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OPTIMAL PLANNING AND DESIGN OF INVERTER LOADING RATIO ON SOLAR PHOTOVOLTAIC SYSTEMS FOR PROSUMERS

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ABSTRACT

Global energy demand and the rapid depletion of fossil fuels have significantly increased the need for renewable energy sources (RES) such as solar photovoltaic (PV) panels. These developments have led to the widespread use of microgrid networks with hybrid power systems (HPS). This study analyzed the technical, economic, and environmental implications of optimal inverter sizing in hybrid power systems with PV panels installed in microgrids. In particular, the system sizing and economic impacts of changing the optimal PV-inverter capacity (DC/AC) were evaluated using optimization analyses in the case of İstanbul. In addition, sensitivity analyses were carried out, considering the constraints on energy sales to the grid and the targets for increasing the share of renewable energy. The results showed that the inverter load was 1.52 in the optimal scenarios. This ratio increases to 1.99 when there are constraints on energy sales to the grid. In addition, it was observed that although the share of renewable energy approached 95%, the annual capacity utilization of the inverter was only around 31%. The findings underscore the necessity of determining the optimal inverter capacity to enhance economic efficiency and system performance.

Keywords: *DC/AC ratio, hybrid power system, inverter capacity, optimization, renewable energy.*

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INTRODUCTION

Technology development has led to a significant increase in the demand for conventional energy resources to meet the increasing energy demand, especially in the last 10 years. This situation has caused both the rapid depletion of underground resources and global warming because of increased greenhouse gas emissions. Although this situation is known, it continues to be used as the main energy source (Ab-BelKhair, Rahebi, and Abdulhamed Mohamed Nureddin 2020; Lei, Song, and Rodriguez 2020). As a result, the need for renewable energy sources (RES) (solar, wind, hydro, biomass, geothermal, etc.) has increased in recent years. These sources are largely non-renewable, non-polluting and have great potential, but their energy production is irregular due to the unpredictability of environmental conditions (Jaszczur et al. 2020). These RESs reduce dependence on limited fossil resources, reduce carbon dioxide (CO_2) emissions and increase the diversity of energy sources (Hemeida et al. 2020). One of the most common of these sources is solar PV power plants. A huge number of PV power plants have been established worldwide and meet the energy needs of many small or large hybrid power systems, whether on-grid or off-grid. Especially in places where solar radiation is high, the energy need is easily met with a system with a lower PV capacity, while this capacity grows where it is lower. Another issue affecting energy production in PV systems is the ambient temperature and their installation is more preferred in regions within a certain temperature range. Hybrid power systems (HPS) have become widespread to integrate PV panels into the system and to meet the energy production at the appropriate power from multiple energy sources in accordance with the needs of the load. By integrating various energy sources into these systems, it provides the most optimal use of energy. In addition, they provide continuous power supply to end users, are reliable, efficient systems, cost-effective, contribute significantly to the reduction of greenhouse gas emissions and the need for the grid (Rehman 2021). Inverters are also used to convert the DC power generated by the PV into AC power required by the load. Therefore, the size of the inverter to be used in the HPS is as important as the PV capacity.

In literature, optimization analysis evaluations of various HPSs installed with PV and inverter have been examined (Ammari et al. 2022; Benlahbib et al. 2020; Ghiasi 2019; Güven,

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Yörükeren, and Samy 2022; He et al. 2021; Irshad et al. 2023; Kharrich et al. 2021; Mahmoud et al. 2022; Roy, He, and Liao 2020; Taghizadeh et al. 2020; Xu et al. 2020; Yang, Yang, and Duan 2022; Yazdani, Baneshi, and Yaghoubi 2023). Investments increasing in the world are also in question for Türkiye. Although Türkiye still lags the world in renewable energy production, it has important RESs. Solar radiation is the most important of these. In Türkiye, the PV generation rate in 249 MW total installed capacity in 2015 was 0.34%, in 2019 the PV generation rate in 5995 MW total installed capacity was 6.57% and in 2022 the PV generation rate in 8479 MW total installed capacity was 8.35% (Garip, Sulukan, and Celiktas 2022; Renewable Energy Source 2022). In addition, with the decisions taken by this government and some agreements, it is aimed to increase these figures in the future years. In this planned direction, microgrids with HPS have become widespread and in parallel with this, it has become very important to choose the correct capacity of the inverters in the system to be installed. This study analyses the technical, economic and environmental impacts of inverter sizing in hybrid power systems with solar panels integrated into microgrids. Specifically, the economic implications of system sizing and changing the optimum PV-inverter capacity (DC/AC) are evaluated through optimization analyses on the example of İstanbul, Türkiye. In addition, sensitivity analyses are performed by considering the constraints on energy sales to the grid. This study can serve as an example and guide for systems with high energy demand and in need of various renewable energy sources.

MATERIAL AND METHODOLOGY

1. Load Profile and Meteorological Datas

In this study, PV-inverter sizing in a hybrid power system (HPS) by integrating a solar PV panel on an electrical load profile in a sample region in the province of İstanbul is examined in regard to the technical, economic and environmental reflections of the PV-inverter sizing on the system. The design of this HPS is shown in Figure 1. İstanbul has an annual average solar radiation value of 3.94 kWh/m^2/day and an annual average temperature value of 14.66 ºC (NASA 2023). The electricity consumption of a sample electrical load profile was determined as 15 kWh/day and 3.09 kW/peak.

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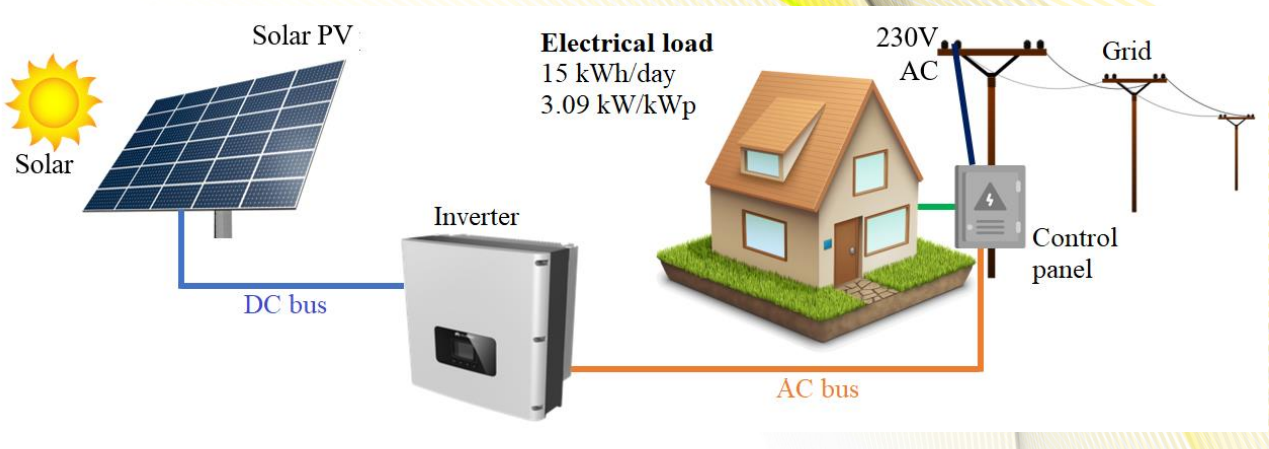


Figure 1. Hybrid power system modelling

2. Hybrid Power System Optimization Software

In order to meet the interconnected or off-grid electrical load requirements in a hybrid power system, various software are used to optimize and size multiple energy sources in the most economical way. HOMER PRO software, which is called hybrid optimization model for multiple energy sources, is one of the most accurate and effective software and is preferred in this study. This software can perform feasibility, techno-economic optimization and sensitivity analyses of stand-alone and grid-connected renewable energy systems. It simulates the operation of the system by performing energy balance calculations in minutes or hours at each time step of the year. At each time step, it compares the electricity demand at that time step with the energy that the system can provide at that time step and thus calculates the energy flow to and from each component. It also analyses the system at various powers with the optimization algorithm and lists the systems according to the most economical costs in applicable configurations (HOMER Pro Manuel Help 2023; Ozturk, Terkes, and Demirci 2024; Singh et al. 2020).

3. Solar Photovoltaic Panel

Solar photovoltaic panel (PV) generates electrical energy using the solar radiation from the sun. It is the most preferred renewable energy source that is environmentally friendly. The energy produced from the PV module varies depending on the climatic conditions in which it is

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installed, the angle of the irradiance from the sun, the ambient temperature and environmental factors. The power output formula of PV is given in Equation (1) (Terkes et al. 2023). Where; P_{PV} is the power generated from the output of the PV panel (kW), Y_{PV} is rated capacity value of PV under normal temperature (25ºC) (kW), f_{PV} is the reduction factor in PV losses (%), G_T is the value of solar radiation on the PV module (kW/m^2), α is power temperature coefficient (%/ºC) and T_C is the cell temperature on the PV module (ºC).

$$P_{PV} = Y_{PV} \cdot f_{PV} \cdot \frac{G_T}{1000} \cdot [1 + \alpha \cdot (T_C - 25)] \quad [kW] \tag{1}$$

4. Inverter

HPS uses AC voltage for the load while PV panels produce DC voltage. Therefore, inverters are needed to maintain the energy flow between AC and DC systems and to transfer the power generated from PV to the load. The output power of the inverter is calculated using Equation (2) (Jahangir et al. 2020; Mousavi et al. 2021). Where; P_{inv} is output power of the inverter (kW), P_{peak} is peak value of the load (kW), and η_{inv} is the efficiency of the inverter (%). In this study, an inverter with 95% efficiency was preferred.

$$P_{inv} = \frac{P_{peak}}{\eta_{inv}} \quad [kW] \tag{2}$$

5. Economic Parameters

NPC and LCOE values are the two critical main optimization objectives of this study, calculated based on the optimization algorithm in HOMER PRO software. Accordingly, the design of the HPS that reflects the lowest NPC or LCOE cost should be considered. NPC (net present cost) value is the cost value obtained by subtracting the present value of all investment costs incurred during the lifetime of the project from the present value of all lifetime revenues. It is a necessary parameter in determining the system. In Equation (3), the formula for the NPC and in Equation (4), the formula for the nominal interest rate (i) are shown (Mousavi et al. 2021). Where; $C_{ann,tot}$ is total annual cost of HPS [$/year], C_{cap} is total capital cost of all components in the

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HPS [$], C_{rep} is total replacement cost of all components in the HPS [$], $C_{O\&M}$ is total operation and maintenance cost of all components in the HPS [$], $C_{salvage}$ is salvage cost [$], i is annual real interest rate [%], N is project lifetime [year], $CRF(i,N)$ is capital recovery factor, i' is nominal interest rate [%], and f is an inflation rate [%].

$$NPC = \frac{C_{ann,tot}}{CRF(i,N)} = \frac{C_{cap} + C_{rep} + C_{O\&M} - C_{salvage}}{\frac{i\,.\,(i+1)^N}{(i+1)^N - 1}} \quad [\$] \tag{3}$$

$$i = \frac{i' - f}{1 + f} \quad [\%] \tag{4}$$

LCOE (levelized cost of energy) is the average electricity cost per kWh of useful electricity generated by the HPS during the project lifetime. The formula of LCOE is shown in Equation (5) (Ahmed and Demirci 2022). Where; E_{served} is total annual electricity demand [kWh/year].

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \quad \left[\frac{\$}{kWh}\right] \tag{5}$$

Renewable energy fraction (RF) is a ratio expression that shows the proportion of the total energy supplied from solar PV that is transferred to the load. It is an important parameter that shows how much renewable energy the load uses. The formula of RF is shown in Equation (6) (Terkes et al. 2024). Where; E_{ren} is the total annual electricity generated from PV [kWh/year].

$$RF = \frac{E_{ren}}{E_{served}} \quad [\%] \tag{6}$$

Excess energy (EE) is the amount of excess energy that cannot be utilised by the HPS because it is not needed by the load or can't be sold to the grid. The formula of EE can be seen in Equation (7) (Das and Hasan 2021). Where; EE is ratio of total annual residual energy to total

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generated energy [%], E_{excess} is total annual residual energy amount [kWh/year], and $E_{production}$ is the total annual amount of energy produced from all energy sources [kWh/year].

$$EE = \frac{E_{excess}}{E_{production}} \quad [\%] \tag{7}$$

Inverter capacity factor (CF_{inv}) is a ratio that shows how efficiently the inverter is used over a period of one year and is expressed as a percentage. This ratio is higher, indicating a more efficient and consistent inverter operation. Equation (8) shows the formula of this factor (Annual Capacity Factor Calculator 2023). Where; E_{out} is total annual energy output of the inverter [kWh/year], E_{in} is total annual energy input to the inverter [kWh/year], and E_{inv} is total annual energy loss of the inverter [kWh/year].

$$CF_{inv} = \frac{E_{out}}{E_{in} + E_{inv}} \quad [\%] \tag{8}$$

The capital cost (IC) is defined as the total installed cost of the component at the start of the project. The total capital cost of each component in the HPS explains the total installed costs in the initial year. It gives necessary information about the investment of the project.

6. Hybrid Power System Parameters

The economic parameter values of the components in the hybrid power system are shown in Table 1. Accordingly, the project lifetime of the HPS is evaluated as 20 years. The economic values of the components of the system and the economic parameters of Türkiye are taken from (Ozturk and Demirci 2023) and this system is analyzed.

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Table 1. HPS Parameters

HPS Components	Capital Cost	Replacement Cost	O&M Cost	Lifetime
Solar PV	1,000 $/kW	900 $/kW	10 $/year/kW	20 year
Inverter	300 $/kW	300 $/kW	0 $/year/kW	15 year
Grid Tariff	One Tariff; 0.100 $/kWh (Grid Purchases), 0.017 $/kWh (Grid Sales)			

ANALYSIS RESULTS

1. Effects of Changes in Solar PV Capacity on HPS

The effects of the change in PV capacity on inverter capacity and HPS optimization results are shown in Figure 2. HPS with 3.38 kW PV and 2.22 kW inverter capacity is seen as the most optimal system where the economic break in the NPC value is realized. It is seen that the DC/AC ratio and inverter capacity factor take values of 1.52 and 20.3%, respectively, from this value. This shows that the PV capacity with 1.52 times the inverter is ideal for this system and the inverter is used at 20.3% capacity annually. As a result of increasing the PV capacity up to 15Kw, 86.7% of the PV energy generated was transferred to the load and 2.41% of the unused energy was generated due to the inverter capacity.

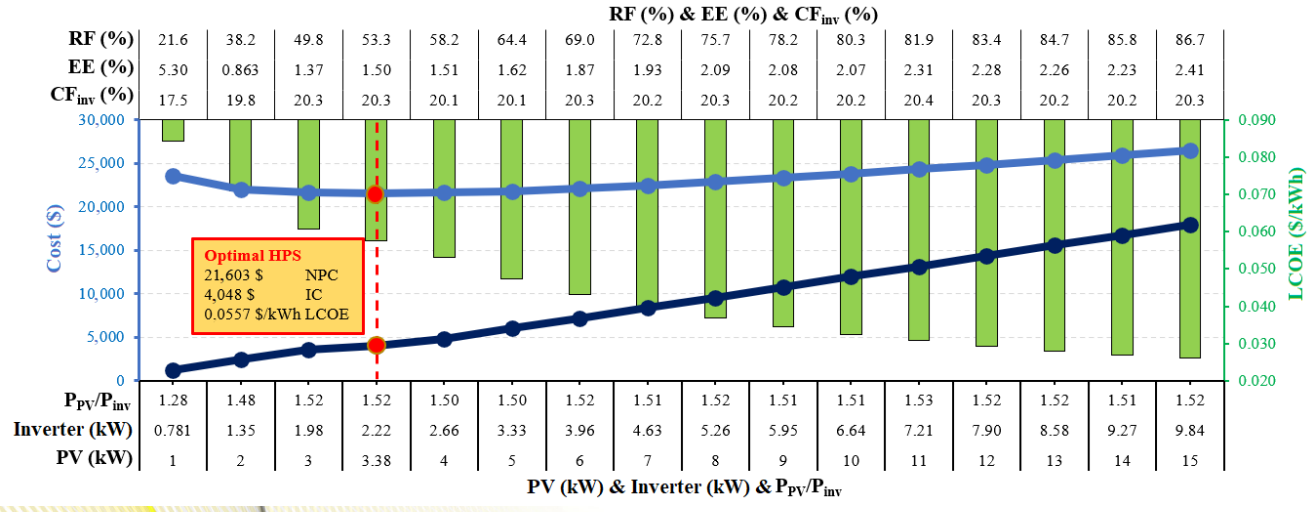


Figure 2. Solar PV capacity variation effects on inverter capacity and HPS optimization

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The effects of the optimal PV-inverter capacity on the annual operation are shown in Figure 3. The increase in solar radiation value during the summer months increased the inverter capacity factor. In cases where the power value from PV exceeds the 2.22 kW capacity value of the inverter, if it cannot be transferred to the load and cannot be sold to the grid (due to the energy sales limitation of the grid), an excess energy situation occurs and this energy appears as a loss. On the other hand, as can be seen in the figure, more energy is purchased from the grid in the winter months when the energy demand is high and solar energy is low.

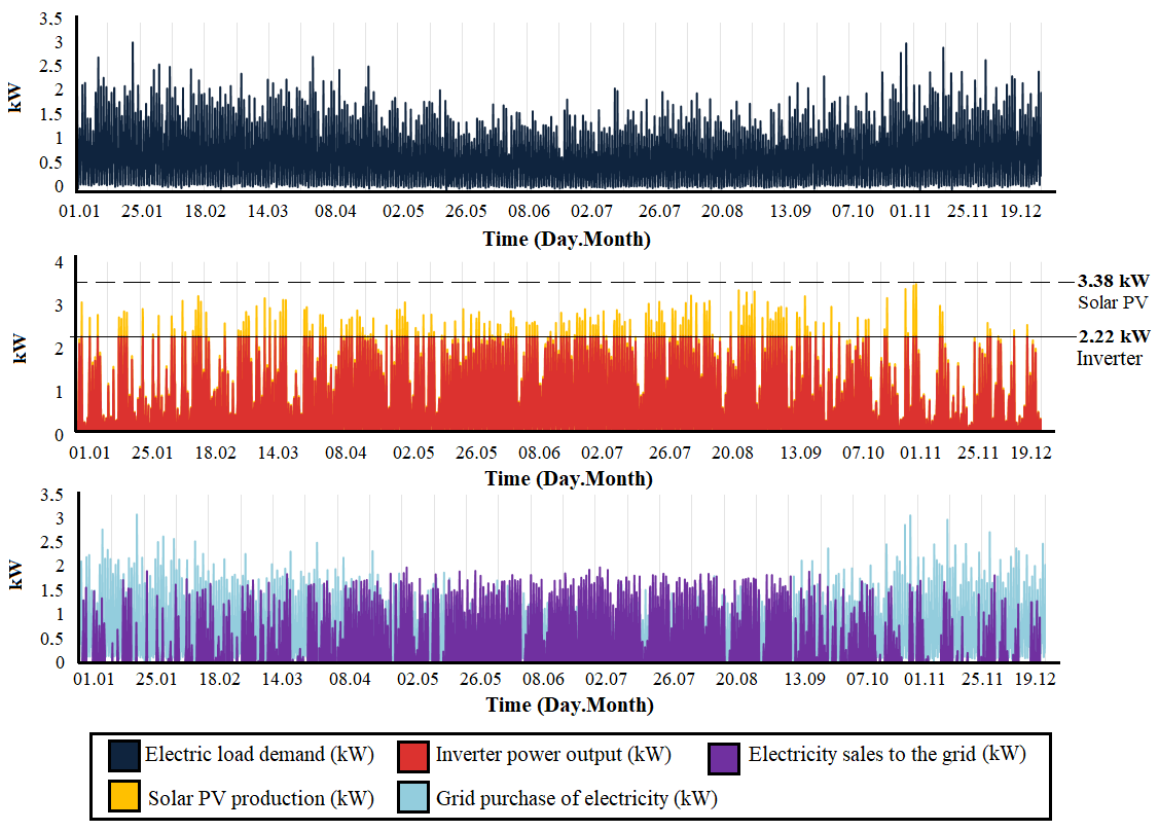


Figure 3. Solar PV capacity variation in the optimal PV-inverter capacities reflected in the HPS

2. Effects of Change in Grid Sales Constraint on HPS

Table 2 shows the effects of the change in the grid sales constraint on the HPS optimization results. Without grid sales, PV and inverter capacity decrease, and the DC/AC ratio increases

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from 1.52 to 1.99 in the optimal scenarios. As a result, EE increases by 12.8%, NPC increases by 4.2%, and CO_2 emission decreases by 8.1% compared to the scenario without sales constraint.

Table 2. Optimal DC/AC Ratio and Performance Analysis Based on Changes with Grid Sales Constraint

Grid Sales?	PV (kW)	Inverter (kW)	$\frac{DC}{AC}$	NPC ($)	IC ($)	LCOE ($/kWh)	CO_2 (kg/yr)	RF (%)	EE (%)	CF_{inv} (%)	E_{inv} (kWh/yr)
No	2.17	1.09	1.99	22,518	2,495	0.0816	2,371	31.5	14.3	18.0	90.7
Yes	3.38	2.22	1.52	21,603	4,048	0.0577	2,193	53.3	1.5	20.3	208

3. Effects of Changes in RF on HPS

One other analysis is on the effects of renewable energy rate increase targets on HPS sizing and is shown in Table 3. Increasing the RF gradually starting from 50% has different results on PV and inverter capacity values. As the results are analyzed, it is determined that the RF increases to 95% in parallel with the increase in PV installed capacity and the inverter capacity factor is 30.5% in this case. On the other hand, it is determined that up to 29.4% energy cannot be utilized depending on the inverter capacity. In economic terms, this scenario increased the NPC by 2.64 times and the investment cost by 12.86 times. The data shows that scenarios with 80% RF and below are more feasible and optimal results will be obtained at DC/AC ratios between 1.39-1.51.

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Table 3. Optimal DC/AC Ratio and Performance Analysis Based on Changes in RF

RF (%)	PV (kW)	Inverter (kW)	$\frac{DC}{AC}$	NPC ($)	IC ($)	LCOE ($/kWh)	CO_2 (kg/yr)	EE (%)	CF_{inv} (%)	E_i (kWh/y
50	3.39	2.29	1.48	21,604	4,082	0.0574	2,191	1.21	19.9	2
60	**4.31**	**2.86**	**1.51**	**21,680**	**5,167**	**0.0513**	**2,105**	**1.57**	**20.2**	**26**
70	6.16	4.43	1.39	22,190	7,487	0.0421	1,981	0.85	18.9	3
80	**9.91**	**6.86**	**1.44**	**23,796**	**11,972**	**0.0323**	**1,825**	**1.44**	**19.5**	**61**
90	19.7	14.3	1.38	29,505	23,950	0.0225	1,633	0.98	18.7	1,2
95	**48.0**	**15.0**	**3.20**	**57,128**	**52,500**	**0.0267**	**1,499**	**29.4**	**30.5**	**2,11**

CONCLUSION

Optimization results show that the ideal DC/AC ratio is 1.52. On the other hand, in scenarios without grid sales, the DC/AC ratio increases to 1.99. Increases in PV capacity sharply increase the NPC to increase the self-consumption rate so that the NPC for 95% RF increases by more than 2.5 times, and the hybrid power system costs are maximized. In addition, in this scenario, approximately 30% of the energy could not be used due to the energy sales constraint in the grid, and the investment costs increased. The results show that determining the appropriate PV and inverter capacity size by considering technical, economic, and environmental objectives and grid constraints will contribute to modeling a more economical and suitable hybrid power system and developing larger systems.

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