoral School of Mechanical Engineering, Szent István University, Páter K. u. 1., Gödöllő, H-2100, Hungary

^b Department of Physics and Process Control, Szent István University, Páter K. u. 1., Gödöllő, H-2100, Hungary

^c Department of Energy Systems Engineering, Koforidua Technical University, Box 981, Koforidua, Ghana

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ABSTRACT

The first part of this paper assesses the state of solar PV in Hungary, considering available government support in terms of policies, targets, and the conducive environment for exploiting solar PV. The study further analyses a 15-year-old 9.6 kWp roof-mount grid-connected solar PV system while comparing its performance parameters with similar installations in the sub-region. Findings show that Hungary possesses a relatively high solar energy resource which has not been exploited as expected compared to most of the countries in the European sub-region. Hungary has in place the necessary policies and diverse incentives for the adaptation of renewable energy sources as required by the European Union. However, complexities in land acquisition and legal definitions of PV systems still exist. The installed solar PV capacity in Hungary as of 2018, is 790 MWp. The target of the Hungarian Renewable Action Plan is to have 14.65% of the electricity demand supplied by renewable energy sources by 2020. The experimental study shows that the total energy output from the 9.6 kWp system is 8838.95 kWh for the year of assessment. The energy outputs for the subsystems are 3761.98 kWh, 2608.88 kWh and 2468.10 kWh for ASE (pc-Si), DS2 (a-Si) and DS1 (a-Si) respectively. The annual sub-system efficiencies are 9.8%, 2.9% and 2.8% for ASE (pc-Si), DS2 (a-Si) and DS1 (a-Si) respectively. Thus, 42.6% of energy fed into the grid was from the ASE (pc-Si) system, 29.5% and 27.9% from the DS2 (a-Si), and DS1 (a-Si) respectively.

1. State of solar PV in Hungary

Energy consumption in Hungary over a decade and a half now has not seen any significant change; it has remained fairly unchanged. In 1990, the country's energy consumption was 20,689 ktoe. As of 2016, the consumption rate stood at 19,387 ktoe [1], even though there had been disparities in the mix of the constitution of energy consumption over the same period [1]. Hungary imports about 28.6% of electricity and other fuels from its neighbouring countries, such as Slovakia, Austria, and Ukraine, from which electricity is generated [2]. The main electricity export destinations by Hungary are Croatia and Serbia. The other sources of electricity generation include 35.7% Nuclear Energy, 18% Oil and Gas, 10.6% Hydrocarbons and 7.1% composed of Renewables, which sums up the gross electricity consumption as of 2017 [2].

However, the total domestic sources of electricity generation at the end of 2017 are made up of 50% Nuclear Energy, 25.2% Oil and Gas, 14.8% Coal, and 9.9% Renewables. The renewables comprise of 0.63% Biogas, 4.80% Biomass, 1.24% Waste, 0.28% Solar, 2.29% Wind, and

0.66% Hydro. The installed capacity of electricity generation as of 2017 stood at 8617 MW. The country's total domestic energy production at the end of 2017 stood at 32,181.0 GWh, whereas the energy imported was 12,876.24 GWh [2].

Regarding solar energy resource potential, the sunshine hours in Hungary range from 1950–2150 hours annually, with the annual global horizontal solar radiation received being 1280 kWh/m². These values characterise Hungary as having a comparatively high potential for solar energy exploitation [3]. Fig. 1 and Fig. 2, respectively, show the Global solar radiation (GHI) intensity of Hungary and the photovoltaic power potential in Europe.

Fig. 2 indicates an annual average PV energy potential which ranges between 700 and 1900 kWh/kWp depending on the geographical location [5]. In Hungary, the annual average PV energy potential ranges between 1050 and 1450 kWh/kWp, as shown in Fig. 2. Hungary's PV energy potential portrays her as a country having an average PV power potential in Europe [6] (see Table 1).

In 2017, the installed grid-connected solar PV system capacity in

* Corresponding author.

E-mail address: Farkas.Istvan@szie.hu (I. Farkas).

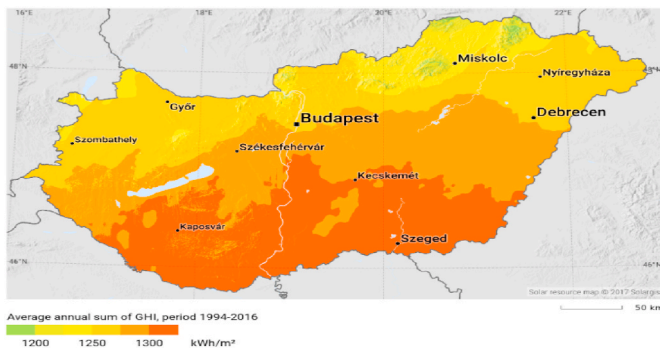


Fig. 1. Global solar radiation (GHI) of Hungary [4].

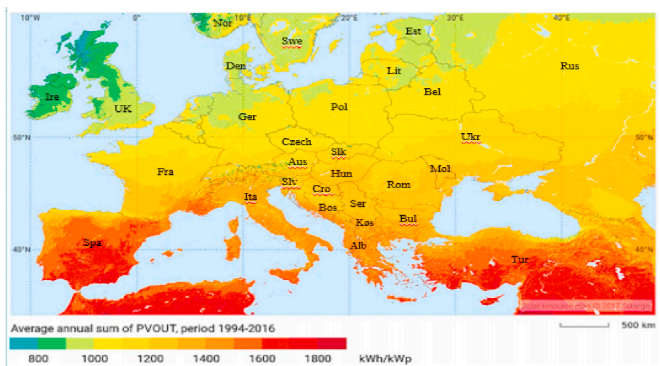


Fig. 2. Solar photovoltaic power potential of Europe [4].

Hungary was about 90 MWp; this raised the cumulative installed capacity to 380 MWp by the end of 2017 [7]. In 2018 the installed capacity of solar PV was 410 MWp [8]. Thereby, increasing the cumulative installed PV capacity to about 790 MWp in 2018 [9]. This installed capacity provides a 72-Watt capacity per inhabitant. The over 100% growth experienced in 2018, was as a result of government's policy support, PV regulation and PV investment attractiveness of the country [10]. Hungary's PV capacity has been growing at a very fast rate in the past few years and becoming one of the vibrant solar PV markets in Europe [11]. Fig. 3 shows the domestic energy generation mix of Hungary as of 2018. It indicates 11% of total domestic energy generation from renewables. This 11% from renewables represents 3405.24 GWh of energy generation for 2018, as illustrated in Fig. 3. Out of this, solar energy makes up 0.8%, which amounts to 251.66 GWh in 2018, as shown in Table 2.

Based on the assessment of favourable conditions for investment in

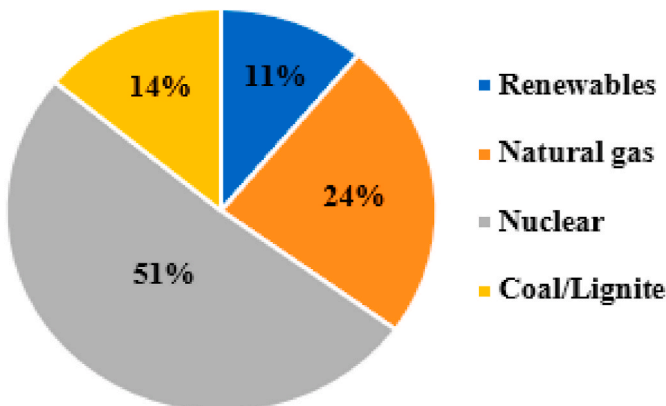


Fig. 3. Total domestic energy production by source in Hungary –2018 [12].

Table 1

Total domestic energy production - 2018) [12].

Nuclear	Coal/Lignite	Natural gas	Renewables	Total
15,733.70	4526.86	7403.91	3405.24	31,069.7
GWh	GWh	GWh	GWh	GWh
50.64%	14.57%	23.83%	10.96%	100%

solar PV systems development, Hungary has been ranked among the top ten most attractive countries among the Central Eastern European and South-Eastern European countries (CEE & SEE) [3]. This is an indication of the conducive environment that exists for solar PV to flourish in Hungary.

Table 3 presents some installed large PV plants in Hungary as of 2019.

The primary key driver for the rapidly increasing growth in the installed capacity experienced in Hungary over the past few years, is the net-metering programme for PV installations up to 50 kWp. The current net metering programme is supported by a subsidized loan facility offered by the Hungarian Development Bank (MFB). Another solar PV support programme is the METÁR programme. This was a reformation of the FiT programme (KÁT system), which existed at the initialization stage of the support programme. Both programmes run concurrently, but new entrants can only be admitted on to the METÁR programme [1].

Within the FiT initiative, different opportunities exist for different capacities of PV installations. Installations from 50 kWp to 500 kWp benefit from the FiT, however, the Market Premium facility holds for installations with capacities between 500 kWp and 1 MWp. PV plants with capacities of 1 MWp and above, will have to go through a tendering process to benefit from the Green Premium facility. In other policy support systems, owners of solar PV installations who benefit from the FiT facility will get a bonus if there is a less than $\pm 50\%$ deviation for 15 min intervals between measurements. For example, there is a 20% bonus for $\pm 30\%$ divergence for the period [13,14]. However, the PV system owner does not have the privilege to sell his CO₂ savings individually and cannot be compensated for it by the government [13].

The Energy and Public Utility Regulatory Authority of Hungary, (HEA) has the mandate to determine the acceptable capacity of PV power and the period when it could be fed into the grid under the FiT programme. The FiT rates vary depending on the size of the plant, date of licensing, time of the day (peak or valley or deep-valley period; these variations in the period and rates, exclude solar PV power which is tied to a single tariff) and type of technology. The periods are defined based on the location of the plant, and whether it is weekday, weekend, holiday, winter or summer [15].

The FiTs for power plants whose applications were submitted before 2017, had their rates either increased or decreased annually, deducting 1% from the preceding years' price index. For applications submitted beginning 2017, only installations less or equal to 0.5 MW qualify under the programme. However, wind energy was not considered under the FiT system but qualified for tendering under the Premium Tariffs. Technologies captured under the FiT system are Solar, Biomass, Geothermal Energy, Hydro Power Energy and Biogas. The FiT for electricity generated from Solar energy is HUF 31.77 per kWh (approximately, \$0.11/kWh), and it is fixed for all periods [15]. However, for the other technologies captured under the FiT system, the tariffs vary for the predefined (by decree) periods, even though the tariffs are the same for all the four remaining technologies as shown in Table 4.

In their efforts to making member states energy sustainable, the EU has set renewable energy targets for all member states. The EU aims to achieve 20% renewable energy mix in the total energy consumption by the year 2020, and 32% by 2030 [16]. In furtherance of the EU's set target, the Hungarian Renewable Action Plan aims to achieve 14.65% of the electricity demand supplied by renewable energy sources by 2020 [16,17].

Even though fossil fuel resource in Hungary is minimal, about 89% of

Table 2
Renewables in energy generation mix – 2018 [12].

Biogas	Biomass	Waste	Solar	Wind	Hydro	Geothermal	Total
186.52 GWh 0.61%	1755.44 GWh 5.65%	397.69 GWh 1.28%	251.66 GWh 0.81%	590.32 GWh 1.9%	214.38 GWh 0.69%	6.21 GWh 0.02%	3405.24 GWh 10.96%

Table 3
Some large PV plants in Hungary as of 2018.

Name of Plant	Capacity	Location	Year of commissioning	Module type
MET Dunai Solar Park	17,6 MW	Százhalombatta	2018	pc-Si
Pécs Tüskésrét PV	10,0 MW	Pécs	2016	pc-Si
PAKS PV	20,6 MW	Paks	2019	pc-Si
Felsőzsolca PV	20,0 MW	Felsőzsolca	2018	pc-Si
Mátra PV Park	16,0 MW	Visonta	2015	pc-Si

Table 4
Feed-in tariffs for renewable energy sources in Hungary [15].

Technologies	Peak period	Valley period	Deep-valley period
Geothermal, Biogas, Hydro, Biomass	HUF 35.50/kWh ≈ \$0.12/kWh	HUF 31.77/kWh ≈ \$0.11/kWh	HUF 12.96/kWh ≈ \$0.044/kWh

its primary energy is obtained from nuclear power and fossil fuel. The above fact indicates its dependence on non-renewable energy sources from neighbouring countries, which is the primary factor that inhibits its adaptation of renewable energy sources and poses a major climate concern [18,19]. The consequence of the country's primary energy sources in the energy mix is evident in its per capita carbon emissions of 5.38 metric tonnes [20]. Practitioners in the energy sector in Hungary have identified gaps in the energy and climate policies, claiming that the energy-saving capacity is more than has been predicted. They are of the view that the policies are not ambitious enough [21].

Though solar PV in Hungary has seen some level of growth in the past few years, complexities in land acquisition and the legal classification of PV plants from investors' point of view still exist. Data by the Hungarian Central Statistical Office shows that 79% of the country's territory is suitable for agricultural purposes [22]. It is therefore evident that most of the available land for possible PV investment is ideal for agricultural purposes. However, according to the country's laws pertaining to the use of agricultural lands, it is forbidden for companies to purchase or acquire ownership of such lands [23]. Obtaining a permit for such lands becomes onerous. The final phase of the acquisition process requires a collaboration between the investor and the actual landowners to complete the process. The other risk relates to the legal classification of PV plants pertaining to civil law and sectoral law [23]. These discrepancies and risks involved in land acquisition require careful and comprehensive contractual agreements and other prevailing bottlenecks, making investors a bit sceptical about investing in large PV plants.

To continue the promotion of PV system adaptation, the government has put in place plans to arrange large scale auctions of PV power projects [11]. It is expected that the Government will launch the Renewable auction in July 2020. The upper limit for eligibility has been increased from 20 MW to 50 MW. This is part of the Government's pursuit to speed up installed capacity and have 390 GWh generating capacity added each year. The Government's strategy is to have several initiatives that will make room for both centralised and decentralised exploitation [24]. The PV market in Hungary is still small but growing rapidly, which requires research and dissemination of findings on its market suitability and

performance of the different PV technologies as well as the possible limitations for further development. However, literature has shown lack of comprehensive information on the current situation of grid-connected solar PV systems in Hungary as corroborated by Pintér et al., 2020 [25]. Support schemes and policies for PV utilization are diverse and continuously changing across various countries, making it a daunting task to keep track with the current trends [26]. The most worrying aspect is that the data maybe scanty and not reliable. The growing market of Hungary faces similar problems where information about PV status is very scattered and challenging to obtain [25–28]. Research on the long-term performance of solar PV and status is thus very critical to the continuous growth of the technology in Hungary.

2. Performance analysis of a 9.6 kWp capacity PV installation

2.1. System description

A performance assessment is conducted on a 15-year-old grid-connected solar PV system installed at Szent István University, Gödöllő, Hungary (System installed in 2005). This PV system was the first grid-connected PV system installed and still in operation. The system is made up of two different PV technologies: polycrystalline silicon (pc-Si) PV technology (ASE-100) and amorphous silicon (a-Si) PV technology (DS-40). It is divided into three sub-structures and installed on the flat roof of the student dormitory 'C' (47°35'45.4"N 19°21'51.7"E), as shown in Fig. 4. Sub-system 1 comprises of 32 pieces of the pc-Si modules (RWE Schott Solar). Sixteen (16) modules are connected in series and two modules connected in parallel. Sub-systems 2 and 3 are made up of seventy-seven (77) pieces each of the a-Si modules (Dunasolar). Seven (7) of these modules are connected in series and eleven (11) connected in parallel [29].

The total system has an array area of 152.5 m². The array is mounted at a fixed inclination of 30° facing true-south. Each sub-system is connected to a separate inverter. Sub-system 1 is connected to the SunPower SP3100-600 inverter, while sub-systems 2 and 3 are each connected to SunPower's SP2800-550 inverter. The characteristics of the modules at standard test conditions (STC) and the inverter characteristics are presented in Tables 5 and 6, respectively. Fig. 5 shows the graphic representation of the installation.

3. Methods of data acquisition and analysis

The quantities measured and data logged include irradiation at the plane of the array (PoA), the total horizontal radiation using the silicon sensor. The module and ambient temperatures were taken using the Pt 100 sensors and the PV array DC power. The different output signals are converted by the signal converters at various voltage levels to a 4–20 mA signal, which is then sent to the AD converter unit at the final storage point. Measurements taken by the sensors are averaged at 10 min intervals and then stored on the PC [29]. Measurements on the system have been continuous since the time of installation; however, data utilized for the analysis in this current study is extracted from January 2016 to December 2017.

3.1. Performance indices

Performance investigations are done by either using any of the several simulation software tools that are available or by performing on-

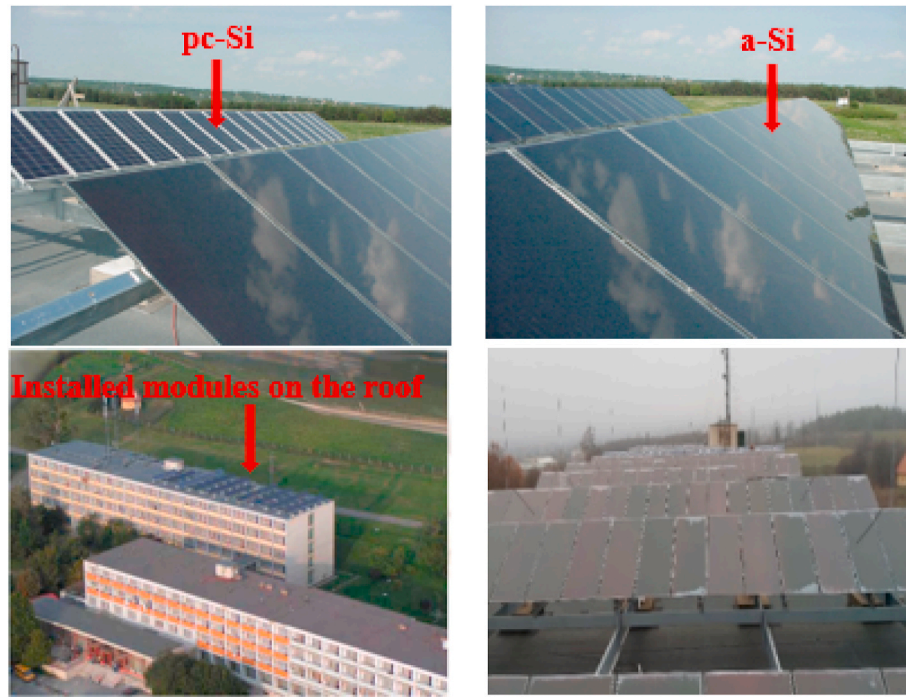


Fig. 4. Installed PV array.

Table 5
Characteristics of PV modules at STC.

Parameters	pc-Si (ASE 100)	a-Si (DS40) 1	a-Si (DS40) 2
Peak power (Wp)	105	40	40
Voltage at maximum power point (V)	35	44.8	44.8
Current at maximum power point (A)	3	0.8	0.8
Short circuit current (Isc) (A)	3.3	1.15	1.15
Open circuit voltage (Voc) (V)	42.6	62.2	62.2
Surface area of module (m ²)	0.845	0.813	0.813
Temp. Coeff. Of Voc (%/°C)	-0.38	-0.2797	-0.2797
Temp. Coeff. Of Isc (%/°C)	0.10	0.0897	0.0897
Temp. Coeff. Of power (%/°C)	-0.47	-0.190	-0.190
Nominal operating cell temperature/NOCT (°C)	45	50	50

Table 6
Inverter characteristics.

Model	SP 3100-600	SP 2800-550
Peak power of PV generator	4.2 kWp	3.8 kWp
Rated output power	3.1 kW	3.0 kW
Maximum no load voltage	600 V	500 V
Rated voltage (MPPT)	280–600 V	210–550 V
Efficiency max	94%	94%
Euro efficiency	92%	92%
Number of phases	1	1
Rated mains voltage	400 ± 10%	400 ± 10%
Input current max	15.0 A	10.8 A
Output frequency	50 ± 2%	50 ± 2%
Cos φ	1	1

site assessment by measuring system output and the environmental parameters that affect the performance of the PV installation. However, the latter option presents the most precise results when assessing solar PV power production for different geographical locations [30].

Several studies have been undertaken to assess the real performance of different technologies of solar PV installations in various locations

[31–33]. Most performance indices employed are to assess and compare different kinds of PV systems and ascertain their overall performance in comparison with other studied installed systems in different geographical settings. These performance indices provide the system's output, considering the site conditions and system losses. The assessment is conducted per the IEC standard 61,724 [34].

A. Energy output is the total AC power produced by the solar PV system over a defined period. It is determined by Eq. (1) [32].

$$E_{AC} = \sum_{t=1}^N E_{ACt} \quad (1)$$

where E_{ACt} is AC energy output (kWh) for the period t and N is the number of observations in the data set [33,35].

B. The final yield (Y_F) is defined as the energy output per the system's rated capacity. This shows the hours per day that the PV system must operate at its rated maximum power to produce the equal value of energy as was measured [30,32]. It is determined by Eq. (2).

$$Y_F = \frac{E_{AC}}{P_{PVrated}} (kWh / kW_p) \quad (2)$$

where Y_F is the array yield, E_{AC} is the total inverter energy output (kWh), and $P_{PVrated}$ is the PV system capacity (kWp) [33,35].

C. The reference yield (Y_R) is defined as the solar radiation at the plane of array (PoA) divided by the irradiance at the standard test conditions (1 kW/m²). It is the theoretically determined available energy over a specified period, determined by the expression,

$$Y_R = \frac{H_t}{G_R} (h / day) \quad (3)$$

where H_t (kWh/m²) is the plane of array (PoA) radiation and G_R (kW/m²) is the irradiance for standard test conditions, 1 (kWh/m²) [32,33,35].

D. Performance ratio (PR) provides the negative impact of losses on the system performance (output) through its current conversion process. The PR of a PV system indicates the nearness of the actual field performance to the ideal situation. It is also a critical measuring index that

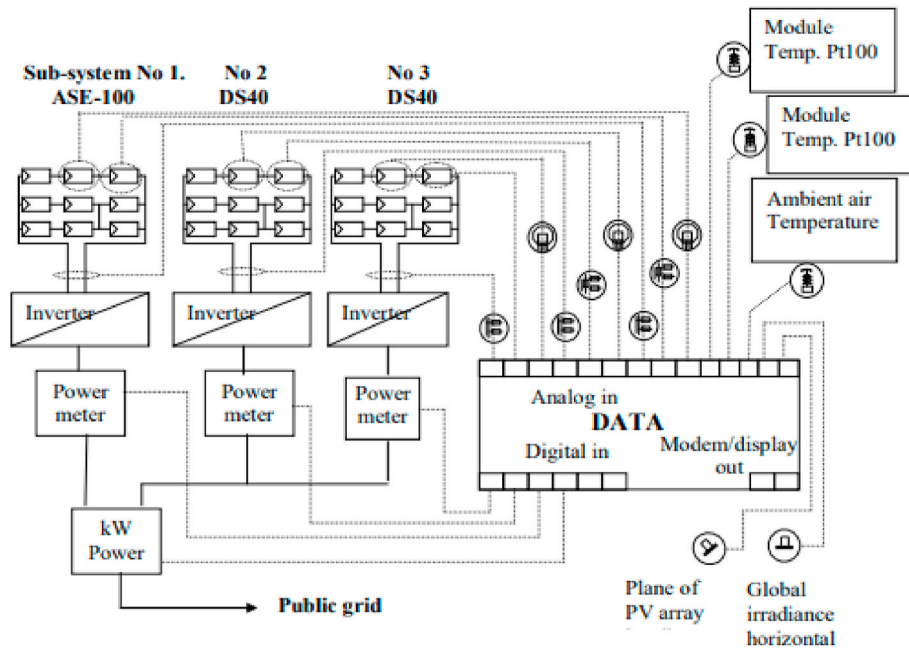


Fig. 5. Schematic diagram of the installation.

compares PV systems irrespective of location, tilt angle, orientation, and their rated capacity. It can be defined as the ratio of the measured on the field output to the theoretical energy output of the PV system with respect to time. The higher the PR of the PV system, the more efficient the system is [31–33,35]. PR is calculated by Eq. (4).

$$PR = \frac{Y_F}{Y_R} = \frac{E_{Grid}}{GlobInc} \quad (4)$$

where PR is the performance ratio, Y_F is the final system yield, and Y_R is the reference yield. E_{Grid} is the AC energy injected into the grid in kWh, and G_{lobInc} is the global incident radiation at the plane of the collector [35]. The PR represents the cumulative effect of inverter and wiring losses, effects of temperature, module and component failures, reflection losses and soiling on the expected AC output of the PV installation. The PR determines areas or components of failure. A decreasing trend in the yearly PR shows a permanent decline in the performance output. If soiling is seasonal, it will reflect in the seasonal differences in the PR.

The energy density (E_D) is the PV system energy output per the unit area of the installed array. E_D determines the land or space needed for the array installation [30]. E_D is essential in areas where the decision on land availability is crucial. It is expressed as:

$$E_D = \frac{E_{AC}}{A_m} \quad (\text{kWh/m}^2) \quad (5)$$

where A_m (m^2) represents the total array area.

Availability of land for PV installation is a critical issue, especially in locations where the siting must be close to use. For instance, in the case of prosumers or decentralised systems, it will be difficult if not impossible to have ground mount systems; hence all installations are roof mount. It is therefore expedient to judiciously use the limited space available. Thus, the energy density of the system must be taken into consideration in the selection of the modules taking into account the space available. The higher the E_D , the better the system for space use.

E. Capacity factor (C_f) is the ratio of the total energy output by a PV system per a given period to the energy that is produced if the PV system is functioning at the rated output capacity for the same period [28]. C_f is determined by Eq. (6).

$$C_f = \frac{100 * \text{Total annual energy output, } E_{AC} (\%)}{P_{PV \text{ rated}} * 8760} \quad (6)$$

where C_f (%) is the capacity factor. The nearer the C_f of a PV system is to unity, the more efficient is the system.

F. System efficiency (η_{sys}) The monthly efficiencies of the various sub-systems, as well as the total system efficiencies, are determined from the expression in Eq. (7).

$$\eta_{sys,m} = \left(\frac{E_{AC,d}}{G_t A_a} \right) \times 100\% \quad (7)$$

where $E_{AC,d}$ is the AC power output of the system, G_t is the incident radiation on the plane of the array (PoA) and A_a is the area of the array [32].

G. Array capture losses (Lc) defined as the Reference yield minus the array yield. This (Lc) occurs as a result of the temperature rise of the cells, dust accumulation, shading, mismatch losses, and powerpoint errors.

$$Lc = Y_R - Y_F$$

where Y_R is the reference yield and Y_F is the final yield of the system [31, 33].

4. Results and discussions

In this section, the system yield, the energy densities of the various systems, performance ratios, and the other performance indices, as well as the system losses for the different systems are presented and discussed.

Fig. 6 presents the measured monthly horizontal and inclined (on the plane of the array) solar radiation. The annual inclined and horizontal solar radiation recorded are 1418.6 kWh/m² and 1272.2 kWh/m², respectively. These measured irradiation values are marginally higher than the site's average values, as recorded in Ref. [36]. The inclined solar radiation ranges from 42.6 kWh/m² in December to 180.2 kWh/m² in July. The global horizontal radiation at the site ranges from 24.4 kWh/m² to 192 kWh/m² for December and July, respectively.

Fig. 7 shows the energy outputs for the different module technology

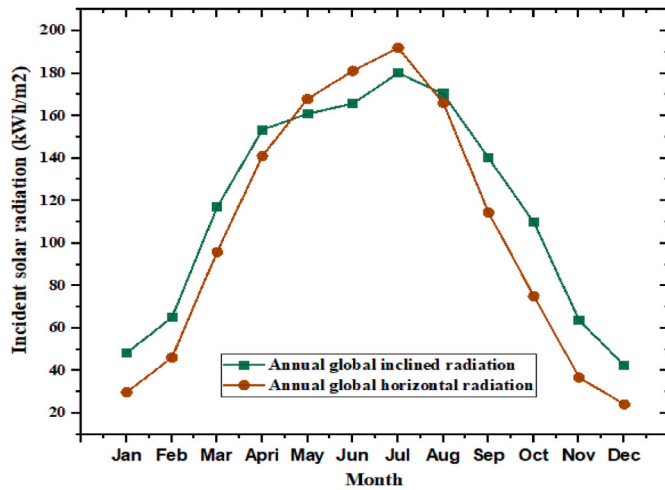


Fig. 6. Measured horizontal and inclined solar radiation.

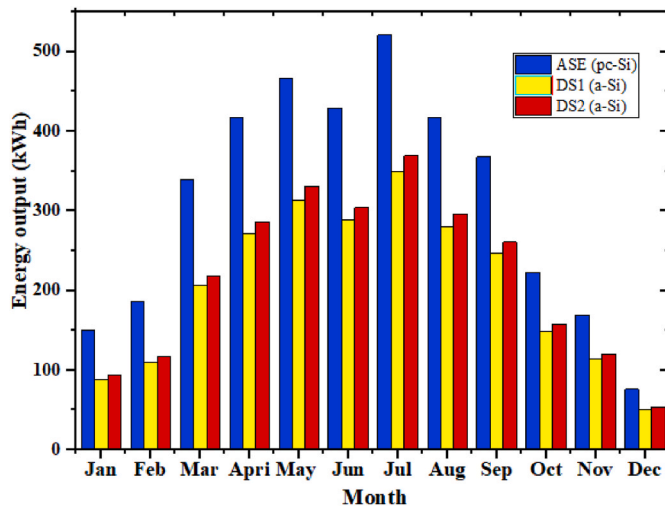


Fig. 7. Energy output of the different PV systems.

sub-systems. The annual energy produced by the various sub-systems are 3762 kWh, 2468 kWh and 2609 kWh for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si) respectively. Even though the sub-systems DS1 (a-Si) and DS2 (a-Si) have the same components and configuration, the energy produced by DS2 (a-Si) marginally exceeded that of the DS1 (a-Si) by about 5% annually. The total energy fed into the grid by the whole 9.6 kWp system, is 8839 kWh for the year of analysis. The average monthly energy production by the various systems are 313.5 kWh, 205.7 kWh, and 217.4 kWh for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si) respectively. The annual specific final energy for the different technologies is determined as 1106.5 kWh/kWp, 796.2 kWh/kWp, and 841.6 kWh/kWp for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si) respectively. However, it is evident that the energy output from the various units linearly correlated with solar radiation measured at the site.

The average daily energy output recorded for the period of assessment, as shown in Fig. 8, are 10.28 kWh/d, 6.74 kWh/d and 7.13 kWh/d for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si) respectively.

The efficiencies of the different systems are determined from Eq. (7), and results presented, as shown in Fig. 9. The monthly efficiencies of the ASE (pc-Si) subsystem range between 6.6% in December to 11.5% in January. It, however, recorded an annual system efficiency of 9.8%. December, which registered the least efficiencies for all subsystems, is obviously as a result of the low irradiation levels for the month. The DS1 (a-Si) and DS2 (a-Si) sub-systems had the highest system efficiencies of

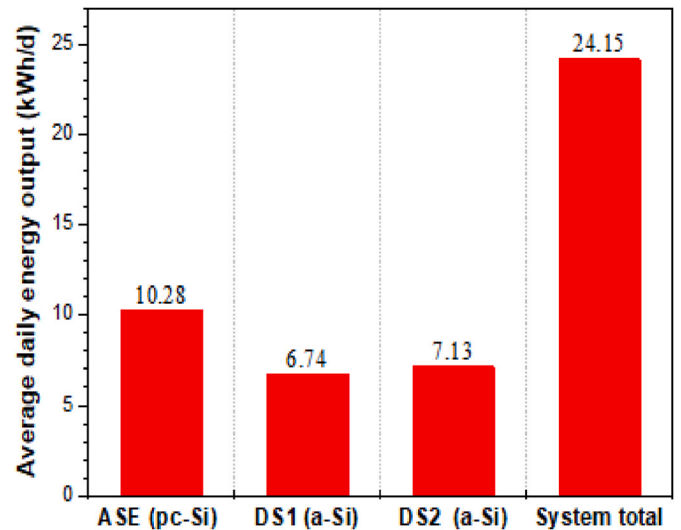


Fig. 8. Average daily energy output.

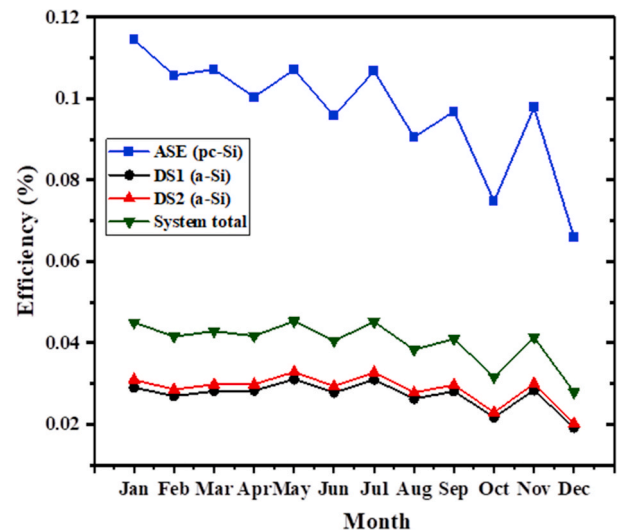


Fig. 9. Monthly system efficiency.

3.1% and 3.3% in May while the least efficiencies of 1.9% and 2.0% were recorded for DS1 (a-Si) and DS2 (a-Si) respectively for December. The annual efficiencies for the DS1 (a-Si) and DS2 (a-Si), subsystems are 2.8% and 2.9% respectively.

Simulation results for system losses determined by using the PVsyst (6.8.1) software, as shown in Fig. 10, reveals reasons for the significant decline in efficiencies as observed for the DS1 (a-Si) and DS2 (a-Si) systems. The significant losses are the PV loss due to irradiance and temperature levels, which were 14.2% and 10.5%, respectively for the a-Si subsystems, while it is 0.9% and 3.3% respectively for the ASE (pc-Si) subsystem. Losses due to module quality for the a-Si modules was 5%, which is 2% higher than the ASE (pc-Si) subsystem. However, the a-Si subsystems performed relatively better for the inverter losses recording 6.2% against 8.1% recorded by the ASE (pc-Si).

Besides the significant losses that can be attributed to the high negative impacts of temperature observed for the a-Si modules (sub-systems), a visual inspection conducted on the installation reveals widespread electrochemical corrosion and delamination of the thin film modules. These could result in the low performance ratios recorded by the a-Si subsystems. Also, there have been significant differences in the outputs of the two a-Si subsystems even though they have the same

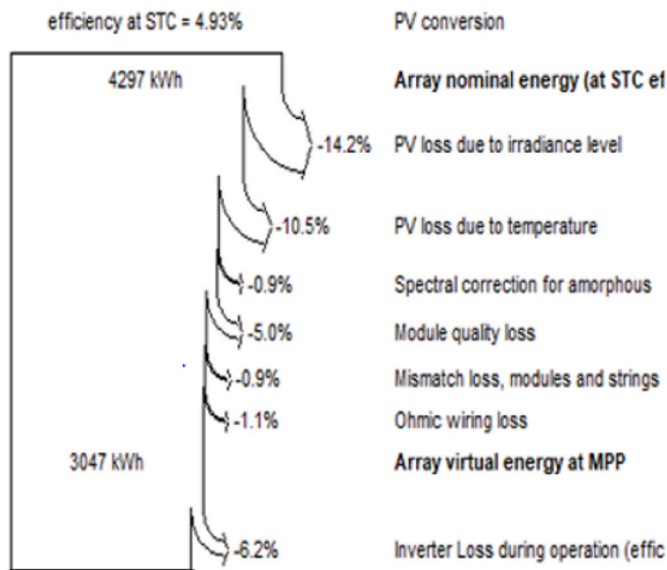


Fig. 10. Simulation results of system losses for DS1 (a-Si) and DS2 (a-Si).

system properties and configurations. DS1 (a-Si) subsystem recorded a lower performance output (about 3%) than the DS2 (a-Si).

As part of the several factors that are considered in the siting of solar PV systems, especially medium and largescale systems, which are mostly ground mount, land availability plays a very critical role. This is because available land could be put to several uses such as housing, farming, recreational centres. Therefore, in the siting of PV systems for energy generation, expedient use of land is critical, especially areas where land is constrained. In choosing the appropriate PV technology for a particular site, beyond the consideration made on the output efficiency of the various technologies, the energy densities of the different technologies are also taken into consideration. Fig. 11 presents the energy densities of the different systems. The highest energy density of 137.29 kWh/m² was determined for the ASE (pc-Si) system. The energy generated by the DS2 (a-Si) system per unit area is 41.68 kWh. The least energy density was determined for the DS1 (a-Si) sub-system as 39.43 kWh/m². The higher the conversion efficiency per unit area, the higher the energy density and the least installation space required.

The capacity factor of a power generating system shows how much of the rated power is being produced by the system under study. The nearness of a system's capacity factor to unity tells how close the output

is to the rated power. The determined capacity factors of the various systems are shown in Fig. 12. The ASE (pc-Si) showed the highest capacity factor, 12.6%, followed by the DS2 (a-Si) and then DS1 (a-Si) with capacity factors of 9.6% and 9.1% respectively.

The performance indices mostly used to compare PV installations at different locations are the annual average daily final yield and the performance ratio. The PR of a PV system indicates the nearness of its on the field operation performance to the ideal situation [32]. The daily final yield and the PR of the various systems are presented in Fig. 13 and Fig. 14, respectively. The annual daily final yields were 3.02 kWh/kWp/d, 2.18 kWh/kWp/d, 2.30 kWh/kWp/d, for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si), respectively. Comparing the measured annual daily final yields to the simulated normalised system production from PVsyst software, results showed a decrease in the measured yields for all the studied systems; however, it was a marginal reduction for the ASE (pc-Si) subsystem. The simulated annual yields were 3.14 kWh/kWp/d, 2.54 kWh/kWp/d and 2.54 kWh/kWp/d for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si) respectively. The final yield of the total system was determined as 2.52 kWh/kWp/d. The annual specific energy output was 1106.47 kWh/kWp, 796.16 kWh/kWp and 841.57 kWh/kWp for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si) respectively. The total system annual specific energy output was 920.72 kWh/kWp. The determined annual average daily final yield and the PR were compared to results from other studies in the sub-region as presented in Table 7.

The monthly performance ratios of the systems, as presented in Fig. 14, provides the measured on the field performance of the systems with respect to the ideal output at a given period. The PR ranges from 51.93% in December to 90.19% in January for the ASE (pc-Si). The minimum and the maximum performance ratios for the DS1 (a-Si) and the DS2 (a-Si) subsystems were (38.25% and 62.17%) and (40.42% and 65.69%), respectively. The minimum values for both DS1 (a-Si) and DS2 (a-Si) occurred in December, while the maximum values were recorded in May. The annual performance ratios are 77.22%, 58.75%, and 55.58% for ASE (pc-Si), DS2 (a-Si) and DS1 (a-Si), respectively.

Comparing the results of the current study with findings of other similar installations, the pc-Si system (ASE) recorded values of PR and Annual system yield that are relatively higher, whereas the PR and Annual system yield of the a-Si (DS1 and DS2) systems were lower than all the compared system.

5. Conclusion

The performance of a fifteen-year-old grid-connected roof mount

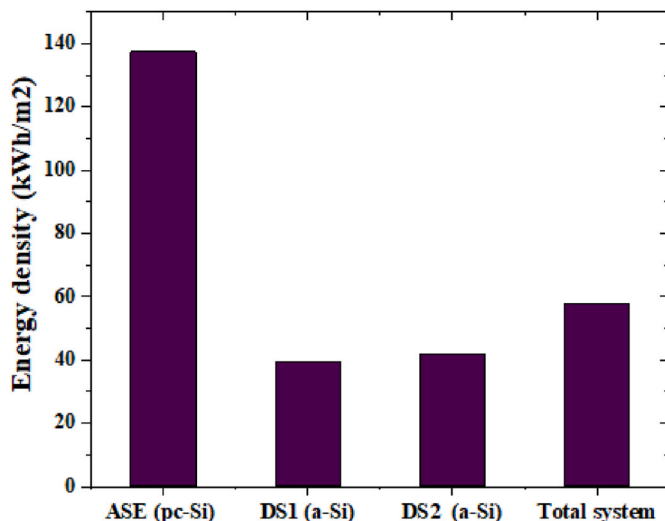


Fig. 11. Energy densities of the different PV systems.

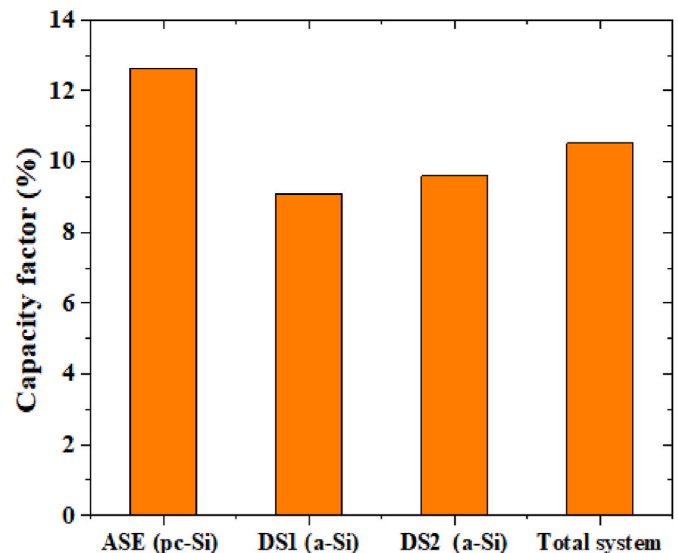


Fig. 12. The capacity factor of PV systems.

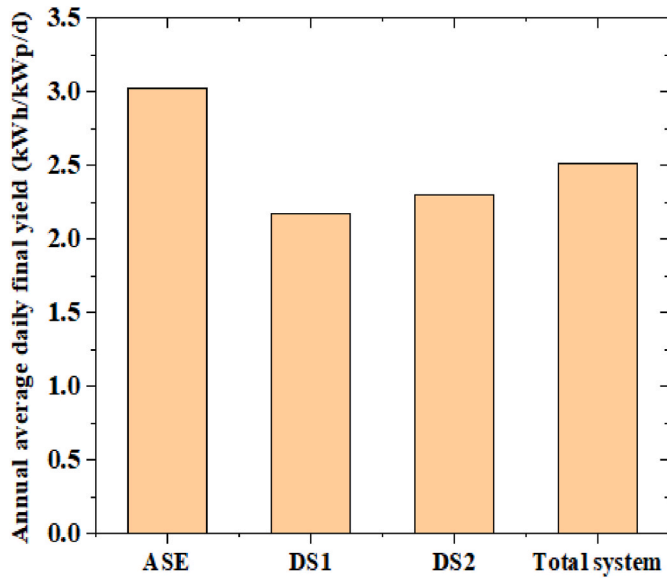


Fig. 13. PV systems annual average daily final yield.

solar PV systems has been analysed. The state of solar PV in Hungary has also been presented. Hungary possesses a relatively high solar energy resource that has not been exploited compared to most of the countries in the European sub-region. The installed solar PV capacity in Hungary as of 2018, was about 790 MWp. The target of the Hungarian Renewable Action Plan is to have 14.65% (2568 MW) of the electricity demand supplied by renewable energy sources by 2020. Even though Hungary has the necessary policies regarding the adaptation of renewable energy resources as required by the EU, some aspects still have discrepancies that deter potential investors. The removal of these bottlenecks will attract more investors. Most practitioners in the energy sector are of the view that the policies are not ambitious enough. The results of the experimental study of the installed rooftop PV system have been compared with results of similar installations in Europe. The annual measured inclined and horizontal radiation for the period was 1418.6 kWh/m² and 1272.2 kWh/m², respectively. The average monthly

radiation on the plane of the array varies from 42.6 kWh/m² December to 180.2 kWh/m² in July. The total energy output from the 9.6 kWp system was 8838.95 kWh. The energy output for the subsystems was determined as 3761.98 kWh, 2608.88 kWh and 2468.10 kWh for ASE (pc-Si), DS2 (a-Si) and DS1 (a-Si) respectively. The annual specific energy output determined was 1106.47 kWh/kWp, 796.16 kWh/kWp and 841.57 kWh/kWp for ASE (pc-Si), DS1 (a-Si) and DS2 (a-Si), respectively, while the total system annual specific energy output was 920.72 kWh/kWp. The ASE (pc-Si) system recorded higher annual PR (77.2%) than the other similar studies conducted in the sub-region, except for installations in Dublin, Ireland and Norway. The annual specific energy output for the ASE (pc-Si) subsystem, (1106.5 kWh/kWp/Yr) was also higher than the compared systems except those of Greece and Spain. However, the DS2 (a-Si) and DS1 (a-Si) systems recorded annual Performance ratios that were lower than all the compared systems. Their annual specific energy outputs were also lower than all compared systems, except those at Ballymena, N. Ireland. The system efficiency of the ASE (pc-Si) subsystem ranges between 6.6% in December to 11.5% in January with an annual system efficiency of 9.8%. The annual efficiency of the DS1 (a-Si) and DS2 (a-Si) subsystems are 2.8% and 2.9%, respectively. The underperformance of the a-Si subsystems, especially

Table 7

Performance parameters for similar solar PV systems.

Location	Technology	PR (%)	Energy output (kW h/kWp/Yr)	Reference
Warsaw, Poland	a-Si	70	830	[37]
Málaga, Spain	pc-Si	64.5	1339	[38]
Jaén, Spain	pc-Si	62.7	892.1	[39]
Thailand	a-Si	65–70	–	[40]
Norway	pc-Si	83	931.6	[41]
Dublin, Ireland	mc-Si	81.5	885.1	[32]
Godollo, Hungary	pc-Si	77.2	1106.5	Present study
Godollo, Hungary	a-Si	55.6–58.8	796.2–841.6	Present study
Crete, Greece	pc-Si	67.4	1336.4	[42]
Ballymena, N. Ireland	mc-Si	60–62	616.9	[43]

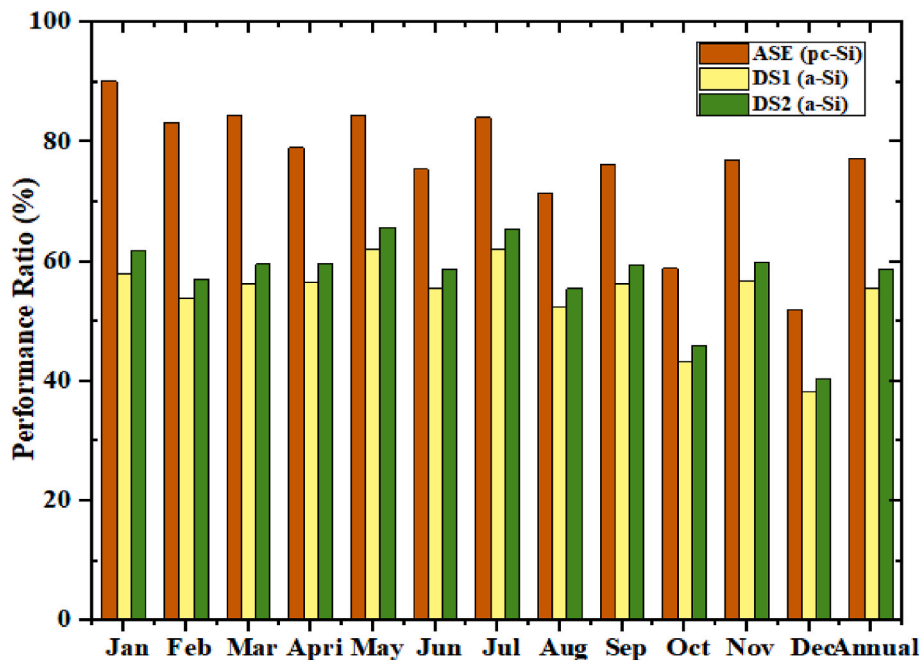


Fig. 14. Monthly Performance ratios (PR) of PV systems.

the DS1 (a-Si), and the evidence of module delamination necessitates a future study to investigate the reliability and degradation rates, and the failure modes of the various subsystems. These will provide detailed reasons for the recorded malperformance of the DS1 (a-Si) subsystem.

Credit author statement

Divine Atsu: Conceptualization, Methodology, Investigation, Data curation, Software, Writing- Original draft preparation. **Istvan Seres:** Investigation, Data curation, Software. **Istvan Farkas:** Conceptualization, Methodology, Writing- Reviewing and editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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