Renewable Energy Production and Storage Options and their Economic Impacts in Hungary

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Summary
The study reviews the most relevant renewable energy sources, focusing on their possible application, economic aspects and potential for Hungary. Feasibility and economic analysis is made for plant-sized photovoltaic devices, wind turbines, geothermal power plants and biomass power plants. It was found that solar cell technology has the highest revenue. However, its further spread is limited by several factors, such as the reactive effect on the energy market, grid problems, and weather dependency. A possible solution for these problems is to use energy storage systems. For the sake of simplicity, only the economically mature technologies are investigated, including pumped hydroelectric storage, batteries, green hydrogen production, and thermal energy storage connected to a heat power plant. The payback calculations require a simple simulation algorithm to calculate the revenue using Hungarian data. With the simulation, the most important economic indicators are estimated. As a result of these calculations, we suggest a pumped hydroelectric storage to be built, or if it is impossible, the Paks 2 nuclear plant should be completed with a thermal energy storage facility.

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Carbon-neutral energy production is one of the major challenges of the present and the next decade. This is reflected in Directive 2018/2001 of the European Parliament and of the Council (Council, 2018), according to which 32% of total EU energy consumption must stem from renewable energy sources and, together with increased energy efficiency, carbon emissions must be reduced by 40% compared to 1990. This was renewed with the European Green Deal (Commission, 2020), which sets a new target of reducing carbon dioxide levels by at least 55% by 2030. Under the EU directive and the Green Deal, each Member State was required to draw up its own energy strategy, which Hungary has also completed. In the National Energy Strategy issued by the Ministry of Innovation and Technology (ITM), the Government projects a 40% reduction in greenhouse gas emissions compared to 1990, the baseline figures for which were set by Parliament in Act LXIV of 2020. According to the Climate and Nature Protection Action Plan, Hungary's electricity generation will be 90% carbon neutral, and the installed capacity of solar panels will increase to 6,400 MW (equivalent to the peak capacity of 3 Paks power plants) by 2030. Plans for 2040 include a further increase in the share of solar energy to a peak of 12,000 MW. The Hungarian energy policy intentions are currently focused on increasing solar capacity. While this will allow for a 30% share of renewable electricity generation, and around 40% by 2040, the weather dependency of generation poses significant risks and costs. As the share of weather dependent renewable energy increases, low-utilisation back-up power plants and energy storage will need to be provided. If carbon-free power generation (weather dependent and independent renewables and nuclear) exceeds consumption, the surplus should be exported, the production reduced, or the energy stored. As solar capacity will grow significantly not only in Hungary but also in neighbouring countries, the forced loss of production and exports are expected to result in similar losses from a financial point of view. The problem can be mitigated by diversifying weather dependent renewable energy sources as much as possible (even across borders), and by addressing storage. We first look at the more abundant renewable energy sources available in our country, focusing on their price, sustainability and energy security. We seek to answer the question of how the share of renewable energy in Hungary can be increased economically. The answer is the key to sustainable energy production, and while it may not be achieved, it can help to create economic incentives that require as little public money as possible.

In order to identify economical technologies, we will rank the renewable energy generation options, estimate their main economic indicators based on international and Hungarian experience, and then do the same for storage options. The study is not intended to estimate future prices, but only to present and analyse current options.

OVERVIEW OF RENEWABLE ENERGY OPTIONS IN HUNGARY

Methods

Determining the economic indicators of renewable energy production is relatively easy in some cases, because the number of built power plants statistically reaches the level needed for an accurate analysis year after year. In other cases, the number of investments is insufficient. When local statistics are not available, international experience and statistics are used to estimate costs. The indicators to be established by estimation or from statistics are: capital expenditure (CAPEX), operating expenditure (OPEX) and life cycle (possibly broken down by component). The most common indicator in the economic analysis of renewable energy is the so-called life cycle levelised cost of electricity (LCOE), calculated by the following method:

$$LCOE = \frac{CAPEX + \frac{\sum_{t=1}^{t=LT} OPEX_t}{\sum_{t=1}^{t=LT} (1+d)^t}}{\frac{\sum_{t=1}^{t=LT} E_t}{\sum_{t=1}^{t=LT} (1+d)^t}}$$

where LT is the lifetime, for each year of which the terms are summarised, E_t is the amount of energy produced in year t (kWh), and d is the expected interest rate of return, best estimated by the weighted average cost of capital. However, this approach is flawed because, in addition to the cost of capital (unlike other investments), there is also a significant depreciation cost, i.e. it is assumed that the assets are destroyed after their lifetime. The weighted average cost of capital is usually considered a trade secret and is therefore very difficult to estimate, but the AURES EU project has succeeded in estimating its magnitude (Roth et al., 2021); the calculated interest rates can be obtained from this study. We calculate depreciation costs on a linear basis and incorporate them into OPEX.

By calculating the LCOE, we obtain the price at which the investors' profit reaches the expected level. A selling price (in Hungary, a take-over price) above the LCOE results in extra profit, so take-over prices can be used to heat or slow down the renewable energy market.

Solar energy

Solar energy can be used directly to generate electricity (photovoltaic devices) or for thermal energy (solar thermal). The latter can later be converted into electricity, called solar thermal power. The climatic conditions in Hungary do not allow for the electrical use of solar heat, so solar generation is the main source of electricity in Hungary. The actual production of a solar cell depends on the amount of light energy reaching its surface, so its production is time and weather dependent. For comparison, the production curve of a solar panel with a peak power of 1 kW (1 kWp) is shown in *Figure 1* in winter, and in *Figure 2* in summer. We looked for production curves where the weather conditions are ideal. The daily production was 3 kWh around the winter solstice and 6 kWh around the summer solstice.

Solar panel production (above 10%) is limited to 7–8 hours in winter and 11–12 hours in summer. There is uncertainty due to weather dependency, in cloudy weather solar panel production can drop to a few per cents of the capacity in sunny weather.

Monthly production can be estimated using the PVGIS system (Rusen, 2020). The simulated production data for an ideal (south facing, 35-degree tilt) installation are shown in *Figure 3*, with estimated standard deviation.

The annual energy production is 1,200 kWh (in Budapest). Let us define the utilization indicator as the ratio of the annual average power to nominal power. Calculating the same for solar panels, we get 13%.

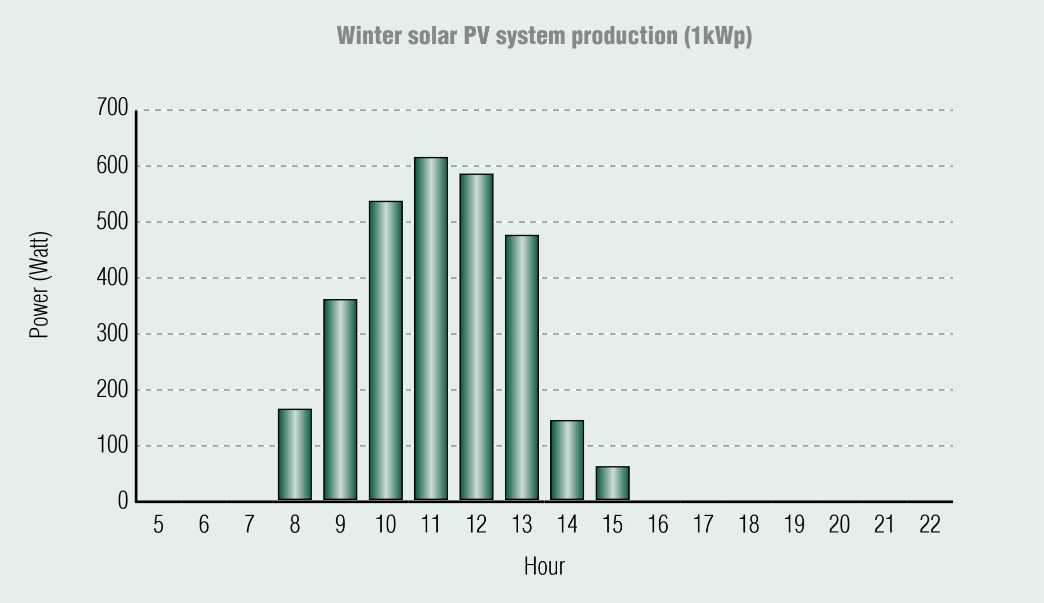
The main elements of the cost of a solar power plant are as follows:

- Solar panel (energy production unit),
- Support structure,
- Inverter (to feed energy to the grid),
- Connection costs,
- Land area,
- Buildings, fencing.

Based on 2022 market conditions, the price of monocrystalline solar panels will be at least €240/kWp. The support structure

Figure 1

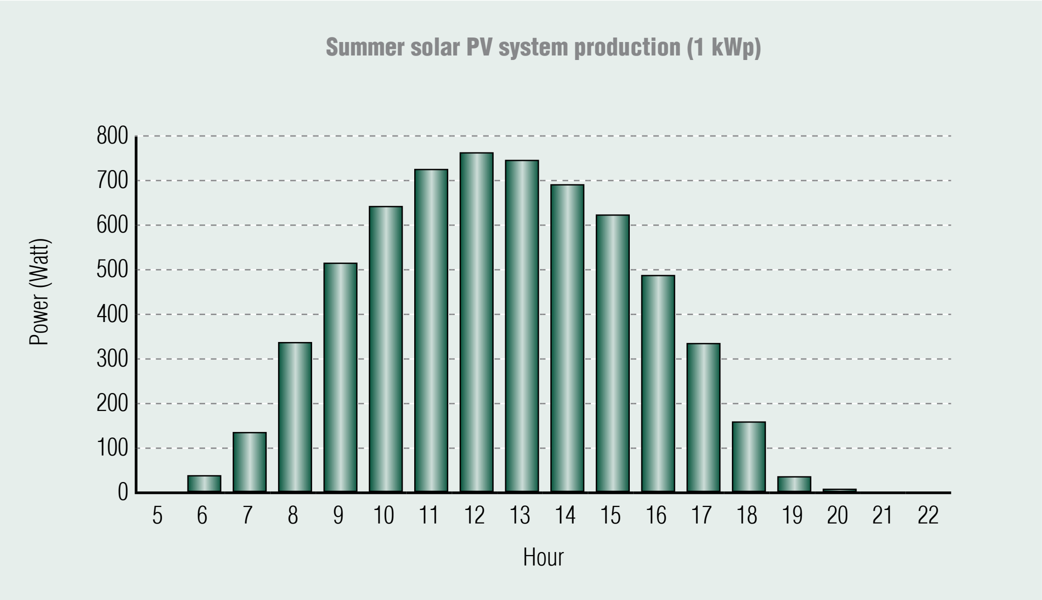
PRODUCTION OF A SOLAR PANEL WITH A NOMINAL CAPACITY OF 1 KW ON 21.12.2014, IN CLEAR WEATHER (PVGIS, 2022)



Source: own editing

Figure 2

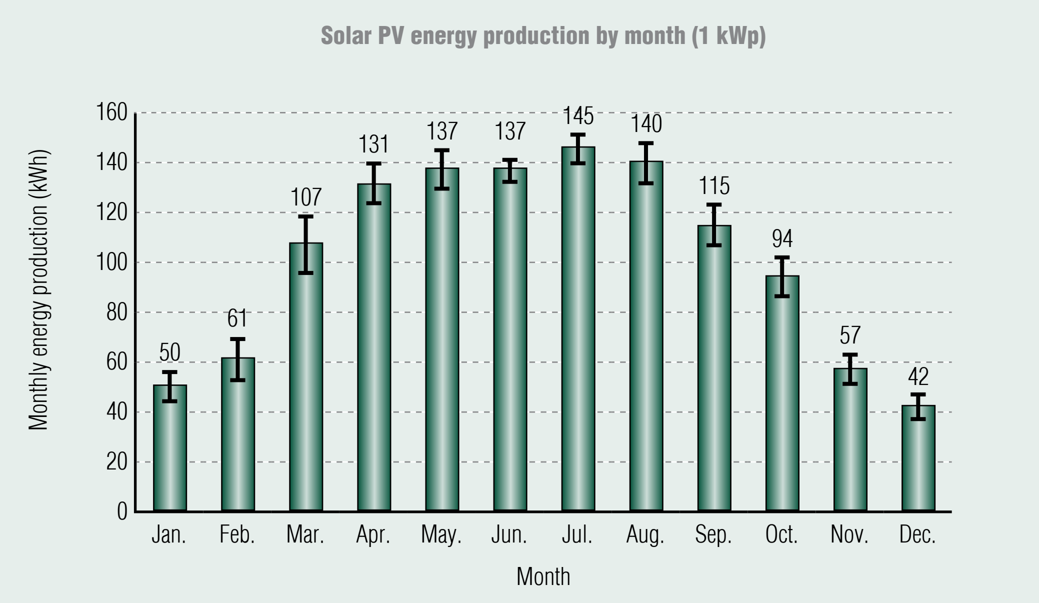
PRODUCTION OF A SOLAR PANEL WITH A NOMINAL CAPACITY OF 1 KW ON 13.06.2013, IN CLEAR WEATHER (PVGIS, 2022)



Source: own editing

Figure 3

ESTIMATED ANNUAL SOLAR PV PRODUCTION FOR A SOLAR PV SYSTEM WITH A PEAK POWER OF 1 KW



Source: own editing

will cost an additional €80/kWp, and the inverter will cost around €70 per kilowatt-hour. In addition, about EUR 60 per kW can be charged for wiring, accessories, installation, administration and planning. For power plant size, the number of solar panels is increased by about 30–40% (this is reflected in the price of the panel and the mount) to maximise profit, as this allows capacity utilisation to be kept at a higher level while the price of the other components remains the same. The cost components are shown *in Table 1.*

The cost of a bare solar plant is around EUR 540–600/kWp. In addition, there is the cost of purchasing and installing transformers, connection lines and accessories, land rental, of which roughly 0.022 ha/kWp is required, the cost of the various service units and the cost of road construction. The cost of a solar PV system at power plant scale (5–10 MW) is around €700–850/kW (IRENA, 2021). The location of solar power plants is of paramount importance because ideally, they should not only be accessible by road, but also have a suitable transmission line nearby, typically within 1 km. It is important that the planned capacity can be connected to the power line. In that respect, the number of ideal sites is diminishing. For example, according to the maps published by EON, the unconstrained area in the North and South Transdanubian region has been reduced to roughly 10% of the total area due to the small power plants already implemented and licensed (EON, 2022). This is due to the decreasing availability of suitable grid resources.

Maintenance and administration cost roughly €10/kW per year. In terms of obsolescence, the life expectancy, which is 10 years (10%) for inverters and 25–30 years for other components, as well as the degradation of solar panel performance (0.5–1% per year)

Table 1

COMPONENTS OF A SOLAR PV SYSTEM

Cost element	Price (€/kWp)	Source
Solar panel module	190–280	(PV-magazine, 2021), verified: (Alibaba, 2022)
Support structure	50–110	(IRENA, 2021), verified by: (Alibaba marketplace, 2022)
Inverter	60–80	(IRENA, 2021) verified by: (Europe solarshop webshop, 2022)
Maintenance and administration, installation	75–100	(IRENA, 2021)
Connection costs	20–120	(IRENA, 2021) verified by: ENERTECH Hungária Kft. (general information on request by phone)

Source: own editing

must be taken into account (Skoczek, 2009). Overall, assuming an ageing rate of 3.3% and a capital cost of 5% based on the source provided, the LCOE is 5 eurocents/kWh. This is about HUF 18/kWh, which is slightly higher than the METAR-tendered takeover prices. This leads to the conclusion that solar investment with a guaranteed takeover price is considered by the market to be extremely low risk. It is also an indication that METAR is working well.

The previous example assumed a fixed solar farm with a capacity of 2–10 MW. At present, the area that can be economically installed with solar panels (free transmission line capacity) is shrinking, so the solutions that can increase the capacity utilisation rate are becoming more common. The yield of such solar PV systems can be up to 60% higher, while the peak power remains unchanged. Such solutions include increasing the number of solar panels, but also E-W orientation and solar tracking. By using these technologies (with additional investment and maintenance costs), additional yields can be achieved, while renewable output is better distributed over time. Among the input costs, the cost of solar modules, support structure, installation and accessories increases, and after conversion, the payback for both solar tracking and E-W orientation is similar to those of a fixed south-facing installation. Their installation is recommended primarily where space, or even more so where the peak power that can be connected is limited. METAR trends in recent years show that they are becoming more widespread as suitable installation sites become scarce.

When deploying solar panels, it should be remembered that they feed directly into a grid with consumers who may not be affected by either quality or security of supply. As solar panels are usually fed into the medium or low-voltage grid, i.e. a grid that cannot be individually regulated, voltage variations must be taken into account. As long as this change is within tolerance, there is no need for grid upgrades, but this limits the expansion of solar power plants. It is likely that new substations will have to be added to the high-voltage grid, or expanded and reinforced. The cost of reinforcing the grid is estimated to be around €20–30/kW, but this increases with solar capacity (Holweger, 2022), which increases the LCOE cost by around 0.2 cents.

An additional cost of solar PV power generation is due to the need to maintain a sufficiently powerful, non-weather dependent power plant in the system to ensure a continuous supply of energy. These cannot be back-up power plants, as they have to operate every day, but their capacity utilisation is reduced, which increases the unit cost of the electricity produced. The cost of unused capacity depends on the type of power plant chosen as an example. As Hungary's energy strategy favours natural gas-based generation for this purpose, the cost of this is estimated through a case study of two combined cycle gas turbines. Based on the case studies published by the U.S. Energy Information Administration (EIA) (Sargent & Lundy, L.L.C. to U.S. Energy Information and Administration, 2019), the initial cost of a gas turbine is about EUR 900/kW, and the annual cost of a gas turbine independent of production is EUR 13/kW. On an annual basis, at a depreciation rate of 2.5%, the cost of keeping 1kW of capacity in the system is EUR 35. The capacity utilisation of solar panels is 13–19% (depending on technology and oversizing), so the grid cost of the loss of production of the gas plant is EUR 4–6 kW per year. In LCOE terms, this is 1–1.5 cents per kWh produced by the solar plant. The latent subsidy requirement for solar panels is at least 1.2–0.7 cents per kWh generated, which is a subsidy of about 25%. This is true for all weather dependent renewable energy sources, including wind. Gas-fired power plants are needed not only to make up for lost production due to weather conditions, but also to ensure the stability of the electricity grid thanks to their fast response times. Storage facilities can also be used to replace gas-fired power plants. In the case of planned replacement, e.g. at night, the power can of course come from other power plants (e.g. biomass), but electricity generated from conventional fossil fuels has higher specific greenhouse gas emissions and pollution.

Wind power

No new wind power generation units have been commissioned in Hungary since 2010 due to legal restrictions. Hungary's energy strategy does not particularly take this opportunity into account, as capacity utilisation (21–26%) is lower than the international average (36%) (IRENA, 2021). In 2010, the global average was only 27%, from which the Hungarian power plants deviated little, so it has to be examined whether the increase in the technological level of wind power plants has increased the capacity utilisation rate in Hungary as well. The increase in the capacity utilisation rate is explained by the increase in the rotor diameter of wind turbines (2010: 80 m, 2020: 120 m) and the increase in their height (2010: 120 m, 2020: 200 m). Another aspect of the energy strategy against wind power is that it cannot be regulated. This is not the case for modern turbines with storm protection (Amrane et al., 2021), because they already have the means to shift the turbine blades to a different position from the ideal one.

Below we will investigate the cost of installing wind turbines and the energy price that could be achieved by using them. In 2020, the average cost of installing a wind turbine in Europe was €1,300 per nominal kW. This covers all the costs not related to grid development, just as for a solar power plant. A conservative estimate of capacity utilisation is in line with the average of recent years (23.3%), as the best sites are occupied, but the technology has improved a lot. The annual maintenance and refurbishment costs are €35–50 per nominal kW. Wind turbines typically have a lifespan of 20 years (Ziegler et al., 2018), which can be extended in many cases, so we expect a depreciation of 5%. The calculated LCOE is 8.5 eurocents/kWh. Compared to the expected electricity price for solar PV generation, wind-generated electricity is significantly more expensive while still retaining its weather-dependent characteristics. The LCOE calculated for wind power is much higher than the LCOE in Western European countries. The reasons for this are twofold: on the one hand, the increase in capacity utilisation associated with the development of the technology is not taken into account (e.g. in Germany it increased from 25% in 2010 to 35% in 2020), and on the other hand, the cost of capital (4%) is much higher than the typical cost of capital in Western Europe (1%). The main argument for installing wind farms is that they have a higher capacity utilisation rate than solar plants, and experience shows that they are most active in winter and can therefore somewhat balance the seasonal variation in solar generation. If further studies show that the capacity utilisation rate is significantly higher than what is known so far, then wind farm deployment could be an economically viable investment, largely increasing the share of renewable generation without exacerbating grid problems due to infrequent simultaneous generation.

Geothermal power plants

Hungary has a good position in terms of geothermal energy, but its extraction is expensive and risky. There are two types of geothermal power plants: the direct steam generating ones, and heat exchangers. In the first case, high temperatures (190 °C) are required to generate electricity, but even higher temperatures are needed to achieve good efficiency. In Hungary, this would require water to be brought up from a depth of at least 3–4 km, at a cost of at least 3–5 billion HUF (for two holes), and the success of drilling at such depths is highly doubtful. Traditionally, geothermal electricity generation requires finding an aquifer with sufficient depth to reach higher temperatures and a sufficiently large surface area for continuous high energy production. This will require mapping of the area and test drilling. In the case of lower temperature sources, electricity generation does not take place in a watery medium, only heat is extracted from it via a heat exchanger. Such plants can already be operated economically with water temperatures of up to 120 °C. Their great advantage is that the depth of the borehole does not exceed 2 km and their efficiency can be around 15%. (Altun & Kilic, 2020).

For regions in a better position than our country, the cost of geothermal power plants for electricity generation in 2020 ranged between €2,000 and 4,000/kWp. The expected cost of € 4,000–6,000/kWp in Hungary (with a heat exchanger plant) is not in itself a barrier to such an investment, but the uncertainties of construction mean that the investment is far from being risk-free (Subir, 2016). The uncertainties in this case relate not only to the success of drilling, but also to the water yield that can be extracted and the temperature. This is why, for example, the German government subsidises geothermal power plants at €0.25/kWh, despite the fact that the return on investment of a successful project is good even without this. Geothermal power plants do not have an infinite operating time because the water temperature decreases over time; this is because the heat supply from the aquifer is usually insufficient. Experience has shown that efficiency drops to a level that is no longer worth using for electricity generation after 25–50 years (Budisulistyo et al., 2017). Although such power plants use renewable energy, they may not be sustainable in the long term.

Heat exchange power plants are less risky because the depth of drilling can be much shallower. The only geothermal power plant in Hungary that produces electricity is the one in Tura, which is also of the heat exchanger type. Its total cost was HUF 5.5 billion, with a capacity of 2.7 MW, or about HUF 2 million per kW. At 90% capacity utilisation, the energy produced is 7,800 kWh with a 30-year lifespan and a world average maintenance cost of €100/kW/year, so we can expect the price of the electricity produced to be even lower than that of solar panels. Because of the high risk, the financing costs of such projects are very high (Wall, 2017), WACC = 12–20%. Calculated at 15%, the LCOE is 11 eurocents per kWh. Another advantage of geothermal power generation is that it is not weather dependent, with a capacity utilisation practically equivalent to the availability of an average power plant. In addition, it may be well regulated and can produce heat energy (residential or industrial) in quantities suitable for other uses. The use of geothermal energy can be a priority because there is no need to maintain spare capacity or to create storage capacity in case of overproduction. In this sense, the price of the energy produced is already favourable and it is in the interest of the community to eliminate risks. Most of the risks are related to the preparations for and the actual drilling. The risk can be reduced if the initial steps (e.g. survey, exploratory drilling) are already available, or are provided by a risk community or the state. In Hungary, the geological strata are relatively well documented due to hydrocarbon extraction, and drilling data are available.

Biomass

The term biomass covers a wide range of energy carriers – e.g. energy crops, firewood, agricultural by-products, combustible gas from wastewater and combustible gas from organic compounds in landfills. The use of by-products, in particular methane-containing gas mixtures, is virtually a mandatory task. The production of biomass for subsequent energy purposes should be considered for a number of reasons. The energy efficiency of crop production ranges between 1–2% (solar: 20–22%), while the use of the resulting fuel in conventional thermal power plants has an efficiency of 15–32%. A major advantage is that availability can be up to 90%, biomass can be stored and is an excellent feedstock for biofuels and biogas. Biomass-based electricity generation in Hungary in 2021 had an installed capacity of 282 MW (MAVIR, 2021), from which 1,988 GWh (MEKH, 2022) electricity was produced. Biomass is the largest renewable energy source in Hungary, with more than 80% used as fuel. When estimating the cost of biomass power plants, one of the most important factors is the cost of acquisition, which, based on international experience, ranged from €1,500 to €5,000/kW (IRENA, 2021). Economies of scale are decisive in this case, with larger plants being cheaper to build and operate on a per unit basis. The European average cost value of € 3,500/kW is used for the calculation. The plant is expected to have a lifespan of at least 40 years, with a fixed cost of 2–6% of the cost price where, again, economies of scale prevail. The fuel cost per kWh produced is between 1 and 6 eurocents, of which a large proportion is accounted for by transport charge. The cost of electricity production, calculated with a 5% capital cost, is 6–11 eurocents/kWh, which corresponds to 22–38 HUF/kWh. In the last METAR tender, the takeover price was HUF 38.15. It is important to note that the efficiency of biomass-fuelled power plants is basically low, ranging from 15–30% for electricity generation, depending on the technology and the biomass material. A low-cost value can be achieved by converting obsolete coal and lignite plants to biomass power, but their efficiency is low. Taking advantage of the fact that biomass can in some cases be easily gasified, i.e. converted into a gas that can be burned at the right temperature, combined cycle power plants can be built with 35–45% efficiency (Soltani et al., 2013). It is also possible to interrupt the cycle to produce biogas, which can be used for long-term energy storage.

Estimates of the sustainable level of biomass potential and production are highly uncertain, but they mostly suggest that today we are using about half of the total sustainable potential. (Dinya, 2010).

Biomass is an excellent starting point for biogas and biofuel production and should therefore be promoted in the first place. If we look at biomass in terms of electricity supply, it is a quasi-carbon neutral energy source that can help to smooth out energy supply imbalances. To do this, it is important to use power plants with the highest possible efficiency and rapid response.

SUMMARY OF RENEWABLE ELECTRICITY SUPPLY OPTIONS IN HUNGARY

We have looked at the renewable energy sources where significant growth can be achieved in Hungary. We have found that solar panels are the cheapest way to generate electricity, but cannot be relied on exclusively as they are weather dependent. In addition to the deployment of further carbon neutral technologies, significant improvements of the electric power distribution network and energy storage solutions are needed. *Table 2* summarises the characteristics of the renewable energy sources studied.

Sustainability issues concerning the main renewable energy sources

The most important environmental issue in the use of solar panels is the production and recycling of solar cells, as the supporting structure and the service units are built from traditional materials (copper, glass, aluminium, iron), which can be reused or recycled. However, the production of silicon-based cells is highly polluting: it requires large amounts of energy, water and high-purity raw materials. During production and transport, various greenhouse gases, acid rain and toxic gases and solutions are produced. It also generates significant amounts of hazardous (dissolved) waste, such as mercury, lead, acetone, toluene, etc. These require considerable effort to dispose of, which gives a significant competitive advantage to companies that do not comply or to countries where the standards are less stringent. The key to reducing the environmental impact of production is recycling. The relevant EU directive requires solar panels to be collected and recycled, but at present this primarily means breaking them down into raw materials. However, dismantling into raw materials is not the most environmentally friendly solution, because degradation of solar cells mainly occurs on the coatings. This is a laminated layer system that transmits light to the active zone and occurs secondarily on the electrical contacts. The coatings are removed by chemical, thermal and mechanical cleaning, which means additional environmental stress. At present, not all aspects of solar cell degradation are known precisely, but based on other semiconductor industry experience

Table 2

PROPERTIES OF THE STUDIED RENEWABLE ENERGY SOURCES

	LCOE (HUF/kWh)	Risk	Network cost	Constraints to exploitation
Solar panel	16–20	Low	High	Unlimited
Wind turbine	28–33	Low	High	Moderately limited
Geothermal	38–50	High	Low	Limited
Biomass	22–38	Low	Low	Limited

Source: own editing

(LED), it is likely that temperature, humidity, the amount of incoming UV radiation and the total current flowing through the cells play a key role in the efficiency loss. More research is needed on this. If the above considerations are correct, the lifetime of solar cells in certain conditions (e.g. in cold and dry climates) could be well over 25–30 years. The following steps can be taken to reduce environmental damage:

- Decommissioning of solar panels should only be allowed if there is a significant reduction in output;
- The cells and joints of decommissioned modules should be certified. Whatever is possible should be reused without modification or with minimal modification (e.g. re-soldering);
- Any remaining waste should be treated or recycled.

The resulting refurbished solar panels are marketable, although their lifespan is expected to be less than that of new solar panels.

For wind turbines, the biggest challenge for circular management is the material of the wind turbine blade, which is typically a carbon or fibreglass composite. Recycling the other elements is possible. The blade material can be recycled mechanically or chemically. For the former it can be ground to produce granules with mechanically similar properties to the original material, which can be used as an additive for asphalt or concrete structures. The chemical process uses high temperatures to extract the constituents of fibre-reinforced plastics, but this yields a lower quality material and requires a significant additional energy investment. By increasing the temperature, combustible gases can be obtained by further decomposition of the constituents. Landfilling is currently the most common process.

The sustainability of geothermal energy requires consideration of several aspects. One is the environmental impact, which mostly involves the emission of gaseous substances (mainly hydrogen sulphide and sulphur oxides), which cannot be recovered because of the air bubbles that are created. Further environmental impacts are technology dependent. From the point of view of energy production, power plants are generally built from materials that can be recycled. In low-temperature power plants, leakage of working fluids can be a problem, as these are generally more potent greenhouse gases (as in air-conditioning plants). Conventional extraction and injection are generally not a major risk, but more recently the HDR (Hot Dry Rock) process has become more common. The idea is to use a layer fracturing process to break a suitable path for water between wells that are spaced up to kilometres apart, which absorbs the heat from the rock. The risk-benefit analysis of this technique is controversial.

A further problem with the sustainability of geothermal energy is that, for economic reasons, it takes more heat out of the system than it replaces. Therefore, in contrast to solar and wind energy, the recoverable power decreases over time and the regeneration period is well beyond the lifetime of the projects.

The sustainability of biomass depends primarily on responsible and renewable forest management. As discussed in previous chapters, there have been conflicting studies on the renewable biomass potential of Hungary. Other environmental and sustainability issues include the neutralisation of gases produced during incomplete combustion, which can be significantly reduced by the gasification process, and it is also accompanied by an increase in efficiency.

Energy storage options

Energy storage options are technical solutions that can store energy for shorter or longer periods of time (hours, months). New concepts are being developed almost every week, but their viability is often questionable. We calculate the storage capacity needed to make more economic use of weather dependent renewable energy for 2030 (6,400 MW of integrated solar power plant capacity) and 2040 (12,000 MW of photovoltaic capacity). Among the many energy storage solutions, we look at pumped storage, battery storage, green hydrogen production and molten salt storage, which are currently considered as standard.

Methods

A major issue in weather dependent renewable energy production is how to store the surplus energy produced for later use. Hungary's energy strategy mainly proposes the expansion of solar photovoltaic systems, and we considered the future values specified. The storage capacity that may be needed to expand photovoltaic capacity to 6,400 MW and 12,000 MW is examined. For this purpose, we take into account production and consumption data for 2021 (MAVIR). We assume that we can simulate the 2030 and 2040 power generation with appropriate scaling. We use the generated production and consumption data to run a simple simulation to see how much storage capacity can be used with what efficiency.

By 2030, Hungary will have around 6,400 MW of installed photovoltaic capacity, with an additional 2,000 MW of installed capacity in the old units of the Paks NPP and a total of 2,400 MW of installed capacity in the new units planned for 2030. Part of the photovoltaic capacity is power plant capacity and part of it is household capacity. The production of household-scale photovoltaic systems is generally different from that of power plants, because the photovoltaic capacity of these plants is usually not much or not at all higher than the inverter capacity, i.e. the nominal capacity of the system. Therefore, the yield of these systems is about 1,100 kWh per kW installed per year, compared to power plant generation, where it is 1,400 to 1,600 kWh. Since household-scale photovoltaic systems are not under distribution monitoring, the time series of the output power is not available and therefore not included in the MAVIR data. However, these power plants reduce the system load, i.e. the apparent consumption.

We assume that by 2030, about one third of the photovoltaic capacity is expected to be small household-scale power plants, following the current structure (currently, the National Energy Strategy's projected small power plant capacity of 800 MW by 2030 has already been reached). Our estimate is based on following the trends to date.

To estimate photovoltaic electricity generation, we can use the following formula:

$$P_{2030}(t) = \frac{P_{2021}(t)}{1500} \times \left(4266 + 2133 \times \frac{1100}{1500}\right),$$

where $P_{2030}(t)$ is the expected time series of photovoltaic generation in 2030, which can be estimated by dividing the 2021 generation [we divide $P_{2021}(t)$] by the annual average installed capacity of 1,500 MW and then divide this by the assumed installed capacity of 6,400 MW in 2030 in a 2:1 ratio. The 1/3 share for households is corrected by a multiplier of 1,100/1,500 to determine the production of a household-scale photovoltaic system.

In the meantime, the standard consumption has to be corrected, as it excludes household photovoltaic production. Basically, the method would be to add the estimated production from household-scale solar power plants to the measured consumption data by the appropriate multiplier. However, this would not be correct because of the 2021 household photovoltaic boom, so in principle we could use the 2020 data, but this would not be a good idea either because of the distorting effects of the pandemic. Therefore, we use the 2019 data adjusted by the average capacity of household-scale solar power plants at that time (405 MW).

To estimate the output of nuclear power plants, we use the 2021 production data for Paks 1 on the one hand, and on the other hand, for the two new units, assuming 3 weeks of planned maintenance per year in the spring and autumn, and a total of 10 days of 50% output reduction in random periods.

The output of biomass power plants is estimated over time so that their output is just the difference between production and consumption until the expected nominal production capacity of 280 MW is reached. In this sense, biomass is already considered as energy storage. The production of all other renewable energy production units was adjusted according to the year 2021.

In modelling the energy storage units to be simulated, we consider five main properties: effective capacity, storage efficiency, storage loss, the capacity to maximum output ratio, and the energy loss of storage (or how much energy it consumes to operate) if no grid event occurs.

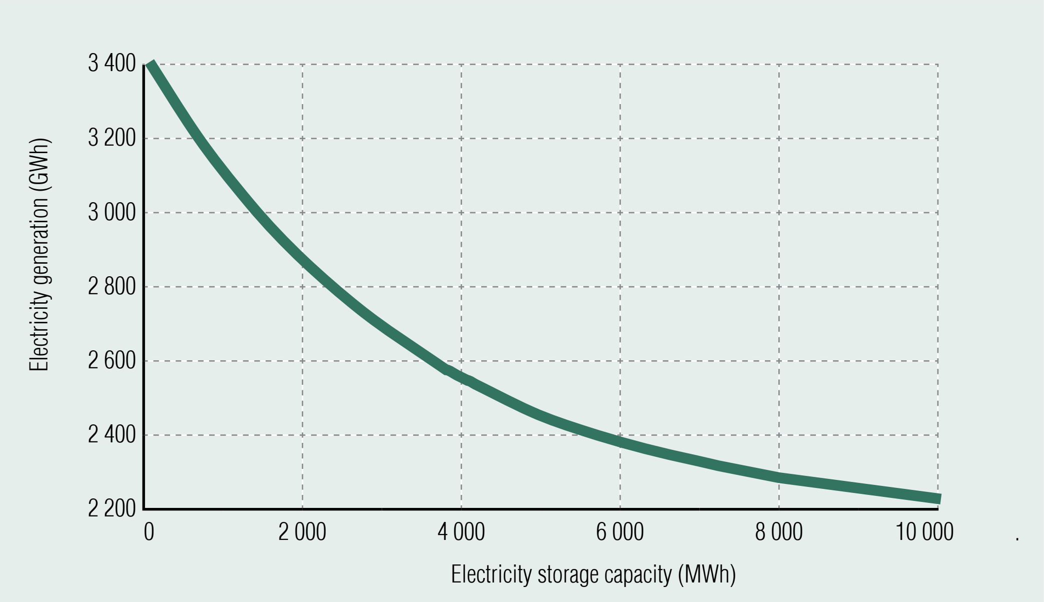
The simulation is a simple computer program in which the preset energy production and consumption data are processed by the program on a half-hourly basis and a decision is made on the biomass production capacity and the management of storage. The simulation is purely a demonstration and does not search for the best storage strategy, as no predictive algorithm is built in. Another shortcoming is that it does not consider the detailed balance of the grid either.

The above model can be used to determine the amount of electricity to be generated from fossil fuels with the installation of different storage capacities.

As a result of the simulations, the electricity generation from fossil fuels in 2019 with the same consumption data and the planned generation data as determined above is shown in *Figures 4* and *5*. The loss of entry into and removal from storage was assumed to be 20 and 10%, respectively, the 24-hour self-discharge was assumed to be 5%, and the maximum output was set to 1 kW/kWh (1-hour storage). It can be concluded that in the 2030 scenario (when we are expected to become electricity exporters due to the joint operation of the two nuclear power plants), 318 MWh of electricity generation per MWh of storage in the initial phase of storage capacity growth can be expected, which will gradually decrease to 100 MWh (at 4,500 MWh storage capacity). For the 2040 scenario, the linear model fitted to the initial

Figure 4

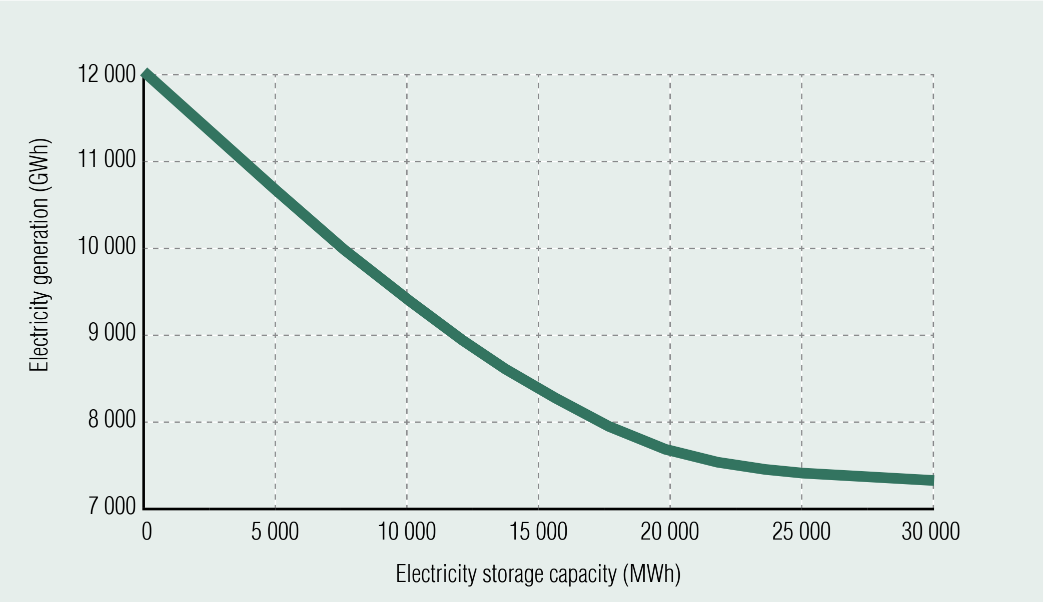
ANNUAL REQUIRED FOSSIL ELECTRICITY GENERATION WITH DIFFERENT STORAGE CAPACITIES IN 2030



Source: own editing

Figure 5

ANNUAL REQUIRED FOSSIL ELECTRICITY GENERATION WITH DIFFERENT ENERGY STORAGE CAPACITIES IN 2040



Source: own editing

phase shows that 1 MWh of storage per year will replace 283 MWh of fossil generation per year while the storage capacity is below 1,000 MWh. This then decreases to 250 MWh at a storage capacity of 4,500 MWh, and drops to 100 MWh at 6,000 MWh. *Figure 4* and *Figure 5* show that in 2030, the fossil fuel demand is low (3,400 GWh even without storage) in the case of simultaneous operation of Paks 1 and Paks 2, while it is well above this in the case of a Paks 1 outage, even with the installation of large storage capacities.

The optimal level of storage capacity depends mainly on the ratio of peak import and daytime export prices and the cost of building the storage facility. If the simulation is extended to take into account the import price as well as the take-over price of the electricity generated, the revenue generated by the operation of the battery can be calculated at 2021 prices. The revenue is virtual and represents the import cost avoided. With the take-over price set at HUF 18/kWh, but not stored below HUF 27, and taking into account the 2021 HUPX data (HUPX, 2022), the simulation was performed for each hour. The simulation provides the curve in *Figure 6* depending on capacity.

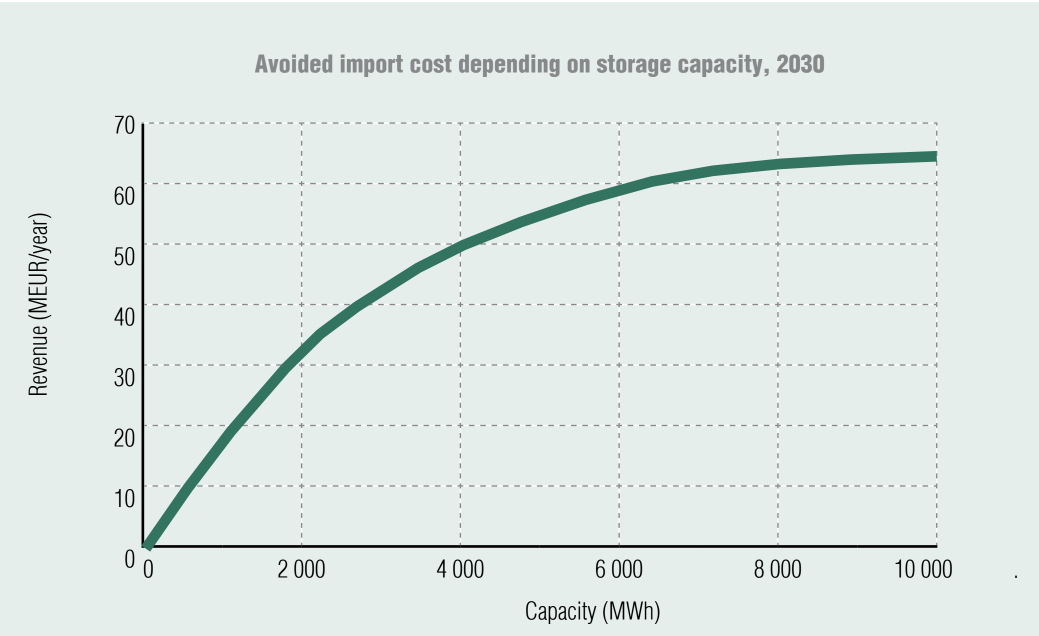
Fitting a straight line to the steepest initial part of the curve, it can be concluded that under these conditions the annual yield of the storage facility is EUR 18.54/kWh/year. With a better buy-sell strategy, the profit can be further increased (Kusakana, 2018).

The simulation above requires the following comments:

- In 2021 the electricity market was highly volatile, with prices averaging EUR 50–60/MWh at the beginning of the year, and rising to around EUR 250/MWh by the end of the

Figure 6

ESTIMATED STORAGE YIELD IN 2030 DEPENDING ON CAPACITY



Source: own editing

year. This is mainly due to the exceptional increase in gas prices in the second half of the year. However, such anomalies may occur in the future as well, and it is not known at this stage at what level the market will stabilise, if at all.

▸Electricity use is expected to increase by about 20% by 2030, which does not change the return figures based on the simulations alone, but the adoption of heat pump systems could change the current energy use curves, as could the adoption of electromobility. It is expected that these will increase rather than decrease storage profitability.

▸The energy strategies of neighbouring countries foresee large photovoltaic capacity similar to that of Hungary (Aszódi, 2021), which is expected to result in very low electricity prices during sunny hours. Accordingly, for storage facilities, the market price, which is significantly cheaper during the period of storage, should be taken into account for recharging, rather than the obligatory take-over price.

ENERGY STORAGE OPTIONS

In this section we present some relevant and operational technologies that are in principle available in Hungary. We start our analysis with the pumped storage solution, as this type is the most common type of grid energy storage in the world, accounting for more than 95% of the total capacity (Koohi-Fayegh & Rosen, 2020). A pumped storage power plant requires a water source and a reservoir with different elevations above sea level. The principle of operation is simple: when charging, water is pumped to the higher elevation, and when generating, the system is transformed into a hydroelectric power plant and the accumulated energy is recovered. Traditionally, the source of the water is at the bottom, which is usually a river, and the reservoir is located on higher ground. The reservoir can be artificial or natural. There is virtually no location in Hungary where the design of such a system would not be detrimental to nature conservation interests, except possibly in the vicinity of the Mátra Power Plant. The reservoir could also be constructed underground by reversing the roles, currently mainly in closed mines. Natural hazards could also include the construction of a water supply system and at least one pool. Considering a 200 m difference in level, the size of the pool should be about 2 million cubic metres per 1 GWh, which can be visualised as a cuboid, 20 m deep with 320 m sides. The direct destruction of nature, which in this case affects around 25 hectares, and the construction of roads and electricity grids, which will take several hectares of land away from nature, must be taken into account, too.

The cost of a conventional above-ground pumped storage power plant varies between EUR 900–3,400/kW depending on the site and the installed capacity. Maintenance cost is EUR 13–25/kW, with an estimated lifespan of 40–60 years (Stocks et al., 2021; U.S. Department of Energy, 2020; Budapest University of Technology and Economy, College of Energetics, 2016). For this type of storage, the large price ranges show a strong dependence on system size and location, but the region itself is also of particular importance due to the high demand for manpower and raw materials (Sospiro et al., 2021). One such example is the 600 MW power plant in Zemplén with a capacity of 6,000 MWh, planned in the early 2000s. The estimated cost value of such a power plant is approximately EUR 720 million (indexed to 2022). Based on international examples, the cost is more likely to be EUR 1 billion, which is what we use going forward. Taking into account a depreciation of 3% (replacement time for electrical components is 20 years), the annual cost is EUR 39 million. Based on the simulations for 2030, the expected return is EUR 56 million at the obligatory take-over price and EUR 72 million for 2040. It can be clearly seen that in 2030 the realisable yield is 1.7% based on the simulation, but by 2040 this rises to 3.3%, which could already be financed from the market. Unfortunately, the construction of a power plant with above-ground storage inevitably destroys the landscape, and local residents and NGOs are likely to oppose it. Similar solutions exist with the exploitation of natural underground reservoirs. This mostly means mines, but natural underground reservoirs can also be considered. Such solutions cost at least 30% more than the above-ground price (Madlener & Specht, 2020); (Menéndez et al., 2020), which reduces the overall rate of return by a similar proportion. It is important to note that only the difference between the price of energy injected at the compulsory take-over price of EUR 50/MWh and the price of energy sold at the time of withdrawal at non-optimal times was taken into account. Other benefits, e.g. capacity maintenance costs and sales optimisation, have not been realised, therefore margins are expected to be around one and a half times the margins in the article.

The development of power plants with above ground reservoirs seems to be an economic reality, as these reservoirs can also be abandoned surface mines on uncultivated land, which causes less landscape destruction, but also at lower cost.

Overall, considering the situation of storage power plants in Hungary, their construction is economically viable, especially if we take into account that the power plant can also act as a reserve capacity for grid management. The main obstacle to the construction of such power plants is the destruction of the landscape, which can perhaps be minimised by careful site selection. It can also be seen that the return on investment of such a power plant is faster in the case of a high share of renewables and the closure of Paks 1. It should also be noted that such centralised solutions do not address the problems of sub-grid capacity, i.e. the overloading of sub-grids, reverse power flows and possible overvoltage. These problems can be addressed by significant grid upgrades or distributed storage solutions.

Batteries

For batteries, the cost estimation is relatively straightforward, as the installation of such storage does not require any particular geographical considerations and can therefore be installed virtually anywhere on the grid. The relatively easy portability and high production volumes result in almost uniform world market prices, which are easy to analyse statistically. With battery energy storage, the higher storage capacity and performance due to high scalability reduces unit costs only slightly. What makes estimation difficult, however, is the diversity of batteries, both in terms of operating principle and materials used. For grid storage, the most common battery on the market today is the lithium-iron phosphate system, which has the advantage of being able to store and discharge high power, while offering longer operating life (10 years, about 6,000 charge-discharge cycles) and thermal stability compared to other lithium-based batteries. The price of such systems has been decreasing rapidly recently, to EUR 270–300/kWh (4 kW/kWh) in 2021, with an estimated cost value (He et al., 2021) based on maintenance costs (Steckel et al., 2021) of EUR 4–10/kWh (EUR 15–40/kWh) per year (Zhang, 2021). Battery degradation is estimated to be around 1–3% (2% is assumed), module replacement cost is around EUR 130/kWh (based on a 10-year period), which can be halved by refurbishment (Steckel et al., 2021). Recent results show that regeneration can be performed without disassembling the batteries (Jing et al., 2020), but the performance of the regenerated battery lags behind that of the new one. Therefore, full recycling is inevitable after a few life cycles. In the calculations, we assume that the battery is charged by a photovoltaic system and uses the inverter already installed in the photovoltaic system, i.e. the cost of this is not calculated again. The amortisation period for cost elements other than modules is estimated at 30 years, as was the case for solar panels. The cost of batteries in this system is between EUR 40–55/kWh per year. Assuming a capacity of 1,000 MWh in 2030, the revenue is EUR 25 million, compared to an annual maintenance cost (including degradation) of at least EUR 40 million. It is clear that the installation of batteries for energy storage (not grid stabilisation) is not profitable. This is mainly due to the high energy density of battery systems, which require active, preferably heat-pumped, cooling even at low (a few%) charge/discharge losses. This is supported not only by safety considerations but also by economic aspects, as the lifetime of batteries decreases significantly with increasing temperature (Sui et al., 2021). Further rapid degradation is caused by total discharge, which can be avoided by using only a fraction of the capacity. The use of batteries is economically disadvantageous.

The Hungarian energy strategy does not take a clear position on storage issues, but underlines that in the long term hydrogen production could be the solution. The concept of producing hydrogen in large quantities using electricity (green hydrogen) is still in its early stages. Only a few pilot projects have been implemented, the largest of which have a capacity of only 6–10 MW.

Hydrogen production using electricity starts with the electrolysis of water. There are several technical solutions, but at the moment the conventional (alkaline electrolysis) technology with an efficiency of up to 77% is considered to be a marketable technology. It is expected that a proton exchange membrane electrolyser with a similar design to fuel cells will be commercially available by 2030, resulting in an efficiency of 83–86%. (UK Department of Business, 2021). Currently, there is no significant difference in efficiency between the two technologies, but the membrane technology has half the life expectancy of the membrane compared to the conventional case. The cost of the electrolyser is assumed to be EUR 900/KW (conventional) and its efficiency 77% (UK Department of Business, 2021). The gas produced in electrolysis has to be dried, compressed and stored. Storage can be in a gas transit pipeline, in a tank, or in natural storage. Storage tanks and pipelines, usually made of steel, are a safety problem because hydrogen diffuses well in steel, where it interacts with carbon and other additives, and changes the mechanical properties of metals by forming metal hydrides. In the event of cracking or fracture, the leaking gas can easily explode, even without an ignition source.Natural storage would be suitable for long-term storage of large quantities of gas, but hydrogen can interact with rocks, so at present only salt mines are proposed for this purpose. The use of reservoirs (sandstone and limestone) in Hungary should be further investigated. The cost of storage cannot be estimated at this stage, but is unlikely to be relevant to the final result. To convert hydrogen back into electricity, either a combined cycle power plant (about 55% efficiency) or a fuel cell is used, which is very expensive. Combined cycle power plants cost EUR 850/kW and have an efficiency of 55%. In terms of maintenance costs, the variable costs are about EUR 0.25/kWh and the maintenance of the electrolysis cell is about EUR 50/kW/year. Including scheduled replacements, the depreciation of the electrolyser is estimated at 6%/year. In comparison, the maintenance cost of the plant is low: EUR 10/kW fixed and EUR 0.002/kWh variable cost elements. With infinite storage possibilities and a maximum capacity of 10 MW, the revenue is below EUR 1 million per year and the obsolescence and maintenance costs are above EUR 1 million. Therefore, under the present circumstances, the technology is not profitable. This estimate is very different from the price of green hydrogen, mainly because the system can only operate at 5–10% capacity utilisation using only the additional energy provided by solar panels. Hydrogen energy storage can be a preferred option when there is a significant surplus of electricity that needs to be stored for the long term or for mobility purposes. This is not likely to be the case in Hungary. Even in 2030, the combined production of renewables and nuclear power plants will not exceed the total electricity demand, only at certain times (e.g. early morning dip, sunny hours at midday), for which short term storage is more economical.

Thermal storage should not be used for storing electricity in principle, because the efficiency of the heat-to-electricity conversion is low, between 20 and 40%. Nuclear energy makes up a significant part of Hungary's electricity mix, which on the one hand produces heat and from it electricity cheaply (the variable costs of generation are low), and on the other hand it is recommended to operate them at their nominal power output at all times during operation, so that maintenance costs (and hazards) can be minimised. Weather dependent renewable energy producers will in many cases alone meet or exceed the total energy demand in 2030–2040. Consequently, nuclear power plants may be scaled back. This should be avoided as far as possible, and therefore the re-regulation of solar power plants could be a solution. Both solutions also mean throwing away the carbon neutral energy produced, provided that no other large-scale storage is used. An option is to store the heat generated by the nuclear power plant (Paks 2). This would create a concept of energy storage where the stored heat is not directly derived from electrical energy and can therefore be converted into electrical energy for later use with almost the same efficiency as it would have had without storage. In this sense, energy storage can achieve efficiencies of up to 75–80%, compared to 20–40%. To determine the thermal storage capacity, let us take the capacity of the Paks 2 plant, which represents a thermal capacity of around 3,700 MW per unit, i.e. a total of around 7,400 MW. The temperature of the secondary circuit of the Paks 2 plant, from which heat can be extracted, is 283 ºC (MVM PAKS II. ZRt., 2020). Due to the specificities of photovoltaic operation, we are considering a storage system capable of absorbing the entire heat production for 4 hours, i.e. the capacity of the thermal storage should be around 30 GWh. However, projections for 2030 and 2040 indicate that a maximum of 4 GWh of electrical storage capacity (12 GWh thermal) would be economically justified, with possible expansion options. The maximum achievable temperature is 280 ºC. As the turbines at Paks 1 are currently operating with steam at 260 ºC, they may be suitable for back-generation after the closure of the reactor, so the investment only concerns the thermal elements and the storage facility. As an example, as stated in an article (Jeffrey M. Gordon, 2021), the cost of molten salt storage (with hydraulics) is about EUR 15/kWh (thermal), add to this the conversion cost of the turbines at EUR 0.2/W, i.e. a system with a thermal capacity of 12,000 MWh with a turbine capacity of

500 MW, and it could cost a total of EUR 280 million. Assuming the depreciation and maintenance costs of the storage at 10% of the acquisition cost, the annual cost is EUR 28 million, and the yield generated is EUR 48 million (2030) and EUR 58 million (2040). Using two turbines, the profit could be even higher, but since the whole calculation is only of a demonstration nature (no such storage facility has been built yet), optimisation is not performed here either. The addition of a thermal store to a nuclear power plant appears to be a solution that is viable in principle, but safety and feasibility studies do not yet support its practicability.

Linking the nuclear power plant and the thermal storage systems will therefore both generate profits and protect the plant from re-regulation. It does not, however, provide an answer to the grid problems, and the load of photovoltaic generation on the distribution grid still needs to be solved.

SUMMARY AND CONCLUSION

We looked at renewable energy production and the related storage issues. We analyse the expected costs, weather dependence and returns of different renewable energy sources. We have found the photovoltaic-focused approach to energy strategy to be appropriate, as it can be economically viable on its own, but its weather dependence requires major changes to the grid infrastructure. A further problem is that the proliferation of solar panels is increasingly disrupting the European market, with the result that electricity is already becoming unsellable at the peak of photovoltaic generation. This threatens the return on investment. For this reason, and to further reduce carbon emissions, storage is needed alongside photovoltaic systems. In order to assess the financial return on the introduction of storage, a simple model for the time-dependent production and price of electricity has been introduced. Production was based on the last year before the Covid–19 pandemic and the household photovoltaic boom, that is 2019, which we have modified according to Hungary's energy strategy to estimate the supply side in 2030 and 2040. The international electricity price estimate was based on the price of electricity imports in Hungary in 2021. The recent energy price shocks are included in this dataset, which may result in a significant overestimation of the expected return on storage. On the other hand, the significant growth in solar and wind power volumes in the European market suggests similar volatility. Of the storage solutions considered, pumped storage and nuclear thermal storage are economically mature and profitable choices. The nature of these power plants shows that they can only be operated at large scale and high capacity, which offers a solution to the carbon problem but does not substitute for grid upgrades. This would require a solution that is economical even on a small scale. Based on our current knowledge and market trends, the solution would be to use batteries, the cost of which is not too high. However, the calculations show that they are not profitable because, based on our current knowledge, the cost of operation (monitoring and cooling) is high and the lifespan of the modules is short. A significant future reduction in module costs is also hampered by the use of similar modules in the electromobility sector. ■

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