IT energetika, II. előadás: az energiatárolás alapjai

Dravecz Tibor INTEGRITY Kft.

"Engineers know that there are three major parts of a large-scale energy system: **generation**, **storage**, and **delivery**."

"**intermittent renewable sources** like wind and solar is wasted if it cannot be **used immediately** or stored for **later use**"
by Bill Schweber, https://www.edn.com/using-gravity-for-energy-storage-viable-idea-or-impractical/

Villamosenergia nagybani tárolása

Electric energy consumption and production

	yearly	
Electric energy consumption in Hungary[1] 2021	43.63 TWh	
per capita	4200 kWh	
Gross electricity production in Hungary 2021	36.130 TWh	
electricity production from natural gas	9.621 TWh	
nuclear electricity production	15.990 TWh	
solar electricity production	3.849 TWh	
wind electricity production	0.661 TWh	
hydro electricity production	0.207 TWh	
Hungarian energy import 2021		
Paks Nuclear Power Plant throughput	1902 MW	Units operational 4 x 500 MW

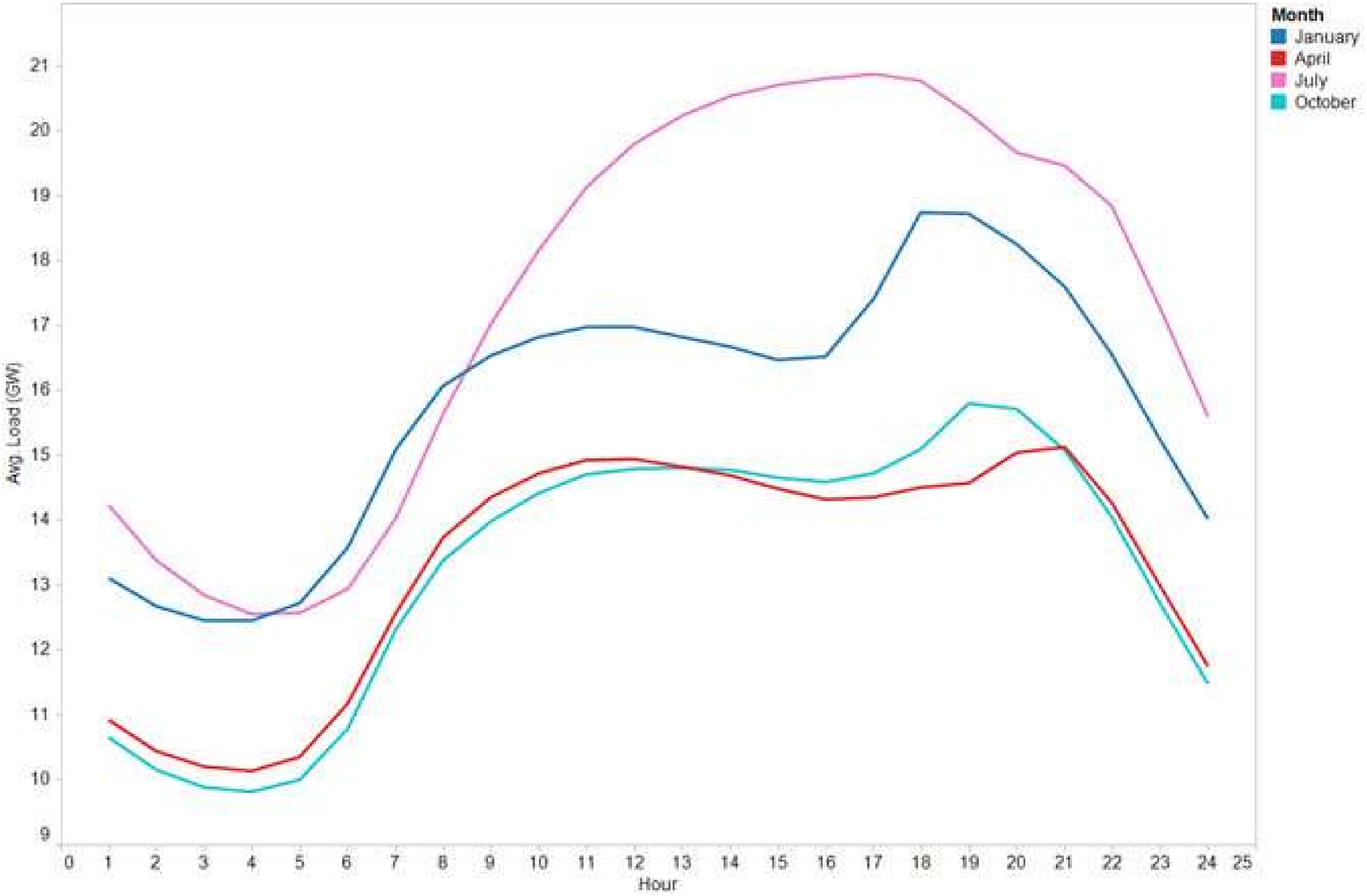
[1] https://www.ksh.hu/stadat_files/ene/en/ene0009.html, https://www.iea.org/countries/hungary

Power, and energy usage

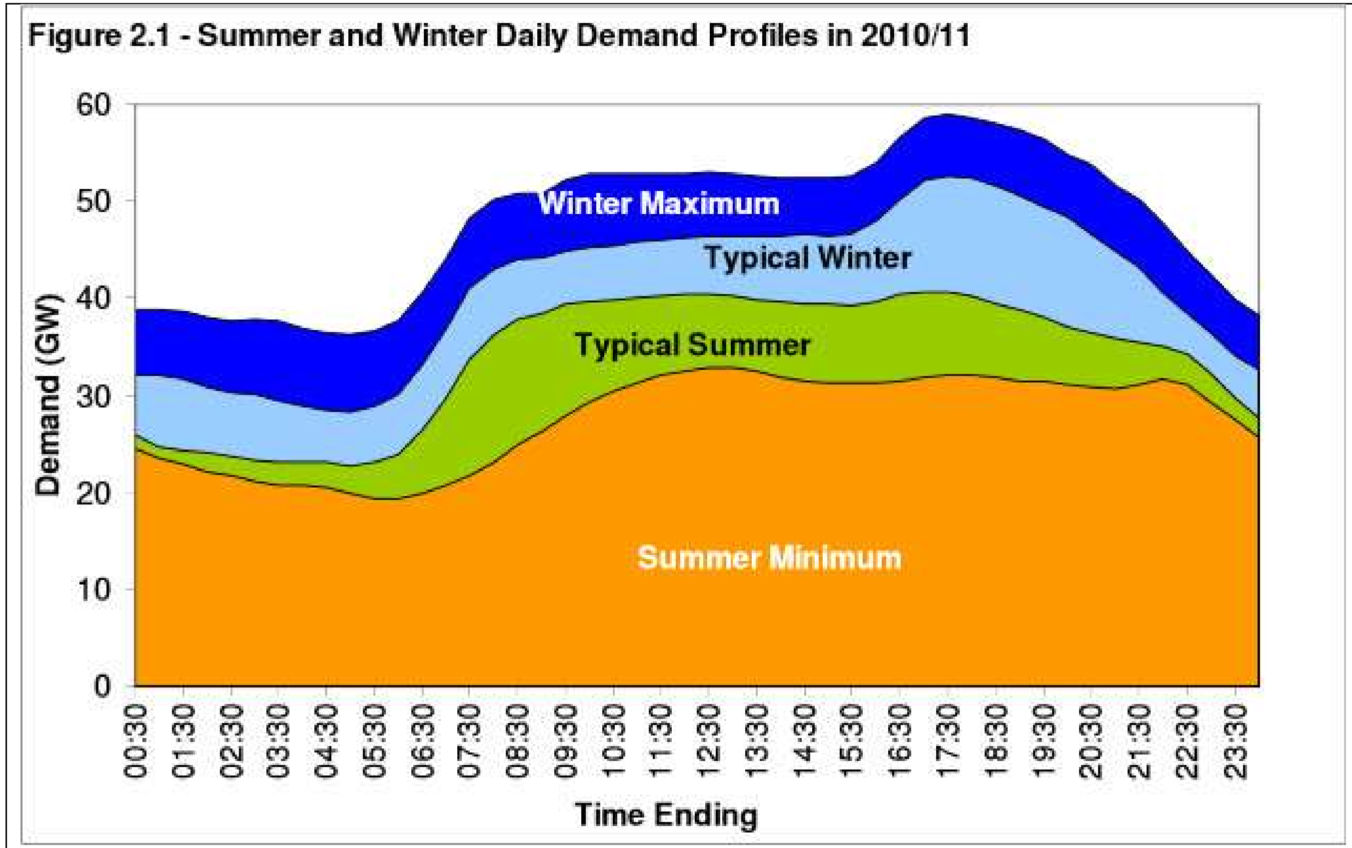
electric energy consumption per capita in Hungary	4200 kWh per year 11.5 kWh per day 0.48 kWh per hour
2-processor server computer	avarage 150 W 70-600+ W
GPU-server (8 GPU-card)	2000+ W
server rack	2-88 kW
data center	up to 650 MW
minimum energy usage of an adult human being	35+ W
Tour de France rider power output[2]	hourly 230-250 W explosive one-hour 500 W sprint finish up to 1500 W
Gasoline new passenger car	4.1 L/100 km (2020, NEDC) 38.95 kWh/100 km

[2] https://www.alpecincycling.com/en/pro-peloton/from-body-fat-to-power-output-anatomy-of-a-tour-de-france-rider/, https://en.wikipedia.org/wiki/Fuel_economy_in_automobiles

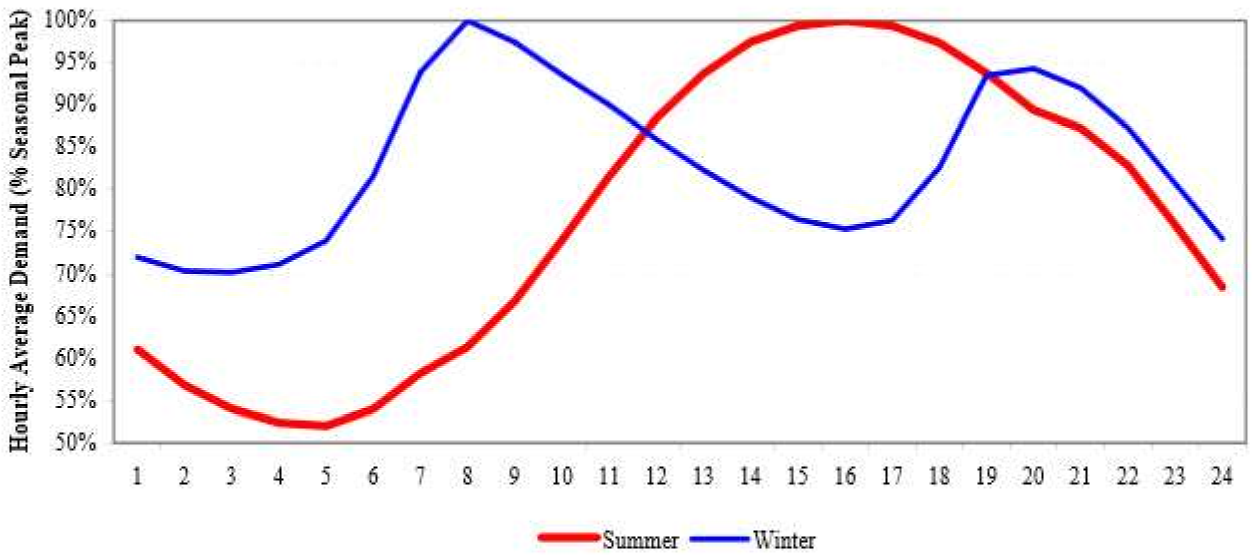
Daily energy demand curve



Daily demand for the New England Independent System Operator



UK Daily Demand © 2011 National Grid plc, all rights reserved



Daily Demand for Florida winter and summer (source Florida Public Utility Commission)

Ne tároljuk ez elektromos energiát,

- **hanem csökkentsük**
- **és tegyük egyenletessé a fogyasztást!**

Bizonyos szintű tárolás mindig szükséges lesz,

- különösen igen rövid távú tárolás (másodperces – tíz másodperces elkerülhetetlenül) szükséges;
- rövid távú (perces, tíz perces nagyságrendű – óránál rövidebb) fontosabb lesz,
- több órás vagy hosszabb elkerülendő és elvben el is kerülhető.

Unit	Symbol	Conversion		
Joule	J	= W·s = N·m = Pa·m^3 = kg·m^2·s^{-2}	3.6 MJ = 1 kWh	SI ISO 80000
watthour	Wh	= 3600 J	1 kWh = 3.6 MJ	
kilopondmeter	kpm	= 9.80665 N·m = 9.80665 J	1000 kpm = ≈ 2.724 Wh	
thermochemical calorie	cal$_{th}$	= 4.184 J	≈ 1.1622 mWh	
… calorie	cat$_4$, cal$_{15}$, cal$_{20}$, cal$_{MEAN}$, cal$_{IT}$ …			
electronvolt	eV	1.602176634·10$^{−19}$ J		
British thermal unit	BTU, Btu	https://en.wikipedia.org/wiki/British_thermal_unit		
kg (*E=mc*^{2})		= 8.987551787368176 · 10^{16} J ≈ 90 PJ		

Olajegyenérték vagy kőolaj-egyenérték (tonne of oil equivalent)

Nemzetközi Energiaügynökség (International Energy Agency, IEA) definíciója szerint 41,868 GJ/tonna, azaz 11,63 MWh/tonna.

1 MWh	**=**	**0,086 toe**
1 toe	**=**	**11630 kWh**

Energy requirement			
1 very sedentary female person daily energy requirement	6,276 kJ (1,500 $kcal_{th}$)		1.75 kWh
Energy density			
Methane	55.50 MJ/kg	37.8 MJ/m^3	10.5 kWh/m^3
Natural gas	42-55 MJ/kg		
Petrol/gasoline	44-46 MJ/kg	34.2 MJ/L	9.5 kWh/L
Diesel fuel	42-46 MJ/kg	38.6 MJ/L	10.7 kWh/L
Natural uranium, in LWR (normal reactor)	500 GJ/kg		
Natural uranium, in LWR with U & Pu recycle	650 GJ/kg		
Uranium enriched to 3.5%, in LWR	3900 GJ/kg		
Natural uranium, in FNR	28,000 GJ/kg		
U235 fission in reactor[3]	83.14 TJ/kg		
Hydrogen (fusion: $4H \rightarrow {}^4He$)	639.78 TJ/kg		
Lithium-6 deuteride (fusion: ${}^6LiD \rightarrow 2\,{}^4He$)	268.85 TJ/kg		
material+antimaterial	90 PJ/kg		25 GWh/kg

https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx, https://en.wikipedia.org/wiki/Energy_density

[3] ${}^1_0n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^1_0n$

Energy density			
Methane	55.50 MJ/kg	37.8 MJ/m^3	10.5 kWh/m^3
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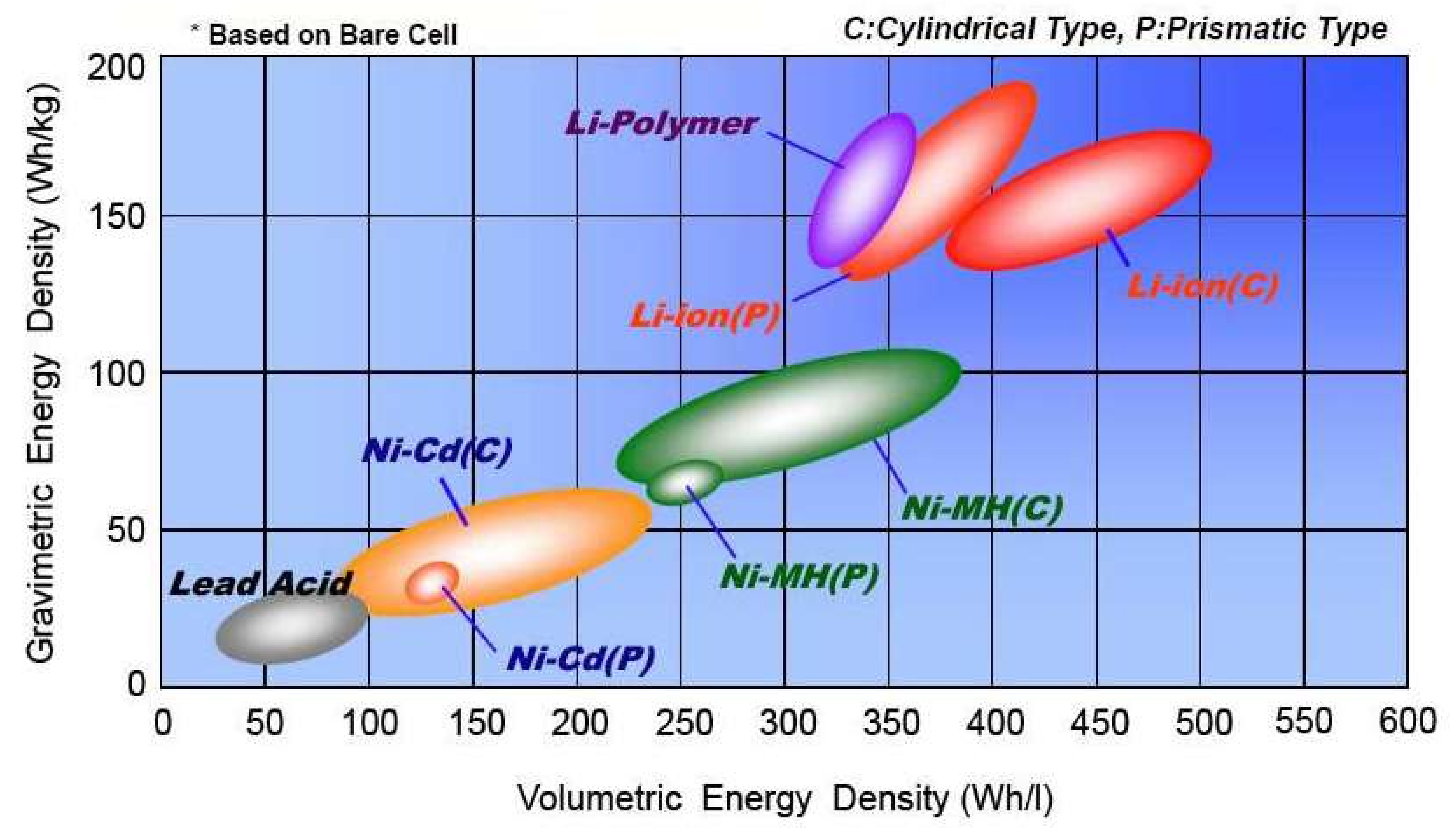
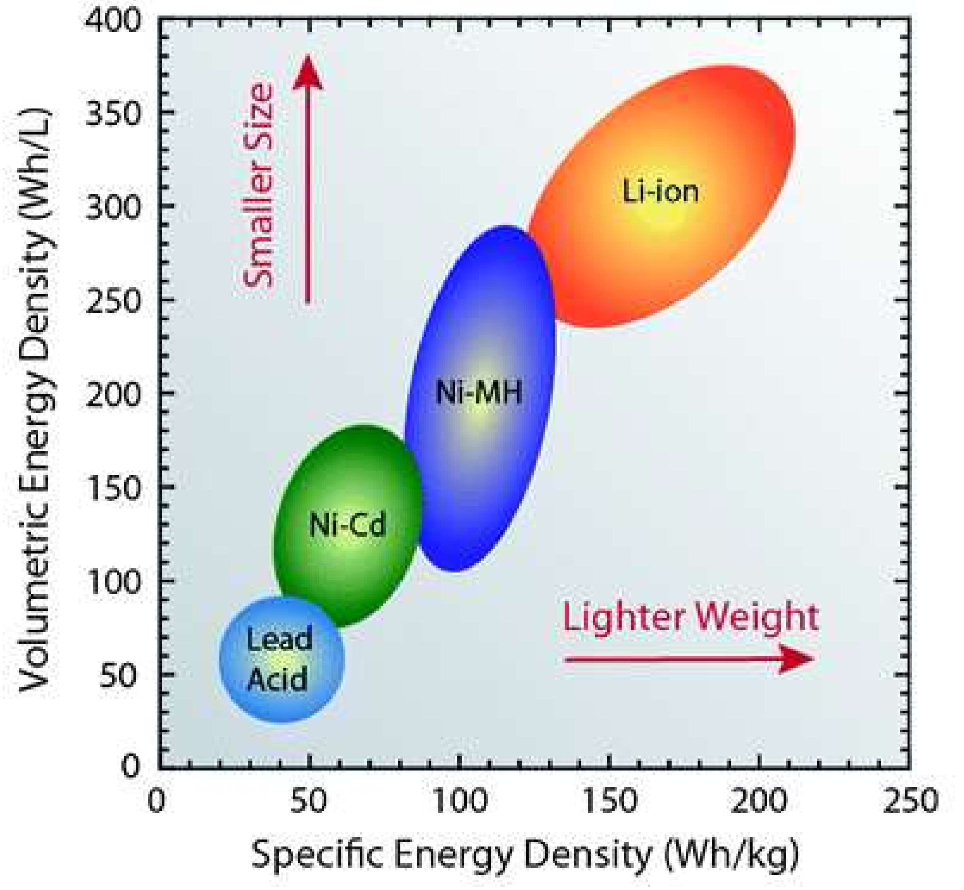
Diesel fuel	42-46 MJ/kg	38.6 MJ/L	10.7 kWh/L
1 million meterkilopond (10^6 mkp)	9.8 MJ		1.2 kWh
fly wheel			under 8 Wh/kg *up to 2600 Wh/kg*[4]
lead acid battery			30-50 Wh/kg
Li-ion battery			90-190 Wh/kg
Li-MH			60-120 Wh/kg
Hydrogen on 700 bar (42 kg/m^3)	120 MJ/kg	5 MJ/L	1.38 kWh/L
Liquid hydrogen (-252.9 °C, 71 kg/m^3)	120 MJ/kg	8.5 MJ/L	2.36 kWh/L
compressed air (200 bar, 1 m^3 -> 5 dm^3)		0.1 MJ/L	0.03 kWh/L
specific heat of water	4,186 $J \cdot kg^{-1} \cdot K^{-1}$		1.163 Wh* $kg^{-1} \cdot K^{-1}$

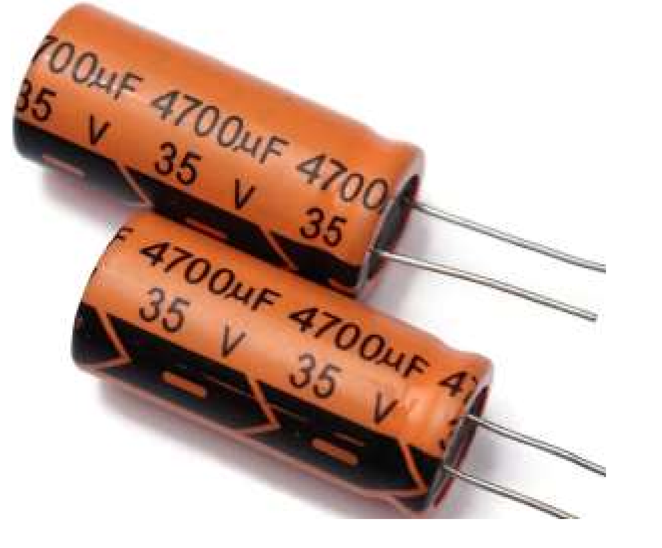
https://www.epectec.com/batteries/cell-comparison.html

[4] https://www.degruyter.com/document/doi/10.1515/ehs-2013-0010/html

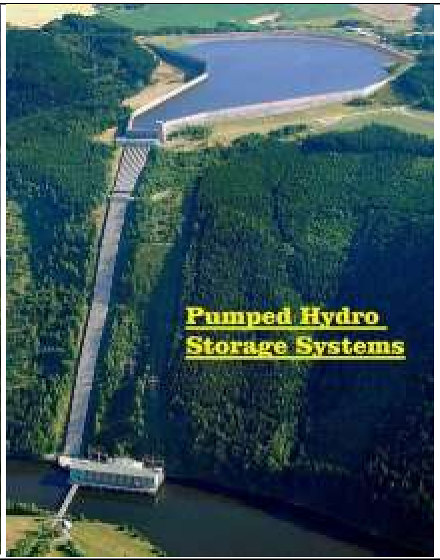




https://www.epectec.com/batteries/cell-comparison.html

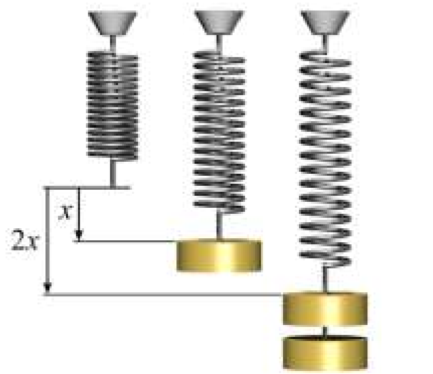

4700μF
35 V


MEDTRONIC
PULSE GENERATOR
LAURENS-ALCATEL
MODEL 9000
RADIOACTIVE
USA


Pumped Hydro
Storage Systems


EVN
Fernwärmespeicher Theiß


20L



Hooke's Law: the force is proportional to the distance. Source: Svjo / CC BY-SA 3.0

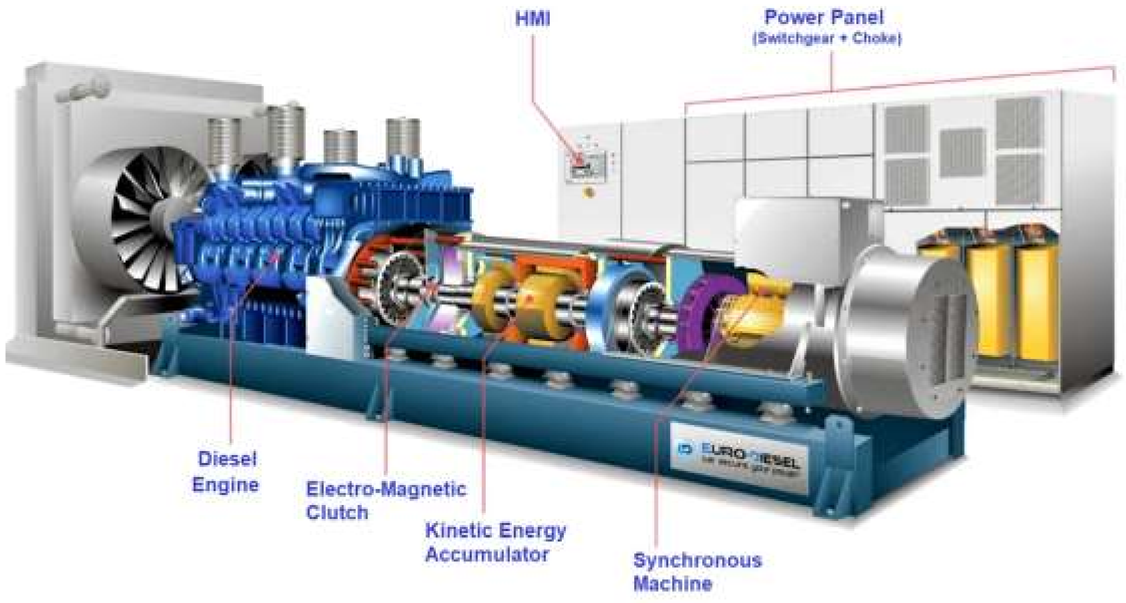


Figure: Rotary Dynamic UPS

Fernwärmespeicher des Kraftwerkes Theiß

2 GWh 50 m in diameter, 50,000 m^3, unpressurized water, heated up to 98 °C

Theiss power station – EVN AG (Wärmekraftwerk Theiß (800 MW))

"Natural gas (and heating oil) is used as the fuel."

"Natural gas is supplied via the West Austria gas pipeline, the heating oil is delivered by transport ship across the Danube and stored in tanks."
https://de.wikipedia.org/wiki/Kraftwerk_Theiß

2 GWh = 2000 kWh – How many households is this enough for, and for how long?

Contra Dam (Verzasca, Ticino)

Height 220 m
Length 380 m
Dam volume 660,000 m^3
Surface area 1.60 km^3

Construction began 1961
Opening date 1965

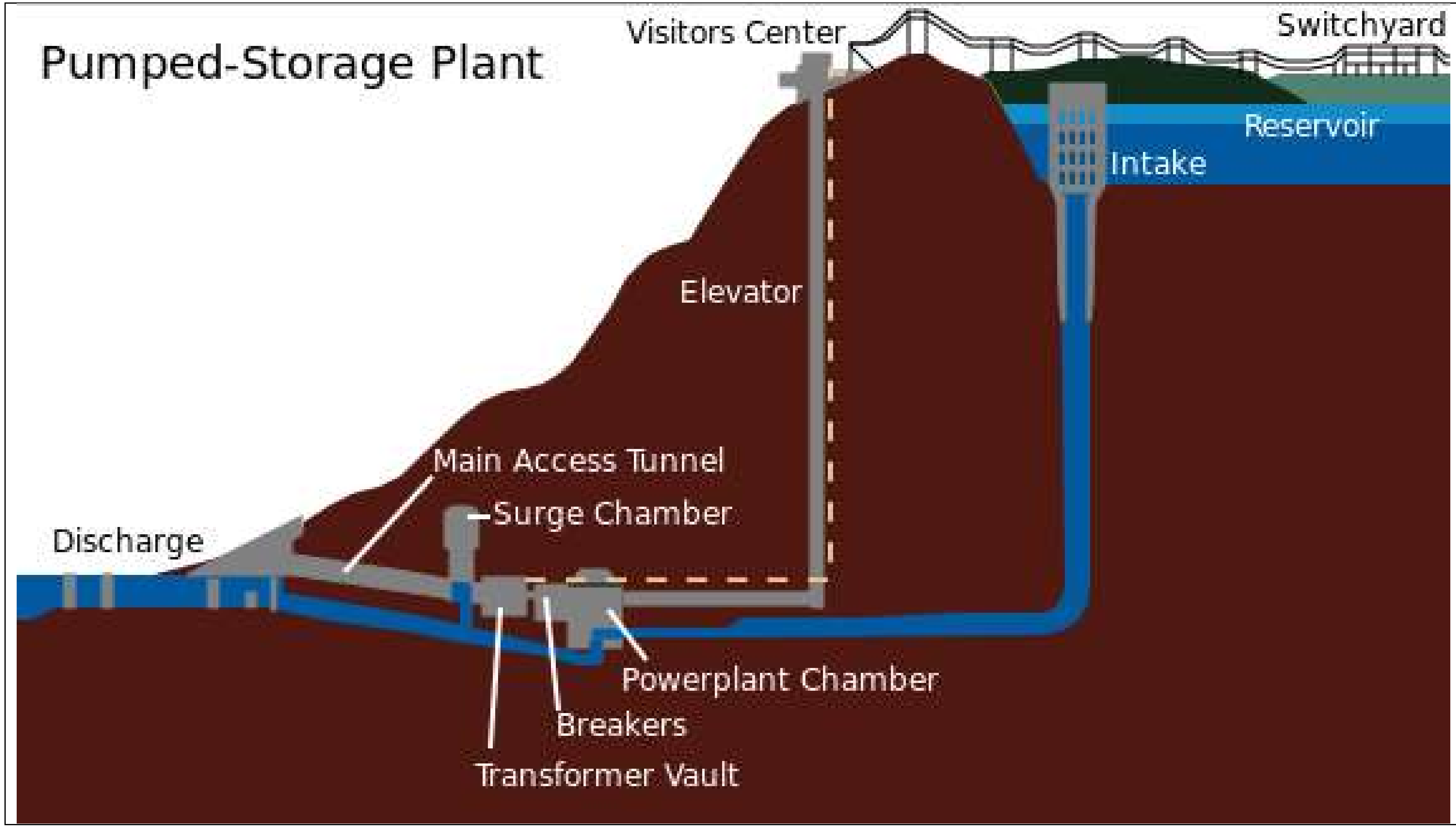
Total capacity 105,000,000 m^3
Hydraulic head 277 m

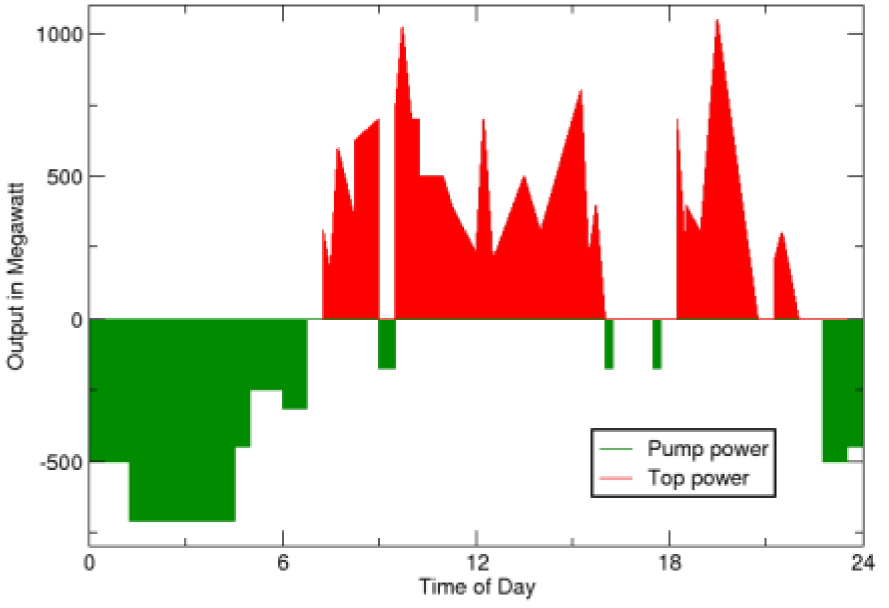
Turbines 3x35 MW Francis-type
Installed capacity **105 MW**
Annual generation 234 GWh
daily avarage: 641 MWh

Hungary electric energy consumption:

- 39.37 TWh/year
- 108 GWh/day avarage
- 4.5 GW avarage

Pumped hydroelectric energy storage





round-trip energy efficiency varies between 70%–80% (? up to 87% ?)

Country	Pumped storage generating capacity (GW)	Total installed generating capacity (GW)	Pumped storage/ total generating capacity
China	32.0	1646.0	1.9%
Japan	28.3	322.2	8.8%
United States	22.6	1074.0	2.1%
Spain	8.0	106.7	7.5%
Italy	7.1	117.0	6.1%
Germany	6.5	204.1	3.2%
Switzerland	6.4	19.6	**32.6%**
France	5.8	129.3	4.5%
Austria	4.7	25.2	18.7%
Portugal	3.5	19.6	17.8%
United Kingdom	2.8	94.6	3.0%
Russia	2.2	263.5	0.8%
Poland	1.7	37.3	4.6%

https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

Pumped Storage	Installed generation capacity	Total storage capacity
Fengning Pumped Storage Power Station • opening year: 2019-2021 • upper reservoir capacity up to 48 830 000 m^3 (40 610 000 m^3) • construction cost: US$1.87 billion	**3600 MW**	**40 GWh** annual generation: 3424 TWh
Bath County Pumped Storage Station • construction began: 1977 • opening year: 1985 • upper reservoir capacity: 58 000 000 m3 • overall efficiency: 79% • consruction cost: $4.03 billion (in 2021 dollars)	**3003 MW** an average of 2772 MW	**24 GWh** (11 hours) 2017 generation: 935 GWh

...

La Muela Pumped Storage Power Station, Spain, located 50 km from Valencia, completed 2013.

1772 MW

Specific energy storage/battery cost

Largest pumped storage:

2-5 thousand USD per kW, 40-100 USD/kWh

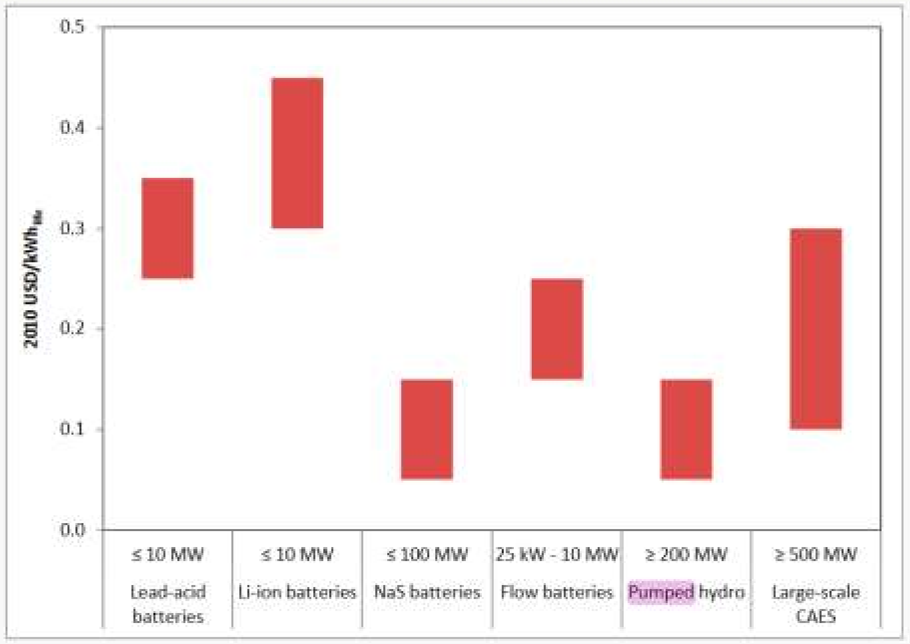


FIGURE 2.3: COMPARISON OF THE LIFECYCLE COST OF ELECTRICITY STORAGE SYSTEMS

Source: IRENA, 20

Lithium battery pack:

132 USD per kWh (2021)

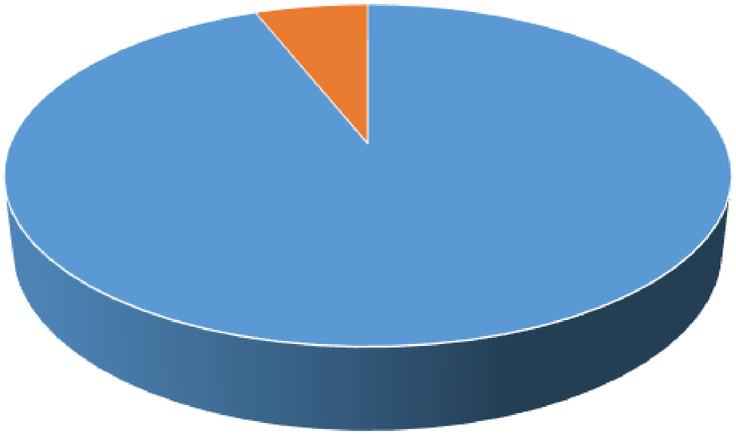
135 USD per kWh (2022)

per power (per kW)

per capacity (per kWh)

per cycle ($(kWh \cdot cycle)^{-1}$)

ROI, amortization, maintenance, risk, environment cost, lifetime cost (TCO)



Energy battery/storage types:

- **pumped hydroelectric**
- **electrochemical**
  - **batteries (e.g. lead-acid, Li-ion, Va-redox, Na-S)**
  - **fuel-cells**
- **compressed-air (CAES)**
- **molten salt**
- **power-to-gas (hydrogen, methan etc.)**
- **fly-wheel**
- **others**

Thermal energy storage

- **hot water**
- **steam accumulator**
- **molten salt**
- **others**

For cooling:

- **ice storage**
- **cold saltwater**

100 kWh Tesla P100D battery

- 444 pieces of nominal 3.6 V 3450 mAh 18650 lithium-ion cells (0.6 g lithium)[5]
- 102.4 kWh nominal capacity
- 625 kg (of which is 266.4 g lithium)
- 0.40 m3
- 160 Wh/kg
- **225 USD/kWh** (**90 000 HUF/kWh**, HUF/USD = 400)
- brand-new batteries might cost up to
- **$22,500 (9 million HUF)**
- remanufactured packs cost between $9,000-$10,000
- Tesla car batteries are said to be designed to last 300,000-500,000 miles (as purported by Tesla CEO Elon Musk), or about 1,500 cycles.

[5] https://www.fenixlighting.com/blogs/news/the-ultimate-guide-to-the-18650-battery

Tesla Powerwall

Total energy: 14 kWh
Usable energy: **13,5 kWh**
Max. max continuous: 5 kW
Maximum output (230 V): 32 A
Round Trip Efficiency: 90%
Dimensions: 1150 mm x 753 mm x 147 mm
Mass: 114 kg
IP67, IP56
Warranty: 10 years

11 500 USD (US), **5x 40 500 USD** (US)
600 to 850 USD/kWh

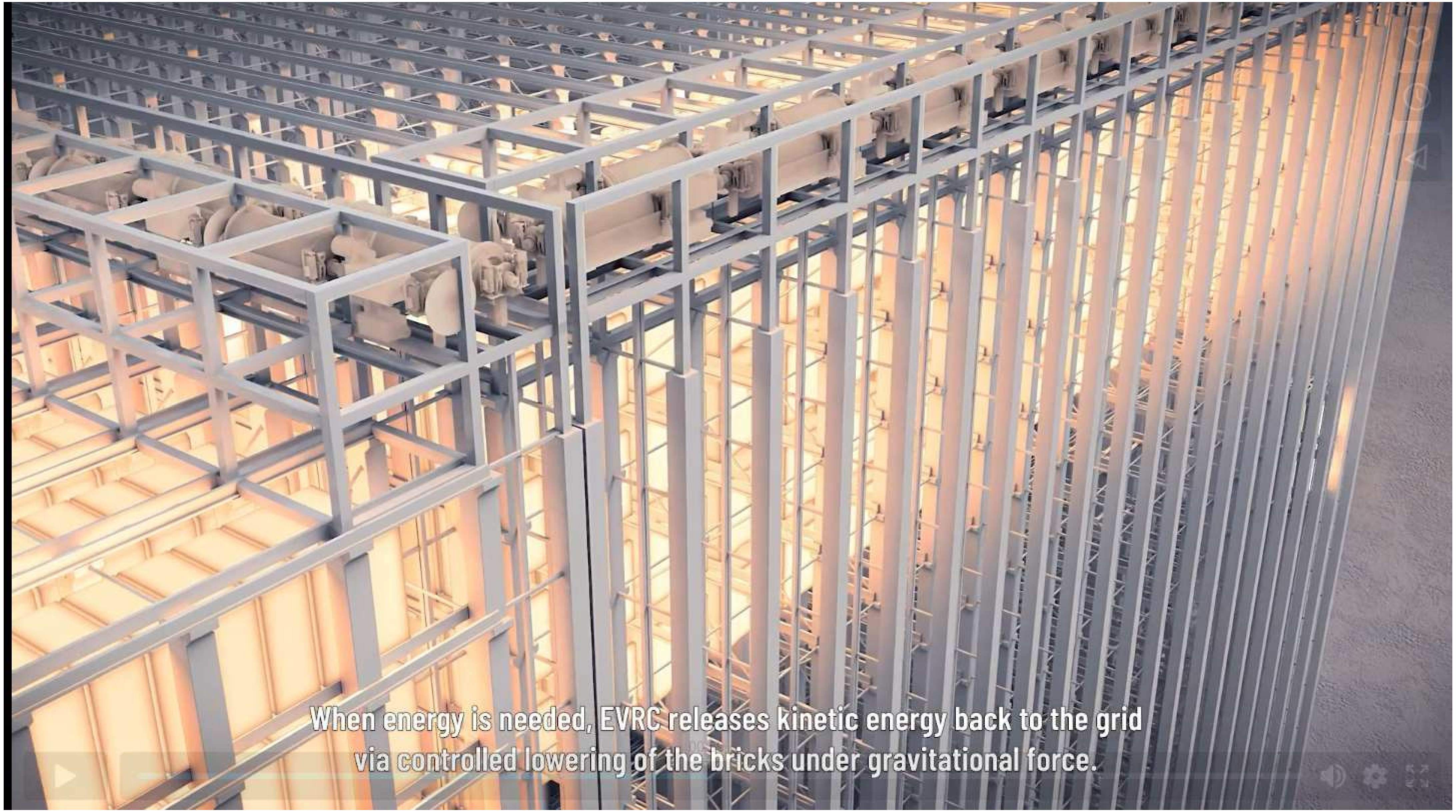
Tesla Megapack

3878 kWh
1927 kW * 2 h, 87%
907 kW * 4 h, 80%
38,100 kg
24 feet ()
2 to 2.5 million USD per Megapack
591 to 622 USD/kWh

'Feltörekvő technológiák'

Gravity energy solid storage [ ]




When energy is needed, EVRC releases kinetic energy back to the grid
via controlled lowering of the bricks under gravitational force.

Construction of the first global commercial deployment of Energy Vault's gravity-based EVx system in Rudong, China. The 25 MW / 100 MWh gravity energy storage system is on track for full customer delivery by mid-year 2023. (Photo: Business Wire)

100 MWh ≈ 36 709 784 Mpm

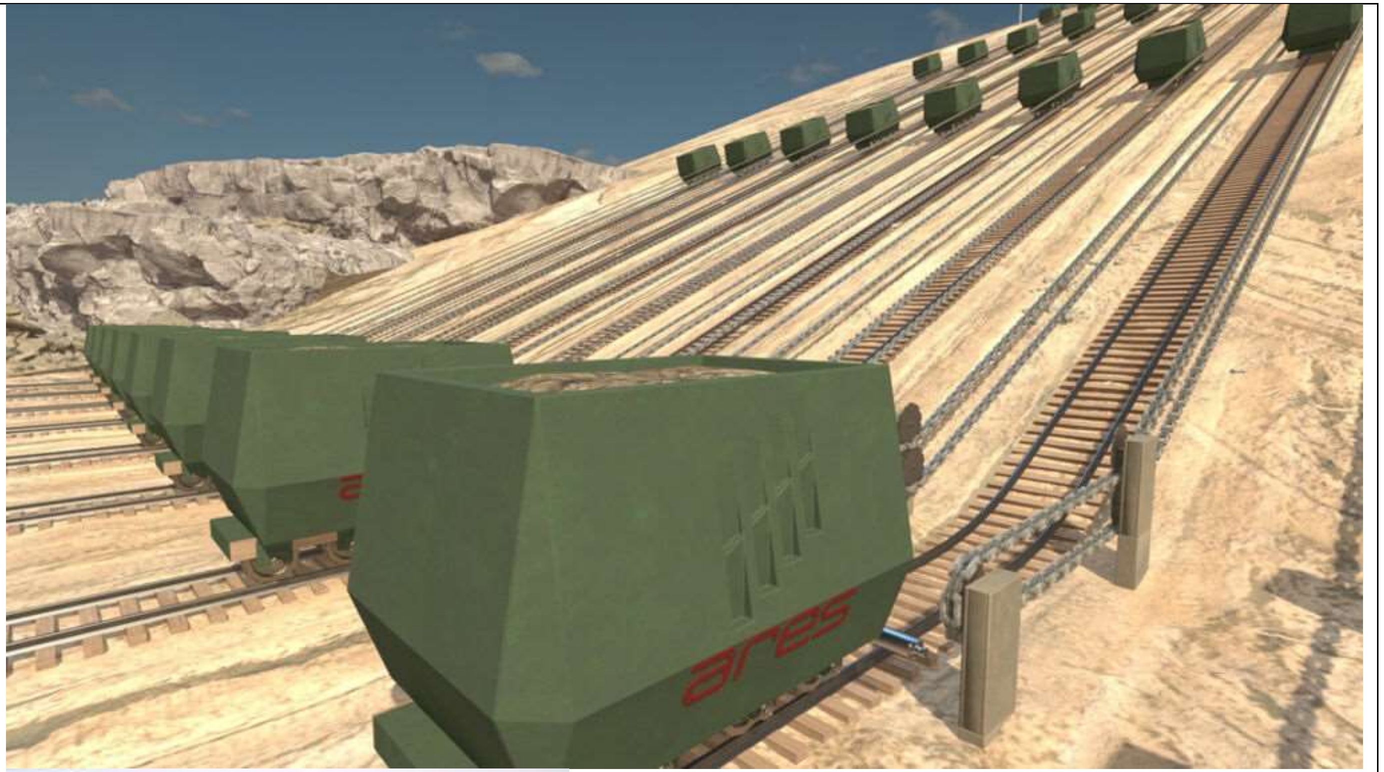
"The 100 MWh EVx system is being built adjacent to a wind farm and national grid site in Rudong outside of Shanghai. [1]

These Concrete Gravity Trains May Solve the Energy Storage Problem

These land based trains take excess electrical energy and store it through potential energy gained in large train masses.

Trevor English
Created: Aug 10, 2017 03:27 PM EST

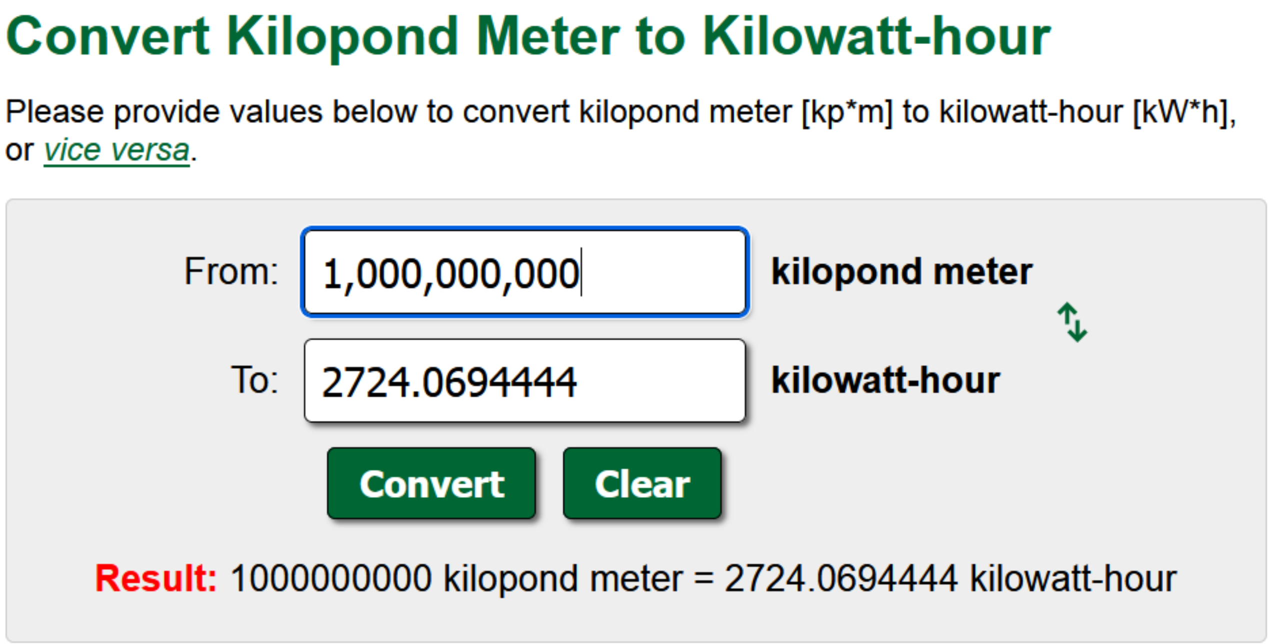
SCIENCE



"There is a lot of energy behind a train travelling downhill with 34,000 tonnes of iron ore."

1 ezer tonna 1000 méter magasba történő emelése

1000 tonna **↑** **| 1000 m** **|**	• 1 milliárd méterkilopond munka, • azaz **2724 kWh** munka • 1-2 ezer kWh visszanyerhető energia



https://www.unitconverters.net/energy/kilopond-meter-to-kilowatt-hour.htm

35 tonna 70 méterre emelése

35 tonna ↑ **| 70 méter** |	több mint 20 emeletes toronyház magasságára emelés • 2,45 millió méterkilopond munka, • kevesebb, mint **7 kWh** munka • 1-5 kWh visszanyerhető energia

1 kWh

37 tonna ↑ **| 10 méter** |	**1 kWh ≈ 367 098 kpm** **emelendő betonsúly önköltsége: több mint nettó 4 millió forint** **teljes költség: 100 millió forintos nagyságrendű** **Hol építhető fel?**

Egy 2021 Tesla Model 3 LR with LG M48 battery pack kapacitása 70 kWh,

- azaz 25.696.848,57 kpm
- azaz megfelel kb. 26 méterre 1000 tonna felemelésének

1000 tonna ↑ | **26 méter** |	1000 tonna olcsó beton ára (2022. július, 23.900,- Ft/m^3 + áfa, 2,2-2,5 kg/dm^3): nettó 9,560,000 Ft, és ez még csak maga az emelendő beton ára önmagában, • több száz milliós költség lenne a teljes emelő és tartó mű felépítése a működtető berendezések, ingatlan stb. nélkül … – és hatásfoka sem lenne 100%-os.

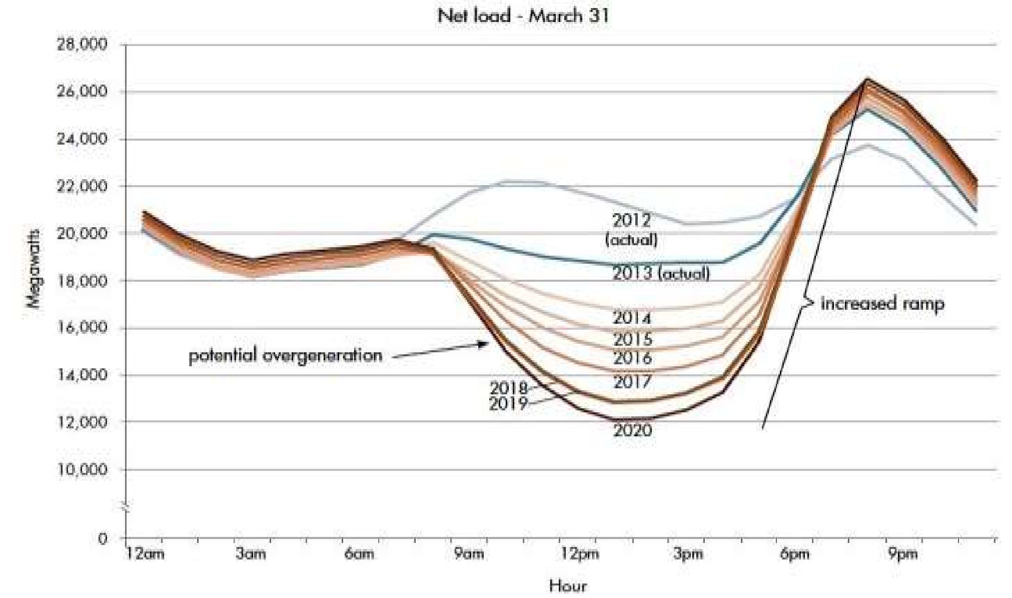
1 millió tonna 1000 méter magasba történő emelése

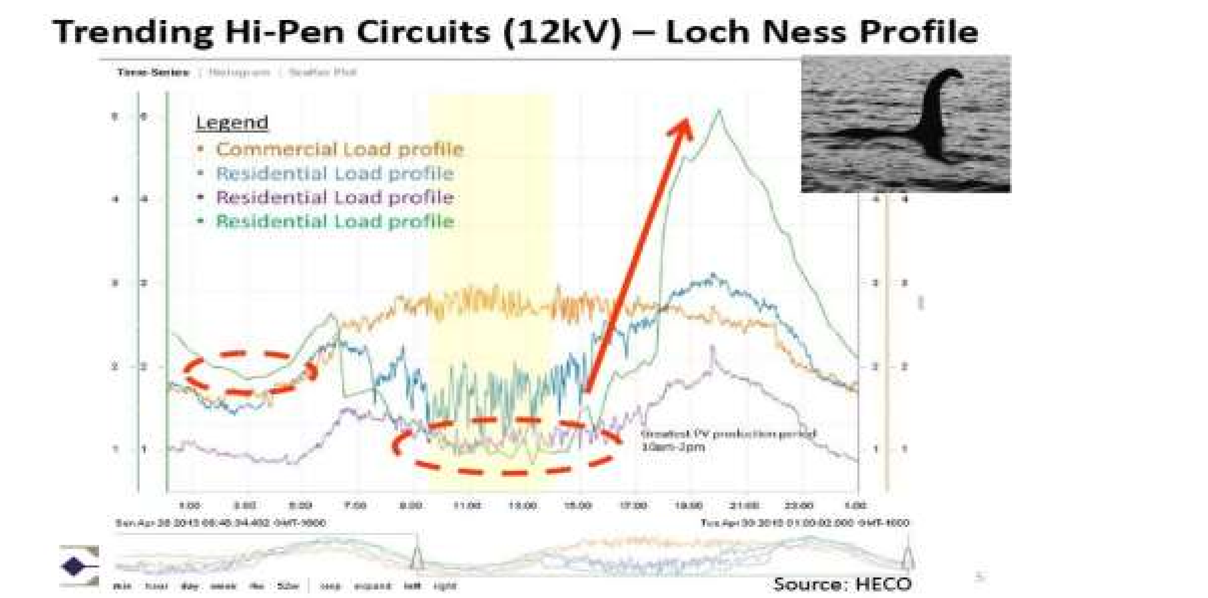
- 1 billió méterkilopond munka, azaz
- 2724 MWh munka,
- Magyarország félórás villamos energiafogyasztása

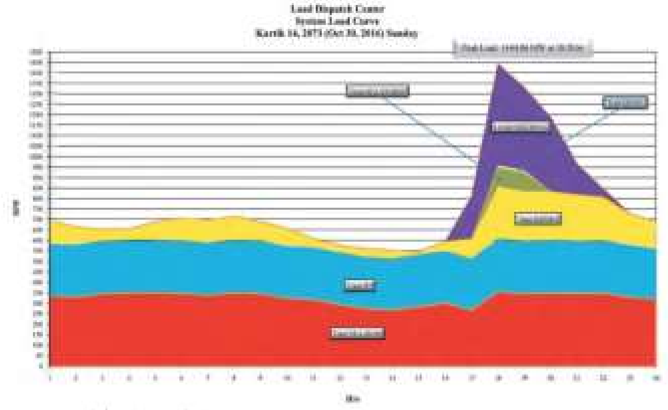
1000 000 tonna ↑ | **1000 méter** |	• **tíz- vagy inkább százmilliárd eurós nagyságrendű beruházás** (Magyarország 2022-re becsült GDP-je: 409 milliárd USD)**,** • **rendkívül jelentős üzemeltetési költséggel,**

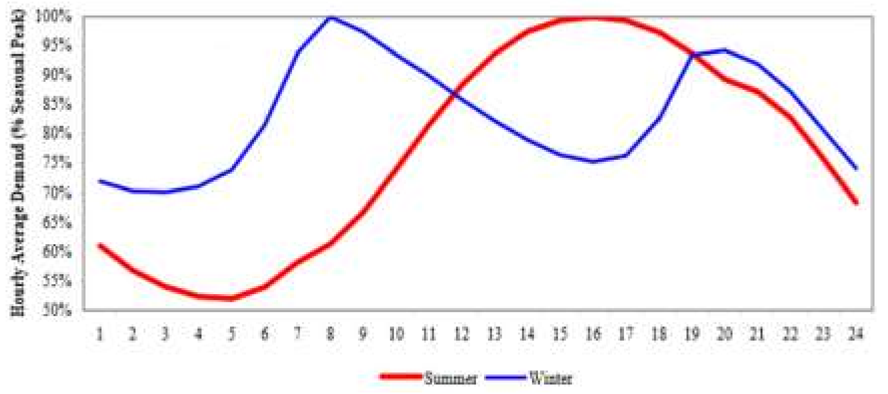
Magyarország nyilvánvalóan nem lehetne 1000 méterre emelni 1 millió tonnát, de lehetne például 10 millió tonnát 100 méter magasra emelni (mondjuk dombokon kiépített pályákon).

The duck curve, the Nessie curve, the shark curve









https://www.actu-solaire.fr/a-7806-la-courbe-de-canard-la-courbe-de-nessie-la-courbe-du-requin.html, 27 May 2018

A nukleáris energia nyújtotta lehetőségek

- új és jobb nukleáris erőmű technikák,
- jobb hatásfokú nukleáris reaktorok,
- jobban szabályozható teljesítményű reaktorok
- mini (esetleg mikro) reaktorok,
    - melyek teljesítménye még gyorsabban változtatható, mint a nagy reaktoroknak;
- nukleáris erőművekkel, amikor azok teljes kapacitására nincs szükség a vegyipar számára azonnal felhasználható hidrogén állítható elő,
- hidrogén felhasználható hidrogénezett szénhidrogének (pl. metán előállítására), mely már szállítható,
- CO_2 bontás (és egyben megkötés) is végezhető az olcsó nagymennyiségű árammal;
- szaporító reaktorok,
- pár évtized távlatában esetleg ^{238}U és tórium felhasználása az ^{235}U helyett,
- jobb hulladéktárolás és jobb fűtőanyag hasznosítás és újrahasznosítás,

…

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