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Energy storage possibility for an Energy Community

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Abstract. Pilisszentlászló is a settlement of 1000 inhabitants in the Budapest agglomeration, in a hilly environment in Hungary. The municipality is committed to sustainability, including energy management. The village intends to establish an Energy Community, installing as many local small Photo Voltaic generation units as possible. Increasing the security of energy availability and energy storage were considered viable options. In this paper we investigate three possible and sustainable energy storage methods. We have also assessed the solutions by the life cycle analysis (LCA) approach, which examines the overall environmental impact instead of short-term financial aspects.
We investigated the kinetic "energy train", the microPSP (Pumped Storage Plant) and the battery storage solutions. Conceptually, we also dealt with rolling stock and track for the “energy train” solution. Specific calculations were made with idealized storage units regarding the maximum amount of energy that can be stored. For certain spring/summer/autumn consumption and PV production scenarios, the optimal energy storage capacities were determined. Finally, we compared the three energy storage options that seem feasible in the village of Pilisszentlászló. Despite all our expectations, and the initial preference of the local community, our current best recommendation is the battery storage. Further studies may lead to other, improved solutions.

Key words. Energy community, energy storage, kinetic energy train, microPumped Storage Plant.

1. Introduction

The small village Pilisszentlászló is hidden in a small basin, at an altitude of 350-400 m surrounded by forests in the heart of the Visegrád Mountains, consisting of volcanic rock and andesite. The village is located in Pest county, 8 kms from Szentendre and 13 kms from Visegrád. The entire inner and outer area of the village is part of the Danube-Ipoly National Park, the Pilis Biosphere Reserve. It can be of great value, duty and limitation. Today's inhabitants of the village, just like their ancestors, consider it important to preserve the character and natural environment of the village [7].
The municipality is committed to sustainability and is keen on exploring new options for efficient energy management, as well. Various energy storage options have been assessed and the concept of creating an energy community has also been studied. In the following sections we will briefly describe the theory behind the examined storage systems and mention some related initiatives.

2. Options examined for energy storage

A. Some basic principles of energy balance/storage

In all cases, there must be a balance between electricity production and consumption, both in DC and AC networks. The surplus energy produced raises the need for energy storage. Direct storage of electricity can be limited, but rapidly mobilizable electricity generation capabilities can be created based on magnetic, gravity or kinetic energy or chemical storage. The energy storage tasks include:

- balancing peak-valley consumption
- storing weather-dependent production
- balancing weather-dependent production
- improving energy quality
- providing emergency power source, etc.

The most important parameters of storage are:

- amount of stored energy [kWh, MWh, (kJ, MJ)]
- charge/discharge power [W, kW, MW]
- mass, volume, number of charging cycles, operating cost, investment cost, efficiency, lifetime, temperature conditions, etc.

Energy storage units are theoretically not able to return all the stored energy, their efficiency is different, which also increases the cost of storage. One of their important parameters is the service life, which is characterized, among other things, by the number of charge-discharge cycles.
A typical form of the mechanical energy storage is a lifted mass or water pumped up against the gravitational force. The energy can be recuperated by lowering the weight or letting the water down from the mountain.

B. Option 1.: The Advanced Rail Energy Storage (ARES)

The ARES technology uses rail cars that essentially transport extremely heavy concrete blocks on rails up and down a hill [1]. All of this is positioned against Elon Musk's electrochemical energy storage, that is, environmentally not really friendly [3]. The project is now in demonstrational phase in the USA before the large- scale roll-out.

- a small current collector sample has been prepared
- a demo is planned for the gravel mine, 80 m elevation difference and approx. 260 m length, demo photo has already been taken
- production of equipment has begun
- with a total power capacity of 50 MW, and total energy capacity of 12.5 MWh (equivalent to 25 train wagons/concrete blocks in parallel)
- there are several major plans, including a height difference of 640 m, a length of 9.2 km, with many 300-tonne train sets

The Pahrump ARES Initial Unit is designed for 5 MW and per 1.25 MWh storage. With a planned efficiency of 80%, this means 25 concrete blocks (wagons) that go up / down for about 15 minutes [4]. The Pahrump demonstration plans to operate with 210 wagons, 75,000 tons, 10 rail systems [5]. Doubts about this solution:

- A "mass train" is in motion for about 1.5 minutes
- the system "fills" up in about 15 minutes of the daily power curve, meaning it cannot absorb any more energy - so it is only designed for very short periods of balancing
- the amount of stored energy is not very large
- has a significant noise effect
- requires maintenance (lubrication, replacement)

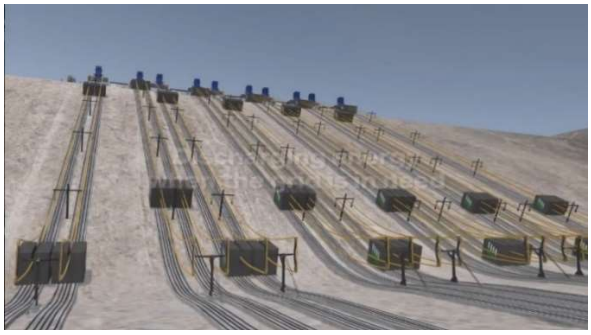

Fig. 1. The ARES energy train vision, 2021 [2]

Advantages that can be mentioned:

- it can store (little energy) for longer periods of time without discharge – although this is not beneficial in terms of cost recovery
- in its mass contains traditional, non-aggressive materials (iron, concrete, copper)

While the completed small sample extracts the electricity generated on the wagon with current collecting pantographs, the large system without motors is dragged by a chain driven by a motor/generator that drives it.

Table I. – Main data of Pahrump train with 100% efficiency

Pahrump demo train	**1 carriage**	**25 carriages**	**10 x 25 pcs carriages**	**unit**
height difference	80	80	80	m
mass	300	7500	75000	t
gravitational energy	235,4	5886	58860	MJ
gravitational energy	65,4	1635	16350	kWh
trail length	0,268	0,268	0,268	km
speed	20	20	20	km/h
charge duration time	0,0134	0,33	0,33	h
power	4,88	4,95	49,55	MW

C. Option 2.: The micro Pumped Storage Plant (PSP)

There are more than 500 pumped storage power plants in the world, dozens of which have a capacity of more than 1000 MW – so the technology isn't new. In Hungary in the early 2010s an idea had already emerged to store the electricity generated by the wind power plant "at the wrong time" in a small-scale PSP. The reason to seek a solution was that the number of wind farms that could be connected to the grid was temporarily limited. Its advantage could be that it works in a natural environment, distributed source, on a small scale, instead of several million m^3 works with 10-20 thousand m^3 of water.

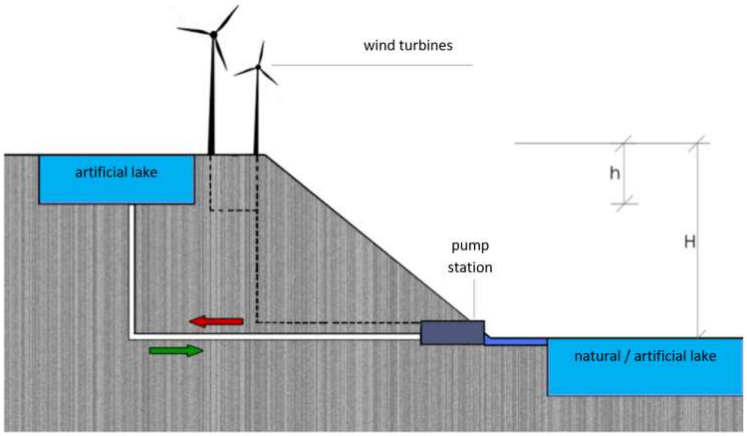

Fig. 2. MicroPSP concept [6]

The country's first experimental microPSP (nanoPSP) was established at Óbuda University back in 2010. Although it is very small, all the necessary parameters can be calculated and measured on it. The model can be used to demonstrate the operation of hydroelectric power plants, hydroelectric turbines and the principle of pumped storage – reservoir power plants (PSP). The microPSP equipment formed from LPH00052 type turbine works with a water niveau difference of approx. 15 m, 1000 l water, 5 l/s water flow, max. 300 W power, Pelton turbine.
The water drain pipe installed with alpine technology runs down from the top of a building of the university on the outside to the turbine house in the courtyard. It contains the lower reservoir tank (half recessed into the ground), solenoid, pump, generator. From here the wires to the laboratory remote control panel start.
Until today unfortunately, no "human-scale" version of this has been implemented.

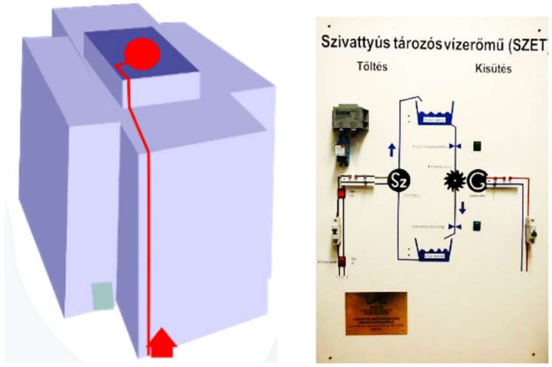

Fig. 3. NanoPSP at Óbuda University

Fig. 4. Pelton turbine of NanoPSP at Óbuda University

D. Option 3.: Use of battery for storage

Nowadays the electrochemical battery storages are off-the-shelf products. There are several scalable mobile and fixed technologies. Compared to the previous options its dimensions are really compact. As drawbacks can be mentioned the life-time of the battery solutions that are about 10 years. The battery doesn't seem to be an environment friendly approach but we keep it in mind as references base.

3. Exploring the suitability of options at the location

A. Possible location

In the following, we describe how the energy train could be located with respect to the terrain. The approach is theoretical, we do not consider environmental, licensing, economic, etc. aspects.

Pilisszentlászló is surrounded by several peaks (590 m, 549 m, 567 m and 510 m). The environment is articulated and diverse. It is physically possible to construct a track with a suitable incline and "hide" it at the same time.

The valley sloping west between Rózsa hill (549 m) and Szentlászló hill (590 m) may be suitable for placement. Its base point can be the valley of Apátkút (350 m), while its highest point is the 540 m saddle. Both points are easily accessible by vehicles, they are relatively covered, the landscape is not disturbed by the facility, the slope has a uniform rise. 4 possible trail versions have been investigated.

Fig. 5. The proposed site for the energy train

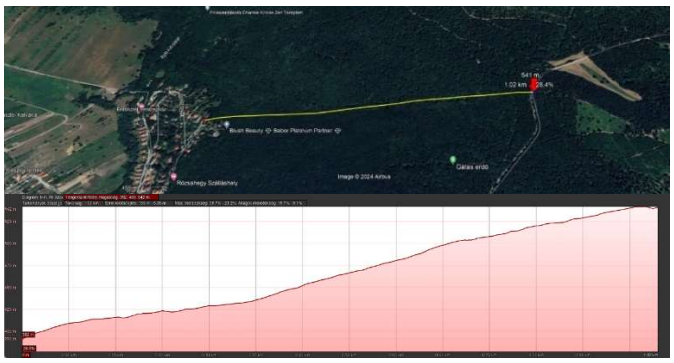

Fig. 6. The proposed location for the energy train (Google Earth)

Table II. – Trail variations on the hill side

Trail version	length [m]	height [m]	max steepness %	average rise %
I. 3 breakpoints	1263	196	43	16
II. 2 breakpoints	1245	191	42	16
III. 1 breakpoint	1197	185	48	16
IV. without breakpoint	1004	150	38	15

Fig. 7. The possible location for upper station

B. Possible rolling carriages

According to the primary ideas, standardized railway or railway-type carriages could be run on the track. The advantage of this is that the rolling stock is available for purchase (possibly used, second hand). The traction suspension has to be solved, but it can be put into operation on suitable near-standard tracks without any special development. In addition to the above, within the design limit, the load of each wagon can be adjusted with ballast load.

C. Possible track

The track of the "Energy Railway" should be implemented with a solution close to a standard, partly because of the possibility of procurement and partly because of the available calculations. The technology of railway tracks was developed and standardized in the last century and a half. The development had its heyday a century ago, but of course it has been unbroken ever since. For the present application the basics were known already in the 19th century. Important parameters at all times:

- radius of curvature – a straight implementation without a breakpoint is advisable
- increase/steepness – given > 16%
- wagon load capacity – narrow gauge railway 760 mm < 10 t/wagon < main railway 1430 mm gauge
- reactive load ratio – currently indifferent because the weight of the car is involved in energy storage
- rail size – together with the substructure, the load capacity is determined, measured in kg/m

When choosing a possible rail type, it is worth considering the track of a recently renovated Forest Railway in Hungary. The 7 km section of the 20.8 km long Szob–Nagybörzsöny 760 mm gauge single-track forest railway was renovated in 2006 [8]. The track consists mainly of 23.6 kg/m rails, the track speed is 40 and 35 km/h, and the permitted axle load is 8 t. Stage I was built with an ideal rail system of 48 kg/m [10].
In summary, the narrow-gauge rail system can be loaded up to approximately 10 tons, above which standard gauge must be used. It should also be mentioned that on normal mixed-use main lines the elevation is usually no higher than 7 thousandths (7 ‰), on branch lines you can find steeper ones. In the present case, nearly 16 %, i.e. 160 per thousandth (160 ‰), is more than an order of magnitude higher. That is why the track cannot be made with a conventional substructure due to the downward migration of crushed stone. The special concrete foundation could raise the cost extremely.

Fig. 8. A possible train track (2006) [11]

D. Rough energy calculation

Below we have also calculated the amount of gravity energy that can be stored and an approximate power value – for three wagon alternatives, without taking into account losses. A slightly larger than possible elevation difference of 200 m and a track length of 1.2 km were assumed here.
For a load of 25 tons, with a power of approx. 100 kW and a journey time of 8 minutes, the maximum energy that can theoretically be stored isn't more than 13.6 kWh. Regarding the available energy densities this energy can be stored in a 0,1 m^3 battery pack.

Table III. – Energy train's energy calculations for Pilisszentlászló

	35 t carriage	**25 t carriage**	**small gauge carriage**	**unit**
height difference	200	200	200	m
mass	35	25	6	t
gravitational energy	68,670	49,050	11,772	MJ
gravitational energy	19,1	13,6	3,3	kWh
trail length	1,2	1,2	1,2	km
speed	10	10	10	km/h
travelling time	0,12	0,12	0,12	h
power	0,16	0,11	0,03	MW

4. Exploring options to establish an energy community with energy storage facility

Although the legal framework has not yet clarified all the details, the European trend is definitely that energy communities can be created to promote self-sufficiency, greater energy security and reduce external dependence. The first energy communities are likely to be created with significant municipal involvement. Energy communities are inclusive and will typically operate dynamically (with continuous entry and exit) with the participation of municipal institutions (5-10) and residential consumers (50-100) (not only with a fixed circle of founders).

In view of the fact that no renewable production is able to compete with the utility service price currently provided to the public in Hungary (approximately 6 €c energy + 6 €c transmission cost/kWh), it is advisable to establish the energy community in the first step with the involvement of the public institutions of the settlement. In addition to the energy community, a 500 kVA solar park (or about 100 kVA solar capacity placed on the roof of buildings) and an energy storage facility can be built. The energy storage can be "freely" scaled in the case of battery version, while in the case of mechanical energy storage, based on the calculations presented earlier, the maximum amount of energy that can theoretically be stored is 13.6 kWh for a load of 25 tons, with a power of about 100 kW and a travel time (charge in/out) of 7 minutes.

A. Scheme of the public energy community

The individual members of the energy community are connected to one another on the local public low-voltage network (taking these into account in the case of several transformer districts). The 500 kVA solar park feeds directly to medium voltage, so the connection is also realized via a transformer ratio.

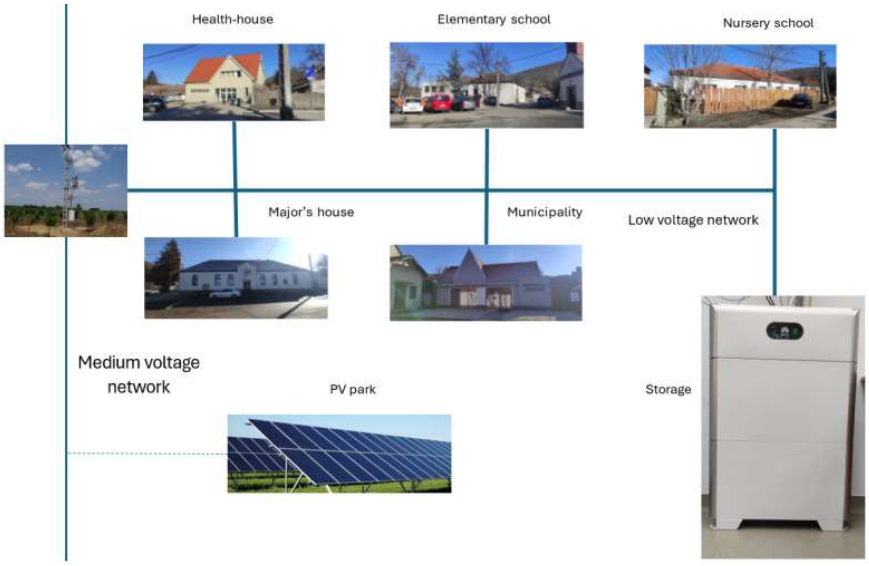

Fig. 9. The public energy community

B. Operation of the public energy community

Even with such a small energy community, there are several ways to operate the system. If the larger 500 kVA solar park is built, it can also produce electricity directly for the electricity market by market price or for feed-in tariff. Experience shows that this mode offers a quick return on investment, but requires a professional operator e.g. for scheduling and risk management. If only the smaller 100 kVA generation system will supply energy, then the sale of energy will offer a very long return on investment under the current gross settlement rules. In this case, the aim may be to replace self-consumption. It is also possible to combine the two modes, but this will require more sophisticated operation.

Depending on the model, the energy storage unit can perform several tasks. It is possible to concentrate on supplying institutions, but in principle it can provide a so-called flexibility service to the local distributor, or it can also offer system-level regulation to the transmission system operator (MAVIR ZRt.) The requirements for system-wide services are very strict, which a mechanical energy storage unit is unlikely to be able to meet. Another obstacle may be that the settlement is connected to the electricity grid only through a medium-voltage line.

Under the boundary conditions outlined above, it is currently possible to implement the local storage-local supply option, so we will examine this option in detail below. Now we briefly present the general calculation methodology with which a complex system can be optimized.

C. Estimation of the required storage capacity

The following steps must be taken when planning a new storage:

- analysis of load/generation curves

- calculation of the storage capacity
- definition of the storage technology

Energy storage devices basically consist of small units, the appropriate number of them can be installed in proportion to the amount of energy stored. In the case of batteries, the number of cells, in the case of an energy train, the number of wagons, and in the case of a pumped storage plant, the amount of water moved is proportional to the energy that can be stored. Since any storage unit of the desired size can be built, the final size is determined not by the possibilities, but by the storage needs. When determining the amount of renewable PV energy production, we start from how much the selected municipal consumers consume. For this, the amount of PV capacity required to be installed can be well determined. In Hungary, 1 kWp PV capacity generates about 1200 kWh of electricity per year. From these data it is possible to calculate the required peak power. When determining the amount of energy to be stored, we take into account the daily excess power. Unconsumed energy is stored daily and used later in the day.

Sizing is performed in the local supply – local storage operation mode. As a boundary condition, we stipulate that with the help of the storage facility we can operate the public institutions listed above at least until spring (from 1st April) to autumn (1st September), usually without purchasing external energy. This means that even in the least sunny period, solar panels must store at least enough energy in the battery to provide consumers with security from sunset to the next sunrise. Of course, the daily fluctuation of consumption and production must also be considered. When calculating both consumption and production, distribution profiles (general business consumer, solar panel generation) were taken into account. It was assumed that the work schedule in public buildings is uniform.

Maximum load considered: 88 kW, feed: from PV park 500 kW + 100 kW solar panels on roofs. The estimation does not take into account cloudy days that may be completely without sunshine. In spring-autumn it tends to undersize, in summer it tends to oversize.

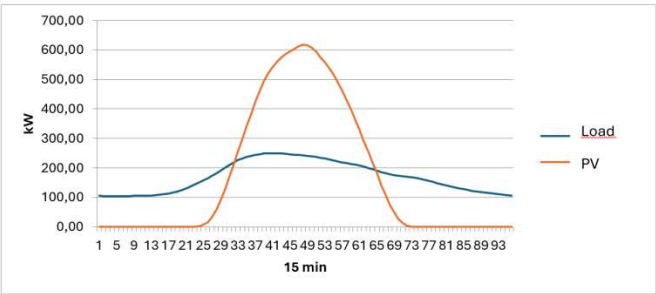

Fig. 10. Battery sizing

If it were possible to sell the surplus summer production rationally, oversizing would not be a problem, moreover, it would be advisable to install more capacity than is due to the above conditions. However, domestic conditions do not allow this. The ratio of production and consumption in quarter-hour resolution, 100 kW photovoltaic.

Considering the boundary conditions, the result of the storage sizing is, we have to apply at least:

in case of 300 kW_p PV production capacity 642 kWh storage with 88 kW power is recommended

In the constructed system, given the degradation of individual elements over the years, these values should be oversized by at least 20 %.

5. Comparison of options

The impact of individual processes, facilities, products is examined by several methodologies. MIPS analyses the amount of material used, ecological footprint analyses sustainability, and life cycle analysis (LCA) analyses environmental emissions. The life cycle analysis methodology is an elaborate, sophisticated technique with which we can compare the effects of e.g. energy storage installations. By default, the life cycle analysis is performed for the entire cycle (establishment + use + dismantling). In the present case, as an illustration, we give the informative result only for the largest component of the installation and we calculated 50 years of operation.
Environmental impact data can be obtained from different public data sources, but the more sophisticated the methodology, the more, specific results can be found, with a very large standard deviation (e.g. 50-500 MJ/kWh for battery production; 10-25 MJ/kg for iron production; etc.).
The three energy storage devices examined

- 'Energy train' is a track about 1 km long with 25 carriages and a significant marshalling yard where the wagons can be sorted. Here we calculated 600 t of iron – until we look at the emissions of concrete, electric motors, etc.
- MicroPSP solution 2 x 1000 m^3 underground concrete tank, 0.5 m wall thickness, 20 x 20 x 3 m. Here, concrete is calculated as an environmental impact, while microturbines and pipelines are not examined.
- Finally, we look at commercially available 5 kWh lithium battery packs, not counting the dedicated building.

Table IV. – Comparison of Storage Options

category	***best option***	***option 1. Energy train***	***option 2. microPSP***	***option 3. battery***
Storage principle	1-2-3	mechanical gravity	mechanical gravity	electrochemical
realistically feasible	1-2-3	25 x 25 t carriage	1000 m^3	100 x 5 kWh
storable energy at 100 % efficiency	1-2-3	440 kWh	550 kWh	500 kWh
Typical performance	1-2-3	100 kW	100 kW	100 kW
Placement nature	3	forest arrows, 10 m wide, lower to upper marshalling station	underground tanks and pipeline	ventilated room
physical space reservation	3	3 ha	0,5 ha	50 m^2
Landscape integration	3	large surface transformation	blending into a environment	a small building in the settlement
Typical cons	2	deforestation, noise pollution	in case of open lake large land occupation	environmental pollution, hazardous substances
typically required	3	Railway safety, forestry, National park / Natura 2000	National Park / Natura 2000	Retail available, no permit required, recommended fire protection
lifetime	2	30 years	50 years	10 years
Approximate investment rt./50 years	2	1,6 x 4 MEUR	3 MEUR	5 x 0,1 MEUR
environmental impact	2	traditional, local environmental impact, few hazardous substances	minimal environmental impact, no hazardous substances	hazardous electrochemical - closed technology
facility's largest LCA element	-	600 t iron	1000 m3 concrete	battery pack
LCA installation energy load	2	13 200 – 20 000 GJ	1000 GJ - 1000 GJ	500 - 2500 GJ [13]
LCA installation CO_2 load	3	600 t – 1000 t [14]	1200 t - 1200 t [15]	35 t - 175 t [16]

6. Conclusion

We investigated possible energy storage options for a currently forming energy community. In spite of the expectations the 'energy train' storage isn't the suitable variant. Based on the calculations, battery storage is the currently recommended option.

PSP is indeed a viable way for large-scale energy storage – nothing else has been invented yet. Unfortunately, it has to be admitted that the "Energy Train" solution, despite all its clarity, simply can store little energy. And even its simplicity cannot be shown compared to the battery solution. From an external expert's point of view, we highly recommend batteries for small-scale storage, and for slightly larger scales we recommend the closed microPSP solution.

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