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Photovoltaics in Swedish agriculture: Technical potential, grid integration and profitability

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Abstract

This paper investigates the realizable potential for photovoltaic (PV) systems in Swedish agriculture. Marginal lands and available building areas for PV systems are quantified, and factors limiting the potential are analyzed. It is shown that the potential for PV in Swedish agriculture is high, but what is fully realizable is limited by the capacity of the rural power grid. A case study in the rural municipality of Herrljunga was conducted and scaled to national level. The study shows that the risk of surges in the medium voltage grid (10 kV) in rural areas are small in case where all roof surfaces with an annual solar irradiance of over 950 kWh/m^2 are used for solar power. The total electricity production from the Swedish agriculture, if all roof areas with this irradiance level were used, is estimated to 4 TWh annually. With solar power on all roof surfaces with an annual irradiance of at least 900 kWh per m^2 problems with voltage rise and overloads in the electricity grid might occur. The electrical grid capacities thus substantially limit how much solar power can be installed. Our results also show that the profitability limits the potential to 0.2 TWh on a national level, but that it could increase if more optimistic economic conditions are assumed.

Keywords: *PV potential, grid integration, agriculture, business models*

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1. Introduction

Agriculture is a sector with a seemingly high potential for photovoltaic (PV) power generation. The abundance of land and different types of farm buildings provide several options for installing PV systems. At the same time, previous studies have shown that rural distribution grids are the grid types that are most sensitive to high PV power injections (Walla et al., 2012), which may limit the achievable generation capacity.

Previous studies of the potential solar power generation in Sweden has mainly been based on building statistics combined with assumptions about key parameters such as building dimensions. For example, Kjellsson (1999, 2000) estimated the building areas in agriculture that were available for solar power generation to 150 km^2. An important task for new studies in this field is to improve the estimates of the total potential by using more refined methods, and to determine the limiting factors in realizing this potential.

The aim of this paper is to quantify the realizable potential for PV power generation in Swedish agriculture, both on land and on buildings. Realizable potential is defined here to be the technical potential (PV capacity on available areas) reduced by constraints in the power grid and by what is economically profitable. The study combines analyses of GIS (geographic information system) data with power flow simulations of power grids. A case study is performed on the rural municipality of Herrljunga in western Sweden. These results are then combined with national statistics to estimate the realizable potential for the whole Swedish agricultural sector. Details on the findings in this paper can be found in the full project report (Norberg et al., 2015).

The paper is structured as follows. The methodology for determining the realizable potential is described in Section 2, the results are presented in Section 3, and a concluding discussion is included in Section 4.

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2. Methodology

2.1. Available land and buildings

It is assumed that the lands primarily considered for PV installations are marginal lands, i.e. lands that are not profitable for agricultural use. The availability of marginal lands is determined from national statistics (Johnsson, 2008). However, all available land in the statistics cannot be used for PV, since the distance from the grid is too large, the land is shaded, difficult to build on or not accessible.

Available building roof areas are analyzed based on LiDAR (Light Detection And Ranging) data and property maps in ArcGIS (ESRI, 2015) for the municipality of Herrljunga, Sweden. Every building is linked to the low voltage (LV) grid connection node within the same property, determined from data provided by the local distribution grid operator (DSO), Herrljunga Elektriska AB. If there are no connections within the property the closest connection within a radius of 200 meters is linked to the building (see Fig. 1). The radius was set to 200 m based on the recommended cost for connection to the LV grid according to the Swedish Energy Market Inspectorate (Energimarknadsinspektionen, 2013a). This radius is of course not universally valid but depends on the profitability of each individual case.

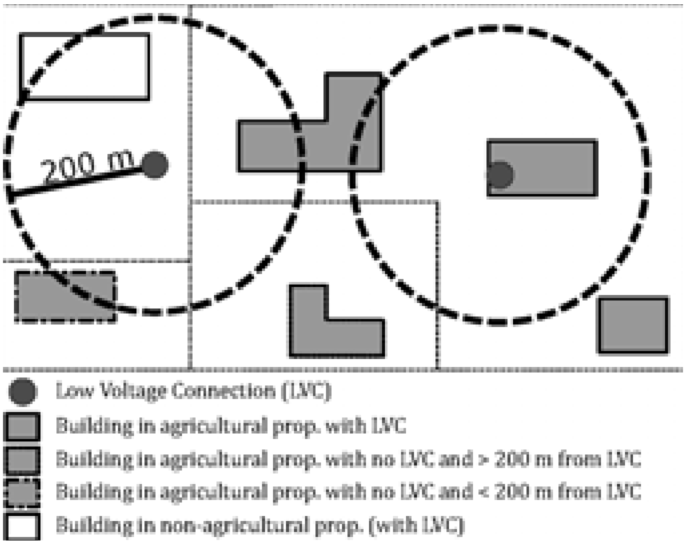

Fig. 1: Methodology for identifying agricultural buildings (grey) with potential for PV installation. Buildings within an agricultural property with a low voltage connection (LVC) or < 200 meter from any LVC are included in the analysis. In this example the south middle building will not be included.

2.2 Solar energy calculations

The solar resource potential on the building areas is quantified using the built-in tool *Solar Area Radiation* in ArcGIS, allowing both internal shading and shading from surrounding terrain, vegetation and buildings to be taken into account (Fu and Rich, 1999). Different thresholds for annual irradiance availability are studied (minimum level for installing PV), for instance 700 kWh/m^2/year meaning that only roof segments having at least 700 kWh/m^2/year are considered for PV installation. For generating data to the detailed grid simulations, PV systems on the available areas were simulated in the modeling environment Matlab using standard models for available solar irradiance and PV output power (Duffie et al., 1994). The following assumptions about losses were made:

(1) 15% of the available roof area was not considered due to obstacles such as chimneys etc. (Kjellsson, 1999).

(2) Shading from surrounding buildings, trees etc. was represented by a general removal of the beam component of the irradiance for solar angles ($\cos(\theta_i) < 0.2$).

(3) 15% efficiency of the PV cells assumed at standard test conditions. Overall PV system efficiency was assumed to be 85%.

(4) 19% of the total potential was excluded corresponding to the share of roofs not in sufficiently good condition for PV installation (Riksantikvarieämbetet, 2004).

2.3 Distribution grid simulations

Access to a very detailed database of grid data from the local DSO for both the medium voltage (MV) and low voltage (LV) grids in the studied area has made it possible to make detailed power flow simulations of the whole distribution grid. Hourly load data are available for all customers and also line-impedances of all connections in the grids. Only active load data were available, thus a constant load factor of 0.95 was assumed to derive the reactive load (Thomson and Infield, 2007). Balanced three-phase power flow for the whole grid was solved using Raphson-Newton's method implemented in Matlab. According to current Swedish regulations, short-term voltage fluctuations deviating 10% from nominal are allowed in the MV grid (Energimarknadsinspektionen, 2013b). To allow further voltage fluctuation in the LV grid, voltage fluctuations are limited to 5% in the MV grid. Furthermore, the maximal current allowed is specified for each line. The maximum PV penetration is thus limited by an overvoltage limit of 5% above nominal voltage or 1.05 p.u. and the specified load of current for each line.

2.4 Profitability limitations

The cost of PV systems has dropped considerably in the last decade. For Sweden the mean price was 13 SEK/W_p for systems larger than 20 kW_p (Lindahl, 2015). This should be compared to the avoided cost of electricity when self-consuming the PV electricity, which in our calculations is set to 0.45 SEK/kWh in the agricultural sector, which pay very low energy tax, whereas the corresponding figure for other businesses is 0.75 SEK/kWh. The excess share of the electricity generated is sold, with an expected price of 0.25 SEK/kWh, according to mean Nordpool spot prices, and additional incomes of 0.05 SEK/kWh from the grid owner and 0.18 SEK/kWh for electricity certificates. From 2015 it is also possible to get 0.60 SEK/kWh as a tax rebate, given annual net consumption, a fuse of ≤ 100 A, and a maximum of 30 MWh fed into the grid. Besides this it also possibly to be granted an investment subsidy of 30% for companies and 20% for others. The application rate is high and it has more been seen as a bonus, as the uncertainty of being granted the subsidy have been high. However, the Swedish government has in the last budget bill proposed significantly more funds the coming years (Brolund, 2015).

When estimating the profitability we therefore assume a maximal production of 60 MWh, of which 50% is fed into the grid. This gives a mean compensation for sold electricity of 0.38 SEK/kWh without tax rebate and 0.68 SEK/kWh including the tax rebate (see Tab. 1).

Tab. 1: Cases for the profitability assessment

	Investment [SEK/kW_p]	Discount rate	Self-consumption	Value of self-consumed electricity* [SEK/kWh]
Base case, agricultural	13 000	6%	50%	0.38
Base case, agricultural incl. tax rebate	13 000	6%	50%	0.68
Base case, other	13 000	6%	50%	0.40
Base case, other incl. tax rebate	13 000	6%	50%	0.70

*Also additional incomes from electricity certificates of about 0.15 SEK/kWh for 15 years.

It is however difficult to find profitability in the cases presented in Tab. 1. Therefore we examined some possible cases were profitability would increase. These are presented in Tab. 2. In the first case (1) a discussed investment subsidy within the agricultural program of Sweden is implemented. In (2) the compensation offered by some electricity suppliers for selling the electricity to the grid is higher than Nordpool spot prices, here assumed as 1.25 SEK/kWh. For how long this generous compensation will last is highly uncertain. In (3) we assume that the farmer has own capital to invest, and thereby lowering the discount rate. In (4) we assume the farmer to install the PV system, and thereby reduce the investment cost. Lastly in (5) we assume a large scale PV system (1 MW_p), for which own capital is used and all generated electricity is fed directly into the MV grid. We assume a distance of 500 meter from the PV field to the MV grid, which means a connection cost of 550 000 SEK (Svensk Energi, 2011).

Tab. 2: Cases for increasing profitability.

	Investment [SEK/kW_p]	Discount rate	Self-consumption	Value of self-consumed electricity* [SEK/kWh]
(1) Investment subsidy 40%, incl. tax rebate	7 800	6%	50%	0.68
(2) Higher sell rate, incl. tax rebate	13 000	6%	50%	1.18
(3) Own capital, incl. tax rebate	13 000	3%	50%	0.68
(4) Self-installed, incl. tax rebate	11 000	6%	50%	0.68
(5) Large-scale (1 MW_p), own capital, investment subsidy, 40%	6 000	3%	0%	0.30

*Also additional incomes from electricity certificates of about 0.15 SEK/kWh for 15 years.

2.5 Scaling to national level

It is difficult to make a fair scaling of the results in the case study in Herrljunga to national level. In Herrljunga there are 591 agricultural properties which can be compared to 350 000 nationally. A previous inventory of agricultural buildings in 10 different regions in Sweden showed that there were on average 6.5 buildings in each agricultural property (Riksantikvarieämbetet, 2004). This can be compared with 5.4 buildings per property in Herrljunga, which is at least in the same range as the previous study.

The solar resource availability varies significantly over Sweden. Therefore the available global annual solar resource was scaled for each county *c* compared to Herrljunga as;

$$G_c = \frac{\bar{G}_c}{\bar{G}_{hl}} G_{hl}, \qquad \text{(eq. 1)}$$

where $\bar{G}_c$ and $\bar{G}_{hl}$ are the mean annual global solar irradiance for 1979-2012 of county *c* and Herrljunga (*hl*) respectively and G_{hl} is the available solar resource on the roofs of Herrljunga derived from ArcGIS *Solar Area Radiation.* The hourly PV production $E_{c,h}$ depends on the incident solar angle $\theta_i^{c,h}$ as;

$$E_{c,h} = \begin{cases} G_{c,h}\eta \ \text{ if } \cos\left(\theta_i^{c,h}\right) > 0.2 \\ D_{c,h}\eta \ \text{ if } \cos\left(\theta_i^{c,h}\right) < 0.2 \end{cases}, \qquad \text{(eq. 2)}$$

where the G_h is the global irradiance and D_h is the diffuse irradiance at hour *h* and η is the fraction of the energy than can be extracted from the total incident solar irradiance and can be expressed as;

$$\eta = \eta_{PV}\eta_{sys}\eta_{obs}\eta_r, \qquad \text{(eq. 3)}$$

where $\eta_{PV} = 0.15$ is the module efficiency, $\eta_{sys} = 0.85$ is the PV system efficiency, $\eta_{obs} = 0.85$ is due to obstacles on the roof and $\eta_r = 0.81$ is due to available roofs of sufficiently good condition for PV installations (see section 2.2). The annual total power that can be extracted from the solar resource is thus;

$$E_c = \frac{N_c}{N_{hl}} \sum_{h=1}^{8760} E_{h,c}, \qquad \text{(eq. 4)}$$

where N_c and N_{hl} are the numbers of agricultural properties in county c and Herrljunga respectively.

3. Results

3.1. Potential PV generation capacity

The available marginal lands are found to be large (the Swedish average is in the order of 1 ha per agricultural property) and are therefore not considered to be limiting for the total PV capacity in the case study. Moreover, a total building roof area of 0.8 km^2 is available in the case study, corresponding to a total installed capacity of 120 MW. The results of allowing different irradiance thresholds for PV on these buildings in Herrljunga are shown in Fig. 2, indicating the total technical potential for PV (at 15% assumed efficiency).

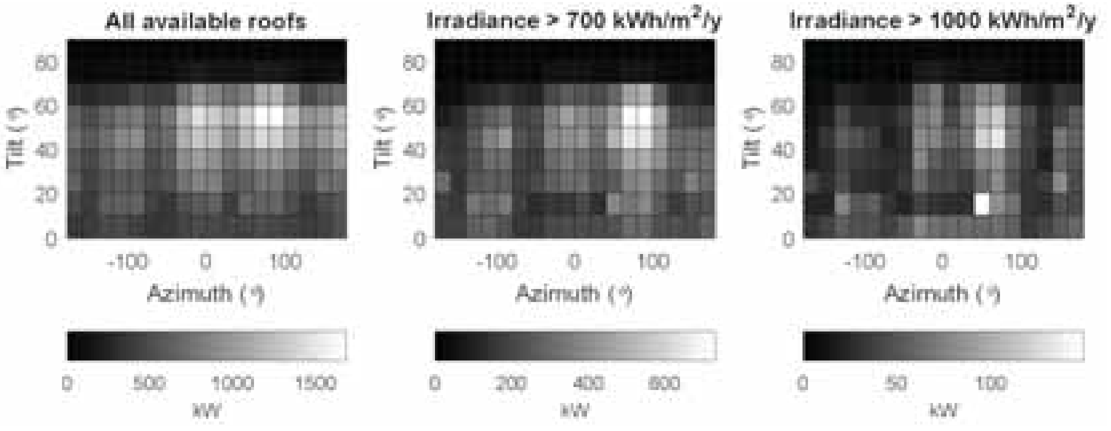

Fig. 2: Potential PV generation capacity on agricultural building roofs in the studied municipality, with three different requirements on annual irradiance. Note that the scale of the color bar differs between the subfigures.

The total potential as function of solar irradiance level is presented in Fig. 3. The total numbers of buildings having at least one roof segment of the solar irradiance level is included, as well as the total roof area and power production. In Tab. 3 key figures of an average agricultural property in Herrljunga are presented for three different solar irradiance levels. If scaling to national levels, following eq. 1-4, the total annual PV production would be 35.7, 13.5 and 2.5 TWh for the solar irradiance levels > 0, > 700 and > 1000 kWh/m^2 respectively.

Tab. 3: Key figures for an average agricultural property in the Herrljunga distribution grid for three different levels of annual solar irradiance; > 0 kWh/m^2 (all roofs), > 700 kWh/m^2, > 1000 kWh/m^2.

Key figures	All roofs	> 700 kWh/m^2	> 1000 kWh/m^2
Roof area (m^2)	1100	410	70
Solar irradiance (MWh/year)	940	360	62
PV capacity (kW)	170	62	10
PV power production (MWh/year)	128	48	8.3

3.2. Hosting capacity of rural distribution grids

In an early stage it was clear that the maximum accepted current in the lines would not be reached as Fig. 4 shows. The figure only displays line currents from the northern part of the grid but power flow simulations for the southern part gave similar results. Resulting histograms for MV grid voltages are shown in Fig. 5 together with the probability for voltage rise outside the allowed ±5% limits. All building areas with more than 950 kWh/m^2 annual irradiation (B) can be utilized without problems, but if building areas in the other categories (C and D) are used, there is a probability for overvoltage. However this risk is small, 0.13 % for C (> 900 kWh/m^2/year).

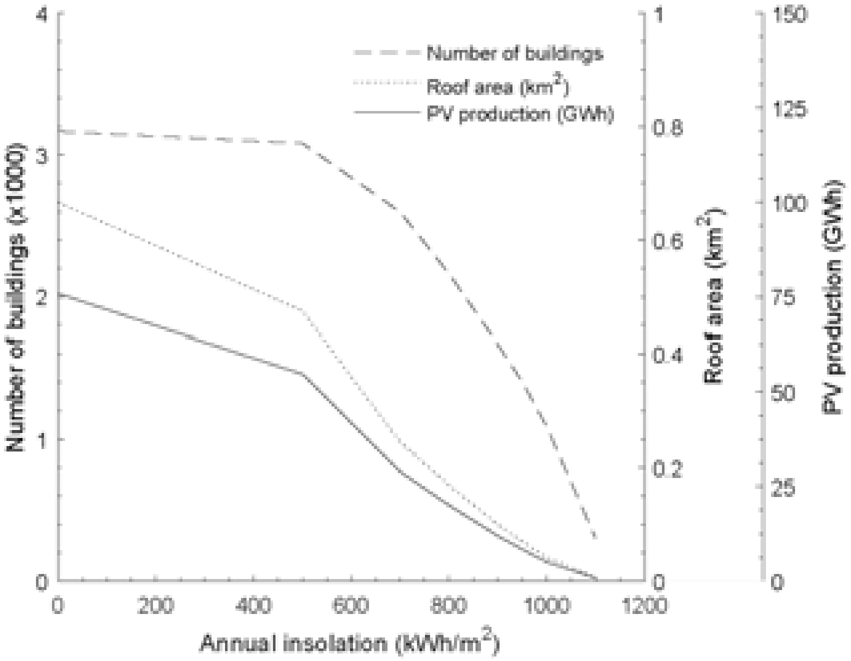

Fig. 3: Total potential for agricultural properties in Herrljunga.

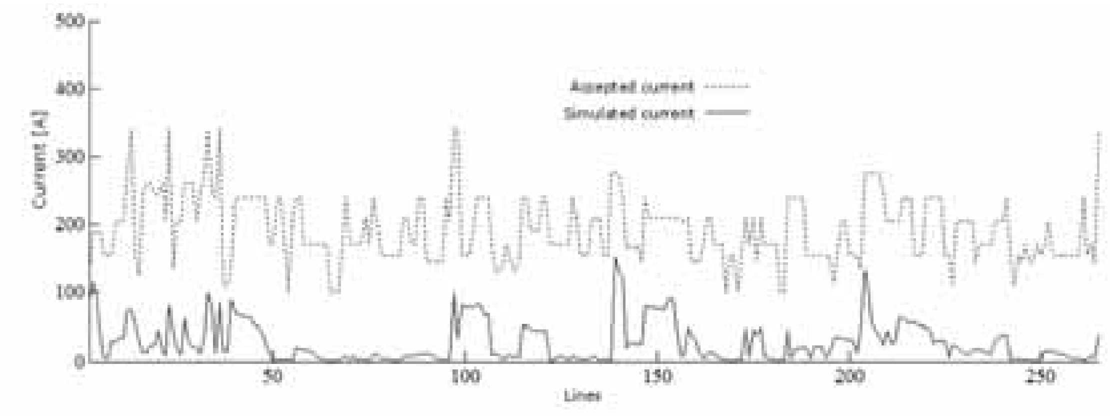

Fig. 4: Accepted current (dashed) and simulated current (solid) for each line in the northern part of the grid. In this figure the solar irradiance level was > 1000 kWh/m^2/year.

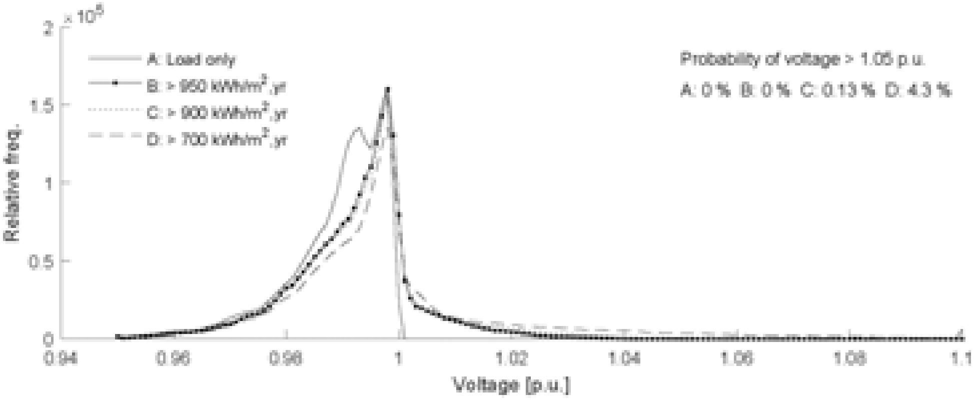

Fig. 5: Histogram of voltage in the medium voltage nodes for some different solar irradiance levels and for load only. All hours and nodes of the northern part of the grid are included. Also the probability for exceeding the overvoltage limit of 1.05 p.u. is presented in the upper right for the different cases.

3.3 Profitability of PV in agricultural sector

Following the assumptions in Section 2.4 it is not profitable to invest in PV without tax rebate. If tax rebate is included it is only profitable on the very best roofs, > 1 150 kWh/m^2/year. In Herrljunga there are almost no buildings with those conditions, scaled to national level only 0.2 TWh. In Tab. 4 an estimation of the annual yield and the scaled national potential is presented. As can be seen the national potential is low for profitable PV systems.

When it comes to the cases of improved profitability as presented in Tab. 2 there is a significant potential since locations with lower solar irradiance will become profitable (see Tab. 5). If own capital is used, giving a discount rate of 3% and a 40% subsidy on the investment is granted it is profitable to deploy large-scale PV fields of 1 MW$_p$, resulting in a total annual generation of 281 TWh, which is about twice as much as the Swedish electricity consumption. It should be noted that this is profitable from the farmers' perspective and only if the subsidies would be sufficient for all PV fields. Still, the potential will be limited by the overvoltage limit in the rural distribution grids of 4 TWh (see Section 3.2).

Tab. 4: Calculated income for a roof mounted PV system and the national potential at different solar irradiance levels.

Solar irradiance [kWh/m²/year]	Annual yield on investment		National potential [TWh/year]	
	With tax rebate	Without tax rebate	Unlimited tax rebate	< 30 MWh tax rebate
700	0,0%	1,7%	14	11
800	0,0%	2,8%	10	8
900	0,0%	3,8%	7	5
1000	0,7%	4,7%	3	3
1100	1,4%	5,6%	0,5	0,5
1200	2,1%	6,4%	0	0

Tab. 5: Potential for cases with increased profitability

Case	Profitable solar irradiance level [kWh/m²]	National potential [TWh/year]	
		Unlimited tax rebate	> 30 MWh tax rebate
Investment subsidy 40%	700	14	15
Higher sell rate	700	14	15
Own capital	850	9	8
Self-installed	1000	-	21
PV field, own capital, investment subsidy 40%	800	281*	

*All electricity from the PV field is assumed to be sold direct to the grid, with no tax rebate.

4. Concluding discussion

The results indicate that there is a considerable theoretical PV potential in the Swedish agricultural sector, but what is realizable is limited by the profitability, which at the current market situation is low, around 0.2 TWh on a national level. However, when including more or less optimistic scenarios, the profitability is no longer limiting; instead the hosting capacity of the rural distribution grid sets the limit to about 4 TWh/year. In this case the hosting capacity could be increased by different means, like curtailment, storage, grid enforcements or as previously shown for the same grid through smart allocation, where PV is only deployed at the strongest nodes (Lingfors et al., 2015).

The accuracy of the scaling to national level from the case study done for the distribution grid in Herrljunga is of course highly uncertain. Herrljunga only represents less than 2 ‰ of the agricultural sector of Sweden and it is not clear if Herrljunga is representative in terms of kind of farming or the condition of the grid. The difference in solar resource has been accounted for as described in Section 2.5, which means that no PV should be installed approximately from the 60th latitude northbound if the current level of solar irradiance of >1150 kWh/m²/year were to be used.

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