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Energy Pay-back Time and CO_2 Emissions of PV Systems

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The energy requirements for the production of PV modules and BOS components are analyzed in order to evaluate the energy pay-back time and the CO_2 emissions of grid-connected PV systems. Both c-Si and thin film module technologies are investigated. Assuming an irradiation of 1700 kWh/m^2/yr the energy pay-back time was found to be 2·5–3 years for present-day roof-top installations and 3–4 years for multi-megawatt, ground-mounted systems. The specific CO_2 emission of the rooftop systems was calculated as 50–60 g/kWh now and possibly 20–30 g/kWh in the future. This leads to the conclusion that in the longer term grid-connected PV systems can contribute significantly to the mitigation of CO_2 emissions.

INTRODUCTION

One of the major environmental issues which we will have to address in the new millennium is the problem of global warming. The reduction of CO_2 emissions by way of energy savings and by introduction of renewable energy technologies is now on the political agenda in most industrialized countries. Photovoltaic energy conversion is one of the technologies for which high expectations exist with regard to its potential for CO_2 mitigation. This is one of the reasons for the existence of government-sponsored R&D programmes on photovoltaic technology. On the other hand, doubts are sometimes expressed as to the Energy Pay-Back Time (EPBT) of PV systems. Because the energy pay-back time is a very good indicator of the net potential for CO_2 mitigation, this discussion is highly relevant for the prospects of PV in the next millennium.

My objective in this paper is to review existing knowledge on energy requirements for manufacturing of PV systems and to give some representative calculations for the energy pay-back time and the CO_2 emissions. I will also investigate the effects of future enhancements in PV production technology in order to evaluate the long-term prospects of PV systems for CO_2 mitigation.

Over the past decade a number of detailed studies on energy requirements of PV modules or systems have been published.[1–10] I have reviewed and compared these studies and tried to establish on which data there is more or less consensus and how observed differences may be explained.[11,12] Based on this review of available data, I have established a 'best estimate' of the energy requirement of crystalline silicon modules, thin film modules and BOS components.

In my analysis I will consider all energy inputs for material production, the processing of cells, modules and other system components and the manufacturing of production equipment (IFIAS level 3 assessment; cf. ref. 12). However, I will restrict my assessment to the *production* phase of the PV system components

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because energy demands in the utilization phase are generally negligible for PV systems, and because there is very little data on recycling or other treatments of decommissioned systems.

Throughout this paper I will present energy data as Equivalent Primary Energy requirements, that is the amount of primary (or fuel) energy necessary to produce the component. So all electrical energy input is converted into primary energy requirements, with an assumed conversion efficiency of 35%.† In the following three sections I will first evaluate the energy requirements of crystalline silicon modules, followed by a discussion of thin film modules and BOS components. On the basis of these data I will subsequently calculate the EPBT and the CO_2 emissions for two typical PV system configurations. Finally I will present some concluding remarks.

CRYSTALLINE SILICON MODULES

Present technology

Previously published estimates[1,2,5,6,9,10] for the energy requirement of present-day crystalline silicon modules vary considerably: between 2400 and 7600 MJ/m^2 for multicrystalline (mc-Si) technology and between 5300 and 16,500 MJ/m^2 for single-crystalline (sc-Si) technology. Partly, these differences can be explained by different assumptions for process parameters like wafer thickness and wafering losses. The most important source of differences, however, was found in the estimates for the silicon purification and the crystallization processes. Currently the majority of silicon solar cells are made from off-spec material that is rejected by the micro-electronics industry. The preparation of two output products with different product quality makes it very difficult to allocate energy consumption in a fair way to the PV wafers on the one hand and micro-electronics wafers on the other hand. On top of this, uncertainties still exist with regard to the actual energy consumption of the purification and crystallization processes.[11] In this analysis I chose to disregard process steps which are specifically needed for the micro-electronics wafers and to use the lower estimates for process energy consumption (with the argument that lower quality requirements may lead to reduced energy consumption). Under these premises I arrive at the estimates given in Table I.

Table I. Breakdown of the energy requirements for c-Si module production with present-day technology (in MJ of primary energy)

Process	mc-Si	sc-Si	Unit
Mg silicon production	450	450	MJ/m^2 module
Silicon purification	1800	1800	MJ/m^2 module
Crystallization & contouring	750	2300	MJ/m^2 module
Wafering	250	250	MJ/m^2 module
Cell processing	600	550	MJ/m^2 module
Module assembly	350	350	MJ/m^2 module
Total module (frameless)	4200	5700	MJ/m^2 module
Total module (frameless)	*32*	*41*	*MJ/Wp*

Regarding the energy requirements for the remainder of the solar cell production process, there is less controversy. After reviewing all available data from previous studies, my best estimate is that about 600 MJ/m^2 is added in cell processing‡ and some 350 MJ/m^2 during module assembly, assuming standard screen printing technology and glass/tedlar encapsulation. We then obtain total energy requirements for mc-Si and sc-Si modules of 4200 and 5700 MJ/m^2, respectively. Note that I consider frameless modules here; frame energy requirements will be discussed later in conjunction with BOS components. Because of

† So 1 MJ of primary energy can supply 0·097 kWh of electrical energy.
‡ Although energy requirements for cell processing are assumed equal for mc-Si and sc-Si on cell area basis, they are slightly different when presented on module area basis because the packing factors are different (0·82 and 0·87, respectively).

the allocation problem and other uncertainties mentioned above, the range of uncertainty in the final values is unfortunately rather high, probably around 40%. Furthermore, I can remark that only a few percent of the total energy requirement is used in a non-electrical form.

If we now assume module efficiencies of 13% and 14% (cell eff. 15% and 17%, respectively) for mc-Si and sc-Si modules respectively we can evaluate the energy requirements on a Wp basis (last row of Table I). We see that despite their higher efficiency, sc-Si modules are at a slight disadvantage compared with mc-Si modules. This is mainly due to the higher energy consumption for the sc-Si crystallization process.

Future technology

For a view on the longer-term potential (up to 2010), we have to look first at the major determinants for the energy requirement of c-Si modules.

My analysis above shows that these determinants are: (1) the energy consumption for Si purification and (2) the silicon content of the cells. For sc-Si cells the Czochralsky process is also a large contributor. So it will be clear that future improvements in wafer production technology may bring down the energy requirements of Si modules. Technologies like EFG or other methods which eliminate the losses from wafer sawing could have significant advantages. A major factor determining future energy requirements will be the way silicon feedstock is produced. In the near future (1–2 years), the supply of off-spec silicon will probably become insufficient to meet the demands from the PV industry so that other feedstock sources will have to be drawn upon. Because standard electronic-grade silicon is too expensive for PV applications, dedicated silicon purification routes will be needed. The introduction of such a solar-grade silicon process might reduce the energy requirement of purified silicon§ to 600–1100 MJ/kg.[2,10] Based on a number of independently performed studies[5,9,10] I expect that future mc-Si production technology may achieve a reduction in energy requirements to around 2600 MJ/m^2, assuming innovations like a dedicated silicon feedstock production for PV applications (solar grade or advanced Siemens) delivering material with an energy requirement of about 1000 MJ/kg, and furthermore improved casting methods (e.g. electromagnetic casting) and reduced silicon requirements per m^2 wafer. This kind of technology will probably become available in the next 10 years. For single-crystalline silicon modules a total energy requirement around 3200 MJ/m^2 may be achieved with similar technology improvements.[9] If we further assume future module efficiencies of 15% and 16% respectively (cf. Table II), we obtain energy requirements per Wp of 17 MJ and 20 MJ for mc-Si and sc-Si technology around 2010.

Table II. Assumptions for module efficiencies for different cell technologies

	Present	2010	2020
mc-Si	13	15	17
sc-Si	14	16	18
Thin film	7	10	15

When looking at the situation beyond 2010, then it seems difficult to achieve major energy reductions for wafer-based siliciom technology. An energy-efficiency improvement in the production process of 1% per year, as is often found for established production technologies,[13] seems a reasonable assumption. Further improvements in the energy requirement per Wp will have to be achieved by improving module efficiency (while not increasing energy consumption). If we assume that in 2020 the efficiency of commercial mc-Si cells has been increased to 20% (the current record for small-area mc-Si cells), then module efficiency would be about 17% and thus the lowest conceivable energy requirement for Si wafer technology might be 13 MJ/Wp. If we consider crystalline silicon *film* technology, we may expect an even

§ Under my assumptions 2 kg of Si feedstock is needed per m^2 module.

more favorable energy figure because of the lower silicon requirements. However, this will depend also on the energy input for the (ceramic) substrates, about which no data are available at this moment.

THIN FILM MODULES

Present technology

Concerning thin film modules, most published studies on energy requirements deal with amorphous silicon technology[1–3,5,7,10] and two with electrodeposited CdTe modules.[4,5] Although estimates for the total energy requirement of a frameless a-Si module range from 710 to 1980 MJ/m^2, many of the differences can be explained by the choice of substrates and/or encapsulation materials, and the consideration or not of the energy requirement for manufacturing the production equipment. A remaining factor of uncertainty, which cannot be explained so easily, is the overhead energy use for functions like lighting, climatization and environmental control (estimated range 80–800 MJ/m^2). On the basis of a careful comparison and analysis of published energy estimates,[12] I arrive at the best estimate for energy requirements of an a-Si thin film module, as given in Table III.

Table III. Contributions to the energy requirement of an a-Si thin film module for present-day production technology (glass–glass encapsulation; in MJ of primary energy)

	Energy requirement (MJ/m^2 module)	Share (%)
Cell material	50	4
Substrate + encapsulation material	350	29
Cell/module processing	400	33
Overhead operations	250	21
Equipment manufacturing	150	13
Total module (frameless)	1200	100
Total module (frameless) @ 70 Wp/m^2	*17 MJ/Wp*	

From Table III we can see that the semiconductor and contact materials constituting the actual solar cell contribute only very little to the module's energy requirement. However, application of processes with low deposition efficiencies ($<10\%$) or high purity requirements will drive up this value. The materials used for the substrate and encapsulation constitute about 1/3 of the total energy input, assuming a glass/glass encapsulation. A polymer back cover will reduce the energy requirement by some 150 MJ/m^2. On the other hand, if not one of the glass sheets of the encapsulation is used as substrate, but an extra substrate layer is added, this will increase the energy requirement considerably (e.g. by 150 MJ/m^2 in case of stainless steel foil).

The actual cell and module processing, comprising contact deposition, active layer deposition, laser scribing and lamination, contributes roughly another 1/3 to the module's energy requirement. Significant variations of up to 25% may be found between different production plants, depending on the deposition technology and the processing times.

For other thin film technologies, most of the energy contributions will be about the same as for a-Si, except with regard to the processing energy. Electrodeposited CdTe, for example, is estimated to require some 200 Mj/m^2 less during processing. On the other hand, a slightly higher overhead energy use is expected (for environmental control). Also, a polymer back cover would be less desirable for CdTe modules.[5] Although no energy studies for CIS were available, we might expect the processing energy for co-deposited CIS modules to be in the same range or possibly higher than for a-Si.

Assuming a 7% module efficiency, we obtain an estimated energy requirement of 17 MJ/Wp for a present-day a-Si module, which is considerably lower than the values found for c-Si technology. However, as we will see below, high BOS energy requirements may partly cancel out this advantage.

Future technology

Because the encapsulation materials and the processing are the main contributors to the energy input, the prospects for future reduction of the energy requirement are less clearly identifiable as was the case with c-Si technology. A modest reduction, in the range of 10–20%, may be expected in the production of glass and other encapsulation materials. It is not clear whether displacement of the glass cover by a transparent polymer will lead to a lower energy requirement. The trend towards thinner layers will probably reduce processing time, which in turn can lead to a reduction in the processing energy and in the energy for requirement manufacturing. An increase of production scale can contribute to lower processing energy, lower equipment energy and lower overhead energy. By these improvements, I expect the energy requirement of thin film modules to decrease by some 30%, to 900 MJ/m^2, in the next 10 years.[5,10] If the module efficiency can be increased to 10% concurrently, the energy requirement on a Wp basis may reach the 9 MJ level.

If we try to make projections beyond 2010, we can note that further reductions in the energy requirement below 900 MJ/m^2 do not seem very probable. Like before, we may suppose a generic 1% per year energy-efficiency improvement in the production process. Only if completely novel substrates and cell encapsulation techniques are developed which require much less (energy-intensive) material we may obtain a more significant improvement. Up to now alternative substrates like stainless steel or synthetic foils have not proven to be more energy-efficient than conventional glass substrates.[7,10,12] Furthermore new methods for cell deposition which require less processing and less overhead operations might help to reduce the energy input of thin-film modules. Of course module efficiency increases will directly improve the energy input per Wp (if energy input per m^2 is constant). In this respect, significant variations may occur between different types of thin films. Moreover, significant efficiency improvements for thin film technology may be achievable. For instance, if we assume 15% module efficiency for 2020, the energy requirement per Wp may come down to 5–6 MJ.

BALANCE-OF-SYSTEM COMPONENTS AND MODULE FRAMES

Like in economic analyses of PV systems, the Balance-of-System cannot be neglected in energy analyses. Therefore, I will shortly analyze the impacts of array supports and module frames. The results of a detailed analysis of the primary energy content of present applications of PV systems in buildings have been published recently by Frankl.[9] This study has considered several applications on rooftops and building facades, as well as a 3·3 MWp ground-mounted system in Serre, Italy. The BOS materials for the Serre plant required an energy input of about 1800 MJ. Note that this plant is very much a state-of-the-art design requiring much less BOS material than similar European plants.[9] Therefore it seems reasonable to take this figure as representative for future plants of this type, except for a 1% yearly improvement in the energy efficiency of the production processes.

For existing rooftop systems, Frankl found an energy requirement of 700 MJ/m^2 for the array supports.[9] Because the analyzed systems of this type showed considerable scope for improvement, through, for example, reduced material requirements and increased use of secondary aluminium, Frankl asserts that future rooftop systems will have a energy requirement for the support structures of around 500 MJ/m^2. The additional contribution from the inverter to energy requirements in rooftop systems is small (cf. Table IV), and cabling is not considered here, but presumably it is small too.

Finally, it is worth noticing the significant contribution of module frames in present-day systems. The wide range of energy content in past studies is due to large differences in the amount of aluminium

Table IV. Energy requirements for balance-of-system components and module frames

	Unit	Present	2010	2020
Module frame (Al)	MJ/m^2	500	0	0
Array support—central plant	MJ/m^2	1800	1700	1500
Array support—roof integrated	MJ/m^2	700	500	450
Inverter (3 kW)	MJ/W	1	0·9	0·8

(or steel) used for the frames. Here I assumed 2·5 kg Al to be used per m^2 module, requiring 500 MJ of energy input. In any case, I assume PV modules to be frameless in all future applications.

ENERGY PAY-BACK TIME

Given the results of the energy analyses above, we can now calculate the energy pay-back time (EPBT) of a PV system as the ratio of the total energy input during the system life cycle and the yearly energy generation during system operation. This EPBT value is also a good indicator of the CO_2 mitigation potential because generally more than 90% of the CO_2 emissions during the PV system life cycle are caused by energy use.¶[8] Figure 1 shows the EPBT for two types of grid-connected PV systems, namely a rooftop system and a large, ground-mounted system, with two different module technologies. The systems are all assumed to receive an irradiation of 1700 $kWh/m^2/yr$ and to have a performance ratio of 0·75. As

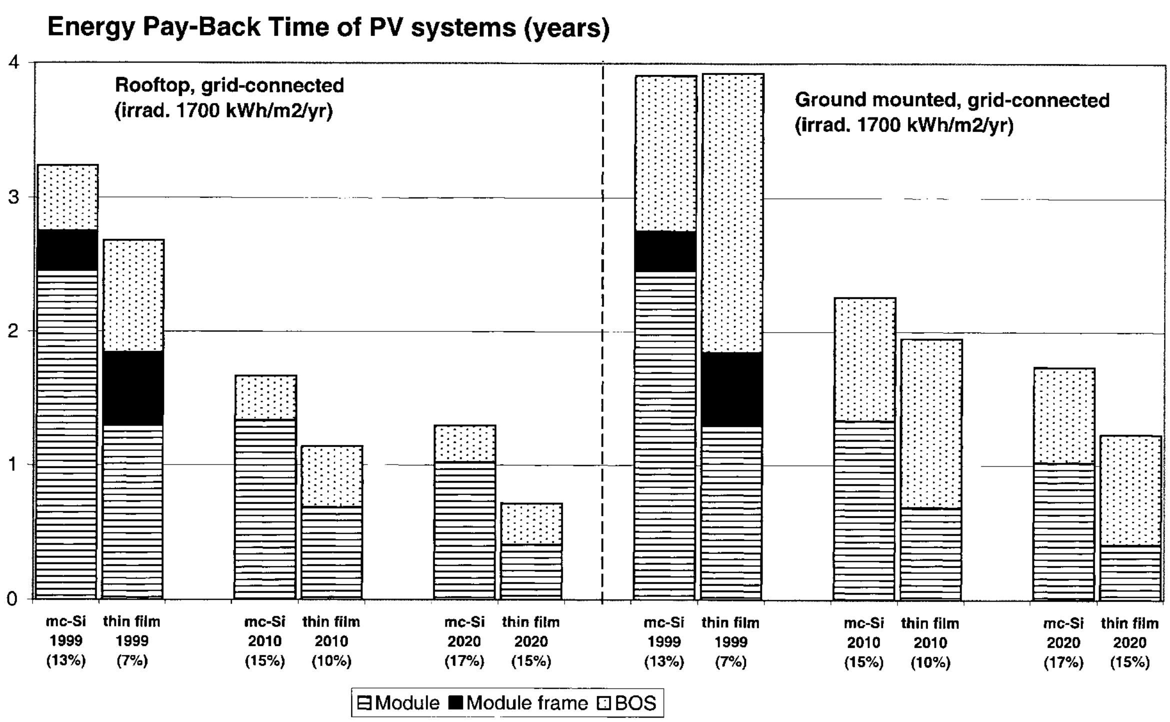

Figure 1. The energy pay-back time (in years) for two representative PV applications, both for present-day and for future (2010 and 2020) technology. The figures in parentheses denote the assumed module efficiencies for each option. Note that actual pay-back times will vary with irradiation and system performance

¶ Other CO_2 emissions stem from material conversion processes, like silica reduction.

before, the conversion efficiency of the conventional electricity supply system is set at 35%. For simplicity, I take this value as fixed for future years too.

We see that the EPBT for present-day systems is around 3–4 years, and that it may decline to 1–2 years in the future. Also note that the contribution from the BOS and frame is already significant today, especially for the ground-mounted systems. Regarding thin film technology, we can see that due to their lower efficiency, the energetic advantages of present a-Si modules are largely cancelled by the higher BOS energy. Future, more efficient, thin film modules, however, may show a small advantage over c-Si technology.

CO_2 EMISSIONS

The CO_2 emissions due to the production of the PV system can be obtained by multiplying all energy and material inputs with their corresponding CO_2 emission factors.[15] Note, however, that the CO_2 emission factor for electrical energy is highly dependent on the fuel mix of the considered utility system. In this analysis I will assume the fuel mix of continental Western Europe (UCPTE region), where about 50% of the electricity is produced by nuclear and hydro-electric plants, as well as 20% by coal-, 10% by oil-, and 10% by gas-fired plants. For this utility system the CO_2-emission factor is presently about 0·57 kg per kWh produced electricity (~0·055 kg/MJ_{prim}).[16] Although the fuel mix is likely to change in the future, the CO_2 emission factor will probably change by less than 7% up to 2010.[8] For simplicity I will therefore take this factor as constant.

In Figure 2 are displayed the CO_2 emissions per kWh of supplied electricity (assuming a 30 year life time) for grid-connected rooftop PV systems. For comparison, a number of conventional power

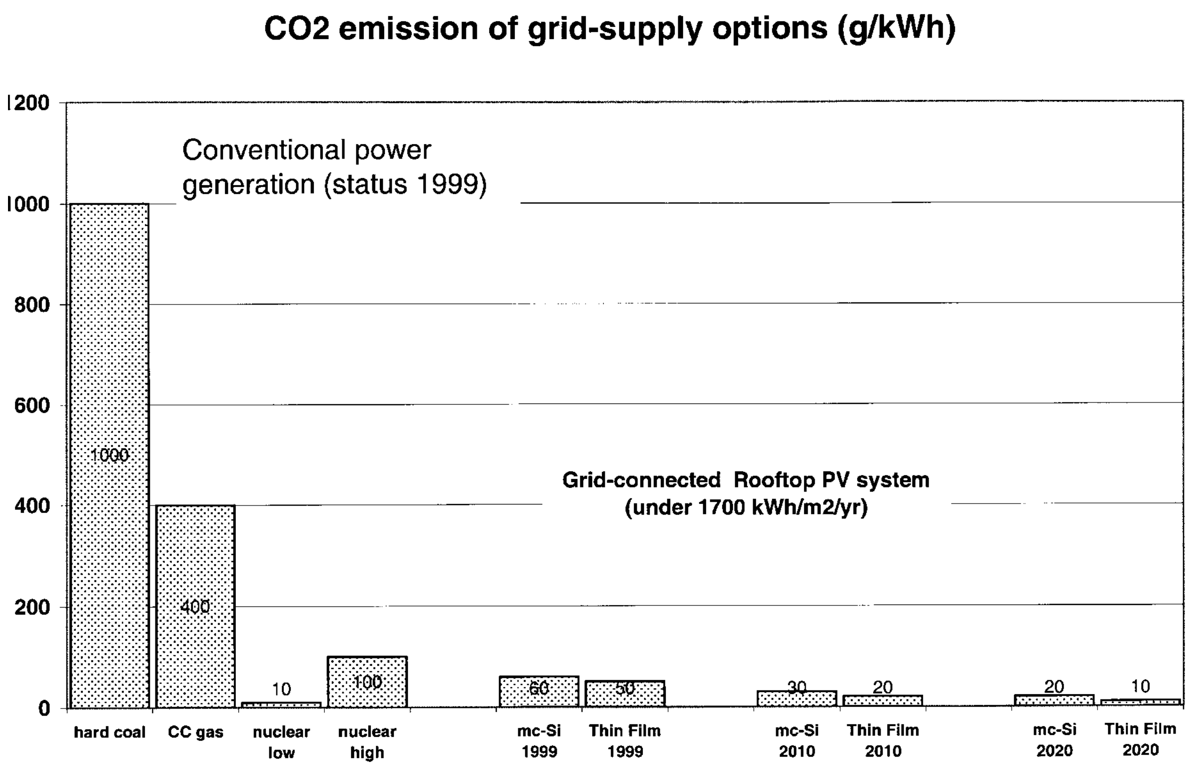

Figure 2. CO_2 emission for grid-connected rooftop PV systems and for conventional power systems (coal, gas, nuclear-low estimates from Ref. 16, nuclear-high from Ref. 17). Note that actual CO_2 emissions for PV will vary with irradiation and system performance

generation technologies are also depicted (status 1999). The results show that, with the present technology, the CO_2 emissions from PV are in the range of 50–60 g/kWh, which is considerably lower than the CO_2 emissions for fossil-fuel plants. With improving technology, PV-related CO_2 emissions may become even lower, around 20–30 g/kWh in the near future, or even 10–20 g/kWh in the longer term. If we consider the limited PV capacity that can realistically be installed up to 2010, in combination with the non-zero CO_2 emissions during system production, we should recognize that the contribution of PV systems to CO_2 mitigation will be limited in the next decade. On the other hand, my analysis also shows that PV technology does certainly offer a large potential for CO_2 mitigation when looking beyond 2010.

CONCLUSIONS

I have reviewed energy requirements for c-Si and thin film PV modules and BOS components. For a grid-connected system under 1700 kWh/m^2/yr irradiation, the energy pay-back time is presently 2·5–3 years for rooftop systems and 3–4 years for large, ground-mounted systems. The share of BOS components in this figure is quite significant. In the coming 10 years, the energy pay-back times of PV rooftop systems may decrease to less than 2 years, if certain technology improvements are realized. For c-Si modules, one of the requirements would be a dedicated silicon purification process with substantially lower energy consumption, while for thin film technology, mainly an improved module efficiency would be necessary. CO_2 emissions from rooftop PV systems were calculated assuming that the PV production facility is located in Western Europe. It was found that the specific CO_2 emission could go down from the present value of 50–60 g/kWh, to 20–30 g/kWh in the next 10 years and perhaps even lower after 2010.

This analysis shows that, although the contribution of PV systems to CO_2 mitigation will probably be limited in the next decade, PV technology does certainly offer a large potential for CO_2 mitigation when looking beyond 2010.

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