

Technical achievable potential of photovoltaic conversion of solar radiation for the conditions of Ukraine

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Abstract. This study investigates solar energy photovoltaic conversion processes while exploring new approaches to identify potential areas for the installation of photovoltaic stations. This research aims to enhance existing methodologies of technical-achievable potential calculation, considering the specificity of territories, the possibility of installing rooftop photovoltaic stations, and the current development of photovoltaic technologies. The developed methodology considers the type of stations, urban building specifics during the calculation of suitable areas for photovoltaic station installation, the potential for installing small and medium rooftop stations, and the modern technical characteristics of photovoltaic modules. The refinement of the PV panels and PV station area ratio calculations revealed that its value depends on the type and power of the station, varying from 0 to 1. This approach simplifies the determination of power capacity of a station that can be installed in a designated area. Consideration of the technical characteristics of the latest photoelectric conversion technologies demonstrates a significant potential increase compared to the existing calculation methodologies. Calculations conducted using the developed methodology revealed that the technically achievable potential of solar energy conversion for Ukraine is 369 TWh/year (254 GWp DC). This figure exceeds the estimations of existing calculation methodologies at least twice. The obtained results showed a significantly greater potential for solar energy in Ukraine, which expands the possibilities of using photovoltaic technologies to supply energy to consumers. This is especially important during the war because of the insufficient electricity production by existing power plants, many of which have been destroyed.

Keywords: Renewable energy sources / photovoltaic conversion / solar irradiance / technically achievable potential / photovoltaic panel

1 Introduction

Over the past decade, the capacity of renewable energy facilities has increased, driven by a shift in energy production towards the use of renewable energy resources. As of 2022, the installed capacity of renewable energy worldwide is 3382 GW, with 58% from wind (899 GW) and solar power (1055 GW) [1]. The most significant development has been observed in Ukraine's photovoltaic and wind power stations, with combined installed capacity of 7586 GW and 1673 GW, respectively, as of 2021. Several factors can explain the significant growth in solar energy in Ukraine:

- High potential for photovoltaic conversion of solar radiation in Ukraine – 82.77 GW (or 99.32 TWh/year) [2].
- State incentives include the ability to sell generated electricity at a “green” tariff and reduced taxes on renewable energy equipment produced in Ukraine [3].
- Commitment to achieving the goals of an energy strategy aimed at reducing dependence on imports of traditional fossil energy resources [4].
- The requirements of the Paris Climate Agreement entail a significant global reduction in greenhouse-gas emissions.

Alongside this, the assessment of the photovoltaic potential according to data from the International Renewable Energy Agency (IRENA) [5] is 70.6 GW (or 88.37 TWh/year). The difference between [2,5] in the forecasted values indicates different approaches for

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Table 1. The main parameters of PV cells of different types [17–20].

Type of PV cell	Efficiency, %	Area, cm ²	Area type	U _{oc} , V	J _{sc} , mA/cm ²	Fill factor, %
Monocrystalline	26.8	274.4	Total	0.7514	41.45	86.1
Dye-sensitized	11.9	1.005	Designated illumination	0.744	22.47	71.2
Thin-film	21	1.0623	Aperture	0.8759	30.25	79.4
Perovskite	23.7	1.062	Designated illumination	1.213	24.99	78.4

assessing the photovoltaic energy potential. These methodologies must consider the specificities of the territories and potential for installing small and medium rooftop stations. With ongoing developments in photovoltaic technologies, there should be a continuous review of their technically achievable potential. Therefore, this study aimed to enhance the methodology for calculating this potential, which is crucial for obtaining accurate data for the planning and design of new stations.

2 Materials and methods

Currently, numerous online resources are available for calculating the technically achievable potential of solar energy at specific locations, such as PVWatts, PV-GIS, MYSUN, Tata Power Solar Rooftop Calculator, GEO-STAR, and Solar Rooftop Calculator [6]. These applications enable the calculation of the solar energy potential for rooftop-type power stations installed in specified locations with limited areas. In contrast, the methodologies outlined in [2,5] focus on calculating solar potential over larger areas.

In [2], a methodology for calculating the solar energy potential across Ukraine's territory is presented. This methodology involves determining the suitable areas for installing solar photovoltaic stations (PV stations) using surface coefficient. The surface coefficient considers the areas occupied by water resources, forests, protected areas, and population density, ranging from 2.45% to 3.41% of Ukraine's total area. Subsequently, to incorporate the technical characteristics of photovoltaic modules, installation features of PV stations, and their capacity, a PV station capacity coefficient was applied. This coefficient ranges from 0.5 to 0.55, varying with the geographical specifics of each region in Ukraine. A limitation of this methodology is that it fails to consider the specific type of station that may occupy certain territories and exclude urban buildings.

In [5], the methodology for calculating solar conversion potential considered a comprehensive range of indicators, including the average annual level of solar insolation, area of territories, technical characteristics of PV modules, archetype of PV stations, and their economic evaluation. The size of the PV stations was categorized into two archetypes based on the installed capacity [7], focusing exclusively on grid-connected ground-based PV stations with high capacity. These archetypes were classified by installed capacity as 10–500 kW and over 500 kW, with average capacities of 250 kW and 1000 kW, respectively. Each archetype was assumed to represent 50% of the total potential installed capacity of PV plants.

A drawback of these methodologies is the exclusion of the potential of small and medium rooftop PV plants in determining total solar energy potential. Additionally, for both methodologies [2,5], it is recommended to establish a review period for assessing the energy potential, considering the evolving stages of photovoltaic technology.

The latest photovoltaic conversion technologies are classified into four generations [8]:

- I – Silicon crystalline (mono- and polycrystalline) [9].
- II – Thin film (including technologies based on amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and polymers) [8].
- III – Dye-sensitized (utilizing donor-acceptor organic materials to form a heterojunction) [10].
- IV – Perovskite (based on hybrid organic-inorganic metal halide compounds that efficiently absorb solar radiation) [11–16].

The technical parameters of photovoltaic modules from these four generations were analyzed and are summarized in Table 1.

To enhance the methodologies for calculating the technical-achievable potential [2,5], it is essential to consider the technical characteristics of the latest photovoltaic conversion technologies, expand the classification of PV station archetypes, include stations with small and medium capacities, and consider the specificity of the involved territories.

This study aims to improve the methodology for calculating the technically achievable potential of PV energy conversion by considering the specificity of territories, possibility of installing rooftop PV stations, and current development of photovoltaic technologies.

To achieve this goal, it is necessary to solve the following problems:

- To develop a methodology to calculate the technically achievable potential for converting solar energy into electricity.
- To develop a methodology to calculate the ratio of PV panels to PV station areas.
- To integrate the latest technical parameters of monocrystalline photovoltaic technology, including those that have not yet been represented as commercial samples, into the calculations.
- To calculate the energy potential for converting solar energy into electricity by using the developed methodology.

The objective of this study is the processes of photovoltaic conversion of solar energy, considering new approaches to engaging potential territories and areas for installing PV stations, as well as the current level and development of photovoltaic technologies.

The major hypothesis of this study is that applying new approaches to assess the energy potential of converting solar energy into electricity will allow more accurate estimation of engaging specific territories for PV station installations, considering critical indicators of such stations. This approach will define new tasks in developing scenarios for integrating new capacities of PV plants into Ukraine's unified energy system.

This study assumed that the area of territories that can be used for PV station installations is 1% of the total area. The calculation includes medium and large ground-mounted stations as well as flat and inclined rooftop stations. When calculating the power of a station installed at a specific location, it is necessary to consider the station type, tilt angle, and size of the PV modules, which are considered in the PV panels and PV station area ratio.

To simplify the determination of the area suitable for installing ground-mounted PV stations, areas such as water bodies, forests, agricultural lands, and built-up areas were excluded according to data [21–48]. Areas suitable for installing rooftop PV stations includes built-up areas only. The average daily annual total solar radiation on an inclined surface at the optimal inclination angle of the PV panels was accepted according to the data [49] for each region of Ukraine. The nominal power of an individual PV panel was assumed to be 560 W. Two types of PV plants were considered in the calculation: rooftop (inclined or flat roof, up to 30 kWp) and ground-mounted (medium >30 kWp and large >100 kWp).

The research was conducted using methodologies [2,5] using Microsoft Excel. In the developed methodology for calculating the technical-achievable potential, rooftop PV plants were included, the calculation of the suitable area for installing PV plants was simplified, the ratio of PV panels to PV station areas was calculated for each type of station, and the technical-achievable potential for converting solar energy into electricity was determined for advanced photovoltaic technology not yet represented as commercial samples.

2.1 The methodology for calculating the technically achievable potential of converting solar energy into electrical energy

The potential was calculated using a generalized block diagram, as shown in Figure 1.

The algorithm for calculating the technically achievable potential is divided into seven stages:

- Definition of input data: area of territories and the coefficient of territory utilization for installing PV plants, solar energy incident on the inclined surface with the optimal tilt angle for PV modules, optimal tilt angle for PV modules, and electrical parameters of PV modules.
- Determination of station types: ground-mounted medium capacity, ground-mounted high capacity, flat rooftop, and inclined rooftop stations.
- Calculation of the land area suitable for installing the PV station, $S_{PVstation}$.
- Calculation of the ratio of PV panels to PV station areas, $\varphi_{PVmodule}$.

- Calculation of the PV panels area installed on the PV station area, $S_{PVmodule}$.
- Calculation of the installed capacity of the PV station, P_{inst} .
- Calculation of the technical-achievable potential of solar energy for electricity generation.

The area suitable for installing PV plants in a specific region was calculated based on its type:

- Ground-mounted, km^2 :

$$S_{PVstation.g} = (S_{region} - S_{water} - S_{forest} - S_{agricultural} - S_{urban}) \cdot k_{PV.g}, \quad (1)$$

S_{region} – region area, km^2 ; S_{water} – area of water bodies for the selected region, km^2 ; S_{forest} – area of forests in the selected region, km^2 ; $S_{agricultural}$ – area of agricultural land in the selected region, km^2 ; S_{urban} – area of urban building, km^2 ; $k_{PV.g} = 1\%$ – area utilization coefficient for installing ground-mounted PV stations [5].

- Rooftop, km^2 :

$$S_{PVstation.rt} = S_{urban} \cdot k_{PVrt}, \quad (2)$$

$k_{PVrt} = 1\%$ – area utilization coefficient for installing rooftop PV stations [5].

The ratio of PV panels to PV station areas is determined as follows:

$$\varphi_{PVm} = \frac{S_{PVmodule}^c}{S_{PVstation}^c}, \quad (3)$$

$S_{PVmodules}^c$ – calculated area of photovoltaic panels used for a PV station of a given capacity, km^2 ; $S_{PVstation}^c$ – calculated area of a PV station, km^2 .

The area of PV panels located on the PV station area, km^2 :

$$S_{PVmodules} = S_{PVstation} \cdot \varphi_{PVm}. \quad (4)$$

The technical-achievable potential of converting solar energy into electrical energy is determined as follows, GWh/year:

$$W = \frac{E_{rr} \cdot \eta \cdot S_{PVmodule}}{10^6}, \quad (5)$$

E_{rr} – the average annual total solar energy incident on an inclined surface for the optimal tilt angle of the PV module, kWh/m^2 ; η – the conversion efficiency of the PV modules.

2.2 The methodology for the ratio of photovoltaic panels area to photovoltaic station area calculation

The coefficient φ_{PVm} varies from 0 to 1 depending on the type of PV plant, location characteristics, and shading from nearby objects that affect the PV panels. In the calculation of the energy potential, φ_{PVm} is determined based on the type and capacity of the PV station, considering the dimensions of the PV panels and their tilt angle:

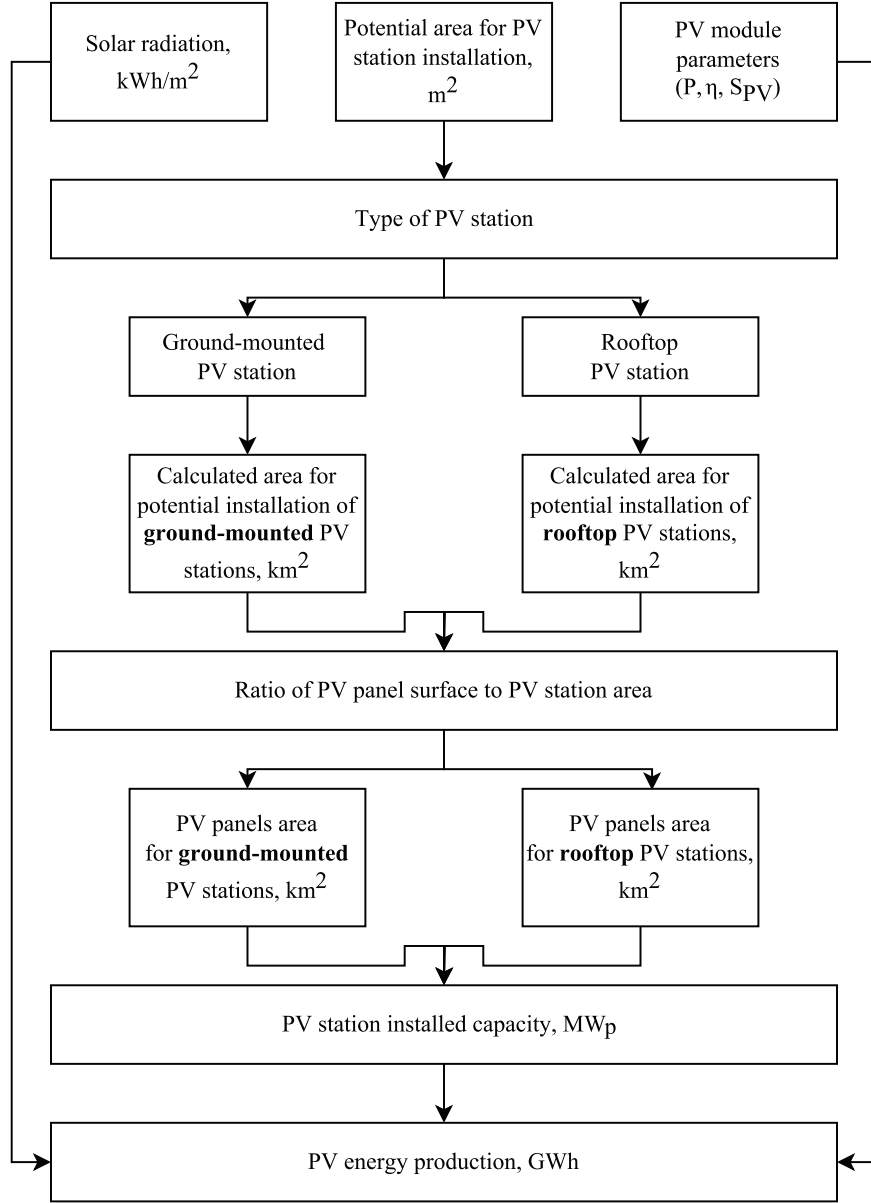


Fig. 1. The generalized block diagram for calculating the potential of converting solar energy into electrical energy [5].

– For a rooftop PV station with tilt surface:

$$\varphi_{PVm}^{tilt} = \frac{l \cdot h}{(l + \frac{\delta}{100}) \cdot (h + \frac{\delta}{100})}, \quad (6)$$

l – the length of the PV panel, m; h is the height of the PV panel, m; δ – the distance between the PV panels, laid on the fasteners, m.

– For a rooftop PV station with flat surface:

$$\varphi_{PVm}^{flat} = \frac{l \cdot h \cdot \cos(\alpha)}{(l + \frac{\delta}{100}) \cdot (h \cdot \cos(\alpha) + H)}, \quad (7)$$

α – the PV panel installation angle, degrees; H – the distance between rows, m.

– For a ground-mounted PV station with medium capacity:

$$\varphi_{PVm}^{gm} = \frac{\cos(\alpha) \cdot l \cdot h \cdot N_{pv}}{(\cos(\alpha) \cdot (2 \cdot l + \frac{\delta}{100}) + H) \cdot (h + \frac{\delta}{100}) \cdot \frac{N_{pv}^t}{2}}, \quad (8)$$

N_{pv}^t – PV panel quantity per 1 table, pce; L – table length, m.

– Coefficient for a ground-mounted PV station with high-capacity is calculated according to (3) based on an actual project, as during the implementation of such stations, in addition to the distance between rows, considerations are also given to setbacks from fences, access roads, the area of administrative buildings, the area of distribution buildings, etc.

Following the above methodology for calculating the ratio of PV panels area to PV station area, as per ((6)–(8)), the standard size of a commercial monocrystalline

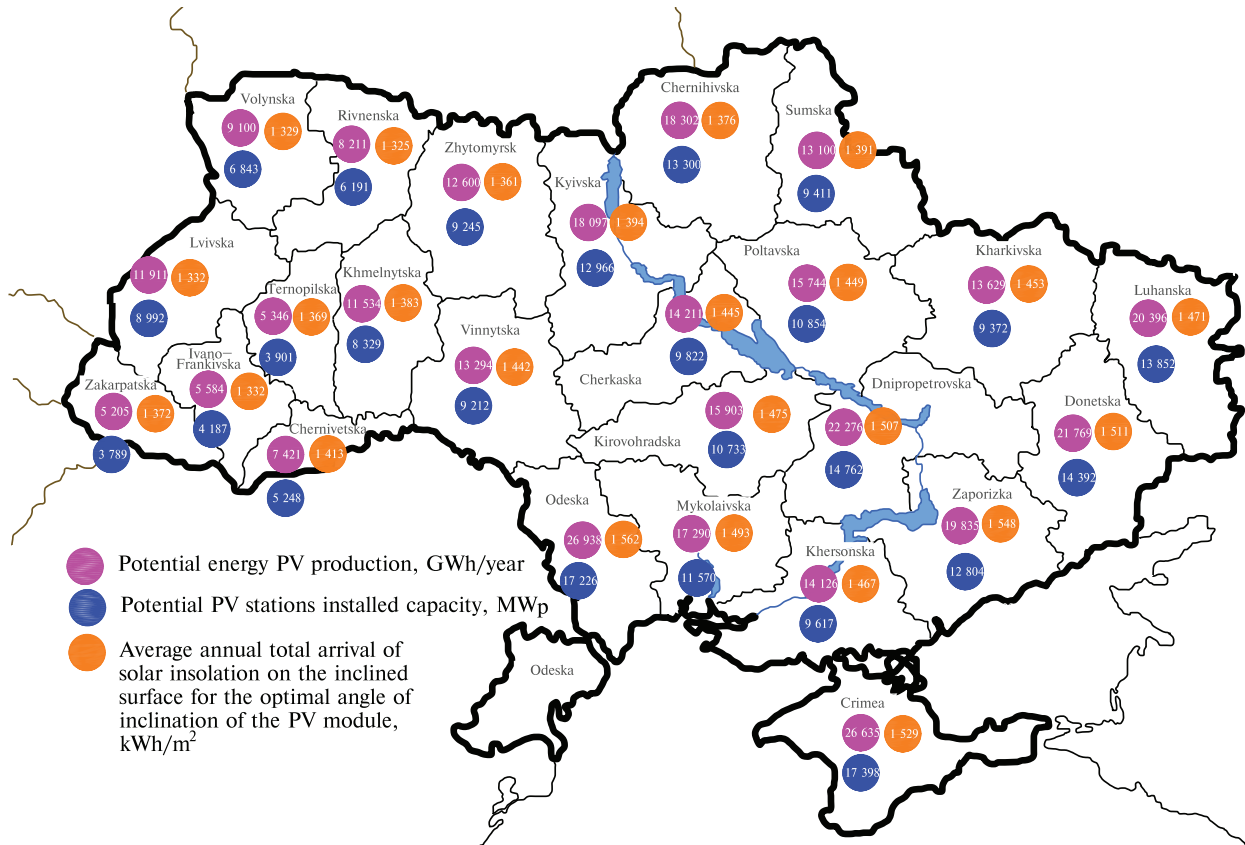


Fig. 2. The technical-achievable potential of solar energy conversion for Ukraine.

photovoltaic module with a power rating of 560 W was adopted [50]. The results for ratio of PV panels to PV station areas coefficient are as follows:

- $\varphi_{PVm}^{tilt} = 0.97$ for a rooftop PV station with tilted surface.
- $\varphi_{PVm}^{flat} = 0.53$ for a rooftop PV station with flat surface.
- $\varphi_{PVm}^{gm} = 0.5$ for a medium-capacity ground-mounted PV station.
- $\varphi_{PVm}^{gm} = 0.22$ for a high-capacity ground-mounted PV station.

3 Results and discussion

Based on the aforementioned data and methodology, the technically achievable potential is determined for each region. The results of the potential PV energy production and installed capacity for each region are shown in Figure 2. These results were calculated in the DC capacities.

This study presents a methodology (Fig. 1) for calculating the technically achievable energy potential. The developed approach considers various station types and factors in urban development for PV station area calculations and assesses the feasibility of small- and medium-sized rooftop PV installations alongside the technical characteristics of modern PV panels. Unlike the methodologies in [2,5], it achieves more precise results by refining the capacity factor calculation, which varies from 0 to 1 depending on station type and

capacity. This factor was found to be highest for rooftop PV stations with inclined roofs and lowest for large-capacity ground-based stations, reflecting their complex construction technology. Incorporating the technical characteristics of advanced photovoltaic technology highlights significant potential growth compared to the approaches in [2,5].

According to the developed methodology, calculations indicated that Ukraine's technically achievable potential for converting solar energy into electricity is 369 TWh/year (254 GWp DC) using monocrystalline technology. This figure surpasses the estimates in [2,5] at least twice.

A limitation of the methodology lies in its scaled approach for calculating the area for PV station installation, which does not account for the installation orientation. This oversight may disregard terrain features that could restrict PV station deployment upon a detailed examination.

In 2021, Ukraine consumed 155 TWh of electrical energy [51] and less than half of the potential output achievable through monocrystalline PV technology in the country. Given the variability in solar radiation influx throughout different periods combined with Ukraine's specific electrical load patterns, exploring options for energy transformation and storage is crucial. This study aims to achieve a balanced integration of environmentally friendly energy generation and consumption, effectively addressing both short-term and annual energy needs. The obtained results expand the potential for utilizing solar

radiation energy and establish new objectives for creating scenarios to integrate new PV plant capacities into Ukraine's unified energy system.

4 Conclusions

This study analyzed existing methodologies for determining the energy potential of solar radiation. As a result of the analysis, a new methodology was proposed, which, unlike existing ones [2] and [5], considers station types, urban development influencing the suitability of areas for PV installations, and the feasibility of small and medium-sized rooftop stations. In addition, it integrates the modern technical characteristics of photovoltaic modules into the calculations.

For the first time, a methodology to determine the ratio of PV panels area to PV station area calculation was developed. This method includes factors such as the station type, capacity, tilt angle, construction technology features, and dimensions of photovoltaic modules. The coefficient varies from zero to one depending on the aforementioned factors.

The energy potential for converting solar energy into electricity for the first-generation PV modules was calculated using the developed methodology. Results indicate power coefficients of 0.97 for rooftop PV stations with inclined surfaces, 0.53 for rooftop PV stations with flat surfaces, 0.5 for medium-capacity ground-mounted PV stations, and 0.22 for high-capacity ground-mounted PV stations. The calculated energy potential for Ukraine using monocrystalline technology is 369 TWh/year.

In summary, the obtained results expand the possibilities of using solar radiation energy by incorporating areas and surfaces that were previously not considered. This sets the task of further options analysis for integrating solar power plants into Ukraine's energy system for its efficient and balanced operation.

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Conflicts of interest

The authors declare that they have no conflicts of interest regarding this research, including financial, personal, authorship, or any other conflicts that could affect the research and the results presented in this article.

Data availability statement

Data is available by link <https://figshare.com/s/4d3af941f0d682c22539>

Author contribution statement

Conceptualization, H. Karpchuk, V. Budko and O. Lysenko; Methodology, H. Karpchuk, V. Budko and O. Lysenko; Software, H. Karpchuk; Validation, H. Karpchuk, V. Budko and O.

Lysenko; Formal Analysis, H. Karpchuk; Investigation, H. Karpchuk, V. Budko and O. Lysenko; Resources, V. Budko; Data Curation, H. Karpchuk; Writing – Original Draft Preparation, H. Karpchuk; Writing – Review & Editing, V. Budko; Visualization, O. Lysenko; Supervision, V. Budko; Project Administration, H. Karpchuk and V. Budko.

Use of artificial intelligence

The authors confirmed that they did not use artificial intelligence technology to create the presented work.

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