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AVAILABLE AND FUTURE METHODS OF ENERGY STORAGE

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PREFACE

Climate change and drastic loss of biodiversity are probably the greatest challenges of the XXI century. To protect ourselves and future generations against the catastrophic effects these processes will have, and to stop species becoming extinct, global climate neutrality needs to be achieved by the middle of the century at the latest. One of the measures needed to do this is change of the way we produce energy. We need to stop burning fossil fuels and cutting down forests for biomass, or for example to cultivate energy plants, and damming rivers. We are mindful of the scale of this challenge: switching power sources, rapid development of the least harmful renewable energy sources, and balancing power grids.

Since the discussion on transformation of the energy sector began, we have been approaching a point at which the question arises of operation of a grid when there is a high proportion of unstable renewable energy sources. For this reason, we have reviewed the energy storage technologies that are available and under development that can help us to build a zero-emission energy mix that is climate- and biodiversity-friendly.

We trust that this report on available and developed energy storage technologies will not only serve as an up-to-date summary of technological development, but also as an important element of discourse regarding decarbonisation of the economy. This report provides intelligible information about the crucial role energy storage plays and will play, the most important storage technologies, and the most promising technologies in particular fields.

We do also encourage you to have a look at the abridged report that presents the challenge in a condensed form:

https://www.wwf.pl/aktualnosci/raport-magazynowanie-energii

We wish you enjoyable reading!

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EXECUTIVE SUMMARY

The following document contains an overview of selected energy storage technologies. The analysis is based on scientific and industry literature and presents development perspectives and main challenges related to these technologies. The development of storage solutions that allow energy to be stored and returned dynamically is an essential element for building a climate neutral economy. The analysis takes into account environmental and economic aspects, sometimes constituting real barriers to implementation of new solutions on a large scale.

European Union has adopted general and specific objectives for reducing CO_2 emissions. Climate change and energy are interrelated elements. Energy conversion and use account for around 79%[11] of EU's CO_2 emission, of which the largest share is in the energy supply and transport sectors. In order to counteract climate change, it is necessary to switch from a centralized system, based on fossil fuels, to a decentralized system, one using energy from distributed and renewable sources. Furthermore, conducting thermo-modernization of buildings, appropriate material management (in a closed cycle) and optimization of logistics (translating onto transport sector, from which approximately 900 $MtCO_2e$ originates throughout the European Union).

Utilization of energy storage technologies will allow for flexible response to increased penetration of renewable energy sources (which feature limited predictability of work characteristics) in the national power grid.

Utilization of energy from renewable resources will contribute to reduction of CO_2 emissions related to energy, heating, as well as land and water transport. The use of forward-looking energy storage technologies will also enable the change of road transport, in particular through the development of electromobility (e.g. electric vehicle fleet) and low-emission transport based on alternative fuels, with less impact on the environment. In addition, use of modern technologies will reduce consumption of fossil fuels and reduce the price of electricity, as well as reducing the costs of seasonal and daily heating and cooling of buildings.

Many energy storage technologies are currently available, and more are in the research and development phase. These include: pumped hydroelectric storage power stations (PHS), compressed air energy storage (CAES), liquid air energy storage (LAES), flywheel inertial energy storage (FES), battery energy storage (BES) and flow cells (VRFB), ultracapacitors (UC), superconducting coils (SMES), chemical energy storage, incl. hydrogen (H_2), thermal energy storage systems, which include phase-change materials and molten salts (PCM / MS) and heat accumulators (TES). Suitable applications for these energy storage technologies are listed below.

Given the key role of energy storage, this report focuses on the costs of energy storage in each of the technologies. The following table presents the technical characteristics of electricity storage and a comparison of different types of energy storage techniques in terms of costs.

Technical characteristics [9,10,25,30,31,32,73]									Costs [26,28,39,40]		
Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Sustained time of energy storage *	Life time [Years]	Discharge time*	Number of cycles [cycles]	Cycle efficiency [%]	Maturity of the technology / Level of technological readiness (TRL)[1]	Capital cost to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation and maintenance costs (O&M)
PHS (Pumped hydroelectric storage)	0,5-2	30-5 000	hours – months.	40-60	1-24 h	10 000-35 000	~70-85	Mature/implemented	750–4300	5-85	~0,0005 USD/kWh/year, ~3-8 USD/kW/year
FES (Flywheel energy storage)	20-80	0,1-20	seconds – minutes	15-20	1 sec – 15 min	~20 000-10 000 000	~89–95	Early commercial/implemented	250-650	1 000-10 000	0.0015-0.004 USD/kWh, ~6.5-20USD/kW/year
Large CAES (Large compressed air energy storage)	2-6	≥300	hours – months	20-40	1-24 h.+	8 000-17 000	~42–54 (~70% for A-CAES)[13]	Commercialized/implemented (for A-CAES – in development/TRL-9)	400–880	2-120	~0,003-0,004 USD/kWh, 3-15USD/kW/year
LAES (Liquid air energy storage)	80–120	15–400	minutes – hours.	30+	1-24+ h	7 000-17 000	55-62	In development/TRL-9	800–1 800	200–450	0,003-0,004 USD/kWh, 19-25 USD/kW/year
UC/EDLC (Ultracapacitors/double layer capacitors)	2-6	~0-0.5	seconds – hours	5-15	mSec.-1h.	50 000-1 000 000	~ 84–97	Commercialized/implemented	25-450	3000-14 000	<0,001 USD/kWh, <0,001 USD/kW/year
SMES (Superconductive coils)	0.2-6	0.1-10	ms – h	20-30	≥30Min.	up to 10 000-	~95–97	In development/TRL-9	200-489	5 000-72 000	~0,001 USD/kWh, 16-18.5 USD/kW/year
TES (Thermal energy storage)	15-80	0.1-300	min – d	5-30	1-24 h+	-	50-90	Commercialized/implemented – not applicable	100-400	3-130	120 USD/kW/year (sum of fixed and variable costs converted to fixed costs)

[1] R.F. Beims, C.L. Simonato, V.R. Wiggers, Technology readiness level assessment of pyrolysis of trygliceride biomass to fuels and chemicals, *Renewable and Sustainable Energy Reviews*, 112, 2019, 521–529.

Technical characteristics [9,10,25,30,31,32,73]									Costs [26,28,39,40]		
Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Sustained time of energy storage *	Life time [Years]	Discharge time*	Number of cycles [cycles]	Cycle efficiency [%]	Maturity of the technology / Level of technological readiness (TRL)[1]	Capital cost to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation and maintenance costs (O&M)
PCM/MS	147.7-200[273]	Up to 50MW	h	Up to 25	Hour.	>1 000 000[2]	60-97[3]	Early commercial/TRL-9, intensively in development	1 000-3 800[4]	16-220[5,273]	112/kW/year (sum of fixed and variable costs converted to fixed costs)[6]
PtG (Power to gas)	500-3 000	0-50	h – months	5-20	s – 24+ h	1 000 – 50 000+	~25–70	In development/TRL-9	500-3 000	2-15	0,0019–0,0153 USD/kW
FC-H2 (Fuel cells with hydrogen)	500-3 000	0-50	h – months	5-20	Sec.-24Hour.+	1 000-20 000	~20–55	In development/TRL-9	2000-5 500	2-35	15–46 USD/kW
Li-ion (Lithium-ion)	150-500	0-100	min – d	5-15	Min.-Hour.+	1 000-10 000	~75–97	In development/TRL-9 (implemented and commercialized)	200-900	176-900	~9-10USD/kW/year, ~0.003-0.004 USD/kWh/year
Pb-A (Lead-acid batteries)	50-90	0-40	min – d	5-15	Min.-Hour.+	500-1 300	~70–84	Mature/implemented – not applicable	300-700	75-500	~8-20 USD/kW/year, ~0.001-0.002 USD/kWh/year
NiCd (Nickel-cadmium batteries)	60–150	~0-0.5	min – d	10-20	Min.-Hour.+	20 000-25 000	~60–83	Commercialized/implemented	500-1 500	400-1 500	~12-20 USD/kW/year, ~0.0012-0.002 USD/kWh/year

[2] G. Cáceres, K. Fullenkamp, M. Montané, K. Naplocha, A. Dmitruk, Encapsulated Nitrates Phase Change Material Selection for Use as Thermal Storage and Heat Transfer Materials at High Temperature in Concentrated Solar Power Plants, *Energies*, 10, 2017, 1318; doi:10.3390/en10091318.

[3] H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza-Ruiz, X. Xu, K. Vignarooban, P. Phelan, Inamuddin, A.M. Kannan, Recent developments in phase change materials for energy storage applications: A review, *International Journal of Heat and Mass Transfer*, 129, 2019, 491–523.

[4] Z. Wang, S. Sun, X. Lin, C. Liu, N. Tong, Q. Sui, Z. Li, A remote integrated energy system based on cogeneration of a concentrating solar power plant and buildings with phase change materials, *Energy Conversion and Management*, 187, 2019, 472–485.

[5] B.C. Zhao, M.S. Cheng, C. Liu, Z.M. Dai, Thermal performance and cost analysis of a multi-layered solid-PCM thermocline thermal energy storage for CSP tower plants, *Applied Energy*, 178, 2016, 784–799.

[6] J. Lizana, M. de-Borja-Torrejon, A. Barrios-Paduraa, T. Auerb, R. Chacartegui, Passive cooling through phase change materials in buildings. A critical study of implementation alternatives, *Applied Energy*, 254, 2019, 113658.

Technical characteristics [9,10,25,30,31,32,73]									Costs [26,28,39,40]		
Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Sustained time of energy storage *	Life time [Years]	Discharge time*	Number of cycles [cycles]	Cycle efficiency [%]	Maturity of the technology / Level of technological readiness (TRL)[1]	Capital cost to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation and maintenance costs (O&M)
Na-S (Sodium-sulphur batteries)	150–250	0.5-35	Min.-Days.	10-15	Min.-Hour.+	4 500-25 000	~75–90	Mature/implemented	350-3 000	300-800	~20-80 USD/kW/year, ~0.0035 USD/kWh/year
VRFB (Valve regulated flow batteries 'REDOX' type)	16–33	0.02-30	Min.-Days.	5-10	Min.-Hour.+	120 000+	~65–85	In development/TRL-9	600-1 500	150-1 000	~12-15USD/kW/year, ~0.001-0.002 USD/kWh/year
Zn-Br (Zink-bromium flow batteries)	30–60	0.05-30	Min.-Days.	5-10	Min.-Hour.+	2 000+	~65–80	In development/TRL-9	200-2 500	150-500	~12-16USD/kW/year, ~0.001-0.0015 USD/kWh/year

*mSec-milisecond, s -second, min.-minute, h.-hour, d – days, mo–month

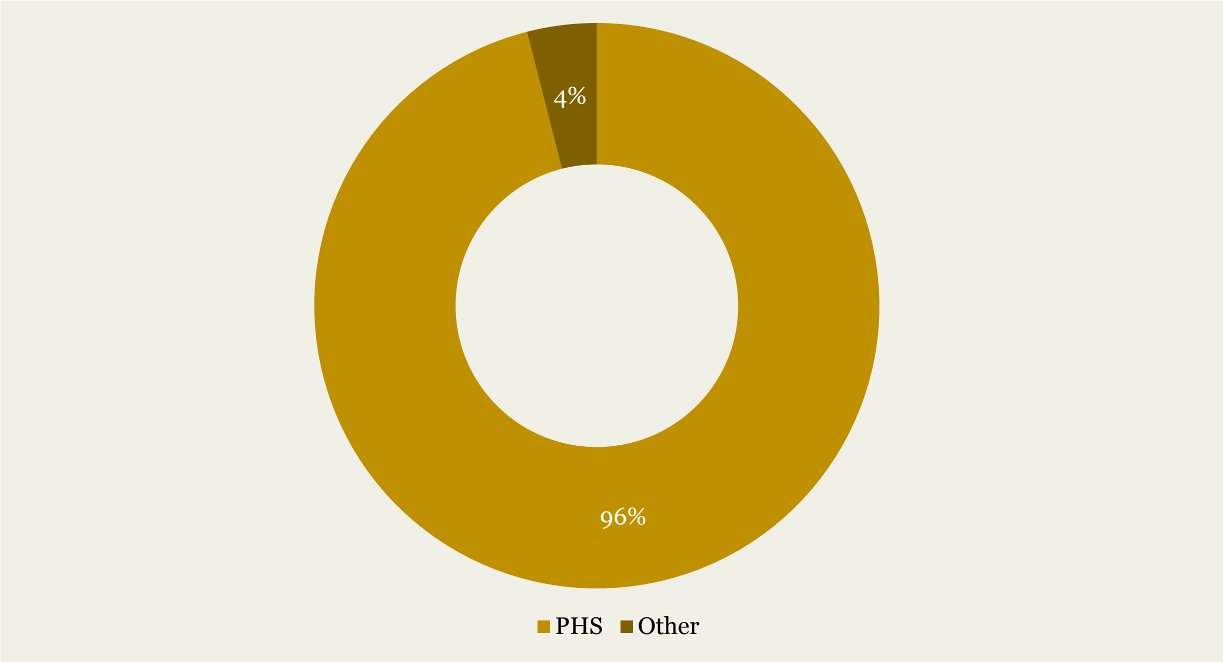
The European Alliance for batteries (cells), support for research, development and innovation for energy storage technologies forms the cornerstones of the European Union policy framework, which is based on legal acts regulating electricity markets and low-emission transport systems, with particular emphasis on development of electromobility and related to development of operational infrastructure. The table below presents main applications of energy storage technologies.

Role	Application	PHS (Pumped hydroelectric storage)	CAES (Compressed air energy storage)	LAES (Liquid air energy storage)	FES (Flywheel energy storage)	Li-ion (Lithium-ion cells)	PbA (Lead-acid cells)	NaS (Sodium-sulphur batteries)	VRFB (Vanadium REDOX flow batteries)	H_2 (hydrogen)	SMES (superconductive coils)	UC (ultracapacitors)	PCM (phase change materials)	MS (molten salts)	TES (thermal energy storage)
Making the energy grid more flexible	Seasonal storage (slow discharge)	▲	▲	▲						▲					
	Daily storage, shifting the peak power demand – hourly demand	▲	▲	▲		▲	▲	▲	▲	▲					
	Grid aid services (stabilisation of voltage, frequency response) – fast reaction				▲			▲			▲	▲			
	Households (prosumers)				▲	▲	▲		▲	▲		▲			
Road transport and shipping Requirements: light, high energy density, high voltage	Vehicles, such as: electric, zero-emission buses, plug-in hybrid vehicles				▲	▲				▲		▲			
	Autonomous off-grid infrastructure based on RES aiding development of electromobility (areas between cities, nature parks, NATURA 2000 etc.)					▲			▲	▲		▲			
Aviation and maritime shipping Requirements: high energy density, high voltage	Autonomous, zero-emission vessels based on energy from RES					▲				▲					
	Low and zero-emission aircraft, based on RES solutions, such as: flexible PV					▲				▲		▲			
	Development of sea charging infrastructure	▲	▲												
Microgrid energetic safety	Limitation of transfer losses on low population density areas					▲	▲	▲	▲			▲			
	Ensuring quality of power supply Protecting the customers from short-term power outages, change of grid voltage or frequency in areas with low population density				▲	▲	▲		▲			▲			
	Ensuring reliability of electric energy supply (limiting blackout effects), fast restoration of power in military conflict areas and natural disaster areas (such as: floods, tornados, fires)				▲	▲	▲	▲	▲	▲		▲			
Performance of heating system	Daily heat storage												▲	▲	▲
	Seasonal heat storage														▲

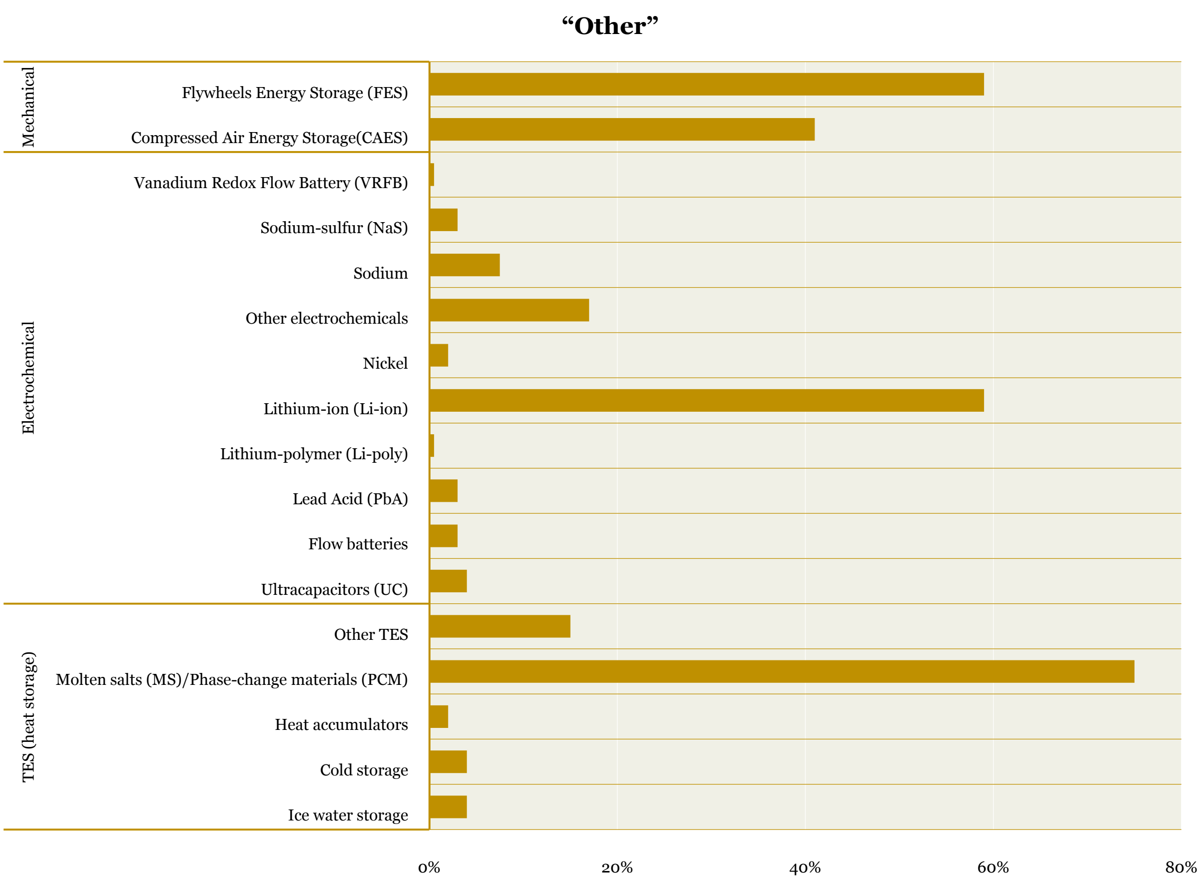
Pumped hydroelectric storage (PHS) plants account for over 96%[7] of global electricity storage capability (with a combined power of over 168GW[8] as of end of 2017).

[7] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2017, 124.

[8] S.F. Michael Manwaring, Pumped Storage Report, National Hydropower Association's Pumped Storage Development Council, Washington 2018.



Other technologies include heat storage, which constitutes 3.3 GW, electrochemical storage – 1.9GW, and mechanical storage – 1.6 GW.



They are intended mainly for large-scale daily and seasonal operation, supporting the operation of the power grid. Storage capacity of PHS can range from 100 MW (small scale installations) to 3 GW (large scale installations). In Europe, the average storage capacity of PHS installation is about 300 MW (the average monthly conversion of electricity from PHS is nearly 3450 GWh for countries in EU28 group [9,10]), which corresponds to an investment cost of about EUR 650 million [11] (excluding land), while with land the cost of a new installation is estimated at around EUR 1 billion (~ USD 3,300/kW). Energy storage efficiency in PHS is up to 85%. By 2030, more than a 10-fold increase in PHS systems on the market is expected, increasing to 2.34TGWh. According to IRENA data[12], in 2030 PHS will constitute about 45% to 51% share on the global energy storage market.

Pumped storage plants (PHS) are recommended for medium-term, long-term and seasonal energy storage applications, in order to make the power grid more flexible. The technology is mature. High potential for underwater development of PHS (StEnSea) in Poland, in the Baltic Sea.

Potential stakeholders include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solutions.

Compressed air energy storage systems (CAES) as of yet are not a commonly used energy storage technique. Currently, there are only two high-power CAES systems in the world: McIntosh (110 MWe) in Alabama, USA, and Huntorf (321 MWe) in Germany[88]. The construction of a 1,000 MW CAES installation, the Western Energy HUB in Utah, USA[89] is planned. Like PHS, CAES systems are designed for large-scale electricity storage to support the operation of the power grid. The investment costs of the large CAES power plants are 400-800 USD/kW installed capacity and 2-120 USD/kWh (depending on whether a natural or artificial reservoir is used) of storage capacity. The efficiency of the energy storage process in diabetic (with energy exchange in heat form with the environment) CAES systems is up to 54%[51,87], an example being the CAES installation in McIntosh, USA, with capacity of 110 MWe. In adiabatic systems, the efficiency may exceed 70%[13].

[9] Kougias I., Szabó S., Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse?, *Energy*, 140, 2017, 318–329.

[10] Eurostat. Infrastructure – electricity – annual data (nrg_113a). Luxembourg: Office for Official Publications of the European Communities, 2017.

[11] European Court of auditors, EU suport for Energy storage, Briefing Paper April 2019.

[12] IRENA, Elctricity Storage and Renewables: Cost and Markets to 2030, 2017.

[13] Sciacovelli A., Li Y., Chen H., Wu Y., Wang, J., Garvey S., & Ding Y., Dynamic simulation of Adiabatic Compressed Air Energy Storage (A-CAES) plant with integrated thermal storage – Link between components performance and plant performance, *Applied energy*, 185, 2017, 16–28.

Compressed air energy storage (CAES) is recommended for medium and long-term energy storage purposes, to make the power grid more flexible (similar to PHS). High development potential in northern Poland due to presence of significant amount of saltdumps[90].

Potential stakeholders include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solutions. CAES systems are developed, among others, at Warsaw University of Technology, Silesian University of Technology and the AGH University of Science and Technology.

Liquid air energy storage systems (LAES) are a relatively new energy storage technology. Currently, only two such systems were constructed in the world. The first of them was built in 2011[95] in London, and then moved to the University of Birmingham[94]. It is a research system with power of 350 kW and capacity of 2.5 MWh[95]. The second system has power of 5 MW and a capacity of 15 MWh. It was built in 2018 in Bury near Manchester, UK[95] and is currently the largest LAES system in the world. Like PHS and CAES, LAES systems are designed for large-scale storage of electricity, supporting the operation of the power grid. The investment costs of a 100 MW LAES system are 1000-1800 USD/kW of installed power and 250-450 USD/kWh of storage capacity[98]. The efficiency of adiabatic LAES systems can reach 60%[98].

Liquid air energy storage facilities (LAES) are recommended for medium and long-term energy storage, in order to make the power grid more flexible. Seasonal storage is not recommended here due to the relatively high investment costs of a LAES system. At this stage, the solution is expensive compared to alternatives, like CAES or PHS. The technology is currently in the research phase.

Potential stakeholders include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solution. LAES systems are developed, among others, at the Warsaw University of Technology.

Flywheel inertia energy storage (FES) is a technique that has been commercialized. Currently, there are many installations based on FES[101] in the world that stabilize the operation of wind farms, among others in: Australia in Coral Bay and **Marsabit** in Kenya. FES systems also perform the stabilizing function for power grid, allowing for greater penetration of renewable energy in the power system. Another example of FES system application is stabilization of frequency[101] in grids with increased penetration of energy from renewable sources, such as New York Independent System Operator (NYISO) in Stephentown, New York, USA. A 20MW flywheel was used in the facility. A similar zero-emission 20 MW system was built in Hazle Township, Pennsylvania. FES systems have a high efficiency of up to 95% and a service life of up to 20 years, with number of operating cycles up to 10 million. FES systems have low volumetric density of energy, up to 80 Wh/L, which is why they were used mainly in primary response, in order to ensure the stability of the network operation with sudden changes in frequency and voltage. The investment costs of a 10 MW FES system are 250-350 USD/kW of installed power and 3 000-10 000 USD/kWh of storage capacity. The highest energy density is featured in high speed inertia FES (rotational speed above 10,000 rpm), where the rotor is made of carbon fibre, the energy density can reach up to 100 Wh/kg[110]. By 2025, the market share of FES is expected to grow more than twice, to more than 2GW[14].

Inertial storage (FES) is recommended for applications in hybrid systems, among others: with fuel cells, electrochemical cells (i.e. Li-ion), flow cells, supercapacitors, small CAES and low-temperature micro-cogeneration systems. FES systems have also found application in KERS /ERS (*Kinetic Energy Recovery System / Energy Recovery System*) in: Formula 1 cars, hybrid vehicle propulsion systems, electric vehicle propulsion systems. FES systems can be used for storing energy from renewable sources (e.g. wind farms). It should also be noted that currently there are no legal regulations in Poland regarding the use of FES with renewable energy sources, especially in mass-scale prosumer applications. High development potential in Poland – support for the development of operational infrastructure for hybrid and electric vehicles.

Potential stakeholders include: construction (including prosumers), road transport. Poland has the appropriate technical facilities and R&D to develop this type of solutions, this technology is being developed, among others, at the Warsaw University of Technology, AGH University of Science and Technology, Poznań University of Technology.

Hydrogen (H_2) is the lightest chemical element, which in its pure form is a material with an extremely high energy density, about three times higher compared to gasoline and natural gas, and about five times higher compared to hard coal. Currently, hydrogen is mainly used as an industrial raw material, however in recent years there has been an increase in its use as an energy material. Potentially, hydrogen can be a basic and common energy carrier in the case of development of so-called hydrogen economy, which assumes a gradual departure from fossil fuels in favor of zero-emission solutions, characterized by significantly higher efficiency of energy production. The use of hydrogen as an energy storage material is virtually limitless. It can be used as storage for stationary and transport applications. Hydrogen production has been successfully demonstrated on a scale of thousands of tons per year in installations producing gas in compressed and liquid form. It is possible to produce hydrogen without a carbon footprint using water or steam electrolysers (PtG) as long as they are powered from renewable energy sources or by photocatalytic decomposition of water. Hydrogen storage is mainly carried out using the high-pressure method, with use of containers with an operating pressure of 200, 350 or 700 bar, which are commercially available in stationary and transport solutions. Storage of hydrogen is also possible by enriching natural gas with hydrogen at a level of 5-20% (hydrogen-enriched natural gas) in order to increase the calorific value of fuel distributed through gas installation. The conversion of hydrogen to electricity or electricity and heat takes place, respectively, in fuel cells (pure hydrogen) or in classic combustion process (pure hydrogen or mixed with methane), steam is the only product of reaction. Costs of hydrogen production in PtG systems are in the range of 4-10 EUR/kg (0.10-0.25 EUR/kWh), depending on the structure and size of the installation. According to IRENA[15] by 2050, 8% of the world's final energy consumption will be hydrogen produced from renewable energy (19 exaJouls ($1EJ=10^{18}J$)).

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[14] Grandviewresearch, https://www.grandviewresearch.com/industry-analysis/flywheel-energy-storage-market [accessed 17.11.2019].

[15] IRENA, Global Energy Transformation – A roadmap to 2050, 2019.

The following table shows the life cycle impact assessment for 1kg of hydrogen[16] used for network support services.

Category of impact	Unit	Unit electrolysis	Set of fuel cells	Road transport	Ferry transport	Electric energy / natural gas	Sum
Climate change	kg CO_2 eq	1,78	3,4e-04	1,34e-03	5,23e-04	-9,59	-7,81
Impoverishment of ozone layer	kg CFC-11 eq	1,1e-05	1,39e-10	2,48e-10	3,87e-11	-4,99e-12	1,10e-05
Toxicity affecting humans	CTUh	2,1e-06	3,08e-10	4,4e-10	2,86e-11	-5,24e-07	1,58-06
Acidification	molc H+ eq	6,93e-07	3,2e-06	9,31e-06	2,77e-06	-0,11	-0,11
Eutrophication	kg P eq	2,38e-05	5,35e-07	3,63e-06	6,62e-07	-3,15e-05	7,68e-04
Exhaustion of water resources	Eq m^3 water	0,1	-7,05e-06	2,07e-07	3,08e-05	0	0,1
Depletion of mineral, fossil and renewable resources	kg Sb eq	3,46e-07	6,48e-08	8,65e-08	1,43e-09	-1,48e-06	-9,78e-07

The following table presents the life cycle impact assessment for 1kg of hydrogen used for transport services and vehicles[16].

Category of impact	Unit	Unit electrolysis	Hybrid vehicles	Road transport	Ferry transport	Electric vehicles	Electric energy / natural gas	Diesel powered vehicles	Diesel fuel consum ption	Sum
Climate change	kg CO_2 eq	1,78	3,31	1,34e-03	5,2e-04	-2,9	-15,6	-	-	-13,4
Impoverishment of ozone layer	kg CFC-11 eq	1,1e-05	1,7e-06	2,5e-10	3,9e-11	-2,4e-07	-8,1e-12	-	-	1,2e-05
Toxicity affecting humans	CTUh	2,1e-06	1,0e-05	4,4e-10	2,9e-11	-6,3e-06	-8,52-07	-	-	5,1e-06
Acidification	molc H+ eq	6,9e-07	0,041	9,3e-06	2,8e-06	-0,022	-0,17	-	-	-0,15
Eutrophication	kg P eq	2,4e-05	5,4e-03	3,6e-06	6,6e-07	2,9e-04	-5,12e-03	-	-	3e-03
Exhaustion of water resources	Eq m^3 water	0,1	-0,023	2,1e-07	3,1e-05	-3,5e-03	0	-	-	0,07
Depletion of mineral, fossil and renewable resources	kg Sb eq	3,5e-07	2,2e-03	8,7e-08	1,4e-09	-2,1e-03	-2,4e-06	-	-	1,5e-04

[16] Allan G.Z., Pedersen S., Life cycle assessment of hydrogen production and consumption in an isolated territory, Procedia CIRP, 69, 2018, 529–533.

Storage of hydrogen (H_2) is recommended for use in the transport sector, seasonal energy storage, making operation of the network more flexible, as well as for the integration of the power grid with the gas network in accordance with the concept of *sector coupling*. High development potential in Poland, given that Poland is the world's fifth largest producer of hydrogen used in industry.

Potential stakeholders include gas companies, energy companies, and the petrochemical industry. Poland has the appropriate technical facilities and R&D to develop this type of solutions, among others: at the Institute of Power Engineering, Institute of Fluid-Flow Machinery, Warsaw University of Technology, AGH University of Science and Technology, Silesian University of Technology, Poznań University of Life Sciences, and Gdańsk University of Technology.

In case of hydrogen production and its injection into the gas network, such solution may be used, however, it requires an appropriate legislative framework, particularly in scope of testing the quality of hydrogen before connecting it to gas transmission or distribution pipelines.

Chemical energy storage using PtX techniques allows for synthesis of a range of energy carriers, such as synthetic natural gas SNG (produced in PtG installations), synthetic liquid fuels (PtL) or ammonia (PtA), in the process of converting carbon dioxide to commercial products using hydrogen produced in the process of electrolysis of water or steam. Due to modular design, installations belonging to the PtX group can be built on a scale from 10 kW to 20 MW. However, it should be noted that size of the installation depends on the availability of electric power supply and the appropriate volumes of electricity to power the cells. For PtG, PtL and PtA systems, the limiting factor may be the availability of carbon dioxide, carbon monoxide or nitrogen, which are reactants with hydrogen in the production of energy carriers in the form of chemicals and liquid or gaseous fuels.

Each of the products manufactured has energy values and is a form of energy storage. The most widespread application may be methane production (SNG), which can be an energy carrier for professional, industrial and distributed energy systems, as well as transport fuel for passenger vehicles or public transport. PtX installations can cooperate with gas networks, which become both a system of storage and distribution of synthetic fuels, which constitute an energy storage medium. PtX installations allow for replacement or supplementation for storage of electricity, by using installations in which liquid or gaseous fuels are produced by means of electricity. It should be emphasized, however, that PtX solutions require capture and storage systems for CO_2 for future use, which is a waste product from the combustion process. Otherwise, the technology is incompatible with creating a climate neutral economy and should not apply in this context.

Power to gas / Power to X (PtG / PtX) is recommended for use in SNG production systems, in sectors such as energy, gas and transport.

Potential stakeholders include gas and energy companies. Poland has the appropriate technical facilities and R&D to create and implement such solutions, e.g. at the Institute of Power Engineering, Institute of Fluid-Flow Machinery, Warsaw University of Technology, AGH University of Science and Technology, Silesian University of Technology, Poznań University of Life Sciences. Currently in the world, including in Poland, the first small research demonstration installations are being developed by, among others, PGE Renewable energy, which in the next step will require rescaling to a size of 1 or 10 MW.

Galvanic cells (BES) are a well-known method of storing electricity in the form of electrode materials combined with each other, exhibiting a difference of potential. Currently on the market there are mainly three types of batteries (secondary cells, reusable cells): lead-acid (**Pb-A**), nickel-metal hydride (**Ni-MH**) and lithium-ion (**Li-ion**), and until recently popular nickel – cadmium batteries (**Ni-Cd**), withdrawn due to the need to use cadmium, which is characterized by high toxicity. The market is completed by single use batteries (primary cells, disposable cells) of three main types: zinc-manganese, alkaline and lithium. Each type of galvanic cells listed here has its advantages, which means that there are applications reserved for each of them. Pb-A cells are used as starter batteries in vehicles with internal combustion engines, they have high recyclability of up to 99%. Ni-MH cells most often power flashlights and are used in hybrid vehicle drives. Li-ion batteries are mainly used for daily storage, in personal and industrial electronics, transport, e.g. electric vehicles (e.g. Tesla). These batteries have high energy density (currently up to 250 Wh/kg), efficiency up to 97% and service life up to 10 000 cycles. A downward trend in storage costs using Li-ion cells has been visible since 2010. In the 2050 perspective, the entire life cycle projection of LCOS energy storage for Li-ion cells is estimated below USD 95/MWh (and projected investment cost below USD 75/kWh). Li-ion cells are recyclable up to 80%.

The following table shows the current and future production potential of lithium-ion cells in Europe[17]. Between 2020 and 2028 Tesla declared the construction of lithium-ion cell factory with a total energy capacity of 35GWh.

Production country	Company name	Energetic capacity [GWh]	Headquarters
Currently operational objects			
Hungary	Samsung SDI Co Ldt	2	South Korea
United Kingdom	Nissan	1,4-1,5	Japan
France	Bollore SA	0,5	France
Germany	Leclanche GmbH	0,1	Switzerland
France	SAFT	0,06 (3)	France
Finland	European Batteries Oy	0,03	Finland
Germany	Custom Cells	0,02	Germany
Objects under construction, planned start of production up to 2021			
Poland	LG Chem Ltd	4 (2019), do 9-12	South Korea
Italy	SERI (FAAM)	0,2 (2019)	Italy
Planned objects, planned start of production after 2021			
Sweden	NorthVolt AB	8 (2020), 32 (2023)	Sweden
Hungary	SK Innovation	7,5 (2022)	South Korea
Germany	CATL	14 (2022)	China

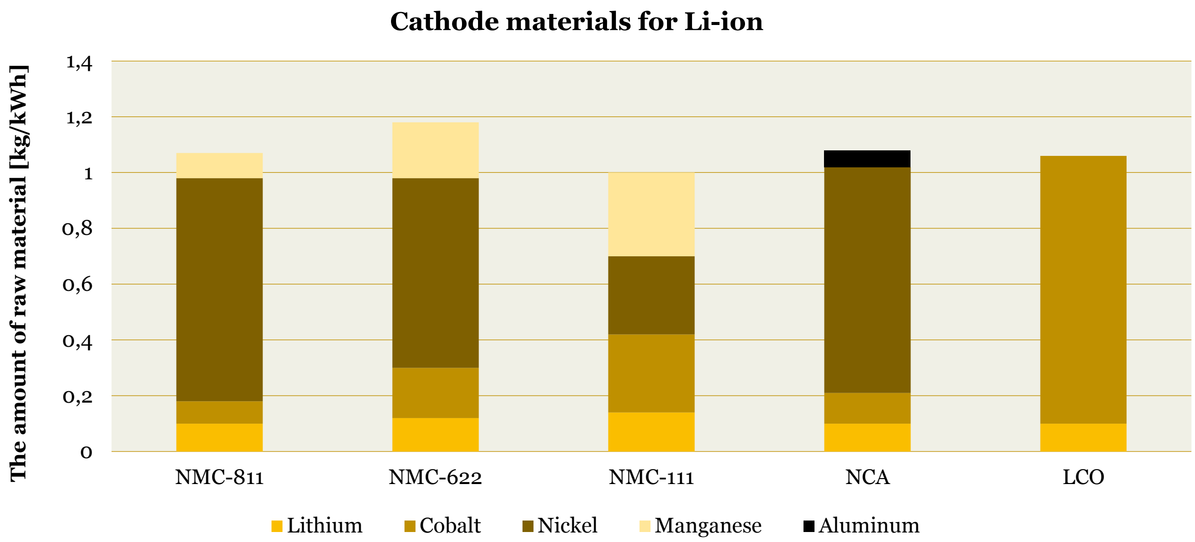
[17] EU JRC Science For Policy Report, Li-ion batteries for mobility and stationary storage applications, 2018.

The key raw materials for production of lithium-ion cells are: lithium, cobalt, nickel, magnesium and aluminum. The table below summarizes the most commonly used cathode materials in lithium-ion batteries and potential market applications17.

Main cathode materials	Main application
Nickel Manganese Cobalt oxide (NMC)	Electric vehicles, stationary storage – power grid support services, other (scooters, bicycles, medical devices)
Nickel Cobalt Aluminum oxide (NCA)	Electric vehicles, stationary storage – power grid support services, others, such as: medical devices
Lithium Cobalt Oxide (LCO)	Electronic devices
Lithium Manganese Oxide (LMO)	Power tools, medical devices
Lithium Iron Phosphate (LFP)	Electric vehicles, zero-emission buses, stationary storage – power grid support services

Nickel-manganese-cobalt cathodes (NMC-111) are used in electric vehicles, among others: Nissan Leaf, BMW i3, GM Chevrolet Bolt and mass storage applications, e.g. Tesla Powerwall. Currently, enterprises such as: LG Chem BYD or SK innovation reduce the demand for cobalt by introducing nickel-rich cathodes NMC-811. After 2025, the replacement of NMC-111 with NMC-811 is expected. Another type is nickel-cobalt cathodes with aluminum oxide, which consume 65% less cobalt than NMC-111. These cathodes are manufactured by Panasonic for Tesla electric vehicles. On the electric vehicle market in years 2011-2017 NMC cells constituted 53%, 4% were NMC cells, while LFPs constituted the remaining part of the market. In 2018, 88% of the bus market was LFP batteries, the rest of the market was NMC batteries. It is expected that by 2028 NMC cathodes will constitute 42% and NMC 58% on the electric bus market.

The following figure shows the structure of raw materials for cathodes, including: NMC-111, NMC-622, NMC-811, NCA and LCO expressed in kilograms, related to the energy capacity expressed in kWh.



By 2028, it is estimated that Li-ion cells will account for over 1.2 TWh on the global market, of which the use of cells in electric vehicles will be 1 TWh, 0.15 TWh – electronics while 0.1TWh – stationary energy storage. Nearly 600 million electric vehicles are expected to appear in the world by 2040[17]. It should also be added that the cells used in vehicles after reaching a 30% capacity loss will be reused in stationary storage market, which in the perspective of 2040 may even amount to 1.3 TWh.

The following table shows the global production of[18,19,20,21,22,46]: lithium, cobalt and graphite in the world, and their geological reserves economically justified for mining.

Raw material	2018		World reserves [in thousands of tons]
	Production [in thousands of tons]	Cena [USD/t]	
Cobalt	158,1	72 923	6 569
Lithium	61,8	14 656	13 919
Graphite	895,6	1 200	306 700
Nickel	2 300	15 355	81 000
Manganese	2 007	2 060	7 092 000

The following figure presents the raw material demand for production of lithium-ion cells by 2028, including graphite, lithium, nickel and cobalt[17]. Over the next 10 years, a huge increase in demand for all key raw materials is expected, due to the expected, more than six-fold increase in Li-ion cell production, from 290 GWh in 2018 to 1859 GWh by 2028.

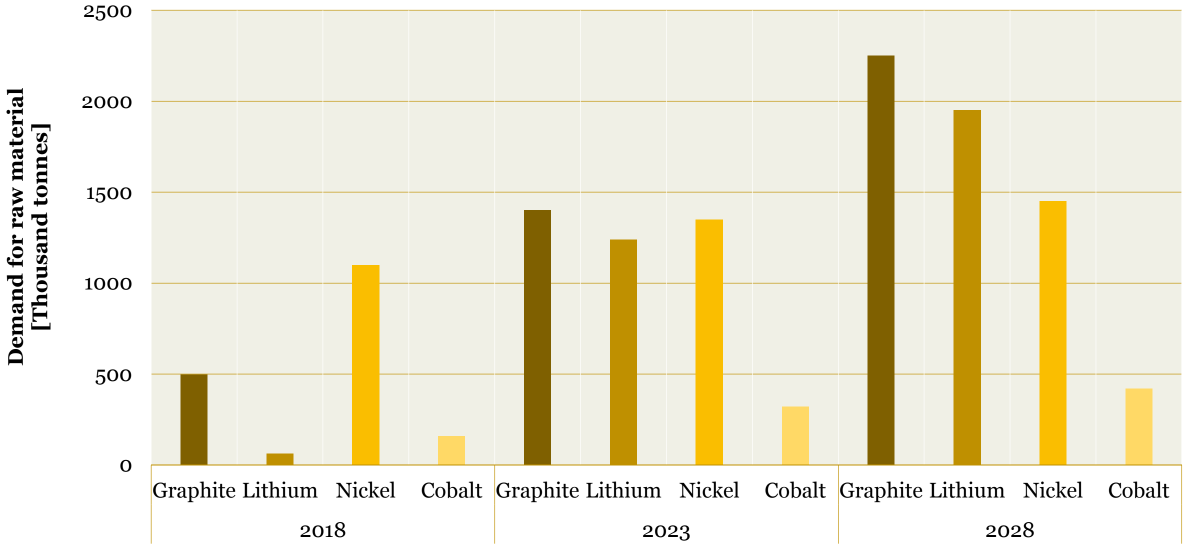
[18] Graphite price, http://www.northerngraphite.com/about-graphite/graphite-pricing/ [accessed: 02.11.2019].

[19] Manganium production, https://www.metalbulletin.com/Article/3856454/World-manganese-ore-production-hit-20mln-tonnes-in-2018-IMnI.html [accessed: 02.11.2019].

[20] Nickel price, https://markets.businessinsider.com/commodities/nickel-price [accessed: 02.11.2019].

[21] Nickel reserves, https://seekingalpha.com/article/4246690-top-5-nickel-producers-smaller-producers-consider [accessed: 02.11. 2019].

[22] Manganase reserves, https://www.statista.com/statistics/264953/global-reserves-of-magnesium-by-major-countries/ [accessed: 02.11. 2019].



Lithium-ion (Li-ion) cells are recommended primarily for use in daily storage, in road transport – in particular in vehicles with hybrid and electric drive. The technology is also used in network support services (making the network more flexible), aviation and shipping. In order to extend their life, they are connected in parallel with ultracapacitors and renewable energy sources, e.g. PV cells (the starting capacity at low / negative temperatures of Li-ion batteries is increased). Very high development potential in Poland, especially in transport sector, network support services and industrial electronics.

Potential stakeholders include: road transport (EV users), freight transport, fuel companies, among others: Lotos, Orlen, BP, Lukoil (autonomous OFF-GRID charging stations based on renewable sources of electric vehicles – supporting the operational infrastructure for EV), prosumers. Poland has the appropriate technical facilities and R&D for the development of such solutions, among others, at the Warsaw University of Technology, AGH University of Science and Technology, Wrocław University of Technology and the University of Warsaw.

Lead-acid/ composite Pb-A / CLAB cells are recommended primarily for seasonal and daily storage, in sectors including transport (vehicles and working machines with a classic drive based on internal combustion engines), construction (prosumer households), aviation and shipping. In order to extend their service life, similarly to Li-ion, they are connected in parallel with supercapacitors and renewable energy sources, e.g. PV cells (the starting capacity at low / negative Pb-A / CLAB temperatures is increased). It should be emphasized that CLABs have a higher energy density than Pb-A and therefore can be used in hybrid vehicles. CLAB batteries are being developed at, among others, the University of Warsaw.

Potential stakeholders include: road transport (users of vehicles with combustion engines), freight transport, prosumers. Poland has the appropriate technical facilities and R&D to develop this type of solution.

Sodium-sulphur (NaS) is primarily used for making the power grid more flexible and for daily energy storage. NaS batteries are being developed at, among others, the AGH University of Science and Technology.

Potential stakeholders include: distribution network operators, Polish Power Systems (PSE).

Flow cells (VRFB) are a specific type of electrochemical batteries without classic solid electrodes, only separated electrolytes (anolyte and catholyte), whose components undergo oxidation and reduction reactions (REDOX). The electrolytes are stored outside the electrochemical cell and are pumped through it during the cell's operation. Spent electrolyte can be regenerated using the same installation. The advantage of flow cells is that their power and capacity can be easily controlled by the appropriate selection of electrolytes, and their shape and size can be adapted to the specific application. The main applications of flow batteries are network support services and daily electricity storage. Flow batteries operate with efficiency of about 85% and have a very long life of up to 10 years or 120,000 operating cycles, significantly exceeding the life of classic galvanic cells, among others: Li-ion (up to 10,000 cycles), Pb-A (up to 1,000 cycles) or CLAB (up to 1500 cycles). Investment costs for vanadium cells are 600–1200 USD/kW installed power and 150 to 1000 USD/kWh (for production of 1 piece for special applications it is 1000 USD/kWh, for mass production 150 USD/kWh). In 2024 perspective[23] (based on data from Sumitomo Electric, UniEnergy Technologies, Gildemeister, Primus Power, redT Energy Storage, EnSync Energy Systems, China Local Manufacturers Covered, Dalian Rongke Power), an intensive, more than double increase in the share of flow cells on the global market is expected, to a level of over 1GWh. In 2027 perspective, Bushveld Minerals forecasts an increase in share of flow cells on the global market to 27.5 GWh[24].

Vanadium flow cells (VRFB) are recommended for use in network support services and daily electricity storage in cooperation with renewable energy and infrastructure for charging purely electric vehicles. VRFB has great potential to achieve the assumed zero-emission goals of economies, i.e. in Germany. High development potential in Poland.

Potential stakeholders include: Polish Power Systems (PSE), Distribution Network Operators (OSD), fuel companies (development of autonomous OFF-GRID charging stations based on renewable sources for electric vehicles – support of operational infrastructure for EV). Poland has the appropriate technical facilities and R&D to develop this type of solutions at, among others, the Warsaw University of Technology, AGH University of Science and Technology.

Systems based on superconducting coils (SMES) accumulate electricity in a magnetic field. As a result of the temperature decrease, the coil winding material embedded in copper or aluminum matrix undergoes phase transformation to the superconducting phase (e.g. niobium-titanium, $NbTi_2$, below 9.2 K), when the stored current can circulate in the superconducting coil[248,249]. The main application of SMES is to make grid services more flexible, e.g. voltage stabilization in RES micro-networks (e.g. wind farms, photovoltaic cells). Fast response time (in the order of milliseconds) and high power density mean that SMES systems can be used for „cold start", just like FES inertia and supercapacitors, among others: in emergency power supply systems, lasers, also in induction loads – for plasma limitation in thermonuclear fusion reactors[251]. SMES systems have high efficiency of 95-98%. The main disadvantages of SMES systems are high self-discharge of 10-15%/day, low energy density: up to 6 Wh/L and risk to health of people in proximity of a strong magnetic field. SMES systems, as a result of high magnetic field generation, affect the operation of nearby electrical and electronic devices.

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[23] Marketintellica, https://www.marketintellica.com/report/MI97555-global-redox-flow-battery-industry-market [accessed: 04. 11.2019].

[24] Bushveld Minerals & Bushveld Energy, http://www.bushveldminerals.com/wp-content/uploads/2018/11/Energy-Storage-Vanadium-Redox-Flow-Batteries-101.pdf [accessed: 03.11.2019].

Investment costs are at the level of USD 200-500/kW of installed power capacity and from 5,000 to 72,000 USD/kWh[47,48,49,50,51].

Superconducting coils (SMES) are recommended for use in voltage stabilization in RES micro-networks, i.e. wind farms. SMES systems can also perform functions in primary response (ensuring network stability in the event of sudden frequency and voltage changes) similarly to inertial systems (FES) and supercapacitors (UC / EDLC), as well as to enable quick recovery of power plant operation after network overload without additional external power supply (cold start). Furthermore, in the future they can act as consumer protection against short-term power loss, change in supply voltage or frequency. It is a very expensive solution, currently in research phase, developed at, among others, the Institute of Electrical Engineering, Lublin University of Technology.

Potential stakeholders include: Polish Power Systems (PSE), Distribution Network Operators (OSD).

Ultracapacitors (UC / EDLC) are an example of energy store that accumulates electrical charge within a double electrical layer (called *Electrochemical Double Layer Capacitors*). Porous conductive carbons are used as electrode material. Supercapacitors, like inertia FES and SMES superconductive coils, are used for short-term energy storage with a very short response time (of milliseconds). They have been used in support of network services (with voltage and frequency stabilization, in transport (in systems with internal combustion engines in large trucks they are connected in parallel with batteries or they replace one of the batteries in the set, an examples of use being cargo trucks in Australia). They were also used in electric vehicles, where they are connected in parallel with Li-ion batteries, stabilizing their work (current load). Ultracapacitors have a long service life of up to one million cycles, high efficiency up to 97%, high power density (current load up to 2,100 A for a single module), low operating costs (~ 0.005 USD/kWh) and maintenance ~ 6 USD/kW/year). The main disadvantages of supercapacitors are: relatively low density of stored energy (up to 5 Wh/kg) compared to Li-ion batteries (250 Wh/kg), self-discharge (~ 6.25%/month, 75%/year) as well as exponential change of voltage value at discharge, which determines use in power electronics systems. Investment costs at the level of USD 25–450/kW of installed power capacity and 3,000–20,000 USD/kWh[47,48,49,50,51]. An increase of supercapacitors on the global market to 0.5GW is expected by 2026[25].

Ultracapacitors (UC / EDLC) are recommended for use in support of grid services, emergency power systems, in the transport, shipping and aviation sectors. Intensive development of hybrid energy storage is taking place currently, such as: battery-ultracapacitor system used for starting vehicles, or inertial FES-ultracapacitor system used for voltage stabilization in micro networks. High development potential in Poland. Poland has adequate R&D facilities for development of this technology. Development research is conducted at, among others, the Warsaw University of Technology, AGH University of Science and Technology, Electrotechnical Institute, Lublin University of Technology.

Potential stakeholders include: prosumers, road transport (in particular electromobility) and freight forwarding, local energy clusters, shipping, aviation, and OSD.

[25] Growth Opportunities for the Global Supercapacitor Market 2017 2026: Trends, Forecast, and Opportunity Analysis, https://www.lucintel.com/supercapacitor-market-2017-2026.aspx [accessed: 17.11.2019].

Phase-change materials (PCMs) are substances or mixtures of substances that exhibit a phase transition in an assumed temperature range, which are able to reversibly store or release thermal energy while undergoing the phase transformation. Importantly, the temperature of the phase change material undergoing the phase change remains constant until the change is over. It is important that the heat of phase change is as high as possible and the thermal conductivity of the material is as low as possible, because only then will the phase change material be able to quickly absorb or release a significant amount of heat at its phase transition temperature. The main applications of phase-change materials are construction (construction materials in form of panels or admixtures for concrete or cement), transport (thermal inserts for transport of chemicals and medicine), industry and electronics (constructions of housings ensuring temperature stabilization of the electronic system), tourism and sport (thermal inserts for local heating of the human body). The average cost of phase-changeable materials is EUR 6/kg. To achieve a temperature difference of up to 6–8° C, approximately 10 kg of PCM material is used per 1 m^2 of a standard room (for PCM material in the form of microcapsules, the latent heat capacity is 110 kJ/kg Approximately 30 kg of PCM material (~ 216 USD/kWh) should be used for 1 kWh[26]. Phase-change materials have a long service life, over 1 million cycles, cycle efficiency up to 97%, quite high investment costs of 1,000-3,800 USD/kW (calculated from heat equivalent). For an example home in Great Britain[27] by using PCM materials, an annual heat saving of 4GJ was achieved, which was a saving of 15% (261.42 USD/year). The installation cost with PCM materials integrated into the building walls was USD 6,450. Return on investment without substitutes is estimated at 25 years. In the perspective of 2022[28], an increase to nearly 2.51GW is expected, while for 2024 nearly to 3.3GW of installations, using MS / PCM and concentrated solar energy.

Phase-change **materials / molten salts (PCM / MS) are recommended** for use in construction (daily energy storage), to support systems with renewable energy sources (improving efficiency of photovoltaic cells that operate at high temperatures), to improve efficiency of cogeneration systems based on i.e. Organic Rankine Cycle (ORC), in transport (cooling of battery packs in electric vehicles), for interior cooling / heating in electric vehicles (heat pump operation support). High development potential in Poland, especially in new, low or zero-emission construction.

Potential stakeholders include: construction (developers), road industry, container buildings, electric vehicles (maintaining thermal comfort of electrochemical cells). Poland has the appropriate technical facilities and R&D for the development of such solutions at, among others, the Warsaw University of Technology, AGH University of Science and Technology, University of Warsaw and Industrial Chemistry Research Institute. Exemplary support for use of PCM in construction could be equivalent programs such as „*Clean Air*", in particular for newly constructed buildings.

Thermal Energy Storage (TES) is a well-known and well-developed technology that finds application wherever the time of heat production does not match its demand. The most common distributed heat stores are water tanks that are part of domestic hot water and central heating installations. These installations are most often heated using boilers powered by natural gas, heating oil or wood / coal.

[26] Micronal PCM, https://www.maisonpassive.be/IMG/pdf/Micronal_EN.pdf [accessed: 07.08.2019].

[27] Bland A., Khzouz M., Statheros T., Gkanas E.I., PCMs for Residential Building Applications: A Short Review Focused on Disadvantages and Proposals for Future Development, *Buildings*, 7, 2017, 78; doi:10.3390/buildings7030078.

[28] Global Molten Salt Solar Energy Thermal Storage and Concentrated Solar Power (CSP) Market 2019 by Manufacturers, Regions, Type and Application, Forecast to 2024.

In recent years, an increasingly common solution is also the use of solar collectors to power this type of installation. Another, quite widespread, distributed heat storage method is the use of electric storage stoves. In turn, the most common way of short-term heat storage in heating networks is to use the accumulative capacity of the heating network itself (storage in the plant)[29]. Heat storage systems are usually used near conventional electric power plants, enabling the production of electricity with reduced heat demand. These systems are also used in conjunction with solar heating plants. In turn, cold storage systems can be used in case of hotels, public buildings, office buildings, shopping centers, and warehouses requiring storage at low temperatures. Investment costs of heat storage are 100-400 USD/kW of installed power capacity and 3-130 USD/kWh (depending on the technology used – technologies using natural geological conditions are much cheaper than in the case of artificial tanks) storage capacity. The efficiency of TES storage using water is 50–90%[30,31]. By 2025[32] the TES share is expected to increase on the market by 3 times compared to 2017, to nearly 10GW.

Heat storage tanks (TES) are recommended for use in storing heat near conventional cogeneration plants, enabling for production of electricity with reduced heat demand, in conjunction with solar heating plants (seasonal and daily storage). In case of cold storage, the main applications are: hotels, public buildings, office buildings, shopping centers, warehouses for goods requiring storage at low temperatures. In order to activate the prosumers it seems necessary to use distributed TES systems. Thanks to this, they can fully use the potential of their generation sources (renewable or non-renewable). High development potential in Poland – distributed heat storage.

Potential stakeholders include: Combined heat and power plants. Poland has the appropriate technical facilities and R&D for the development of this type of solutions at, among others, Warsaw University of Technology, AGH University of Science and Technology, Institute of Power Engineering and Institute of Fluid-Flow Machinery.

[29] Kouhia M., Laukkanen T., Holmberg H., Ahtila P., District heat network as a short-term energy storage, *Energy*, 177, 2019, 293–303.

[30] M. Kwestarz, Heat storage – types of storage, *Czysta Energia,* 12, 2016, 29–35 [In Polish].

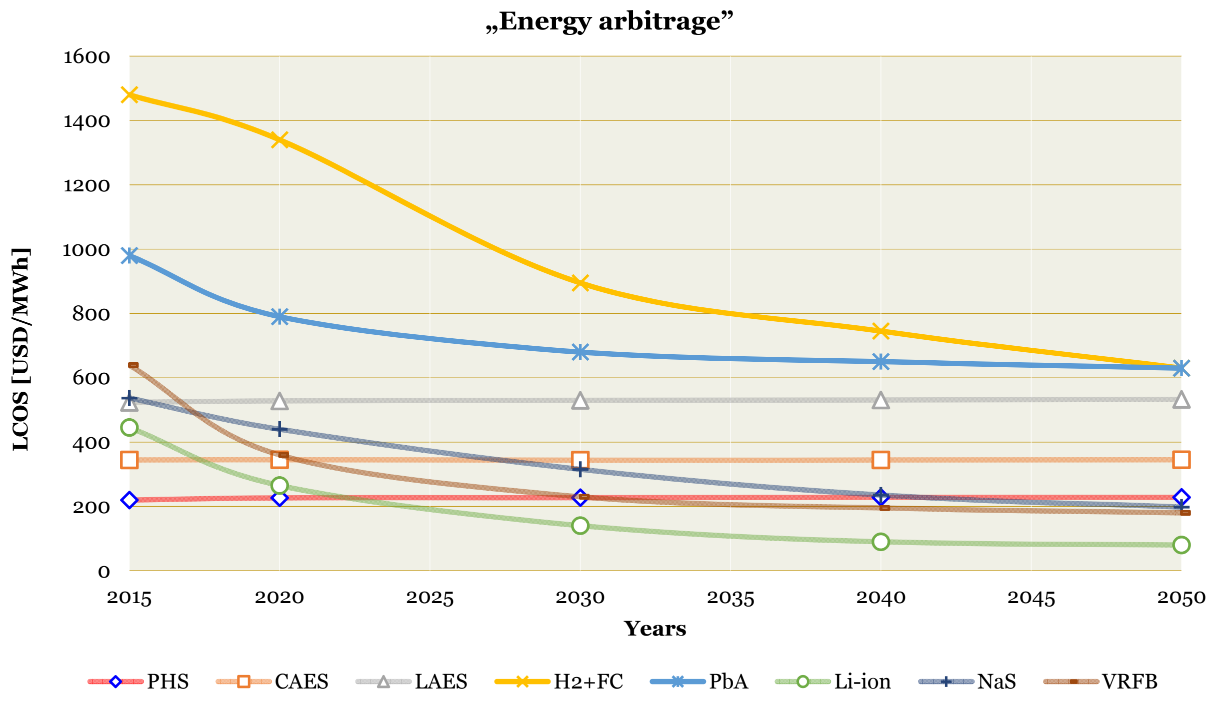
[31] Dincer I., Ezan M.A., Heat Storage: A Unique Solution for Energy Systems, Springer 2018.

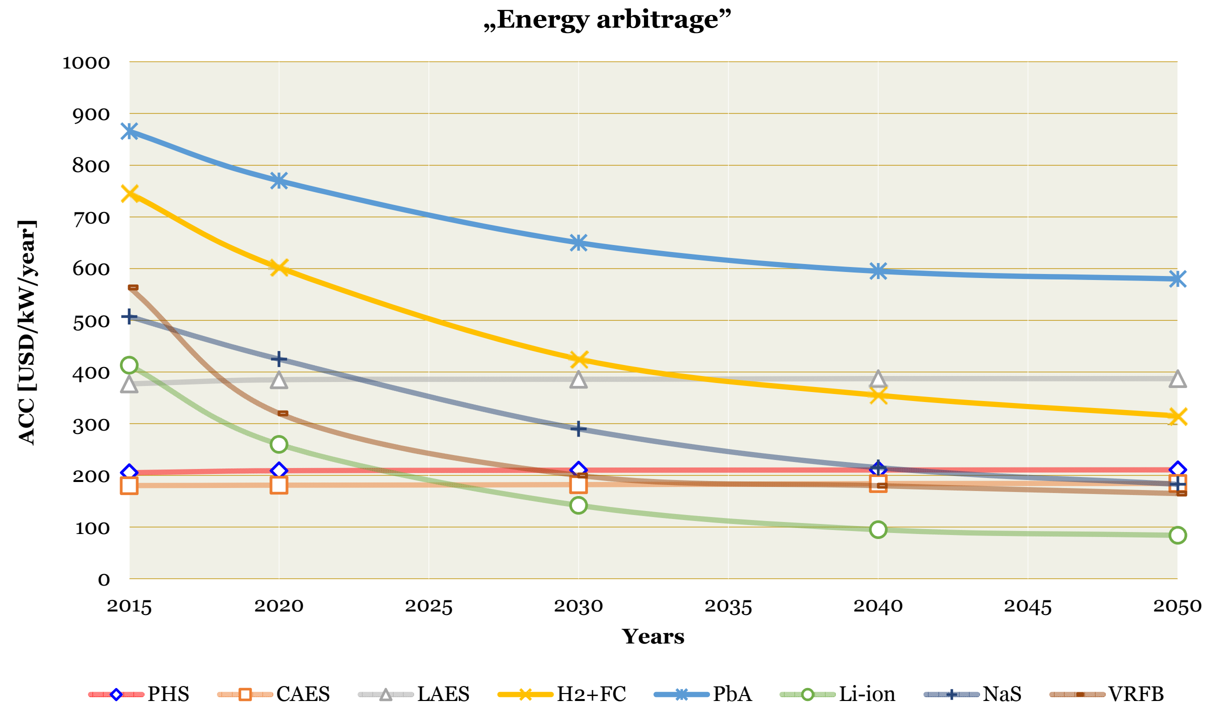
[32] Thermal Energy Storage Market Analysis By Type (Sensible Heat Storage, Latent Heat Storage, Thermochemical Heat Storage), By Technology, By Storage Material, By Application, By End-use, And Segment Forecasts, 2018–2025.

RECOMMENDATIONS FOR POLAND:

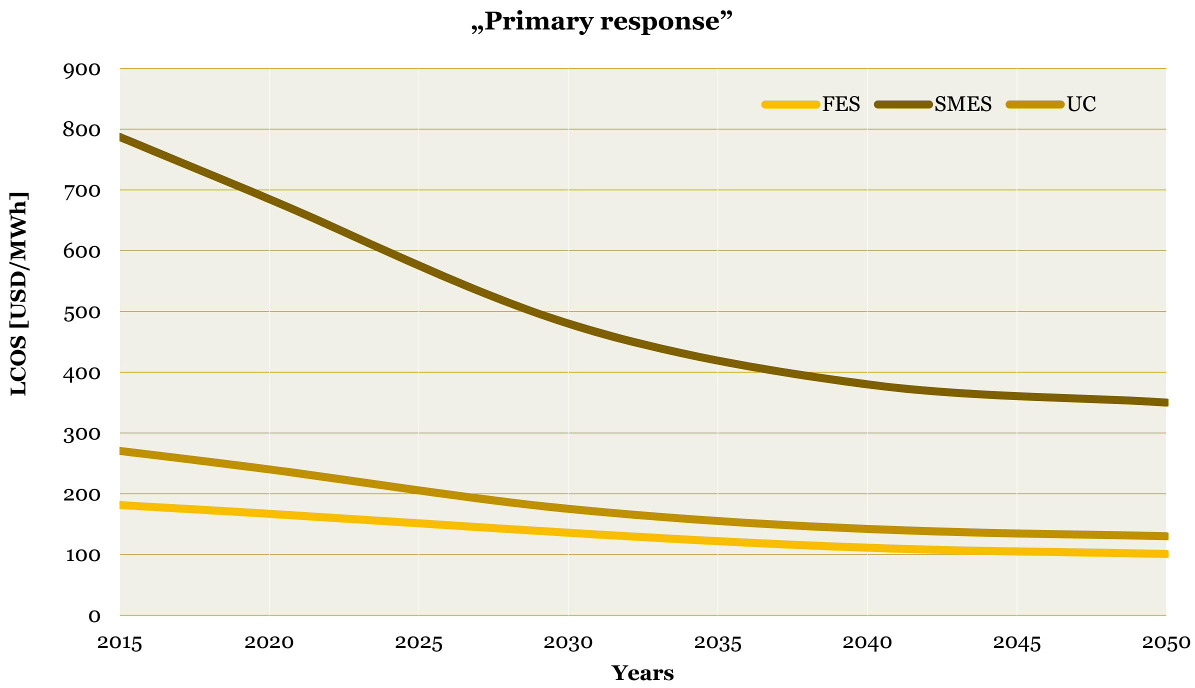
- Including information about **prospective hybrid energy storage techniques in Poland's strategic documents, which have more advantages than each of them separately** (BES-UC, VRFB-UC, BES-VRFB-UC etc.),
- **Determining the support rules** for the aforementioned techniques (including environmental impact, e.g. GHG, GWI) and life cycle, climate neutral economy perspective *in Poland.*
- **Focusing on the autonomy of infrastructure based on storage**, i.e. for the development of electromobility in Poland,
- **Determining the development potential of the domestic market regarding Recycling of energy storage components** in context of closed loop economy,
- **Determining the requirements for the current and future state of national capabilities regarding organization of utilization and recycling** of depleted components of energy storage, including: electric vehicle batteries,
- **Stimulation of incentive programs** in form of, i.e., subsidies (NFOŚiGW, ARiMR, BGK, PFR), innovation programs for enterprises, individuals, etc.
- **Obtaining an increase in the country's energy security** through the development of distributed energy storage with respect for natural resources.
- **Defining strategic research and development programs in the field of innovative and forward-looking energy storage technologies**, with an emphasis on hybrid energy storage (e.g. NCBiR, NFOŚiGW, PFR).

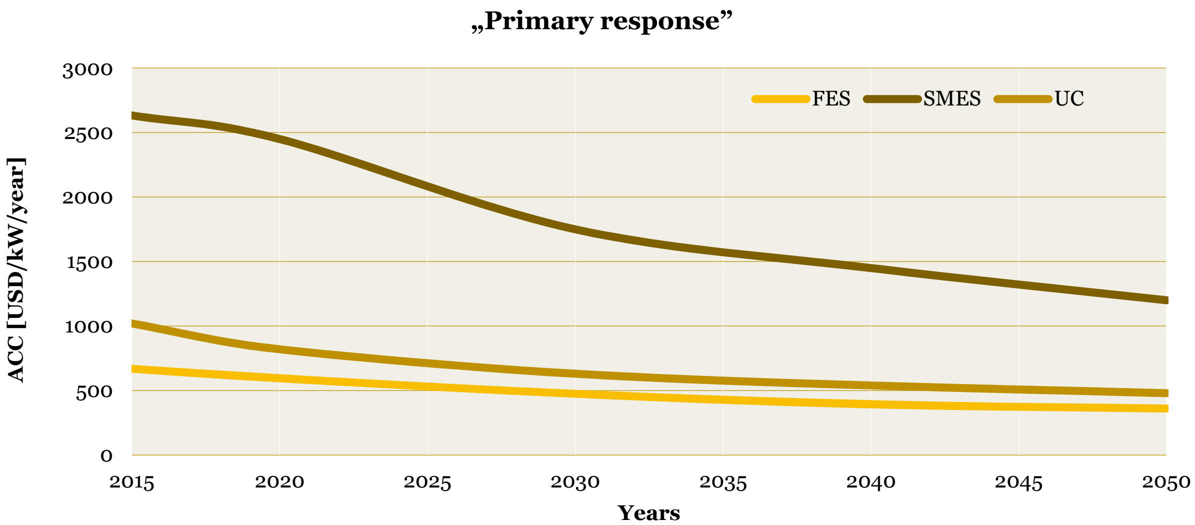
The figures below present collective charts of projection of energy storage LCOS costs and annual ACC costs of energy storage in perspective from 2020 to 2050. Particularly noteworthy is the estimated decrease in costs for Li-ion batteries (in perspective of 2050 LCOS below 95 USD/MWh and ACC below 90 USD/kW-annually). In addition to PHS, LAES, CAES and TES techniques, a decrease in energy storage costs of other techniques is also forecast in perspective of 2050.



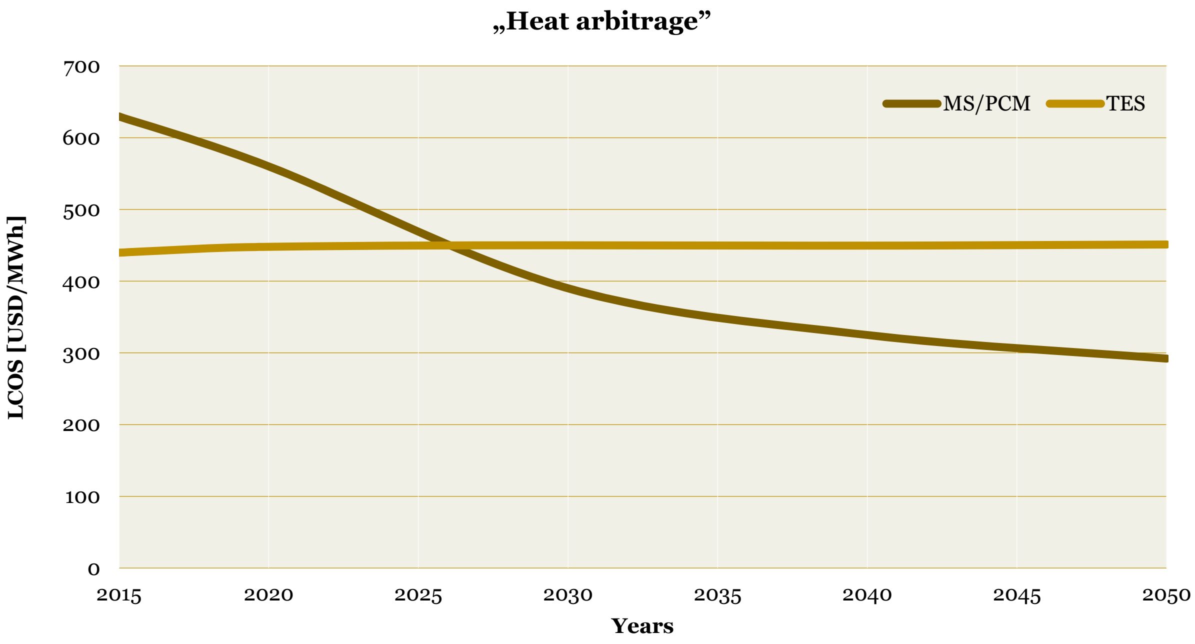


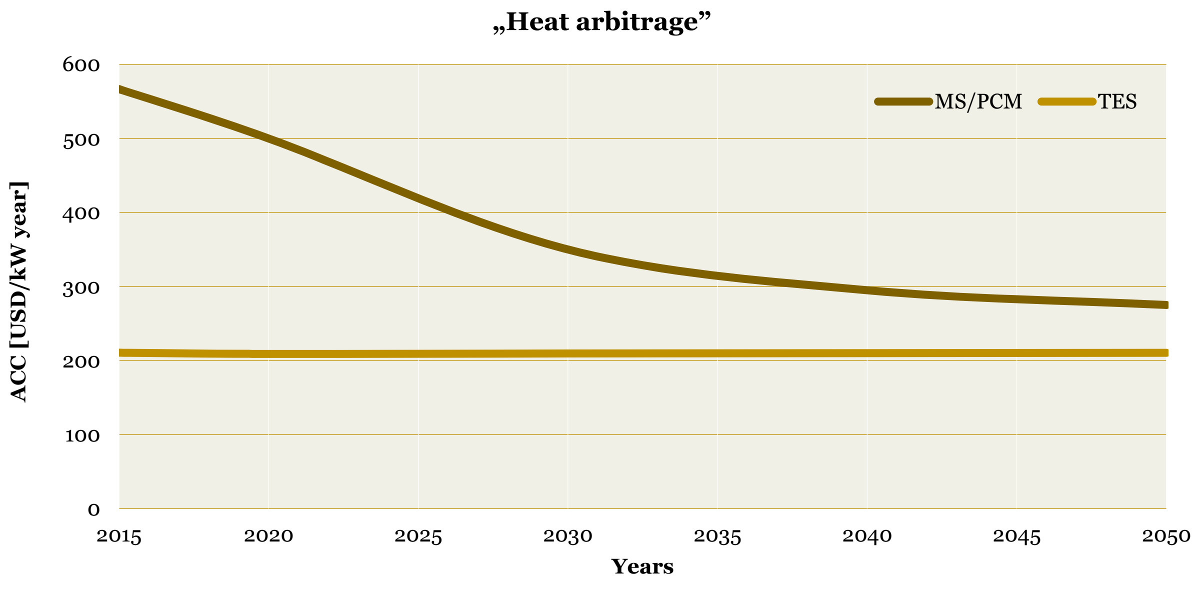
The following figures show the discounted LCOS costs of energy storage, while the figure and the discounted costs of power in the application of the primary reaction for FES, UC and SMES. In the 2050 perspective, UC and FES will be competitive on the market (cost reduction by over 50%), however SMES technology is predicted to remain too expensive to be implemented on the market.





The discounted LCOS costs of energy storage and the discounted power costs in the application of heat arbitration for PCM / MF and TES are presented below. In the case of TES technology, it is competitive on the market and used. No decrease in value of costs is expected in 2050. Considering PCM / MF, in the 2050 perspective, a decrease in LCOS and ACC by over 50% is visible. PCM / MF technology will become market competitive in the 2050 perspective.



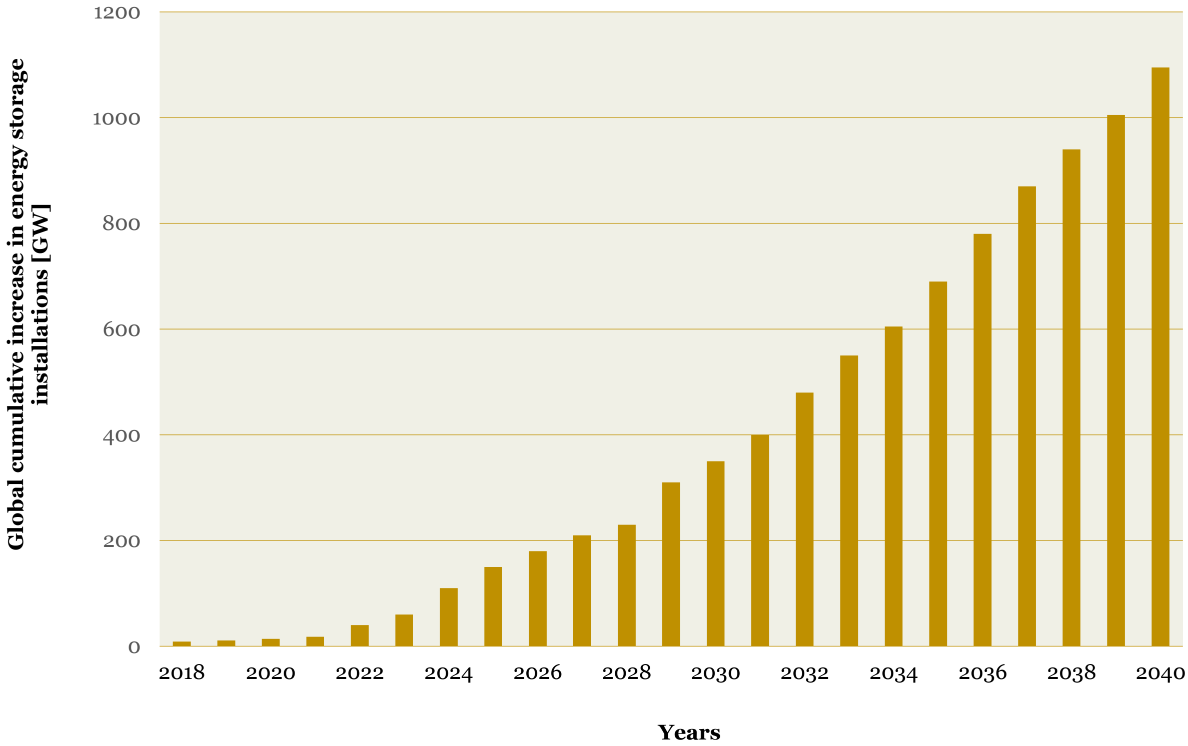


The figure below shows the global cumulative increase in demand for energy storage in the 2040 perspective, excluding PHS[33,34,35], which is a 122-fold increase compared to 2018 (installed 9 GW/17 GWh). By 2040, an increase to 1095 GW (2850 GWh) of installed capacity worldwide (without PHS) is forecasted.

33 World Energy, https://www.world-energy.org/article/1125.html [accessed: 01.11.2019].

34 BloombergNEF, https://about.bnef.com/blog/energy-storage-620-billion-investment-opportunity-2040/ [accessed: 01.11.2019].

35 Green Car Congress, https://www.greencarcongress.com/2019/07/20190731-bnef.html [accessed: 01.11.2019].



It should be stated, taking into account the technical and economic development of energy storage technology, that a world in which we produce energy only from the sun and wind is possible in the long run.

LIST OF DEFINITIONS

Adiabatic CAES system – energy storage system using compressed air, which also stores the heat generated by compression to be used later during the expansion process (while unloading the energy store).

Adiabatic LAES system – energy storage system using liquid air, which also stores heat generated by compression to be later used during the expansion process (during the discharge of energy storage).

Electric energy arbitration – buying and storing electricity at a low price when there is too much of it on the market, and selling at a high price on the wholesale or retail market when its quantity is limited.

Heat arbitration – purchase and storage of electricity for heat production at a low price and sale of heat at a high price on the wholesale or retail market.

A zero-emission bus – a „bus that uses electricity generated from hydrogen in its fuel cells to drive, or an engine, whose duty cycle does not lead to greenhouse gas emissions or other substances covered by the greenhouse gas emissions management system"[36].

Energy security – is „the state of the economy allowing for coverage of current and future consumer demand for fuels and energy, in a technically and economically justified manner, while maintaining the requirements of environmental protection"[38].

Diabatic CAES system – a system that stores energy by compressed air, which transfers heat generated by compression to the environment. When discharging the store, this system uses additional fuel to heat the compressed air before the entry to the turbine.

Diabatic LAES system – energy storage system using liquid air, where heat generated by compression is released into the environment. When discharging the store, this system uses additional fuel to heat the air before entry to the turbine.

Coal power plant – is an industrial plant that produces electricity using the energy from burning coal or lignite.

Gravimetric energy density – energy density stored in a given technology related to the mass unit of the warehouse (for example kWh/kg).

Total electrical installed power of the renewable energy installation – „is the sum of the active rated power (at the rated power factor $\cos\phi_n$) of all the generation devices included in this installation"[37].

Electricity storage – is the use of an appropriate set of methods and technologies allowing for large-scale electricity storage, in order to improve operation of the power grid, or independence from the

[36] Polish Act on electromobility and alternative fuels of 11 January 2018.Ustawa o elektromobilności i paliwach alternatywnych z dnia 11 stycznia 2018.

grid in case of prosumer OFF-GRID micro-installations that contain Renewable Energy Sources, or network balancing and demand / supply.

Energy mix – is the structure of energy production and consumption, according to the criterion of energy carriers (e.g. electricity or diesel) or according to production methods. Is one of the indices useful in the study of energy security.

Installed electrical power – „should be understood as rated active power (*rated power, nominal power*) specified by the manufacturer, expressed in [W] or multiples of this unit ([kW] or [MW], achieved at the rated power factor $\cos\phi_n$"[37]

End customer – is a „customer purchasing fuels or energy for his own use. Does not include: electricity purchased for the purpose of production, transmission or distribution of electricity and gaseous fuels purchased for the purpose of transmission, distribution, storage of gaseous fuels, liquefaction of natural gas or regasification of liquefied natural gas"[38].

Distribution System Operator (DSO / OSD) – is an „energy company dealing in distribution of gaseous fuels or electricity, responsible for network traffic in a gas distribution system or power distribution system, current and long-term security of the system's operation, operation, maintenance, repairs and necessary network expansion distribution, including connections with other gas systems or other power systems"[38]. W In Poland, DSO operators include: Energa Operator SA, Enea Operator SA, Tauron Dystrybucja SA, PGE Dystrybucja SA and INNOGY STOEN Operator Sp. z o.o.

Transmission system operator (TSO/OSP) – is an „energy company dealing in transmission of gaseous fuels or electricity, responsible for network traffic in gas transmission system or electricity transmission system, current and long-term operational security of this system, operation, maintenance, repairs and necessary network expansion transmission, including connections with other gas systems or other power systems. „ In Poland, the TSO operator is Polish Power Grids (PSE)[38].

Alternative fuels – fuels used for propulsion of motor vehicles or watercraft, which are a substitute for fuels derived from crude oil or obtained in its processing (diesel and gasoline). Alternative fuels include: hydrogen, liquid biofuels, synthetic and paraffinic fuels, compressed natural gas (*CNG*), including biomethane derivatives, liquefied natural gas (*LNG*), including biomethane derivatives, liquid petroleum gas.

Electric vehicle (*Battery Electric Vehicle*) – is a car vehicle that uses only[39] rechargeable electrochemical cells, including Li-ion, Ni-MH, Pb-A, serving as secondary power sources. An electric vehicle can be used to transport people or goods, as well as a mobile storage and energy source, so-called *Vehicle to Grid* (V2G), i.e. as an element integrated with the power grid. The main idea of the mobile energy storage is charging the electrochemical cell set in off-peak hours, when the price of electricity is low (the cheapest) and the subsequent use of stored energy for household needs or its resale to the electricity grid when the price is high.

Hybrid vehicle (*Plug-in Hybrid Electric Vehicle*) – is a gasoline-electric or diesel-electric car in which electricity is accumulated in a reversible electrochemical cell, by connecting to an external power source[40].

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[37] Information from the President of the Energy Regulatory Office No. 60/2017 on the use of the concept of "installed electrical capacity", August 21, Warsaw 2017.

[38] The Act of the Energy Law April 10, 1997, consolidated text as at May 23, 2019..

[39] Polish Act on electromobility and alternative fuels – infographic guide, http://pspa.com.pl/assets/uploads/2018/11/RAPORT_PSPA_Przewodnik_po_ustawie_o_elektromobilnosci.pdf [accessed: 05.09.2019]; http://pspa.com.pl/assets/ uploads/2018/11/RAPORT_PSPA_Przewodnik_po_ustawie_o_elektromobilnosci.pdf [accessed: 05.09.2019].

Prosumer – an electricity producer who is also a consumer of electricity. The prosumer uses energy for his own needs, but can also sell or store it. The prosumer can be connected to the distribution network.

Renewable energy prosumer is the final recipient who generates electricity only from renewable energy sources, for his own needs in micro-installations[40].

A vehicle powered by natural gas – is a „motor vehicle that uses compressed natural gas or liquefied natural gas, including biomethane, for propulsion"[36].

Hydrogen powered vehicle – is a vehicle that uses electricity generated from hydrogen in its fuel cells for propulsion[36], including PEMFC (*Proton Exchange Membrane Fuel Cell*) or using a hydrogen adapted *internal combustion engine (*HICEV).

Charging point – is a device allowing for charging a single electric vehicle, hybrid vehicle or zero-emission bus, as well as a place where the battery used to drive the vehicle can be replaced or charged[40].

Standard power charging point – „a charging point with a power less than or equal to 22 kW, excluding devices with a power less than or equal to 3.7 kW installed in places other than public charging stations, in particular in residential buildings"[40].

High-power charging point – „charging point with a power of more than 22 kW"[40].

Primary response / reaction – ensuring network stability in the event of sudden changes in frequency and voltage by using, among others, appropriate energy storage technologies.

An energy cooperative – is a cooperative operating in the area of a rural or urban-rural commune, or in the area of no more than 3 directly adjacent communes. The subject of activity of an energy cooperative is production of electricity, biogas or heat in renewable energy installations and balancing the demand for electricity, biogas or heat, solely for own needs of the energy cooperative and its members connected to a area-defined power distribution network lower than 110 kV or gas distribution network or heating network[40].

Charging station – is a „construction device comprising a standard power charging point or a high power charging point connected to a building or a free-standing building, with at least one standard power charging point or a high power charging point installed – equipped with software allowing for providing charging services, including a parking space, if the charging station is connected to a distribution network"[40].

Volumetric energy density – the energy density stored in a given technology related to the unit of volume (e.g. kWh/L or kWh/m^3)

Discounted energy storage costs LCOS [USD/MWh] – life costs related to the annual discharge, expressed in the volume of electricity throughout the entire life cycle, taking into account: investment costs, operating costs (O&M), replacement costs, utilization costs, electricity costs (charging / discharging).

Discounted power costs (adjusted power cost – ACC or LCOS [USD/$kW_{annually}$]) – life costs related to the annual installed power capacity over the entire life cycle, taking into account: investment costs, operating costs (O&M), replacement costs, disposal costs, costs of nominal power.

[40] Act of 19 July 2019 amending the act on renewable energy sources and certain other acts, http://g.ekspert.infor.pl/p/_dane/akty_pdf/DZU/2019/157/1524.pdf#zoom= 90 [accessed: 05.09.2019].

LIST OF ABBREVIATIONS (Alphabetical)

A-CAES	*Adiabatic Compressed Air Energy Storage*
ACP-WDCAS	*Wind diesel hybrid system with adiabatic air compression and storage at constant pressure*
ARiMR/ARMA	*The Agency for Restructuring and Modernisation of Agriculture*
AUD	*Australian dolar*
ATES	*Aquifer Thermal Energy Storage*
BGK	Bank Gospodarstwa Krajowego
BES	*Battery Energy Storage*
BTES	*Borehole Thermal Energy Storage*
CAPEX	*Capital expenditure*
CO	*Carbon monoxide*
CO_2	*Carbon dioxide*
CAES/C-CAES	*Compressed Air Energy Storage/Conventional Compressed Air Energy Storage*
CLAB	*Composite lead-acid battery*
CHP	*Combined Heat and Power*
CO_2	*Carbon dioxide*
CO_2eq	*Carbon dioxide equivalent*
CTES	*Cavity Thermal Energy Storage*
dCAES	*diabatic Compressed Air Energy Storage*
DOE	*US Department of Energy*
DSM	*Demand Side Management*
DSR	*Demand Side Response*
EDLC	*Electrostatic Double-layer capacitor*
EU	*European Union*
EUR	*Euro*
FC	*Fuel Cells*
FOM	*Fixed Operation and Maintenance costs*
FES	*Flywheel energy storage*
GHG	*Greenhouse gases*

GW	*Gigawatt*
GWe	*Electric gigawatt*
HENG	*Hydrogen-Enriched Natural Gas*
HICEV	*Hydrogen Internal Combustion Engine Vehicle*
HTSC	*high-temperaturę superconductivity*
IEA	*International Energy Agency*
IRENA	*International Renewable Energy Agency*
kW	*Kilowatt*
kWe	*Electric kilowat*
kWh	*Kilowatt-hour*
LAES	*Liquid Air Energy Storage*
LCA	*Life Cycle Assessment*
LCO	*Lithium Cobalt Oxide batteries* ($LiCoO_2$)
LCOE/LEC	*Levelized Cost of Energy/Levelized Energy Cost*
LCOS	*Levelized Cost of Storage*
LFP	*Lithium iron phosphate battery* ($LiFePO_4$)
LHS	*Latent Heat Storage*
Li-ion	*Lithium-ion battery*
LTO	*Lithium Titanium Oxide* (Li_2TiO_3)
LTSC	*Low-temperaturę superconductivity*
LMO	*Lithium Manganese Oxide* ($LiMn_2O_4$)
HES	*Hydrogen Energy Storage*
MCFC	*Molten Carbonate Fuel Cell*
MtCO2e	*Metric tons of carbon dioxide equivalent*
MW	*Megawatt*
MW_e	*Megawatt electrical*
MWh	*Megawatt-hour*
MW_t	*Thermal megawatt*
Na-S	*Sodium–sulfur battery*
NER	*Net Energy Ratio*
NFOŚiGW	*National Fund for Environmental Protection and Water Management*
Ni-Cd	*Nickel–cadmium battery*
Ni-MH	*Nickel metal hydride*
NMC	*Lithium Nickel Manganese Cobalt Oxide*
OPEX	*Operational Expenditure*
OZE	*Renewable Energy Sources*

P2G/PtG	*Power-to-gas*
Pb-A	*Lead-acid battery*
PCM	*Phase-Change Material*
PEM	*Proton Exchange Membrane*
PFR	*Polish Development Fund*
PHS	*Pumped hydro energy storage*
PSE S.A.	*Polish Powe System*
PV	*Photovoltaic module*
SMES	*Superconducting Magnetic Energy Storage*
SHS	*Sensible Heat Storage*
SNG	Synthetic Natural Gas
SOE	*Solid Oxide Electrolyzer*
SOFC	*Solid Oxide Fuel Cell*
TES	*Thermal Energy Storage*
TRL	*Technology Readiness Level*
TTES	*Tank Thermal Energy Storage*
TWh	*Terawatt hours*
UC	*Ultracapacitor*
URE	*Energy Regulatory Office*
USD	*United States Dollar*
VOM	*Variable Operation and Maintenance costs*
VRFB	*Redox flow batteries*
WTG	*Wind turbine generator*
WWF	*World Wide Fund for Nature*
Zn-MnO_2	*Zinc manganese oxide battery*
Zn-Br	*Zinc–bromine flow battery*

1. INTRODUCTION

1.1. EUROPEAN POLICY

Due to progressing climate change, 195 countries jointly responsible for 99.75% of global greenhouse gas emissions (including carbon dioxide, CO_2) signed the Paris Agreement in 2015[41]. These countries have committed an endeavor to maintain the long-term average temperature rise below 2°C over the pre-industrialization temperature level, aiming for 1.5°C, and to inhibit and reduce greenhouse gas emissions. Within the European Union specific objectives have been adopted regarding CO_2 emission in the nearest future, respectively[42]:

- by 2020 – reduction of CO_2 emission by 20% in relation to 1990,
- by 2030 – reduction of CO_2 emission by 40% in relation to 1990,
- by 2050 – reduction of CO_2 emission by 80% or even 95% in relation to 1990.

Currently (October 2019), discussions are ongoing at EU level on the objective of EU climate neutrality by 2050. Discussion over this goal is likely return at the European Council meeting on December 12 and 13, 2019. At the same time, as part of the work of the European Commission and the 'New Green Deal for Europe', a discussion is ongoing on raising the goal of greenhouse gas emissions reduction to 50% or 55% by 2030 in relation to 1990.

Energy consumption and carbon emissions are directly related to each other and affect climate change. In order to counteract climate change, it is necessary to switch from a centralized system based on fossil fuels to a decentralized system, using renewable energy resources in distributed energy systems. At the same time, thermal modernization of buildings, appropriate materials management as well as optimization of energy use in overall terms – from the extraction of raw materials to the development of transformation products in energy installations – is of great importance for improving the use of energy in the global economy. Measures for the gradual implementation of the closed-loop economy serve to improve utilization of critical materials, whose limited availability may result in drastic increase of prices of selected energy technologies or industrial processes. In the European Union, energy production, processing and utilization account for around 79% of greenhouse gas emissions. It should be emphasized that the largest share of emissions comes from transport (around 900 $MtCO_2e$), agriculture, construction and heating sectors, which together account for 60% of CO_2 emissions across the EU.

[41] Paris Agreement, UNITED NATIONS, 2015 (art. 2 par. 1a & art. 4 par. 4) [accessed: 10.06.2019].

[42] EEA Report, *Trends and projections in Europe 2018 Tracking progress towards Europe's climate and energy targets*, 16, 2018, 8–13, 14–17, ISSN 1977-8449.

In order to progress to a low-carbon emission economy, the European Union has set targets that determine the share of energy from renewable sources in final energy consumption, in the perspective of:

- by 2020 r. – 20%[43],
- by 2030 r. – 32%[44].

These values include energy from renewable sources used for, among others: heating and cooling, transport and electricity production. It should be emphasized that regulations contained in Directive 2009/28/EC impose an obligation on EU member states to simultaneously develop and expand the facilities and techniques allowing for storage of heat and electricity, mainly for the purposes of: stabilizing the power system, prosumer development, as well as developing alternative fuels infrastructure for vehicles, in particular with purely electric drive[45] as well as increase of capability for connection of renewable energy sources with the power grid.

In the case of transport, the European Union has set specific objectives regarding the share of energy from RES used in transport, in the perspective of:

- by 2020 r. – 10%[43],
- by 2030 r. – 14%[44].

In 2017-2018, electricity from renewable sources came mainly from wind farms and solar farms, in both sectors a significant increase in production was observed. In 2017, wind farms produced a total of 1,128 TWh of electric energy, and in 2018 as much as 1,270 TWh, which was an increase of 12.59% compared to previous year. In turn, solar installations total for global electric energy production in 2017 amounted to 453.5 TWh, and in the following year it increased to 584.6 TWh, which was an increase of 28.91% year to year[46]. Due to the limited predictability of work and daily variability of the RES load profile, sustainable development should also take into account the need to support these technologies with dedicated energy storage. This will increase the effective annual use of renewable energy installations and, and as a result, increase the share of alternative, clean energy sources in the overall energy balance.

1.2. OVERVIEW OF ENERGY STORAGE TECHNIQUES

Energy storage solutions are referred in literature as energy reservoirs. Depending on the type of energy stored (i.e. mechanical, electrochemical, electrical, chemical or thermal), the energy storage is classified according to the form of stored energy – Table 1.

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[43] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC [pp. 2, par. 13].

[44] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources [par. 8, pp. L 328/83, Art. 25, pp. L 328/125].

[45] Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure [par. 23, 27-30, 33, pp. L 307/4 & L 307/5].

[46] BP Statistical Review of World Energy 2019, Statistical Review of World Energy – all data, 1965-2018, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html [sheet name: Renewables Generation by source].

Table 1. Classification of energy types and storage techniques [47,48,49,50,51]

<table>
<tr><th colspan="6">Energy storage techniques – form of stored energy</th></tr>
<tr><th colspan="2">Mechanical</th><th colspan="2">Mechanical</th><th colspan="2">Mechanical</th></tr>
<tr><td colspan="2">• Pumped hydroelectric storage (PHS)
• Compressed air (CAES)
• Liquid air (LAES)
• Flywheel (FES)</td><td colspan="2">• Batteries (BES), such as:
• Pb-A, CLAB, Ni-MH, Li-ion,
• 'REDOX' type flow cells (VRFB)</td><td colspan="2">• Ultracapacitors (UC/EDLC)
• Superconductive coils (SMES)</td></tr>
<tr><th colspan="3">Chemical + fuel cells</th><th colspan="3">Heat</th></tr>
<tr><td colspan="3">• Hydrogen
• Synthetic natural gas (SNG) and synthetic liquid fuels
• Fuel cell with compressed hydrogen tanks, such as: PEM, MCFC, SOFC</td><td colspan="3">• Phase change material (such as: PCM, molten salts)
• Low temperature energy stores (LT-TES)
• High temperature energy stores (HT-TES)</td></tr>
</table>

This report, commissioned by WWF in Poland, presents the most important solutions of energy storage, including, among others, the principles of their operation, environmental impact, raw material and technological limitations accompanying their development, scalability of technology and technological barriers, main technical and economic indicators, including the level of energy storage costs. This study presents, among others:

1. Pumped hydroelectric storage (PHS),
2. Compressed air energy storage (CAES),
3. Liquid air energy storage (LAES),
4. Flywheel Energy Storage (FES),
5. Hydrogen as a chemical energy storage and fuel cells (e.g. PEM, MCFC, SOFC),
6. Chemical energy storage, including Power-to-X (PtX) installations producing methane (PtN), liquid fuels (PtL) or ammonia (PtA),
7. Electrochemical cells (BES), among others: lithium-ion (Li-ion), nickel-metal hydride (Ni-MH), lead-acid (Pb-A, CLAB), sodium-sulfur (Na-S),
8. Flow cells, incl. REDOX vanadium flow cells (VRFB),
9. Ultracapacitors (UC / EDLC),
10. Superconducting coils (SMES),
11. Phase-change materials capable of heat accumulation (including: PCM, molten salts),
12. Heat reservoirs (including: TES) and cold reservoirs (low, medium and high temperature).

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47 M.C. Argyrou, P. Christodoulides, S. A. Kalogirou, Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications, *Renewable and Sustainable Energy Reviews*, 94, 2018, 804–821.

48 L. Dusonchet, S. Favuzza, F. Massaro, E. Telaretti, G. Zizzo, Technological and legislative status point of stationary energy storages in the EU, *Renewable and Sustainable Energy Reviews* 101 (2019) 158–167.

49 S. Hajiaghasi, Ahmad Salemnia, Mohsen Hamzeh, Hybrid energy storage system for microgrids applications: A review, *Journal of Energy Storage*, 21, 2019, 543–570.

50 M. Aneke, M. Wang, Energy storage technologies and real life applications – A state of the art review, *Applied Energy*, 179 2016, 350–377.

51 J. Wang, K. Lu, L. Ma, J. Wang, M. Dooner, S. Miao, J. Li, D. Wang, Overview of Compressed Air Energy Storage and Technology Development, *Energies*, 10, 2017, 991, doi:10.3390/en10070991.

Table 2 presents the main, collective technical characteristics of energy storage solutions considered in this report, among others: energy density, power range, lifetime, long-term energy storage, discharge time, number of work cycles, cycle efficiency, maturity of the technology (TRL – Technology Readiness Level).

Table 2. Technical characteristics of energy stores[30,31,51,52,53,54,98]

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
PHS (Pumped hydroelectric storage)	0,5-2	30-5 000	h – mo.	40-60	1-24 h	10 000-35 000	~70-85	Mature/ implemented
FES (Flywheel energy storage)	20-80	0,1-20	s – min	15-20	1 s – 15 min	~20 000-10 000 000	~89-95	Early commercial/ implemented
Large CAES (Compressed air energy storage)	2-6	≥300	h – m-ce	20-40	1-24 h+	8 000-17 000	~42-54 (~70% dla A-CAES)[13]	Commercialised /implemented (for A-CAES – in development/TRL-9)
LAES (Liquid air energy storage)	80-120	15-400	min – h	30+	1-24 h+	7 000-17 000	55-62	In development/ TRL-9
UC/EDLC (Ultracapacitors/double-layer capacitors)	2-6	~0-0,5	s – h	5-15	mS – 1 h	50 000-1 000 000	~ 84-97	Commercialized/ implemented
SMES (Superconductive coils)	0,2-6	0,1-10	mSek – h	20-30	≥30 min	od 10 000	~95-97	In development/ TRL-9
TES (Thermal energy storage)	15-80	0,1-300	min – d	5-30	1-24 h+	-	50-90	Commercialized/ implemented – NA

52 A.R. Dehghani-Sanija, E. Tharumalingam, M.B. Dusseault, R. Fraser, Study of energy storage systems and environmental challenges of batteries, *Renewable and Sustainable Energy Reviews*, 104, 2019, 192–208.

53 M.S. Guney, Y. Tepe, Classification and assessment of energy storage systems, *Renewable and Sustainable Energy Reviews*, 75 2017, 1187–1197.

54 P. Nikolaidis, A. Poullikkas, Cost metrics of electrical energy storage technologies in potential power system operations, *Sustainable Energy Technologies and Assessments*, 25, 2018, 43–59.

55 R.F. Beims, C.L. Simonato, V.R. Wiggers, Technology readiness level assessment of pyrolysis of trygliceride biomass to fuels and chemicals, *Renewable and Sustainable Energy Reviews*, 112, 2019, 521–529.

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permanent energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
PCM/MS	147,7-200	do 50MW	h	Do 25	h	> 1 000 000[56]	60-97[57]	Early commerce/ TRL-9, in development
PtG (Power to gas)	500-3 000	0-50	h – mo.	5-20	s – 24 h+	1 000- 50 000 +	~25-70	In development/ TRL-9
FC-H2 (Hydrogen fuel cells)	500-3 000	0-50	h – mo.	5-20	s – 24 h+	1 000- 20 000	~20-55	In development/ TRL-9
Li-ion (Lithium ion)	150-500	0-100	min – d	5-15	min – h+	1 000- 10 000	~75-97	In development/ TRL-9 (implemented and commercialized)
Pb-A (Lead-acid batteries)	50-90	0-40	min – d	5-15	min – h+	500-1 300	~70-84	Mature/ implemented – NA
NiCd (Nickel-cadmium batteries)	60-150	~0-0,5	min – d	10-20	min – h+	20 000- 25 000	~60-83	Commercialized/ implemented
Na-S (Sodium sulphur batteries)	150-250	0,5-35	min – d	10-15	min – h+	4 500- 25 000	~75-90	Mature/ implemented
VRFB ('REDOX' type flow batteries)	16-33	0,02-30	min – d	5-10	min – h+	120 000+	~65-85	In development/ TRL-9
Zn-Br (Zinc-bromium flow batteries)	30-60	0,05-30	min – d	5-10	min – h+	2 000+	~65-80	In development/ TRL-9

* mSec-mile second, s -second, min.-minute, h-hour, d-days, mo.-months

Table 3 presents a comparison of various types of energy storage solutions in terms of their costs. The lower range of cost level refers to the scale of large-scale purchases (wholesale purchase of many thousands of items) while the upper range for small-scale investments (individual items).

[56] G. Cáceres, K. Fullenkamp, M. Montané, K. Naplocha, A. Dmitruk, Encapsulated Nitrates Phase Change Material Selection for Use as Thermal Storage and Heat Transfer Materials at High Temperature in Concentrated Solar Power Plants, *Energies*, 10, 2017, 1318, doi:10.3390/en10091318.

[57] H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza-Ruiz, X. Xu, K. Vignarooban, P. Phelan, Inamuddin, A.M. Kannan, Recent developments in phase change materials for energy storage applications: A review, *International Journal of Heat and Mass Transfer*, 129, 2019, 491–523.

Table 3. Comparison of various types of energy storage techniques in terms of costs [52,54,58,59]

System		Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
PHS		750-4300	5-85	~0,0005 USD/kWh/year,~3-8 USD/kW/year
Large CAES		400-880	2-120	~0,003-0,004 USD/kWh,3-15USD/kW/year
Small surface CAES		517-1 550	200-250	Low
LAES		800-1 800	200-450	0,003-0,004 USD/kWh, 19-25 USD/kW/year
FES		250-650	1 000-10 000	0.0015-0.004 USD/kWh,~6.5-20USD/kW/year
TES		100-400	3-130	120 USD/kW/year (total constant and various costs calculated to contant costs)
PCM/MS		1 000-3 800[60]	16-220[61,]	112/kW/year (total constant and various costs calculated to contant costs)62
SMES		200-489	5 000-72 000	~0,001 USD/kWh,16-18.5 USD/kW/year
VRFB		200-400	500-1 000	13 USD/kW/year, < 0,05 USD/kWh
UC/EDLC		25-450	3000-14 000	<0,001 USD/kWh, <0,001 USD/kW/year
H_2+FC		2000-5 500	2-35	15–46 USD/kW
PtG		500-3 000	2-15	0,0019–0,0153 USD/kW
BES:	PbA	300-700	75-500	~8-20 USD/kW/year, ~0.001-0.002 USD/kWh/year
	Li-ion	200-900	176-900	~9-10USD/kW/year, ~0.003-0.004 USD/kWh/year
	NaS	350-3 000	300-800	~20-80 USD/kW/year, ~0.0035 USD/kWh/year
	NiCd	500-1 500	400-1 500	~12-20 USD/kW/year, ~0.0012-0.002 USD/kWh/year
	VRFB	600-1 500	150-1 000	~12-15USD/kW/year, ~0.001-0.002 USD/kWh/year
	ZnBr	200-2 500	150-500	~12-16USD/kW/year, ~0.001-0.0015 USD/kWh/year

[58] G.J. Maya, A. Davidson, B. Monahov, Lead batteries for utility energy storage: A review, *Journal of Energy Storage*, 15, 2018, 145–157.

[59] L. Goldie-Scot, A Behind the Scenes Take on Lithium-ion Battery Prices, BloombergNEF, March 5, 2019, https:// about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/ [accessed: 28.06.2019].

[60] Z. Wang, S. Sun, X. Lin, C. Liu, N. Tong, Q. Sui, Z. Li, A remote integrated energy system based on cogeneration of a concentrating solar power plant and buildings with phase change materials, *Energy Conversion and Management*, 187, 2019, 472–485.

[61] B.C. Zhao, M.S. Cheng, C. Liu, Z.M. Dai, Thermal performance and cost analysis of a multi-layered solid-PCM thermocline thermal energy storage for CSP tower plants, *Applied Energy*, 178, 2016, 784–799.

[62] J. Lizana, M. de-Borja-Torrejon, A. Barrios-Paduraa, T. Auerb, R. Chacartegui, Passive cooling through phase change materials in buildings. A critical study of implementation alternatives, *Applied Energy*, 254, 2019, 113658.

Table 4. Estimated LCOE costs for various sources of energy production and storage [84,63,64,65,66,67,68]

Generation source	LCOE [USD/MWh]
Wind on-shore	56-65
Wind off-shore	127-170
PV panels	85-98
PV+BES	440-510
PV+CSP	510-524
Hydro-electric	70-110
Atomic	90-120
Natural gas	60-130
Heating oil	110-140
Diesel generator	350-450
Diesel generator (long distance)	450-2 400
Hybrid ACP-WDCAS system	500-1200
Storage source	**LCOE [USD/MWh]**
PHS	15-230
Brayton-CAES	110-210
NaS	250-295
VRFB	430-800
ZnBr	190-880
VRLA/Pb	200-600
FES	350-420
Li-ion	98-360

A very important aspect is also the comparison of LCOE / LEC costs *Levelized Cost of Electricity / Levelized Electricity Cost*) used for traditional power generation, e.g. with a diesel generator, nuclear power plant, heating oil, natural gas as well as hybrid systems, e.g. ACP-WDCAS (*Wind Diesel Hybrid System with Adiabatic Air Compression and Storage at constant pressure*), PV + BES, PV + CSP, and also with other storage techniques, like VRLA / Pb, Li-ion, RFB etc. Table 4 shows the estimated LCOE costs for various sources of energy production and storage. The highest LCOE costs, ranging from USD 450/MWh to even USD 2,400/MWh occur for energy conversion using generators based on diesel

[63] Y. Saada, R. Younes, S. Abboudi, A. Ilinca, Hydro-pneumatic storage for wind-diesel electricity generation in remote sites, *Applied Energy*, 231, 2018, 1159–1178.

[64] U.S. Energy Information Administration, 2017.

[65] J.A. Aguilar-Jiméneza, N. Velázqueza, A. Acuñab, R. Cota, E. González, L. González, R. López, S. Islas, Techno-economic analysis of a hybrid PV-CSP system with thermal energy storage applied to isolated microgrids, *Solar Energy*, 174, 2018, 55–65.

[66] Manasseh Obi, S.M. Jensen, Jennifer B. Ferris, Robert B. Bass, Calculation of levelized costs of electricity for various electrical energy storage systems, *Renewable and Sustainable Energy Reviews*, 67, 2017, 908–920.

[67] F. Klumpp, Comparison of pumped hydro, hydrogen storage and compressed air energy storage for integrating high shares of renewable energies – Potential, cost-comparison and ranking, *Journal of Energy Storage*, 8, 2016, 119–128.

[68] IRENA, Renewable Power Generation Costs in 2018, International Renewable Energy Agency, Abu Dhabi 2019.

engines, for transmission of energy over long distances. In case of PHS, the cost of LCOE ranges from USD 15/MWh to USD 230/MWh, while for on-shore wind farms it ranges from USD 56/MWh to USD 65/MWh.

Table 5 presents the adopted input data for 2015 for energy arbitration techniques (including: PHS, CAES, LAES, H_2+ FC, BES), which were used in subsequent chapters for the LCOS and ACC projection, in the perspective of 2050.

Table 5. Adopted input data for 2015 for techniques in *energy arbitration application* [69,70,71]

Name	PHS	CAES	LAES	H_2+FC	PbA	Li-ion	NaS	VRFB
Accurate power cost [USD/kW]	1 129,2	870,65	1 390	5 420	675	675	660	830
Accurate energy cost [USD/kWh]	80	39,15	345	30,5	460	500	700	760
Constant costs – repairs and maintenance [USD/kW]	7,54	4,35	20,85	45,50	8	9,5	12	12
Various costs – repairs and maintenance [USD/kWh]	0,0005	0,0038	0,0038	0	0,0015	0,003	0,0035	0,001
Power exchange costs in [%] of actual power costs	0,103	0,1069	0,107	0,302	0	0	0	0
Energy exchange costs in [%] of actual energy costs	0	0	0	0	0	0	0	0
Exchange period [cycles]	7 300	1 460	1 460	15 000	1225	3250	3250	8300
Decomission costs as % of investment [%]	0	0	0	0	0	0	0	0
Discount rate [%]	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
Efficiency during cycle execution (charging and discharging) [%]	0,778	0,4425	0,60	0,42	0,8	0,89	0,82	0,735
Self discharge [%]	0	0	0	0	0	0	0	0
Life time [cycles]	33 250	16 250	16 250	15 000	1250	3250	5000	8500
Durability period [years]	55	30	30	15	10	10	14	13
Construction time [years]	2,5	1,5	1,5	0,5	0,5	0,5	0,5	0,5
Discharge level for a given cycle [-]	1	1	1	1	0,94	0,92	0,96	1
Capacity [kW]	100 000	100 000	100 000	100 000	100 000	100 000	100 000	100 000
Discharge time [hours]	4	4	4	4	4	4	4	4

[69] O. Schmidt, S. Melchior, A. Hawkes, I. Staffell, Projecting the Future Levelized Cost of Electricity Storage Technologies, Joule 3, 81–100, January 16, 2019 a 2018 Elsevier Inc.

[70] Lifetime cost of electricity storage, https://energystorage.shinyapps.io/LCOSApp/?fbclid=IwAR0YxhhfoqhzFSO8gfd Nm3qB_qZCb1LRaf_SsPnueyH4dk5vhkguCVfbODA [accessed: 02.07.2019].

[71] Projecting the future levelized cost of electricity storage technologies: dataset, https://figshare.com/articles/Projecting_the_future_levelized_cost_of_electricity_storage_technologies_dataset/7330931 [accessed: 02.07.2019].

Table 6 presents the adopted input data for 2015 for techniques working in primary response application (e.g. FES, SMES and UC / EDLC), which were used in subsequent chapters for the LCOS and ACC projections in the perspective of 2050.

Table 6. Input data for 2015 for *primary response techniques*[69,70,71]

Name	FES	SMES	UC/EDLC
Actual power costs [USD/kW]	640	830	80[268]
Actual energy costs [USD/kWh]	5 400	760	14000
Constant repair & maintenance costs [USD/kW]	6,6	12	0
Variable repair & maintenance costs [USD/kWh]	0,0015	0,001	0
Power exchange costs in [%] of actual power cost	0,31	0	0
Enrgy exchange costs in [%] of actual energy cost	0	0	0
Exchange cycle [cycles]	22 500	8 300	70 000
Decomission costs as % of investments [%]	0	0	0
Discount rate [%]	0,08	0,08	0,08
Cycle execution efficiency (charging and discharging) [%]	0,89	0,735	0,91
Self-discharge [%]	0	0	0
Life cycle [cycles]	145 000	8 500	500 000
Durability period [years]	17,5	13	15
Construction time [years]	0,5	0,5	0,5
Discharge level for a given cycle [-]	1	1	1
Capacity [kW]	10 000	100 000	10 000
Discharge time [hours]	0,5	4	0,5
Number of cycles yearly [cycles/year]	8 285	300	8 285
Charging cost [USD/kWh]	0,05		

Table 7 presents the adopted input data for 2015 for techniques working in heat arbitration application (e.g. PCM / MS and TES), which were used in subsequent chapters for the LCOS and ACC projections, in the perspective of 2050.

Table 7. Adopted input data for 2015 for techniques working in *heat arbitration*[69,70,71]

Technological and economic parameters	PCM	TES
Actual power costs [USD/kW]	3 500	250
Actual energy costs [USD/kWh]	216	68
Constant repair & maintenance costs [USD/kW]	112	120
Variable repair & maintenance costs [USD/kWh]	0	0 included in constant costs
Power exchange costs in [%] of actual power cost	0	0,1069
Enrgy exchange costs in [%] of actual energy cost	0	0

Technological and economic parameters	PCM	TES
Exchange cycle [cycles]	100 000	1 460
Decomission costs as % of investments [%]	0	0
Discount rate [%]	0,08	0,08
Cycle execution efficiency (charging and discharging) [%]	0,75	0,7
Self-discharge [%]	0	0,43
Life cycle [cycles]	500 000	16 250
Durability period [years]	25	30
Construction time [years]	0,5	1,5
Discharge level for a given cycle [-]	1	1
Capacity [kW]	100 000	100 000
Discharge time [hours]	4	4
Number of cycles yearly [cycles/year]	300	300
Charging cost [USD/kWh]	0,05	0,025

In recent years, however, an increase in the share of electricity produced from renewable energy and decrease of production costs has been observed. The total capacity of all wind turbines installed worldwide by the end of 2017 reached 539 291 MW[72]. About one-tenth of this (about 52 552 MW) was added in 2017, slightly more than in 2016, when 51 402 MW supplied the grid. This is the third largest value of newly added power in the power grid system that has ever been installed in one year (except for the record years 2015 and 2014). These numbers translate into a growth rate of about 10%, and the installed capacity corresponds to over 5% of the global demand for electricity. Meanwhile, in Europe, the structure of newly installed power in 2017 clearly indicates that the largest share (over 55%) belongs to onshore and offshore wind farms[73]. Figure 1 presents the share structure of various electricity generation technologies in newly installed capacities in 2017. Figure 2 shows newly installed renewable energy sources in 2017. In fact, unstable energy sources require to be coupled with a sufficient energy storage capacity, otherwise production may not match demand. In view of this imbalance, electricity production in wind turbines and solar power plants must be limited, or an appropriate way of storing the generated electricity should be provided, for example in the form of chemical fuels in power-to-gas technology.

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[72] World Wind Energy Asiciation, https://wwindea.org/blog/2018/02/12/2017-statistics/ [accessed: 18.07.2019].

[73] D. Fraile, A. Mbistrova, *Wind in power 2017 – Annual combined onshore and offshore wind energy statistics*. 2018.

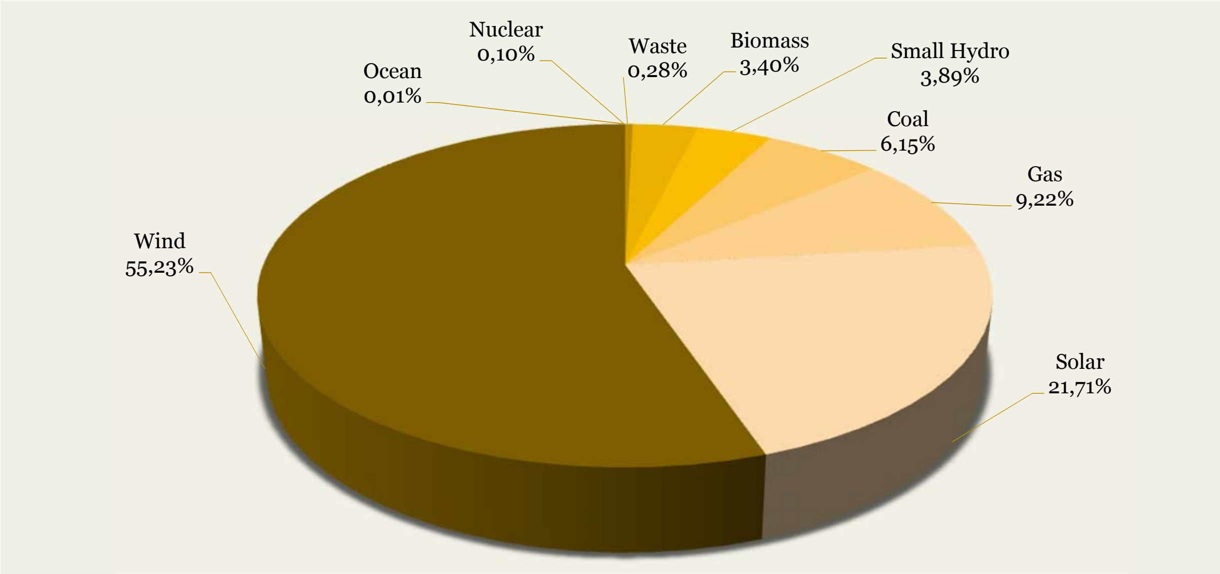


Fig. 1. The structure of technology in new generation power installed in 2017. Based on data[73]

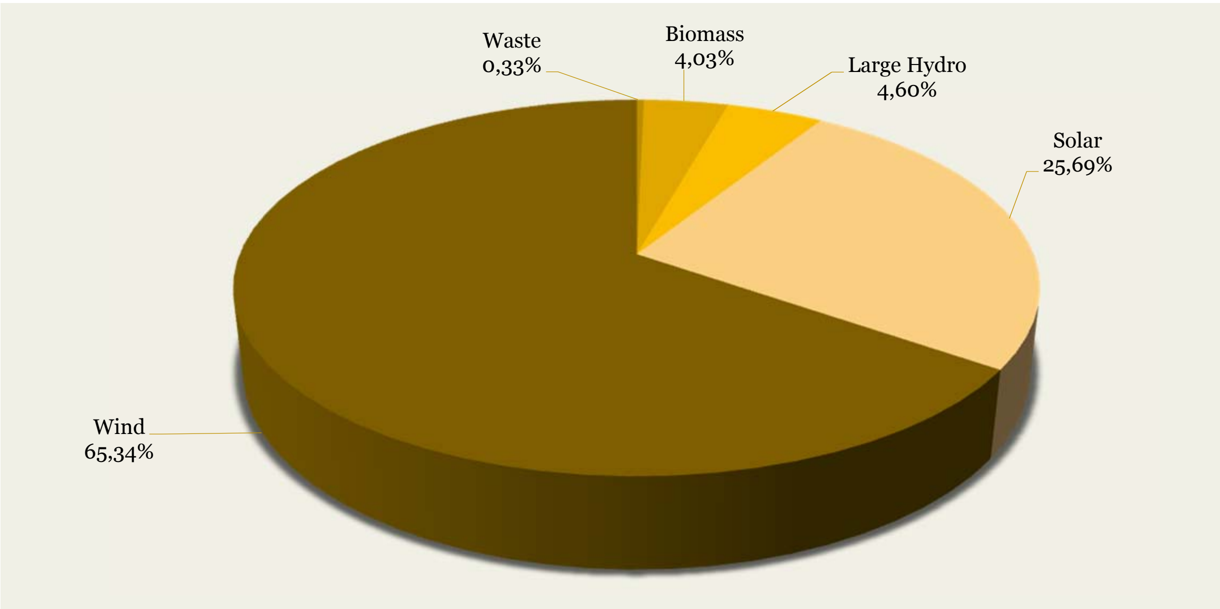


Fig. 2. Current structure (data for 2017) of renewable energy sources in Europe[73]

All of mentioned energy storage techniques are described in dedicated sections, containing recommendations for main area of application, their advantages and disadvantages, scalability, raw material limitations, technological barriers, environmental impact, including LCA (Life Cycle Assessment), carbon footprint and energy storage costs over the entire life cycle in relation to the energy and power of the energy storage under consideration.

2. PUMPED HYDROELECTRIC STORAGE (PHS)

Technical characteristics of **PHS** systems

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
PHS (Pumped hydroelectric storage)	0,5-2	30-5 000	h –months.	40-60	1-24+ h	10 000-35 000	~70-85	Mature/ implemented

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

PHS systems costs

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
PHS	750–4 300	5-85*	~0,0005 USD/kWh, ~3-8 USD/kW/year

*depending on terrain shape (natural reservoirs ane much cheaper than artificial)

2.1. INTRODUCTION

The most popular energy reservoirs in the world are pumped hydroelectric storage power plants. (*Pumped hydro energy storage-PHS*). PHS use the potential energy of water levels stored at different altitudes. A pumped hydroelectric storage power plant is built with two water reservoirs located at different heights (Fig. 3). For generation of electricity, water is transferred between tanks through turbines connected with electric generators. PHS operate in two states: discharging and charging. In discharging state (generation of electricity that is introduced into the power network), water flows from the upper reservoir to the lower reservoir through turbines coupled with hydrogenerators, which convert mechanical energy into electricity. In charging state, the water is pumped into the upper tank from the bottom tank using the same turbines in role of pumps. Electric energy for powering the pumps comes from the power grid.

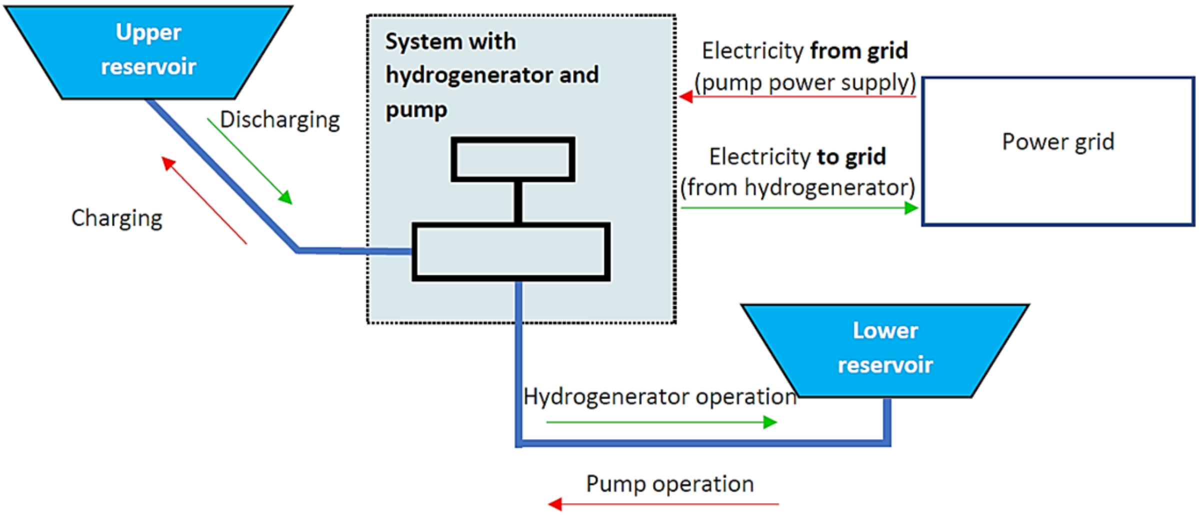


Fig. 3. Principle of operation of a pumped storage power plant – own study

The efficiency of the energy storage process in existing pumped storage power plants exceeds 80%, reaching up to 85%[74] (this efficiency includes both the process of pumping water to the upper reservoir and generating electricity generation during discharge of the reservoir).

The limitations of PHS are natural conditions, since it is not possible to construct such a reservoir everywhere.

An unconventional way of storing energy using PHS technology was developed as part of the StEnSea project, which provides energy storage at sea (*Storing Energy at Sea*)[75]. This project assumes installation of spherical tanks equipped with pumps at the sea bottom. Charging the system consists (Fig. 4) of active pumping of water from tanks. In turn, the discharge of the system consists of re-filling water to the tanks, the flow of water moves the turbine and generates electricity. Systems of this type are possible to use in coastal areas, where there is usually a lack of natural formations that allow for construction of classic pumped storage power plants.

[74] S.F. Michael Manwaring, Pumped Storage Report, Washington: National Hydropower Association's Pumped Storage Development Council, 2018.

[75] Puchta M., Bard J., Dick C., Hau D., Krautkremer B., Thalemann F., Hahn H., Development and testing of a novel offshore pumped storage concept for storing energy at sea– Stensea, *Journal of Energy Storage*, 14, 2017, 271–275.

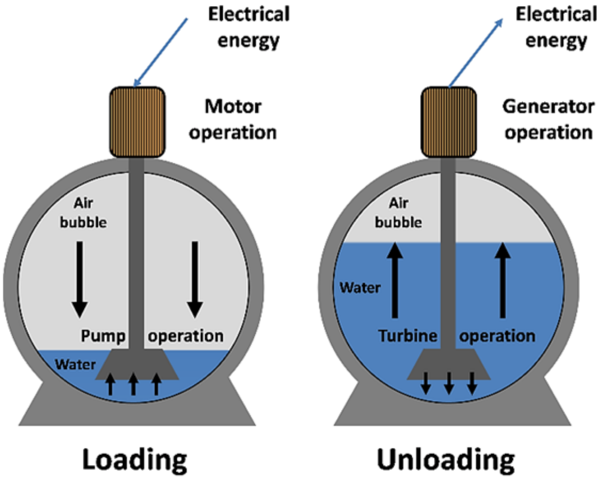


Fig. 4. Principle of operation and simplified construction scheme of the bottom tank of a pumped storage power plant in the StEnSea technology – own study, based on [76].

Pumped storage power plants are the most common electric energy stores in the world, with around 400 plants operating or under construction, with a total capacity of over 160 GW (Fig. 5), of which 36 have electric machines (hydrogenerators) with variable rotational speed (in 2018, 17 of them were operational while 19 were under construction)[74].

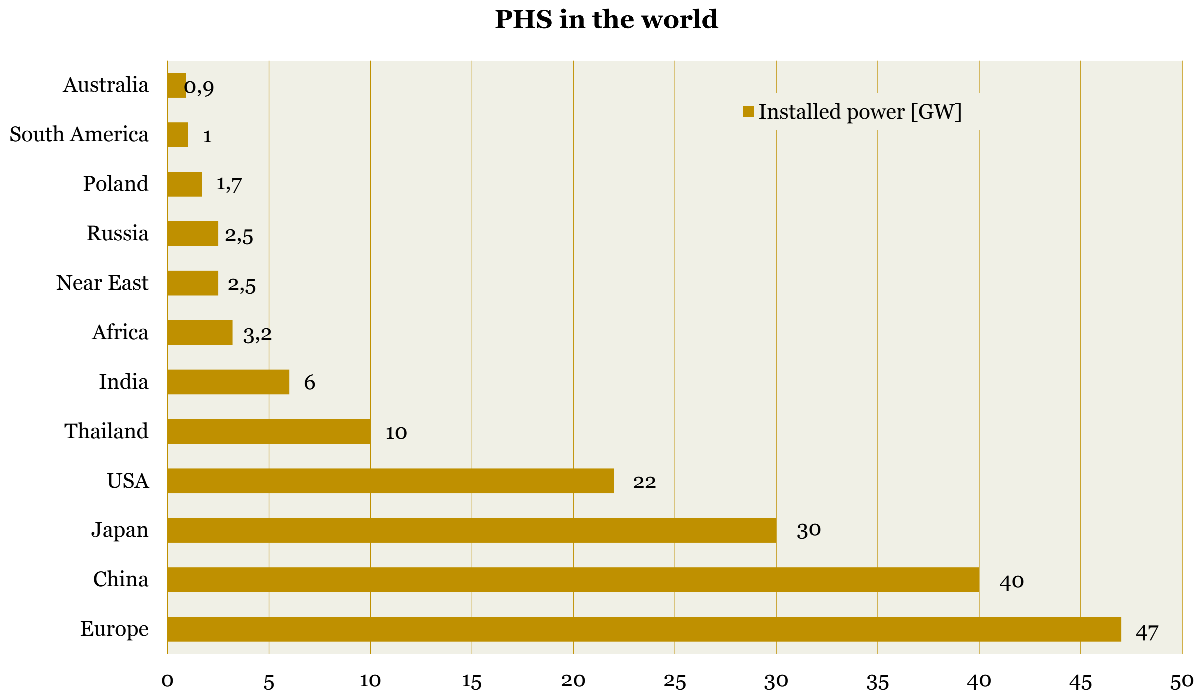


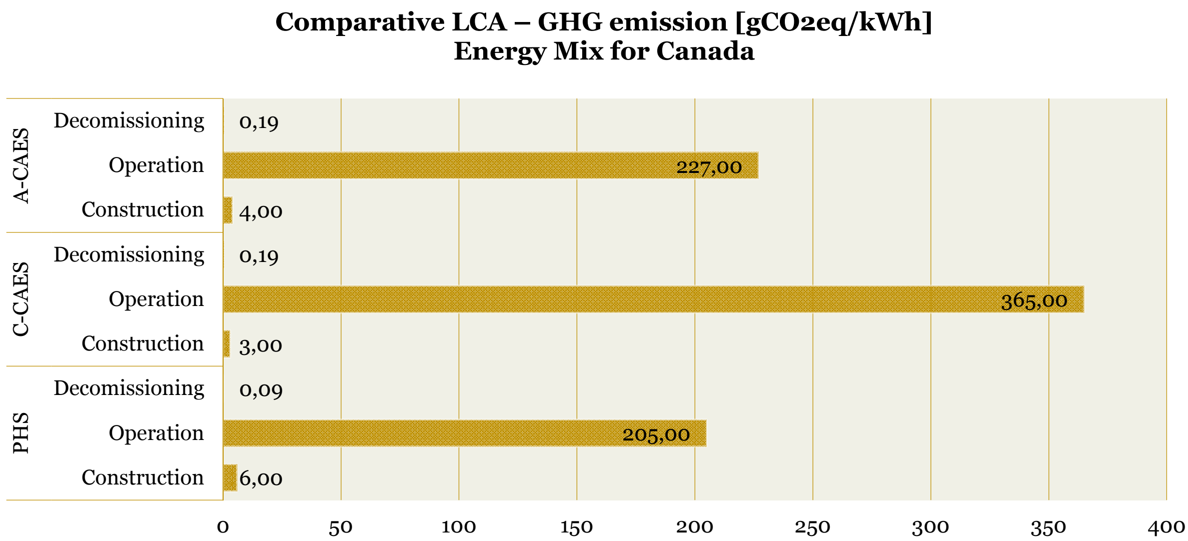
Fig. 5. Pumped hydroelectric storage power plants in the world

[76] Slocum A.H., Fennell G.E., Dundar G., Hodder B.G., Meredith J.D., Sager M.A., Ocean renewable energy storage (ORES) system: Analysis of an undersea energy storage concept, *Proceedings of the IEEE*, 101(4), 2013, 906–924.

2.2. PHS DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Pumped-storage power plants can cover several square kilometers of land and require power lines to connect with electricity consumers. As in the case of traditional hydropower projects, pumped storage power plants must take into account the environmental issues related to the project. The environmental impact for PHS is assessed in the same way as for all infrastructure investments,[77] using for example life cycle analysis (LCA), the results of which are presented in Figure 6, or environmental impact analysis.

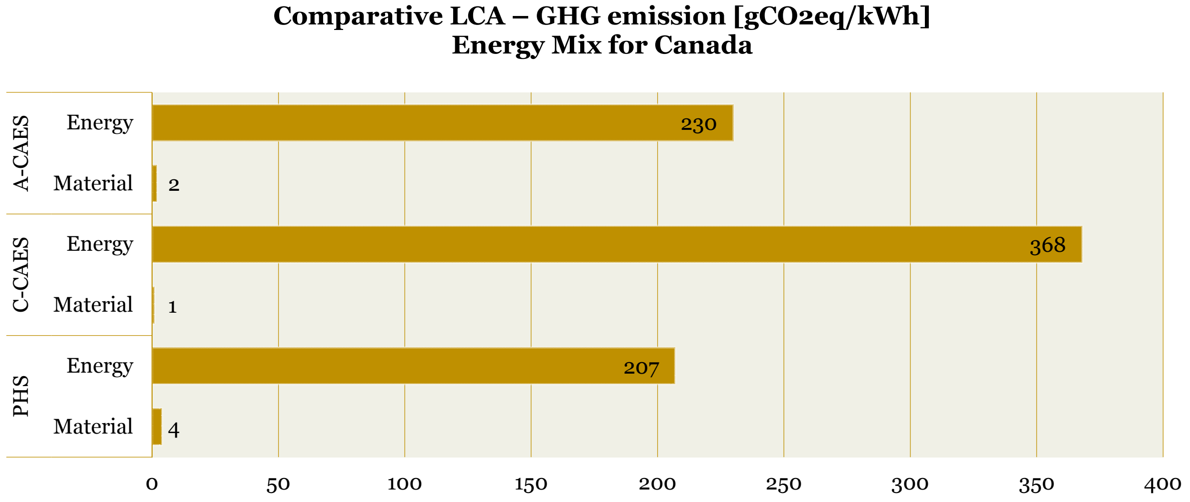
From the point of CO_2 emissions, pumped storage power plants can be treated in two ways. PHS itself does not emit carbon dioxide, but the energy used to drive the pumps when filling the upper tank can come from fossil-fuel power plants. Figure 6 presents an example of a comparative LCA analysis (*Life Cycle Assessment*) for three types of energy storage in accordance with[78]: PHS, A-CAES and C-CAES in Canada. The analyzes assumed the average energy mix for Canada. In 2017, the Canadian energy industry processed 652.3 TWh of electricity. Hydroelectric power plants had the largest share in processing, at level of 60%, second was energy from nuclear power plants at the level of 15%, energy of coal-fired power plants accounted for 9%, while energy obtained as a result of gas / oil processing and others accounted for 10%. Electricity from non-renewable hydroelectric power plants accounted for 7%.



(a)

[77] „Overcoming the barriers to pumped storage hydropower", *ENTURA*, 22, 2017, 2, http://www.entura.com.au/overcoming-the-barriers-to-pumped-storage-hydropower/ [accessed: 09.06.2019].

[78] S. Kapila, A.O. Oni, E.D. Gemechu, A. Kumar, Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems, *Energy*, 170, 2019, 592–603.



(b)

Fig. 6. Comparative LCA of GHG emissions including a) stages of construction, operation, decommissioning, b) energy and materials generation for A-CAES, C-CAES and PHS, respectively[78]

Table 8 shows the input and output energy from a PHS pump station system (*Pumped Hydroelectricity Storage*), a conventional C-CAES (*Conventional Compressed Air Energy Storage*) and the adiabatic compressed air storage A-CAES (*Adiabatic Compressed Air Energy Storage*). NER coefficient (*Net energy ratio*) is defined as the ratio of the total produced (output) energy by a given energy storage to the total input energy to the system throughout the storage period (including energy input during construction, operation and maintenance).

Table 8. Input and output energy and NER for PHS, C-CAES and A-CAES[78]

Energy store	Natural gas [kWh]	Input electric energy [kWh]	NER [-]	Output electric energy [kWh]	Total/sum energy losses [kWh]
PHS	-	1 413	0,78	1 107	306
C-CAES	632	1 151	0,54	969	814
A-CAES	-	1 021	0,70	705	316

The pumped storage power plant has more than 75% lower greenhouse gas emissions than C-CAES (it should be emphasized that C-CAES has natural gas supply for a gas turbine)[78] and more than 10% lower emissions than A-CAES per kilowatt. Depending on the stage in the life cycle, the GHG emission differs, however the highest emission is seen during the operation stage (Fig. 6a) and during the process of energy production and material production (Fig. 6b).

It is also possible to use pumped storage power plants to balance uneven energy production from renewable energy sources.

The analysis, based on Canada's energy mix, where hydroelectric power stations (statistically zero emissions) account for 60%, shows that PHS technology has a total emission of 211.09 gCO2eq/kWh, where the vast majority of life-cycle emissions occur at the operational stage. With the decarbonisation of the electricity generation sector, these emissions will continue to decrease.

2.3. RAW MATERIAL RESTRICTIONS

For construction of pumped storage power plants, no sophisticated or rare raw materials are used on a large scale. The only material limitation in construction of PHS is water – its availability as well as the difference in height of lower and upper water reservoirs[79].

2.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

The process of building a pumped storage power plant can last from 3 to 5 years**Błąd! Nie zdefiniowano zakładki.**, and the entire investment process – more than 4-5 years. Due to complicated nature of the investment, the wait time for the construction permit for the pumped storage power plant is twice as long compared to solar or gas power plants[74].

Pumped storage power plants require significant capital for development. Minimizing construction and operating costs is the key to successful project development. Choosing the right location is a matter of identifying a location with suitable topography, source of water and good proximity to the power grid network.

A relatively new approach in designing pumped storage power plants is location of reservoirs in areas that are physically separated from existing river systems. These projects are known as closed-circuit pumped storage power plants, they have minimal or no impact on existing surface water systems.

The prospective areas for construction of pumped storage power plants far from rivers are, for example: *„dry-gully*" and *„turkey's nest"*[80] (Fig. 7). In the „dry gully" case we are dealing with a gentle gully located near the top of the hill. It is able to retain a certain amount of water, using the existing area as the main part of the dam[80]. A typical example of this type of location is the upper reservoir of the Presenzano hydroelectric plant in Italy[80].

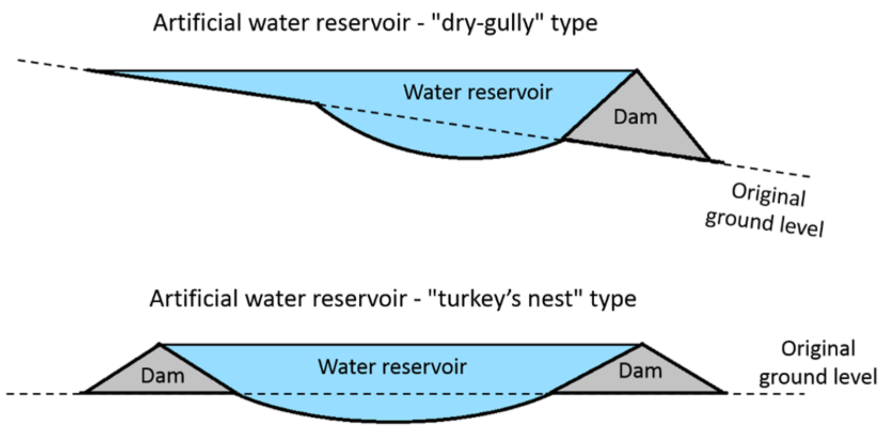


Fig. 7. Types of potential locations of pumped storage power plant reservoirs – own study

[79] S. Karhinen, H. Huuki, Private and social benefits of a pumped hydro energy storage with increasing amount of wind power, Energy Economics, https://doi.org/10.1016/j.eneco [accessed: 2019.05.024] [In press].

[80] Lu B., Stocks M., Blakers A., Anderson K. Geographic information system algorithms to locate prospective sites for pumped hydro energy storage, *Applied energy*, 222, 2018, 300-312.

Other possible locations useful for the construction of pumped storage power plants are, for example, decommissioned mining pits[80]. In Poland, the bottom reservoir could be located in pit created by the Bełchatów power plant. Areas located above would have to be used for construction of the upper reservoir.

It is also possible to use sea water in pumped storage plants[80]. The sea or ocean will then act as the bottom reservoir. An example of a suitable location would be the area located at the top of Spencer Bay in the south of Australia[80].

Despite the fact that pumped storage plants generally have a significantly smaller environmental impact than conventional hydroelectric power plants[11], the features of natural topography that are ideal for building a pumped storage power plant (high, steep slopes or cliffs) are usually places with high natural values or are expensive private land, or have high social value.

StEnSea technology brings great opportunities to increase the number of potential locations of PHS systems, since the lower reservoir is located at the bottom of the upper reservoir[75].

In addition to the above-mentioned criteria for the location of a pumped storage power plants, the difference in levels between the upper and lower tanks is also important (the greater the difference in levels, the more energy can be stored in the same volume). For the PHS underwater storage (StEnSea), the equivalent of the level difference is the depth of the upper reservoir.

2.5. ENERGY STORAGE COSTS IN PHS

The costs of constructing and operating pumped storage power plants depend onmany parameters[81]:

- Topography of the area: defines the possible investment size, the available pump / turbine lift height (value closely related to the level difference), the length of the pipelines between the upper and lower reservoir;
- Geological conditions, water reservoirs and water supply: for various types of dams and reservoirs, the geological conditions for the foundations of these facilities are crucial for correct design of the installation. Type and shape of the dam is directly related to terrain conditions and stability of the water reservoir – especially when large daily variance of water level is planned. It is impossible to estimate the investment costs without evaluation of the particular area.
- Geological conditions for the construction of water pipelines and generation units: new projects of pumped storage power plants often consider underground generation stations with waterways in the form of shafts and tunnels. This however is a main risk that requires local underground research in the design phase.
- Environmental issues and permissions: environmental issues and permissions are issues that can be significantly underestimated. Environmental restrictions and approvals can not be identified without proper review and mapping. GIS layers *Geographic information system*) for natural conservation and cultural heritage objects must be used at the screening stage to identify potential investment sites.
- Flood risk: the risk of flooding for river dams will have a direct impact on the dam category, which will ultimately decide additional costs of the dam and accompanying structures.

Therefore, there is a significant risk to overestimate as well as underestimate the costs.

The CAPEX investment costs of a pumped storage power plant with an installed capacity of around 1000 MW can range from 1700 USD/kW to 2500 USD/kW (this cost does not include land acquisition and costs of connection to the power grid, which can vary greatly depending on the location of the investment)[74]. For a power plant with lower capacity, the unit investment cost will be higher[74].

For pumped storage power plants only fixed operation and maintenance (FOM) OPEX costs can be applied. *FOM – fixed operation and maintenance costs*) OPEX costs[81]. For example, these costs (Tab. 9) for power plants located in Australia are 9,660 USD/ MW/year[81]. Variable costs *and maintenance costs (VOM)* are low[81], negligibly small.

Table 9. Estimated costs of FOM and VOM[81,82,83,84]

	FOM, USD/MW/year	VOM, USD/MWh	Sum USD/MW/year, at assumption of volume coefficient 0,25
Sum – data for hydroelectric and pumped hydroelectric plants	-	10,18	32 320
Pumped hydroelectric plants	3 450-6 335,58	0,29-3,45	10 110-15 950

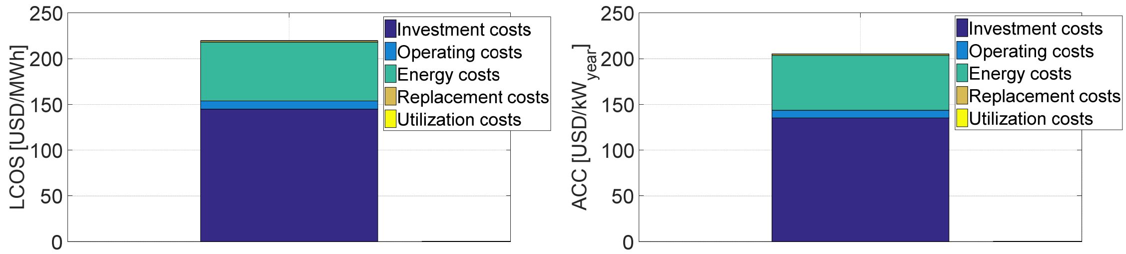
[81] H.-E. Corporation, „Pumped Hydro Cost Modelling," Entura, Cambridge, Australia, 2018.

[82] Electric Power Annual 2016 US Energy Information Administration 2017, revised 2018.

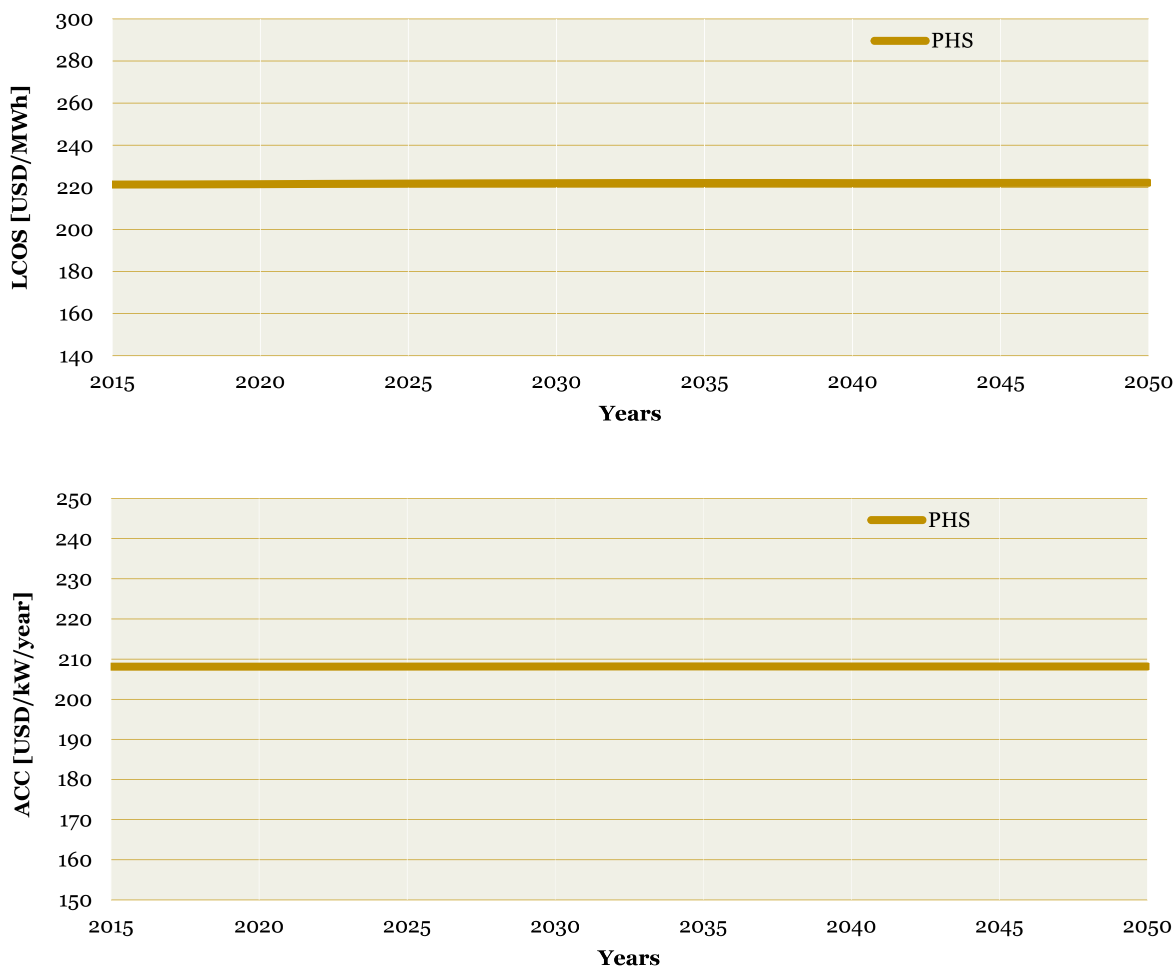
[83] Integrated System Plan modelling assumptions Australian Energy Market Operator, 2018.

[84] DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, September 2016.

Figure 8a) presents LCOS for PHS with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repair, and decommission. Figure 8b) shows LCOS in the 2015-2050 perspective (its value does not exceed 230 USD/MWh for PHS working in energy arbitration application). The current PHS price is competitive on the market, 2 times lower cin comparison to LAES technology and 50% cheaper than CAES.



(a)



(b)

Fig. 8. a) LCOS & ACC of a PHS storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective.

2.6. MAIN APPLICATIONS OF PHS

Main applications of pumped storage power plants are[11] services improving network operation:

1. In the daily cycle (daily energy storage) – in order to shift demand at the peak (morning and afternoon peaks in the case of working days[85].
2. In the seasonal cycle (seasonal energy storage),
3. Network flexibility (quick response to sudden changes in energy demand – Demand Side Management (DSM) and Demand Side Response (DSR) on a large scale**Błąd! Nie zdefiniowano zakładki.**,
4. The ability to stabilize network operation with a higher share of renewable energy sources (photovoltaic, wind) **Błąd! Nie zdefiniowano zakładki.**,
5. Limitation of conventional power reserves**Błąd! Nie zdefiniowano zakładki.**.

2.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR PHS

Advantages of the technology[86]:

- designed for large scale electric energy storage in cooperation with the power grid, over 100 MW, the technology is easily scalable (with available appropriate terrain layout)
- Long life-time, over 20 years,
- High power density,
- Ability to provide energy from a few hours to several days,
- Beneficial influence on the power network operation through, among others: frequency, voltage and reactive power regulation in the system.

Disadvantages of the technology:

- relatively large volume of water reservoirs (energy density depends on the height of the water column),
- limited use (geographical restrictions due to the need to vary the level of water reservoirs). It should also be added that environmental restrictions exist, relating to protected areas, which are characterized by high aesthetic values, including: landscape parks, NATURA 2000 areas, etc.
- low operating frequency (energy storage),

Recommendation for medium and long-term energy storage, as well as seasonal, in order to make the power grid more flexible. The technology is mature. High potential for underwater development of PHS (StEnSea) in Poland, in the Baltic Sea.

Potential stakeholders include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solution.

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[85] Polish Power Grids – Energy demand, https://www.pse.pl/web/pse-eng/data/polish-power-system-operation/basic-data, [accessed: 14.01.2020].

[86] LAZARD, LAZARD'S levelized cost of storage analysis – version 4.0, November 2018, https://www.lazard.com/media/ 450774/ lazards-levelized-cost-of-storage-version-40-vfinal.pdf [accessed: 13.06.2019].

3. COMPRESSED AIR ENERGY STORAGE (CAES)

Technical characteristics of **CAES** systems

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
Large CAES (Compressed air energy storage)	2-6	≥300	h – months	20-40	1-24+ h	8 000-17 000	~42–54	Commercialised /implemented

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

CAES systems costs

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
Large CAES	400–880	2-120*	~0.003-0.004 USD/kWh, 3-15 USD/kW/year

*depending on terrain shape (natural reservoirs ane much cheaper than artificial)

3.1. INTRODUCTION

The principle of CAES (*Compressed Air Energy Storage*) operation is the use of cheap electricity (available outside of peak demand – e.g. at night or during periods of high generation of electricity from renewable sources) to compress the air and store it in large capacity tanks (e.g. underground chambers in the form of caverns rock, salt caves or deep mines). At times of higher electricity demand, the stored compressed air is used to power a turbine and generate electricity. A schematic operational diagram of the adiabatic CAES system (A-CAES) has been shown in Figure 9. In an adiabatic system, the heat generated in air compression process is stored and then used in the expansion process. Thanks to this solution, there is no need to supply additional fuel to the system. However, all CAES power plants in the world that can store large-scale electricity (Fig. 10) are diabatic systems (utilizing chemical energy of fuel for heating compressed air before turbines during storage discharge).

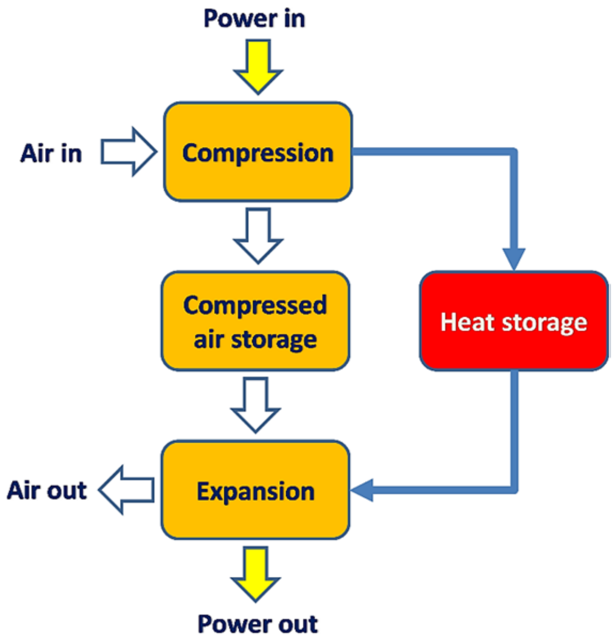

Fig. 9. A-CAES power plant operation principle – own study

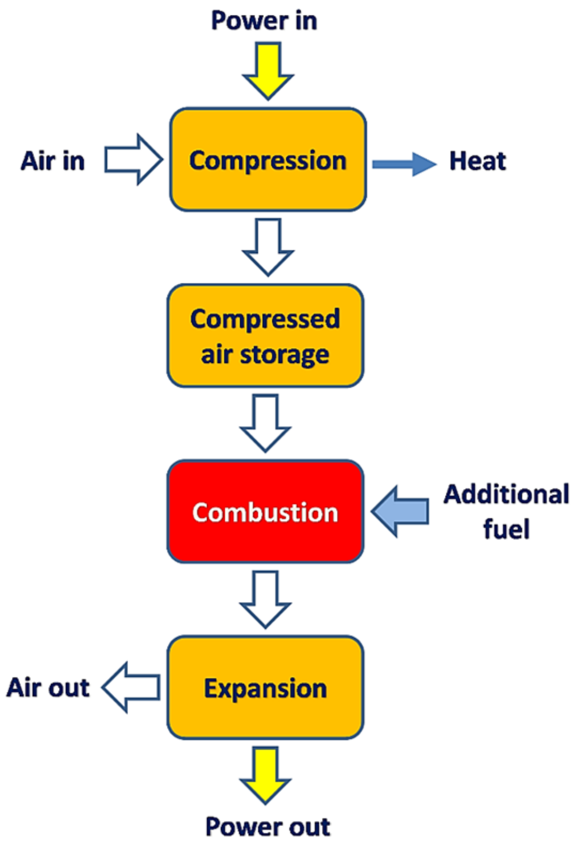

Fig. 10. Principle of d-CAES power plant operation – own study

The efficiency of the energy storage process is up to 54%[51,87], an example being the CAES power plant in McIntosh in the USA, with a capacity of 110MWe.

3.2. CAES DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Currently, there are only two high-power CAES systems in the world: McIntosh (110 MWe) in Alabama, USA, and Huntorf (321 MWe) in Germany[88]. Both installations are diabatic (they require additional fuel). A 1000 MW CAES installation project is currently underway, called Western Energy HUB in Utah, USA, constructed by the consortium of Magnum Development and Mitsubishi Hitachi Power Systems. The project assumes cooperation of the CAES system with renewable energy sources, e.g. wind (storage of electricity generated from wind farms in the form of compressed air)[89].

Considering CO_2 emissions, CAES systems can be treated in two ways. Adiabatic CAES systems do not emit carbon themselves, but the electric energy used for compressors can come from fossil fuel power plants. Figure 6 in subchapter 2.2 presents a comparative *Life Cycle Assessment* analysis for three types of energy storage, accordingly[78]: PHS, A-CAES and C-CAES in Canada.

Table 5 shows the input and output energy from a PHS pump station system (*Pumped Hydroelectricity Storage*), C-CAES (*Conventional Compressed Air Energy Storage*) and A-CAES (*Adiabatic Compressed Air Energy Storage*). The net energy ratio NER is lower for both A-CAES (Tab. 5, NER = 0.7) as well as for C-CAES (Tab. 5, NER = 0.54) compared to PHS, where NER is the highest (Tab. 5, NER = 0.77). NER, as already mentioned in subsection 1.2 when discussing PHS, is defined as the ratio of total energy produced (output) by a given storage to total energy input (input) to the system throughout the storage period (including energy input during construction, operation and maintenance).

C-CAES systems (where natural gas is supplied by a gas turbine)[78] have more than 75% higher greenhouse gas emissions than PHS per kilowatt. Also, the A-CAES system has more than 10% higher greenhouse gas emissions than PHS per kilowatt. Depending on the stage in the life cycle, the GHG emission differs, however the highest emission is seen during the operation stage (Fig. 4a, for C-CAES is 365 gCO_2/ kWh) and the energy production process (Fig. 4b, for C-CAES is 368 gCO_2/ kWh).

3.3. RESOURCE RESTRICTIONS

Similarly to the construction of pumped hydroelectric storage power plants, rare raw materials are not used. The only raw material / element limiting the construction of CAES power plants is the location and geological conditions, and lower compared to e.g. PHS, storage efficiency, especially in the case of a diabetic system. This efficiency also includes additional fuel (natural gas) added to the combustion chambers of the turbine section.

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[87] Meng H., Wang M., Olumayegun O., Luo X., Liu X. Process design, operation and economic evaluation of compressed air energy storage (CAES) for wind power through modelling and simulation, *Renewable Energy*, 136, 2019, 923–936.

[88] Kaldemeyer C., Boysen C., Tuschy I., Compressed Air Energy Storage in the German Energy System–Status Quo & Perspectives, *Energy Procedia*, 99, 2016, 298–313.

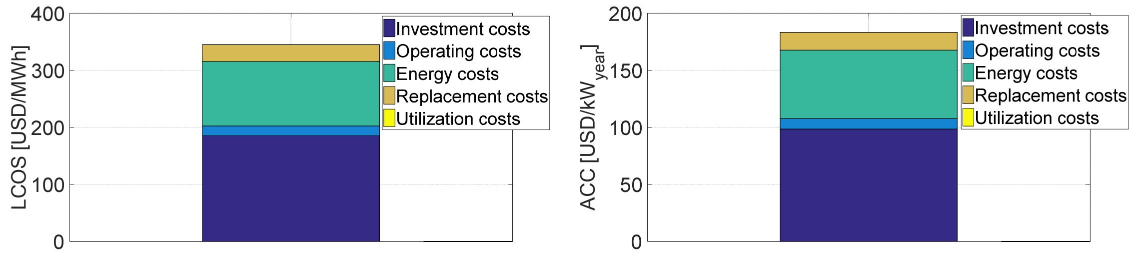
[89] Magnum Compressed Air Energy Storage: https://magnumdev.com/project-information/magnum-caes/ [accessed: 27.07.2019].

3.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

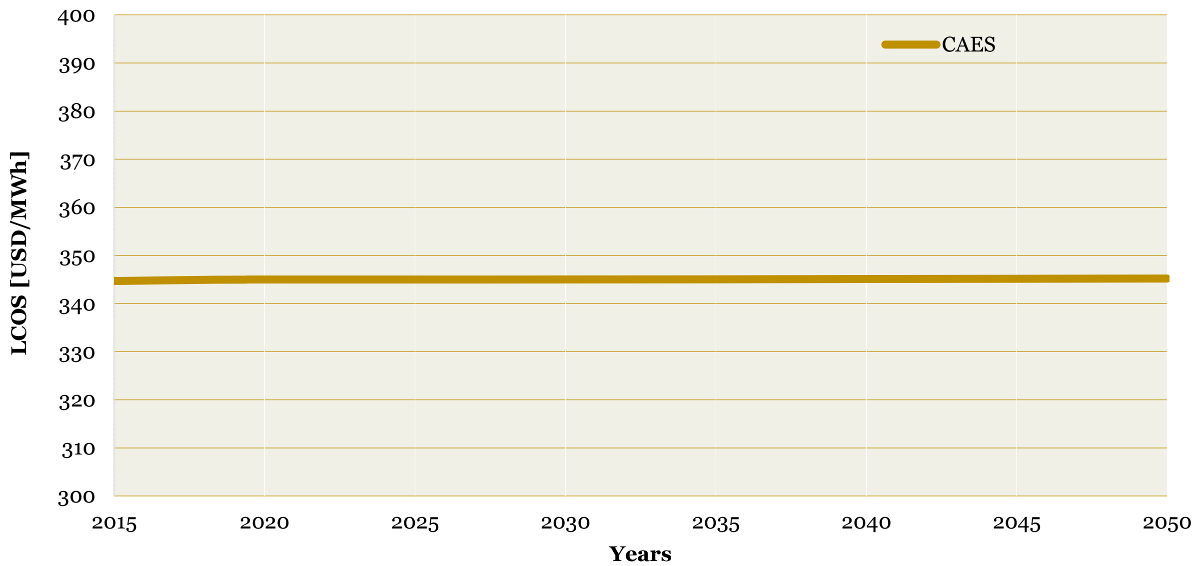
Due to the huge amount of air required and the resulting financial constraints, the only cost-effective option today is utilization of natural reservoirs, such as salt caverns, aquifers, salt mines, limestone mines or other minerals formed in hard rock structures, or even concrete tanks at a relatively small depth[90].

3.5. ENERGY STORAGE COSTS IN CAES

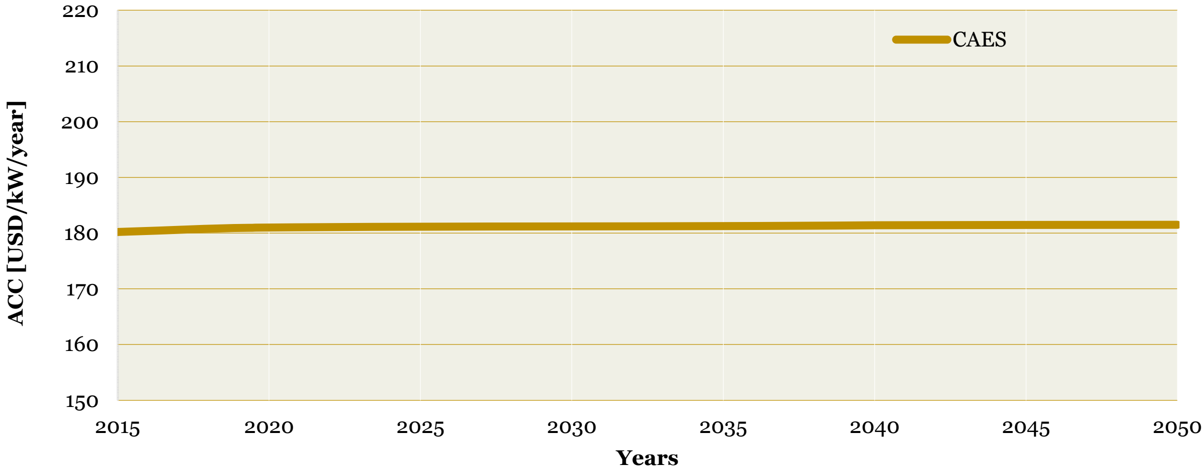
Figure 11a presents the LCOS for CAES with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. The majority of costs for ACC are investment costs, around USD 186/MWh. Figure 11b shows LCOS in the 2015-2050 perspective. The LCOS value does not exceed 350 USD/MWh for CAES operating in energy arbitration application. In the perspective of 2050, there is a slight increase in LCOS and ACC resulting from increase in the cost of purchasing energy carriers.



(a)



[90] Milewski J., Badyda K., Szabłowski L., Compressed air energy storage systems. *Journal of Power Technologies*, 96(4), 2016, 245–260.



(b)

Fig. 11. a a) LCOS & ACC of CAES storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

3.6. MAIN CAES APPLICATIONS

The use of CAES technology is the same as in the case of pumped storage power plants, i.e. they involve the provision of services to improve operation of the power grid (from several hours to several days) to equalize the power demand curve using energy arbitration. The purpose of using both PHS and CAES is also[91]:

1. Energy balance on the supply side (power plants) as well as on the demand side (customers),
2. Greater integration and use of renewable energy sources in cooperation with the power grid, and in further perspective – acheving low-carbon economy (e.g. in Poland, in 2030 perspective a share of at least 27% RES in electricity consumption is expected[92])
3. Stabilization of production and improvement of operational efficiency by Centrally Controlled Generation Units (including: coal power plants),
4. Provision of quick start services.

3.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR CAES

Advantages of the technology[86]:

- designed for large-scale storage of electric energy in cooperation with the power grid, approximately 100 MW and above, easy scalability of the technology (depending on geology of the area – proximity of salt dives),
- Long life-time, over 20 years[93],

[91] Energy Storage Asiciation – Compressed Air Energy Storage, http://energystorage.org/compressed-air-energy-storage-caes [accessed: 24.07.2019].

[92] Energy Policy of Poland until 2040 Ministry of Energy, https://www.gov.pl/attachment/376a6254-2b6d-4406-a3a5-a0435d18beof [accessed: 24.07.2019].

- High power density,
- Ability to provide energy ranging from a few hours to several days,
- Beneficial influence on operation of the power grid through, among others: regulation of frequency, voltage and reactive power in the system.

Disadvantages of the technology:

- a relatively large volume of tanks for compressed air to ensure adequate energy density,
- limited possibility of application (geological limitations resulting from the need for salt deposits, which after leaching can serve as a natural tank for compressed air).
- low frequency of operation (energy storage not often than once a day),
- most of them based on natural gas-based energy supply – there is a risk related to changes in natural gas prices[86].

Recommendations for medium and long-term energy storage applications, increasing the flexibility of the power grid (similar to PHS). High development potential in northern Poland due to presence of significant number of saltdumps[90].

Potential stakeholders include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solution.

[93] N. Khan, S. Dilshad, R. Khalid, A. R. Kalair, N. Abas, Review of energy storage and transportation of Energy, *Energy Storage*, 1(3), 2019, 1–49.

4. LIQUID AIR ENERGY STORAGE (LAES)

Technical characteristics of **LAES** systems

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
LAES (Liquid air energy storage)	80–120	15–400	min – h.	30+	1-24+ h	7 000-17 000	55-62	In development/ TRL-9

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

LAES systems costs

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
LAES	800–1 800	200–450	0.003-0.004 USD/kWh, 19-25 USD/kW/year

4.1. INTRODUCTION

LAES is a method of storing electricity in liquid air. During the charge cycle of such energy store (Fig. 12 and Fig. 13) electricity is used to compress air. To reduce compressor labour, this air is cooled in intercoolers. After compression, the air is further cooled in two stages. Firstly in a conventional cooler with use of water (or with aid of a previously cooled medium from the heat storage – in adiabatic systems) and then in a heat exchanger with gas cooled to a temperature of about -190° C taken from the separator. After cooling, the high pressure air is already converted to liquid state. In order to store liquid air in large capacity tanks, it is necessary to reduce it's pressure to near atmospheric. This process is done though choke on Joul Thompson valve. As a result, in addition to pressure, the air temperature also decreases. However, part of the air evaporates. The resulting mixture is transferred to the separator. Liquid air is directed to the cryogenic tank, while the evaporated part is used to cool the air in front of the valve and recycled to the compressor inlet (due to it's still low temperature) where it mixes with fresh air. This is called the Linde-Hampson cycle. In addition to the above-mentioned system with the Joul Thompson valve, systems with expanders are also used (in this case, the air before the expander is required to be in a gaseous state) as well as combinations of both methods (Calude cycle).

During energy storage is discharge, the condensed air is pumped out of the cryogenic tank. The task of the cryogenic pump is not only to transport the agent, but also to increase its pressure. The liquid air is then evaporated, heated and directed to a gas turbine, where it expands to produce mechanical energy, which is then converted back into electricity by the generator. Depending on the configuration of the system, it is possible to use additional fuel (system with a combustion chamber or in other words a diabetic system – Fig. 12), in order to significantly increase the temperature of the medium in front of the turbine (which results in a significant increase in the power of the entire system), or air expansion without the use of fuel (adiabatic system).

In order to increase the efficiency of the liquefaction process, it is necessary to use the so-called cold storage. This coolness is obtained during heating and evaporation of liquid air in the LAES discharge cycle.

Coolness storage contributes to improving efficiency in both systems with and without a combustion chamber.

In adiabatic systems (Fig. 13) in addition to the aforementioned cold storage, it is also necessary to use a storage for heat produced during air compression process. This heat is then used in LAES discharge cycle. In order to better use the heat from the storage, it is necessary to divide the gas turbine (and thus the expansion process) into several stages. Heat exchangers fed from the heat storage medium should be installed between each stage and before the first turbine.

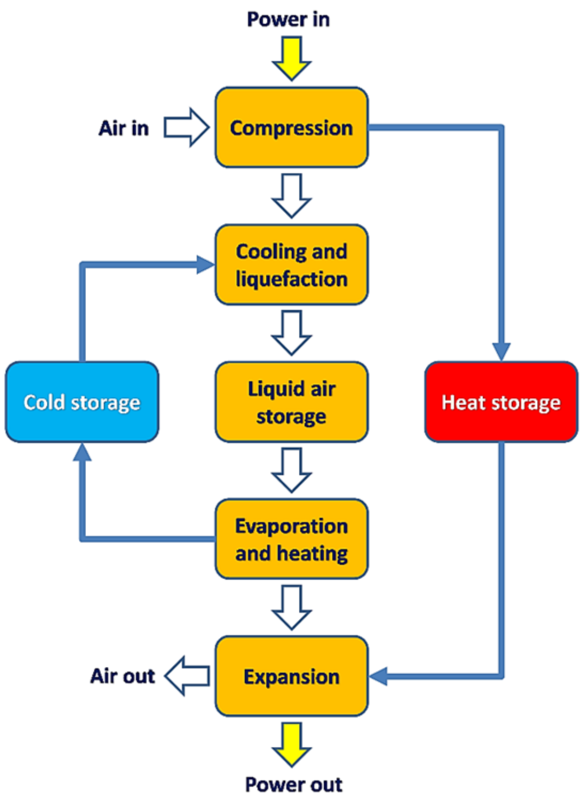


Fig. 12. A-LAES power plant operation principle – own study

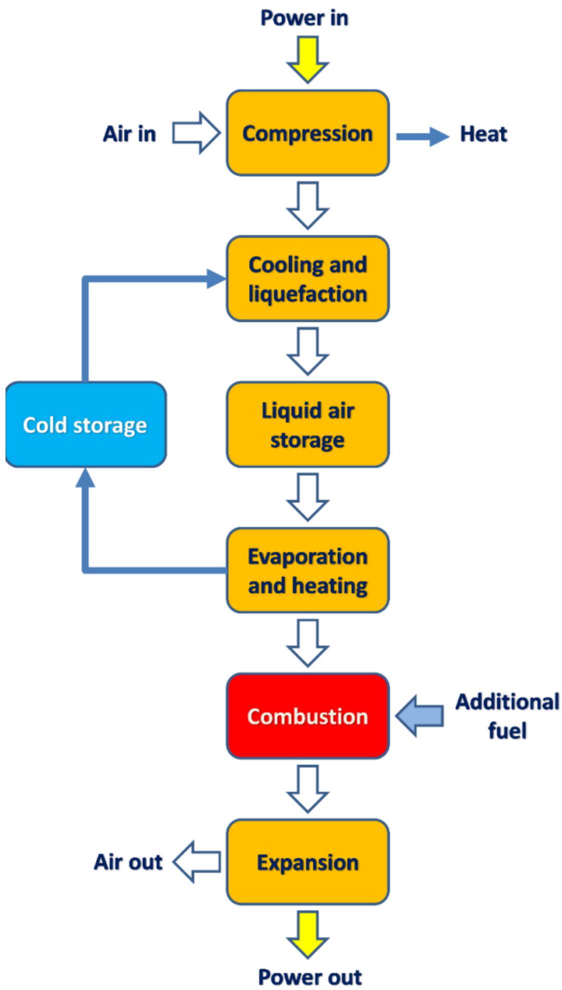


Fig. 13. Principle of d-LAES power plant operation – own study

4.2. LAES DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

LAES is a relatively new energy storage technology. Currently, only two such systems are built in the world. The first system was built in 2011[97] in London by Highview Power Storage and then moved to University of Birmingham[94]. It is a research system with power of 350 kW and capacity of 2.5 MWh[97]. The second system has 5 MW of power and capacity of 15 MWh. It was built in 2018 in the city of Bury near Manchester in the United Kingdom[95] (currently it is the largest LAES system in the world).

The adiabatic LAES system is zero-emission and has no negative impact on the environment[97]. Rare metals or harmful chemicals are not used on a large scale in the construction of the plant, the operation process does not cause carbon emissions[95]. LAES systems will feature emissions similar to diabetic

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[94] Adriano Sciacovelli, Daniel Smith, Helena Navarro, Yongliang Li, Yulong Ding, Liquid air energy storage – Operation and performance of the first pilot plant in the world, Proceedings of ECOS 2016 – The 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, June 19-23, 2016, Portorož, Slovenia.

[95] Highview Power launches world's first grid-scale liquid air energy storage plant, 2018, https://www.highviewpower.com/news_announcement/world-first-liquid-air-energy-storage-plant/ [accessed: 27.07.2019].

CAES systems due to comparable thermal efficiency. The efficiency of a diabetic LAES system with a regenerative heat exchanger can reach about 55%[96], while the efficiency of the diabetic CAES system (also featuring a regenerative heat exchanger) operating in McIntosh, Alabama (USA) is 54%[51,87].

4.3. RESOURCE RESTRICTIONS

Rare raw materials are not used on a larger scale . There are no location restrictions as it was the case of CAES type power plants[96]. The system consists mainly of steel, which can be recycled after use[95].

4.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

LAES technology is based on existing and proven components in the cryogenic industry, whose service life exceeds 30 years[97]. Therefore, it is easily scalable. The main barrier are energy storage costs, which are more than twice as high for LAES compared to PHS and CAES technologies. The level of energy storage costs in LAES is presented in subchapter 4.5.

4.5. ENERGY STORAGE COSTS IN LAES

The unit investment costs for a LAES power plant decrease as the power and storage capacity increase[98], which is shown on Fig. 14.

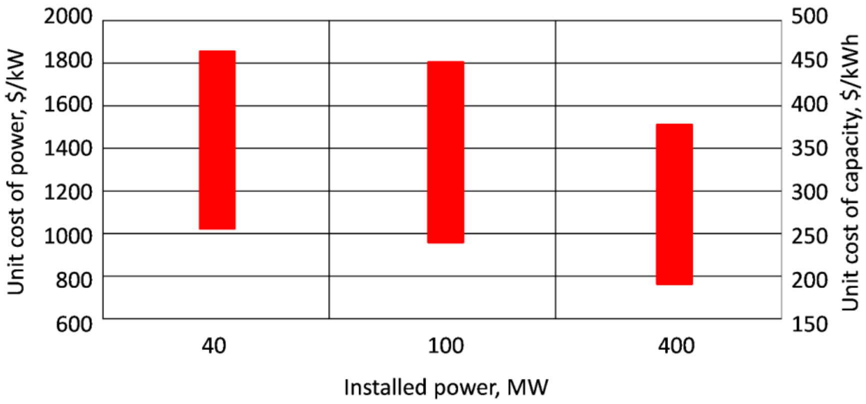

Fig. 14. Impact of LAES installations size on investment costs[98]

Due to the lack of operational data, FOM costs were assumed as 1.5% of investment costs [99]. Data on investment costs, storage efficiency (60%), lifetime (30 years) were obtained from the HIGHVIEW

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[96] Krawczyk P., Szablowski L., Karellas S., Kakaras E., Badyda K., Comparative thermodynamic analysis of compressed air and liquid air energy storage systems, *Energy*, 142, 2018, 46–54.

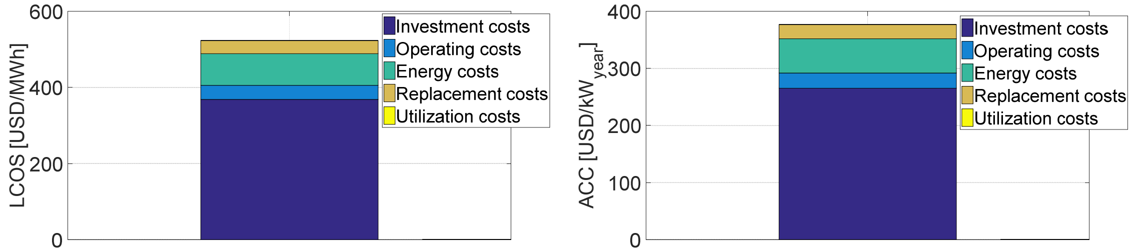
[97] R. Riley, Liquid Air Energy Storage. How cryogenics can support a greener grid. CEC-Madison, WI – July 11th, Highview Power Storage, 2017.

[98] S. Nelmes, Liquid Air Energy Storage (LAES), Pumped Hydro Capability, No Geographical Constraints, Highview Power Storage, 2017.

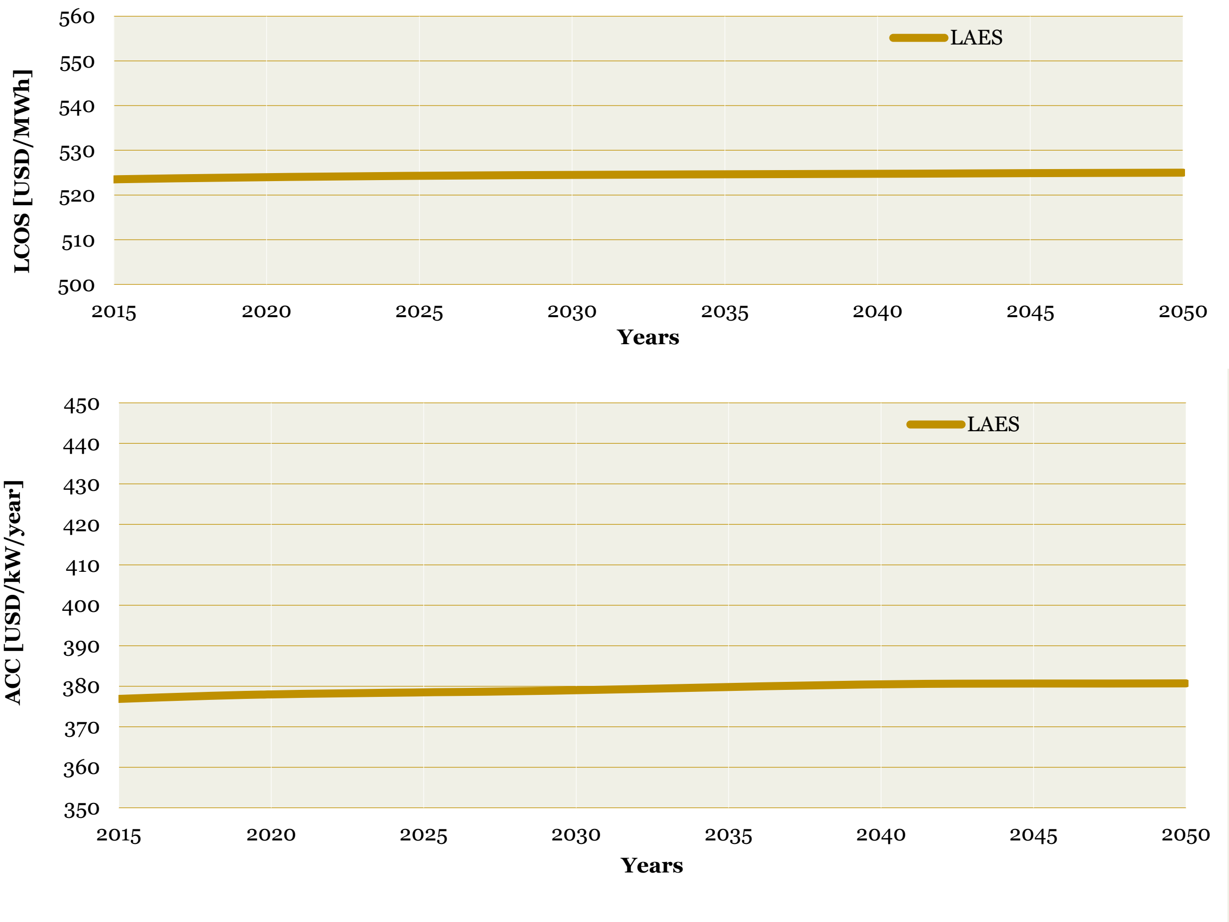
[99] Lin B., Wu W., Bai M., Xie C., Liquid air energy storage: Price arbitrage operations and sizing optimization in the GB real-time electricity market, *Energy Economics*, 78, 2019, 647–655.

POWER STORAGE[98] brochure for a 100 MW system. Due to the similarity to CAES technology, the rest of the assumptions were adopted as for the CAES power plant.

Figure 15a presents the LCOS for LAES with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 15b shows LCOS in perspective up to year 2050 (its value does not exceed 530 USD/MWh for LAES working in energy arbitration application). In the 2050 perspective, a slight increase in LCOS and ACC is visible due to increase of energy processing costs. Higher LCOS value compared to PHS (more than two times) while in relation to CAES the costs associated with energy storage over the entire life cycle are more than 50% higher.



(a)



(b)

Fig. 15. a) LCOS & ACC of a LAES storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

4.6. MAIN LAES APPLICATIONS

The use of LAES technology is the same as for hydroelectric pumped storage and CAES plants.

4.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR LAES

Advantages of the technology[86]:

- designed for large-scale electricity storage in cooperation with the power grid, about 100 MW and above, easy technology scalability (no geological restrictions)
- Long life-time, over 20 years,
- High power density,
- Ability to provide energy ranging from a few hours to several days,
- Beneficial influence on operation of the power grid through, among others: regulation of frequency, voltage and reactive power in the system.
- Approximately 11 times smaller volume of liquid air tanks compared to CAES power plants.

Disadvantages of the technology:

- Lower storage efficiency compared to hydroelectric pumped storage and adiabatic CAES plants.
- low frequency of operation (energy storage not often than once a day).

Recommendations for medium and long-term energy storage purposes to make the power grid more flexible. Seasonal storage is not recommended here due to the relatively high investment costs of a LAES system. The costs of energy storage in LAES are more than twice as high as in the case of PHS, and 50% higher than CAES. The technology is currently in the research phase.

Potential stakeholders include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solutions.

5. FLYWHEEL ENERGY STORAGE (FES)

Technical characteristics of **FES** systems

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permanent energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
FES (Flywheel energy storage)	20-80	0,1-20	s – min	15-20	1 s – 15 min	~20 000-10 000 000	~89–95	Early commercial/ NA-

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

FES systems costs

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
FES	250-650	1 000-10 000	0.0015-0.004USD/kWh, ~6.5-20USD/kW/year

5.1. INTRODUCTION

Among techniques for storing mechanical energy *Flywheel Energy Storage (FES)*[11], which store kinetic energy can be singled out. The flywheel is placed on a shaft, coupled with an electric machine. To reduce rolling resistance, magnetic bearings are used. In addition, a vacuum is created in the space in which the flywheel rotates, using, among others: a vacuum pump Fig. 16. In a FES system, an electric machine (working as electric motor) drives the flywheel / rotor at speeds up to 100,000 rpm. In case when there is a need to use energy from FES, the accelerated flywheel rotor is slowed down by the electric machine, working as a generator (the generator area of operation of the electric machine), as a consequence the electric machine produces electricity.

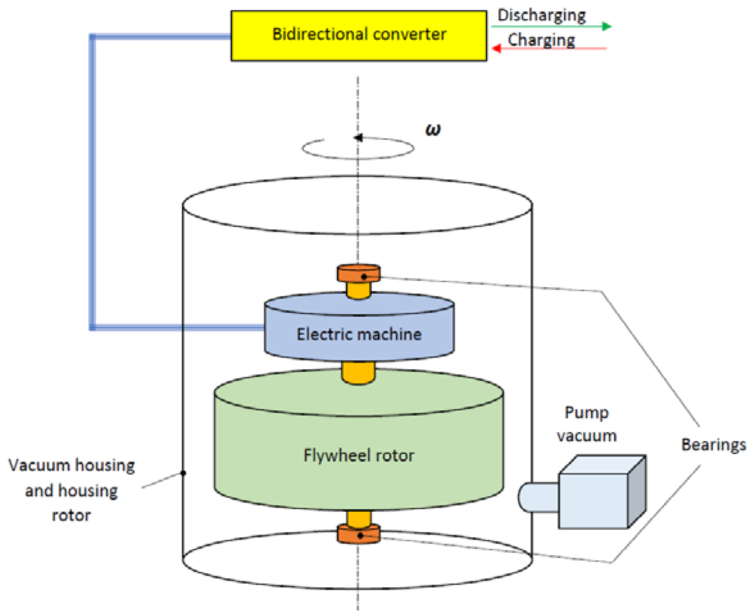


Fig. 16. The principle of kinetic inertia – own study

FES systems are used for short-term energy storage (high power). They are usually used for short-term storage, especially when there is a need for a very short response time in grid services applications. FES systems are not suitable for medium and long-term storage (usually they lose approx. 15% per hour of stored energy)[11].

The flywheel is usually made of steel, turning up to 6,000 rpm, while ones made of carbon fiber can reach up to 100,000 rpm[100]. The energy density for a steel wheel is 5 Wh/kg, while for a carbon wheel – 100 Wh/kg. It should be emphasized that carbon fiber is several times more expensive than steel and constitutes up to several % of the FES installation price.

5.2. FES DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Currently, many applications[101] of FES systems exist in the world, e.g. in UPS systems *Uninterruptible Power Supply), with stabilization of network operation – voltage and frequency regulation. FES is also used in vehicles with hybrid and electric propulsion, in spacecraft,* both with a steel as well as a composite flywheels. In North-Western Australia, in Coral Bay, a 500 kW FES system supports the operation of a 600 kW wind farm (3 200 kW systems) and seven 320kW diesel generators each (with a total of 2.24 MW). The FES inertial system ensures periodic energy storage and stabilization of the power grid operation, which allows to provide up to 95% of energy demand in peak demand periods. It should be emphasized that the system for period of about 900 hours, i.e. 37.5 days a year provides 90% of energy from wind farms. However, nearly 80% of the total power is generated from wind over 120 days. A similar application of the FES system is planned in Marsabit, Kenya, where a 500kW FES store will also be used. It will cooperate with a 550 kW wind farm with and diesel generator system.

[100] X. Dai, K. Wei, X. Zhang, Analysis of the Peak Load Leveling Mode of a Hybrid Power System with Flywheel Energy Storage in Oil Drilling Rig, *Energies*, 12, 2019, 606; doi:10.3390/en12040606.

[101] M.E. Amiryar, K.R. Pullen, A Review of Flywheel Energy Storage System Technologies and Their Applications, *Applied Science*, 7, 2017, 286, doi:10.3390/app7030286.

The entire system will be built by ABB. The FES „Powerstore" system used in Kenya will mainly be responsible for the stabilization of the power grid operation and ensure greater RES penetration in the Kenyan power system. Another example of FES system application is stabilization of frequency in grids with increased penetration of energy from renewable sources, such as New York Independent System Operator (NYISO) installation in Stephentown, New York, USA. A 20MW flywheel was used in the facility. A similar, zero-emission 20MW system was built in Hazle Township, Pennsylvania. This facility has been designed for at least 20 years of operation (~ 100,000 full discharge cycles). The system consists of 100 Beacon Power 100 kW flywheels connected in parallel (25 kWh), with reaction time of less than 2 seconds[101]. In UPS systems, the flywheel cooperates with electrochemical batteries. The flywheel is used in first seconds of a power outage to maintain power, while later the system switches over and drains the battery (thus extending the life of traditional electrochemical cells). A maintenance-free clean energy UPS system based on FES with a capacity of 1MW to protect Internet services in the data center[102] („EasyStreet Online Service's") is located in California, USA. Another example is the use of the 900 kW FES system created in 2018 at the Benito Juárez International Airport in Mexico City [103]. The system is designed to quickly switch to emergency power and maintain the reliability of airport operation. Currently, more and more FES installations are used by the army, among others, for storing energy from all distributed generation sources (e.g. wind farms and photovoltaic modules), an example of which is the FES system (120 kWh) integrated with a micro network serving US Marine Corp. in California[101]. The goal of the FES system cooperating with electrochemical batteries is to ensure energy security of military facilities in the base, powered from renewable energy sources (e.g. photovoltaic systems) and diesel generators in the micro grid with a capacity of 1.1 MW. Another example is the Pilsworth Power Plant currently emerging in England- a project of the hybrid LAES magazine cooperating with UC-FES with a size of 5 MW[104].

FES systems do not emit CO_2. During operation, when powered from renewable energy sources (e.g. wind farms)[101] they also do not emit pollution into the atmosphere (zero-emission system). However, it is worth taking into account the carbon footprint of components / materials used for construction of FES systems and other energy storage systems. *Carbon footprint*). Table 10 presents the carbon footprint of selected materials used in FES components.

Table 10. Carbon footprint in selected materials used in FES components[105]

Material	Carbon footprint of material excavation [kgCO_2eq/kg)]
Low alloy steel	2,2
High strength steel	2,8
Aluminium	9,7-18,3
Magnesium	25,8
Glass reinforced polymers (CFRP)	2,4
Carbon fibre reinforced polymers; based on Poliakrylonitryl – PAN	14,6

[102] EasyStreet, http://easystreet.com/ [accessed: 01.08.2019].

[103] VYCON, https://vyconenergy.com/2018/06/18/mexico-city-international-airport-depends-on-vycons-flywheel-systems-for-critical-backup-power/ [accessed: 01.08.2019].

[104] DOE Global Energy Storage Database, https://www.energystorageexchange.org/projects/1495 [accessed: 02.08.2019].

[105] C. Herrmann, W. Dewulf, M. Hauschild, A. Kaluza, S. Kara, S. Skerlos, Life cycle engineering of lightweight structures, *CIRP Annals – Manufacturing Technology*, 67, 2018, 651–672.

5.3. RESOURCE RESTRICTIONS

Similarly to the construction of pumped hydroelectric storage power plants or CAES and LAES systems, rare raw materials are not used. The main materials used to make flywheels are steel alloys and carbon fibers. Table 11 presents the properties of slow and high speed FES systems.

Table 11. Typical properties of slow and high speed FES systems[113]

Property name	Low speed (LSF)	High speed (HSF)	Micro-high speed (micro-HSF)
Operational rotation speed	< 10 000 obr/min	> 10 000 obr/min	> 10 000 obr/min
Rotor material	Steel	Carbon fibre composite	Carbon fibre composite
Bearing type	Conventional	magnetic (low friction)	Conventional
Energy density	~5 Wh/kg	Up to 100 Wh/kg	~10 Wh/kg
Weight	n/a	n/a	15-60 kg
Number of cycles	10^5-10^7	10^5-10^7	10^5-10^7
Life time	~20 years	~20 years	~20 years

Flywheels made entirely of steel are much cheaper than partially made of carbon fiber. In 2019, the cost of steel sheets did not exceed USD 680/t[106]. By contrast, the cost of carbon fiber in 2019 was over USD 12,000/ton. In the 2020 perspective, a decline in the carbon fiber price to below 10,000 USD/t will be observed (it should be noted that the dynamics of the increase in consumption of carbon fiber between 2018 and 2019 is over 15%[107]).

5.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

The main barriers that affect the FES energy density is the strength of the materials used, which limits the maximum speed of the flywheel rotor. It should be added that when optimizing the construction of a FES system, it is necessary to properly stabilize and support the rotor and shaft bearings. Stabilization should affect the transmission of the least amount of vibration to the body[108,109]. Appropriate bearing of the shaft affects the distribution of lateral and longitudinal forces, which in turn are directly related to losses and heat generation in the bearings, and affects the efficiency of the entire system[109]. Another important element in the FES system is proper mounting of the electric machine on the shaft and ensuring an adequate air gap for the magnetic flux between the stator and rotor as well as between the rotor and the body. Elements for FES are unified, therefore it is very easy to scale the system.

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[106] Steel price, https://www.lme.com/Metals/Ferrous/HRC-N-America#tabIndex=2 [accessed: 08.08.2019].

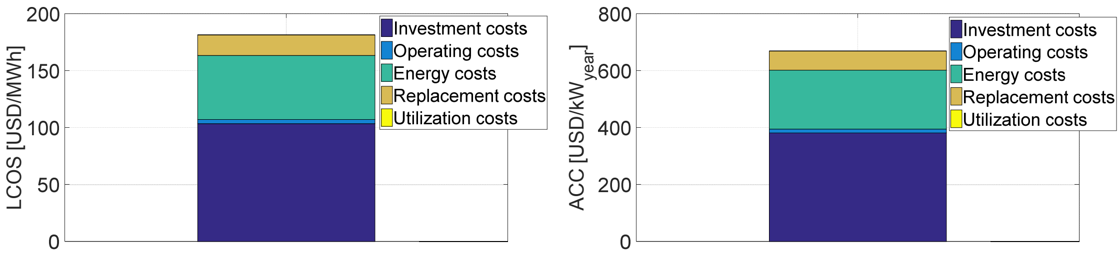
[107] Price and demand for carbon fiber until 2020, https://www.infosys.com/engineering-services/white-papers/Documents/carbon-composites-cost-effective.pdf [accessed: 08.08.2019].

[108] J. Šonský, V. Tesař, Design of a stabilised flywheel unit for efficient energy storage, *Journal of Energy Storage*, 24, 2019, 100765.

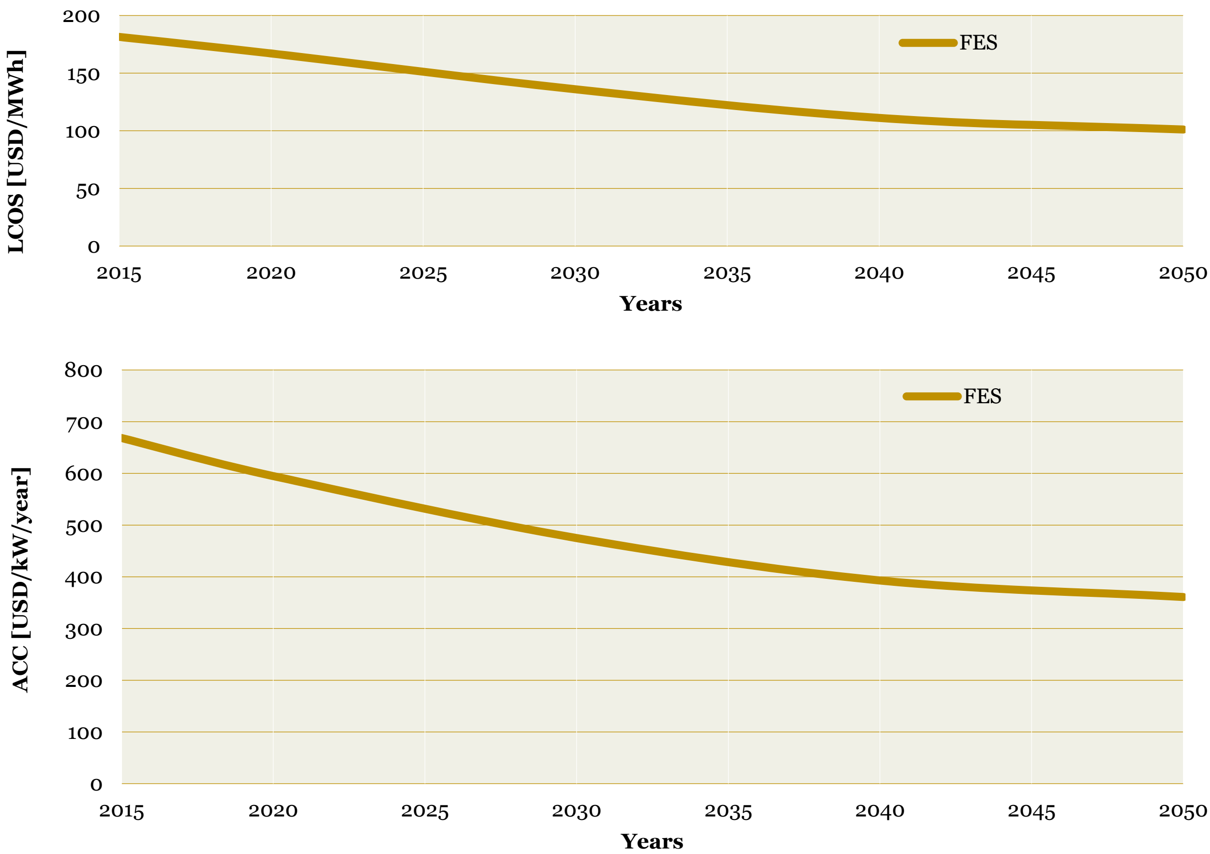
[109] K.R. Pullen, The Status and Future of Flywheel Energy Storage, 3(6), 2019, 1394–1399.

5.5. ENERGY STORAGE COSTS IN FES

Figure 17a presents the LCOS for FES with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 17b shows LCOS in the 2015-2050 perspective (its value does not exceed 181 USD/MWh for FES operating in *primary response* application. In case of ACC cost, it does not exceed 669 USD/kW per year. In the 2050 perspective, a greater than 30% drop in LCOS can be observed, below 100 USD/MWh.



(a)



(b)

Fig. 17. a LCOS & ACC of the FES magazine broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

5.6. MAIN APPLICATIONS OF FES

The use of FES technology mainly concerns the storage of short-term electricity (up to several hours), wherever there is a need for a fast response (high power density), including: support services and making the power grid operation more flexible, aviation, maritime transport as well as road transport[11].

5.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR FES

Advantages of the technology[11]:

- High power density and easily scalable for short-term applications in cooperation with the power grid,
- High discharge depth, to several hundred rpm,
- Compact design with integrated AC (*alternating current*) electric machine,
- High efficiency: up to 85-90% for well-designed FES systems[109],
- Long service life: about 20 years and a very large number of work cycles (up to 10 million)[50,5152].

Disadvantages of the technology:

- Relatively low energy capacity,
- Sensitivity to vibration (need for stabilization)[108],
- Intensive heat emission during FES operation.
- Use only for short-term storage: up to 15% of stored energy is lost per hour[11].

Recommendations for use in hybrid systems, including: fuel cells, electrochemical cells (e.g. lithium-ion batteries)[110], flow cells, supercapacitors, small CAES and low-temperature micro-cogeneration systems. FES systems have also found application in KERS / ERS (*Kinetic Energy Recovery System / Energy Recovery System*)[111] in: Formula 1 cars, hybrid vehicle propulsion systems or electric vehicle propulsion systems[112]. FES systems can be used for storing energy from renewable sources (particularly wind and photovoltaic farms). It should also be noted that currently there are no legal regulations in Poland[92] and Europe[113] regarding the use of FES with renewable energy sources, especially when used in mass scale prosumer installations. High development potential in Poland – support for the development of operational infrastructure for electric vehicles.

Potential stakeholders include: prosumers, road transport, construction. Poland has the appropriate technical facilities and R&D to develop this type of solution.

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[110] S. Dambone Sessa, A. Tortella, M. Andriollo, R. Benato, Li-Ion Battery-Flywheel Hybrid Storage System: Countering Battery Aging During a Grid Frequency Regulation Service, *Applied Sciences,* 8, 2018, 2330, doi:10.3390/app8112330.

[111] F. Meishner, D.U. Sauer, Wayside energy recovery systems in DC urban railway grids, Wayside energy recovery systems in DC urban railway grids, eTransportation, 1, 2019, 100001.

[112] C. Sliwiński, Kinetic energy recovery systems in motor vehicles, *IOP Conf. Series: Materials Science and Engineering*, 148, 2016, 012056, doi:10.1088/1757-899X/148/1/012056.

[113] S. Wicki, EG Hansen, Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage, *Journal of Cleaner Production*, 162, 2017, 1118–1134.

6. CHEMICAL ENERGY STORAGE – HYDROGEN (H_2)

Technical characteristics of **chemical energy storage systems (FC+H_2)**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
FC+H2 (Hydrogen fuel cells)	500-3 000	0-50	h – months	5-20	Sec.- 24h.+	1 000- 20 000	~20–60	In development/TRL-9

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **chemical energy storage systems (FC+H_2)**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
FC+H2	2000-5 500	2-35	15–46 USD/kW

6.1. INTRODUCTION – HYDROGEN: PRODUCTION, STORAGE, UTILIZATION

Hydrogen is considered as a very promising energy carrier, because it's utilization does not directly result in greenhouse gas emission. The only product of hydrogen combustion in air or a fuel cell is steam. Despite the fact that water vapor is a very strong greenhouse gas, assuming that hydrogen is produced from water decomposition, the water vapor emission balance is zero. In addition, hydrogen is particularity attractive due to high heat of combustion (141.9 MJ/kg) and high energy density (143 MJ/kg)[114,115], many times higher than the energy density of conventional fuels, such as gasoline (46.4 MJ/kg), diesel (45.6 MJ/kg), crude oil (41.9 MJ/kg), natural gas (53.6 MJ/kg), hard coal (26-33 MJ/kg) or brown coal (10-20 MJ/kg)[114,115]. Unfortunately, natural hydrogen is practically non-existent on Earth (content in the Earth's atmosphere below 1 ppm), which means it cannot be obtained as fuel, it has to be produced with energy input. There are a number of ways to produce hydrogen, such as: petroleum reforming, carbon monoxide vapor conversion, water electrolysis and catalytic water decomposition.

Oil processing is currently the main method of producing hydrogen. Hydrogen is obtained in reaction of methane and water at a high temperature, in reforming process, which allows for obtaining synthesis

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[114] L. Schlapbach, A. Züttel, Hydrogen-storage materials for mobile applications, *Nature*, 414, 2001, 353–358.

[115] D. Rand, Hydrogen Energy – Challenges and Prospects, RSC Publishing, 2008.

gas (so-called syngas), consisting of hydrogen and carbon monoxide (equation 6.1)[116]. The resulting syngas (substitute for natural gas or synthetic gas) can be used as a reagent in chemical synthesis or as a fuel in gas stoves. However, the processing can be continued in steam conversion process, which leads to an additional portion of hydrogen and carbon dioxide (Equation 6.2).

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad T = 700\text{–}1\,100°C \tag{6.1}$$

$$CO + H_2O \rightarrow H_2 + CO_2 \qquad T = 130°C \tag{6.2}$$

The production of hydrogen in oil processing is not ecologically neutral, because next to four hydrogen molecules one molecule of carbon dioxide is formed. However, it should be noted that methane processing is more advantageous than simple combustion, due to the possibility of controlling the accumulated CO_2 stream and its sequestration or utilization in chemical plants for methanol production.

Similarly to the reforming process, it is possible to produce synthesis gas in coke and steam reaction in the Bosch reaction (equation 6.3). The obtained synthesis gas can be further processed to obtain an additional portion of hydrogen in reaction with steam (equation 6.2) to be used as an energy material or reagent in organic synthesis.

$$C + H_2O \rightarrow H_2 + CO \qquad T = 190°C \tag{6.3}$$

Bosch's reaction, like oil reforming and steam conversion, is not ecologically neutral due to the generation of carbon dioxide. It should be noted that the overall efficiency of hydrogen production in the Bosch reaction is two times lower than in the reforming process, due to coke not containing hydrogen, unlike hydrocarbons.

Due to production of carbon dioxide in the process of hydrogen synthesis by crude oil and coke processing, this hydrogen cannot be considered as a clean energy carrier.

In the context of hydrogen utilization on large scale, its industrial production should be switched to clean technologies, utilizing renewable energy sources. It is believed that the process of electrolytic or catalytic decomposition of water into hydrogen and oxygen will allow for obtaining adequate amounts of high purity hydrogen.

The process of water electrolysis, i.e. the electrochemical decomposition of water into oxygen and hydrogen (equation 6.4), has been known since 1800, thanks to the independent research of William Nicholson[117] and Johann Ritter[118].

$$2H_2O \rightarrow 2H_2 + O_2 \tag{6.4}$$

In 1888 Dmitry Lachinov's work led to the development of the first industrial installation for the production of hydrogen and oxygen by water electrolysis. The process of water electrolysis is very energy intensive, so it can be used in practice only with a cheap and renewable energy source (e.g. solar, wind) or surplus energy (PtG). In addition, the electrolyzed water must be pure, in order to extend the life of the electrodes and ensure high purity of obtained hydrogen. In stationary installations it is possible to utilize a closed water cycle, which only required periodic addition of water. In this case, the water used in the electrolysis process would be recovered in the process of hydrogen combustion, which takes place within the same installation. However, this solution is not an option if the produced hydrogen it to be transported and used in another location, e.g. during combustion in a *hydrogen*

[116] W.F. Maier, *Angewandte Chemie Int. Ed.*, 50, 2011, 426.

[117] C. Russel, Enterprise and electrolysis, Chemistry World, August 2003.

[118] H. Berg, *Review of Polarography*, 54, 2008, 99.

internal combustion engine vehicle (HICEV) or during combustion of enriched natural gas (*hydrogen-enriched natural gas, HENG*).

Photocatalytic and photoelectrocatalytic water decomposition methods are also known. For this, catalysts and semiconductor materials are used, which are able to absorb solar radiation and use it for water reduction. Systems of this type are currently intensively studied and developed in scientific centers around the world, but they are not yet used in the industry. Among the most promising systems for photocatalytic hydrogen reduction that can be mentioned, are systems based on, among others: silicon[119], cadmium sulfide[120], carbon nitride[121], bismuth vanadate[122] or perovskites[123]. However, as of now, classic electrolysis remains the most effective method of hydrogen production, that also allows for elimination of greenhouse gas emissions.

Hydrogen production with PtG method

The power-to-gas technology assumes production of hydrogen on an industrial scale by electrolysis of water with electric energy. Water electrolysis is a process with unfavorable thermodynamics that does not occur automatically in nature, and also requires supply of external energy. To ensure climate neutrality of this process, it is crucial to use electricity obtained from renewable energy sources. Best location for PtG cells is near such power plants to avoid electricity transmission losses.

The process of water electrolysis involves reduction of protons to hydrogen gas at the cathode (negative electrode) and simultaneous oxidation of water to oxygen gas at the anode (positive electrode):

kathode (–) $2H^+ + e^- \rightarrow 2H_{2(g)}$ $\quad$ $E^o = 0$ V [124] $\quad$ (6.5)

anode (+) $2H_2O_{(c)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^-$ $\quad$ $E^o = +1{,}23$ V[124] $\quad$ (6.6)

This process requires high purity water – even small amounts of impurities can result in electrode poisoning and production of contaminated hydrogen and oxygen streams.

Due to the high energy consumption of water electrolysis process, hydrogen produced by this method is much more expensive (4-10 USD/kg H_2, depending on the price of, among others, electricity and electrolysers)[125] than hydrogen produced by the classic method of crude oil reforming (2.69 USD/kgH_2)[126]. For this reason, the PtG technology currently uses relatively cheap surplus electricity, which mostly comes from burning fossil fuels. In recent years, however, an increase in the share of electricity produced from renewable energy and decrease of production costs has been observed.

Three types of electrolysers can be used in PtG systems, of which the highest energy storage efficiency is obtained in installations with solid oxide electrolysers (SOE – solid oxide electrolyzis). This is the only type of electrolyser that can be switched to fuel cell mode for electricity generation, without any change in the structure of the electrochemical cell stack. For this reason, the possibilities of using chemical energy storage in power-to-gas systems have been discussed on their example.

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[119] J.J. Leung, J. Warnan, D.H. Nam, J.Z. Zhang, J. Willkomm, E. Reisner, *Chem. Sci.*, 8, 2017, 5172–5180.

[120] D.W. Wakerley K.H. Ly, N. Kornienko, K. Orchard, M.F. Kuehnel, E. Reisner, *E. Chem. Eur. J.*, 24, 2018, 18385–18388.

[121] A. Mishra, A.Mehta, S. Basu, N.P. Shetti, K. Raghava Reddy, T.M. Aminabhavi, *Carbon*, 149, 2019, 693–721.

[122] V. Andrei, R.L.Z. Hoye, M. Crespo-Quesada, M. Bajada, S. Ahmad, M. De Volder, R. Friend, E. Reisner, *E. Adv. Energy Mater.*, 8, 2018, 1801403.

[123] J.H. Kim, D. Hansora, P. Sharma, J.W. Jang, J.S. Lee, *Chem. Soc. Rev.*, 48, 2019, 1855.

[124] P. Atkins, Physical Chemistry, 6th edition, W.H. Freeman and Company, New York 1997.

[125] S.S. Al-Zakwani, A. Maroufmashat, A. Mazouz, M. Fowler, A. Elkamel, *Allocation of Ontario's Surplus Electricity to Different Power-to-Gas Applications, Energies,* 12, 2019, 2675.

[126] L. Kaiwen, Y. Bin, Z. Tao, Economic analysis of hydrogen production from steam reforming process: A literature review, *Energy Sources Part B Econ. Plan. Policy*, 13, 2018, 109–115.

Operation in SOE mode is the operation of a SOFC cell with reversed polarity – instead of generating electricity at the expense of the fuel supplied to the cell. The electrolyser produces fuel using the supplied electricity. Comparison of both modes of operation is shown in Figure 18. Due to the increasing use of SOFC cells in SOE mode, as well as the possibility of dedicated SOEC cells in SOFC fuel cell mode, a trend of technology unification is observed. For this reason, the solid-oxide electrochemical cell name is used. SOC – solid oxide cell), which, depending on the use, operates in SOFC or SOE mode.

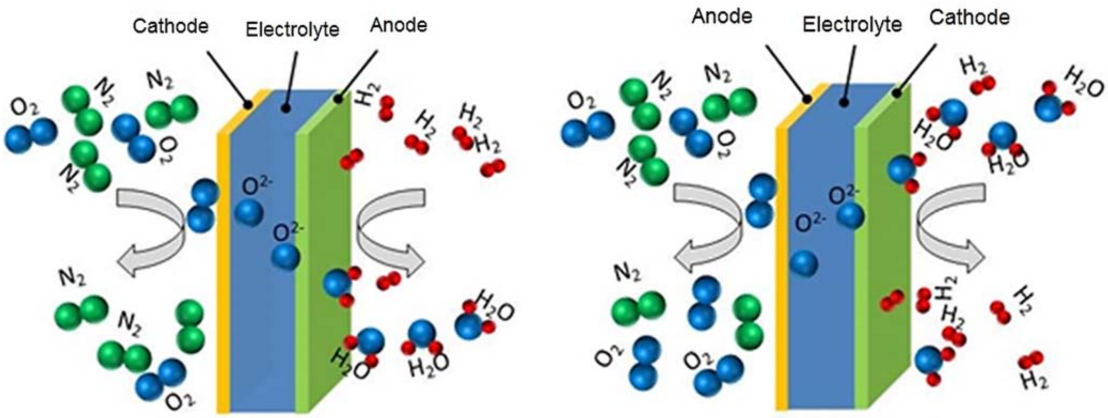
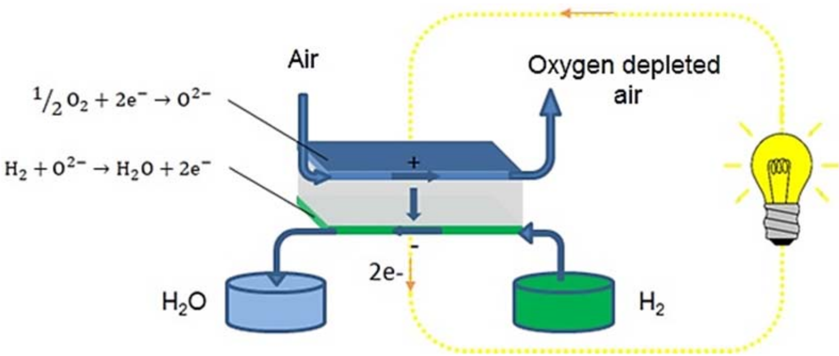


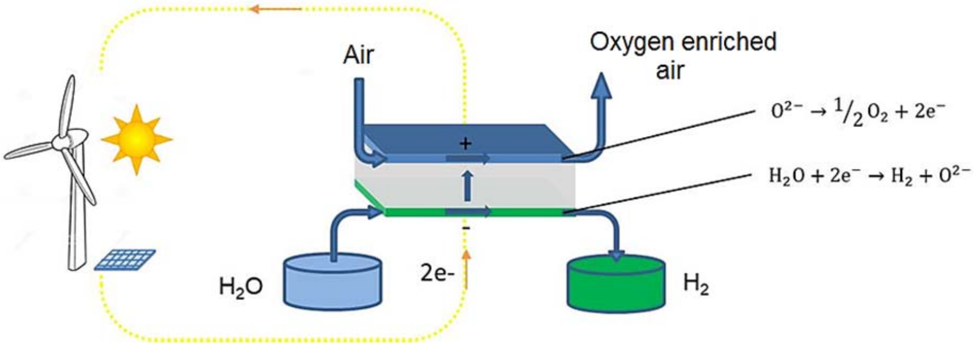
Fig. 18. SOC cell operating in SOE electrolyser mode (left) and in SOFC fuel cell mode (right). Based on [127]

In a system implementing the power-to-gas concept, it is necessary to supply electricity to the SOE cell, while ensuring the reception of produced oxygen and hydrogen, which are produced only if the supply of water or steam is constant. Hydrogen needs to be transported or stored to be used as a fuel, for example in a SOFC fuel cell. Figure 19 shows the difference between SOFC (Fig. 19a) and SOE (Fig. 19b), in system perspective. The main difference is the direction of electricity flow in the system. The SOFC system produces electricity by consuming hydrogen fuel and oxygen from the air, while the SOC system uses electricity (here energy from a wind or solar power plant) producing hydrogen and enriching the air with oxygen.

[127] Kupecki J., Motylinski K., Jagielski S., Wierzbicki M., Brouwer J., Naumovich Y., Skrzypkiewicz M., Energy Analysis of a 10 kW-class power-to-gas system based on a solid oxide electrolyzer (SOE), *Energy Conversion and Management*, 199, 2019, 111934.



(a)



(b)

Fig. 19. Key differences in delivery and reception of media in installations with: a) SOFC and b) SOE

Hydrogen storage

Gaseous hydrogen has a very low volumetric density (0.08988 g/L), which requires a special storage system (e.g. high pressure stores, adsorption stores, chemical storage). In addition, due to the very small size of the H_2 molecule, hydrogen has the ability to diffuse through solid materials, which prevents its storage in conventional cylinders and necessitates the use of special insulating materials. In turn, liquefied hydrogen has a significantly higher density (70 g /L), but requires storage at very low temperatures. Disadvantages associated with the properties of molecular hydrogen make the issue of hydrogen storage a separate branch of scientific research and development. Hydrogen storage, along with renewable hydrogen production and efficient combustion, is a key problem in the way to switching the economy to a so-called hydrogen economy.

The issue of hydrogen storage is not a significant problem when using hydrogen for natural gas enrichment (HENG). Gas installations are then used as both fuel storage and distribution system.

The direction of research and development works on creating an optimal method of hydrogen storage depends on the place of application of this technology. In the case of stationary storage (e.g. scientific laboratories, industrial installations), the most important is the total capacity, ease of use, safety and low price, while the weight of the container itself does not play a key role. High-pressure tanks made of aluminum or steel are used, operating with pressures of 175 bar and 200 bar respectively. However, mobile solutions require a significant reduction of mass of the storage system, due to large possible energy losses resulting from the transport of so-called dead weight of the container. For this reason, mobile hydrogen storage systems are more complex and use more expensive functional materials compared to stationary systems.

Hydrogen fuel should not be inferior to conventional fuels in terms of safety, price and convenience of use. For this reason, in 2003, the *US Department of Energy (DOE)* developed criteria that should be met by a hydrogen storage to ensure its competitiveness with fossil-based technologies, which is particularly important for mobile applications. DOE criteria (last revised in 2017)[128] capacity, operating temperature range, purity of delivered hydrogen, fuel filling time and the cost of stored energy (Table 12). It should be remembered that weight and volume of fuel and all system components, including pipes, valves, housings, etc. should be considered. DOE requirements, although created mainly for mobile applications, can be widely applied to compare various types of hydrogen storage with different storage mechanisms (compression storage, physical storage, chemical storage).

Table 12. DOE criteria regarding the properties of hydrogen storage fuel cells[128]

Parameter	Unit	2020	2025	Target
gravimetric energy density	kWh/kg (kg H_2/kg store)	1,5 (0,045)	1,8 (0,055)	2,2 (0,065)
Volumetric energy density (usable hydrogen relative to system volume)	kWh/L (kg H_2/L store)	1,0 (0,030)	1,3 (0,040)	1,7 (0,050)
Energy storage cost (cost of produced fuel)	USD/kWh (USD/kg H_2)	10 (333)	9 (300)	8 (266)
Operational parameters				
– operational temperature range of hydrogen tank	°C	–40/+60	–40/+60	–40/+60
– hydrogen emission temperature	°C	–40/+85	–40/+85	–40/+85
– system life time	Work cycles	1 500	1 500	1 500
– hydrogen emission pressure range	bar	5–12	5–12	5–12
– mobile efficiency	%	90	90	90
– stationary efficiency	%	60	60	60
Charging / discharging				
– tank filling time	min	3–5	3–5	3–5
– minimal full flow of hydrogen	(g/s)/kW	0,02	0,02	0,02
– average flow of hydrogen	(g/s)/kW	0,004	0,004	0,004
– time to reach full flow (+20°C)	s	5	5	5
– time to reach full flow (–20°C)	s	15	15	15
– temperature variation response	s	0,75	0,75	0,75

Currently, high-pressure hydrogen tanks are most commonly used. Tanks with nominal operating pressures up to 350 bar and 700 bar are used. They are made of modern and lightweight materials, such as glass and carbon fiber, with minimal use of heavy metal elements. Thanks to this, they feature high strength and low weight, which unfortunately translates also into their high price. The biggest advantage of high-pressure tanks is the 100% reversibility of the system, i.e. the ability to recover all stored hydrogen, and the purity of hydrogen emitted, identical to the purity of compressed hydrogen. What's more, the filling time of the tank is short, which is important for both mobile and stationary

[128] Target Explanation Document: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles, USDRIVE, US Department of Energy, 2017.

applications. 4 types of high-pressure hydrogen tanks can be differentiated, due to materials used and the maximum operating pressure:

type 1 – metal tanks: aluminum (p_{max} = 175 bar) or steel (p_{max} = 200 bar);

type 2 – metal tanks with lagging: aluminum coated with glass fiber (p_{max} = 263 bar) or steel covered with carbon fiber (p_{max} = 299 bar);

type 3 – composite tanks: aramid-glass (p_{max} = 438 bar) or aluminum-carbon (p_{max} = 299 bar);

type 4 – composite tanks: carbon-polymer ($_{p}$max = 700 bar).

However, high pressure tanks do not meet all DOE requirements, especially the weight criterion, despite use of specialized materials. The actual hydrogen content by weight in 350 bar and 700 bar systems (i.e. including the weight of the tank itself) is 5.5% and 5.2%, respectively[129]. It is also problematic to meet the volumetric criterion, since it is currently not possible to use a significantly higher operating pressure. Development is currently underway to produce lighter and more durable construction materials. Considered also is the possibility of using adsorption fillers, increasing the effective density of hydrogen in the tank. Despite not meeting all DOE criteria, high pressure tanks are the most reliable type of hydrogen storage and are widely used in hydrogen powered vehicles.

An alternative to compressing hydrogen may be liquid state storage. Unfortunately, it is an expensive and complicated process due to the very low boiling point of hydrogen (20.28 K; -252.87°C) and the critical temperature of hydrogen (33 K; -240°C)[130]. Compressing hydrogen alone is a very expensive process. Converting it to liquid form requires lowering the temperature below 33 K. It is estimated that the process of liquefying hydrogen consumes the equivalent of approx. 36% of energy stored in it[131]. In addition, storage of liquefied hydrogen is problematic due to its incomplete thermal insulation from the environment, which results in the inevitable increase in system temperature and slow evaporation of hydrogen. Due to these disadvantages, liquefied hydrogen is only used in systems that require maximized hydrogen content in a short time. Otherwise, hydrogen storage in high pressure cylinders is more advantageous.

Research is currently underway on the storage of hydrogen in adsorption tanks. Adsorption is a process of binding molecules, it occurs on the surface and allows gas to be stored in a tank with a correct construction and filling. No chemical bonds are formed, the adsorption process is fully reversible and depends on external conditions – adsorption occurs under increased pressure, while desorption requires an increase in temperature. The best adsorbents are porous materials with large surface area per unit of mass or volume. Graphite nanostructures are able to reversibly adsorb up to approx. 3% hydrogen weight, however, this value increases under reduced temperature (7.4% at 77 K[132]). Adsorption tanks are not currently used commercially due to failure to meet many DOE criteria and proposed solutions not being technologically ready.

Chemical hydrogen storage uses the phenomenon of absorption, i.e. permanent binding of hydrogen in the entire volume of the absorbent. The biggest advantage of chemical hydrogen storage is higher volume density of hydrogen, compared to free hydrogen in gas or liquid phase, without the need to generate high pressures or low temperatures (Table 13). During hydrogen storage process, new chemical compounds with a high hydrogen content are created. In turn, the recovery of hydrogen gas requires heating the system to break down previously created compounds. A number of chemical compounds

[129] Hua T.Q., Ahluwalia R.K., Peng J.-K., Kromer M., Lasher S., McKenney K., Law K., Sinha J., *Int. J. Hydrog Energy*, 36, 2011, 3037.

[130] http://www.webelements.com, [accessed: 28.07.2019].

[131] https://www.idealhy.eu/ [accessed: 28.07.2019].

[132] Schlapbach L., Zuttel A., *Nature*, 414, 2001, 353.

with high hydrogen content are known, but so far no material has been found that would meet all DOE criteria[133,134,135]. Among the tested systems, two materials can be distinguished, which show excellent kinetics of hydrogen absorption and desorption. However, the hydrogen content is insufficient, i.e. palladium (1.5%)[136] and titanium doped sodium aluminum hydride (5.5%)[137]. Chemical hydrogen storage has not yet found commercial use, with the exception of hydrophilic alloys used in Ni-MH cells.

Table 13. Hydrogen volume density and hydrogen content by weight of selected substances

Substance	Volumetric density H	Weight percentage H
Hydrogen in standard conditions	$8{,}99 \cdot 10^{-2}$ kg/m^3	100%
Pressured hydrogen 350 bar	$2{,}50 \cdot 10^{1}$ kg/m^3	100%
Liquid hydrogen (T = 20K, p = 1 bar)	$7{,}08 \cdot 10^{1}$ kg/m^3	100%
Liquid hydrogen (T = 20K, p = 240 bar)	$8{,}70 \cdot 10^{1}$ kg/m^3	100%
Methane in standard conditions	$1{,}65 \cdot 10^{-1}$ kg/m^3	25%
Water	$1{,}11 \cdot 10^{2}$ kg/m^3	11%
Aluminum hydride	$2{,}42 \cdot 10^{2}$ kg/m^3	11%
Borazan	$1{,}53 \cdot 10^{2}$ kg/m^3	19%

During scientific research and development, it is usually assumed that the hydrogen tank should be able to be quickly charged with hydrogen gas, and also quickly discharged. This is extremely important for mobile applications, although in this context an alternative system is also being considered, providing for the use of hydrogen fuel cartridges that could be replaced and regenerated in specialized plants after depletion. At the current stage of hydrogen technology development, the use of high-pressure tanks filled with gaseous hydrogen seems to be the most justified for economic and utility reasons.

The use of hydrogen: *fuel cells*

Fuel cells are a special class of electrochemical cells that are electricity and heat generators. They can be used in transport solutions as well as in stationary energy installations. Fuel cells can be powered by alternative fuels, including hydrogen and synthetic fuels produced in chemical energy storage systems – power-to-gas (PtG or P2G) systems, which are discussed in the next section of the study. For this reason, fuel cells are considered technologies belonging to installations that allow high-efficiency generation of electricity and heat from energy stored in fuel.

Fuel cells are classified by type of electrolyte or operating temperature. Classification according to the first criterion distinguishes electrolyte cells in form of a *proton exchange membrane (PEM)* in the form of molten carbonates (MCFC – molten carbonate fuel cell) or solidified ceramic material (*solid oxide*

[133] C. Milanese, S. Garroni, F. Gennari, A. Marini, T. Klassen, M. Dornheim, C. Pistidda, *Metals*, 8, 2018, 567.

[134] M. Paskevicius, L.H. Jepsen, P. Schouwink, R. Černý, D.B. Ravnsbæk, Y. Filinchuk, M. Dornheim, F. Besenbacherf, T.R. Jensen, *Chemical Society Reviews*, 46, 2017, 1565.

[135] R. Owarzany, P.J. Leszczynski, K.J. Fijalkowski, W. Grochala, *Crystals*, 6, 2016, 88.

[136] T. Graham, *Philosophical Transactions of the Royal Society*, 156, 1866, 415.

[137] B. Bogdanović, M. Schwickardi, *Journal of Alloys and Compounds*, 1, 1997, 353–354.

fuel cell, SOFC) Classification by the temperature criterion introduces the distinction between low temperature cells, that make up PEM cells, and high temperature cells, including MCFC and SOFC. The former operate at temperatures up to 80°C[138], while high-temperature cells operate in range of 620–670°C[139] and 550–1000°C, respectively[140,141] . In addition to PEM, MCFC and SOFC, there are other types of fuel cells, however, they are not as widely used as the three above-mentioned types. The fuel cell consists of three basic functional layers: a fuel electrode (anode), an air electrode (cathode) and the electrolyte separating them. Fuel oxidation reaction occurs on the surface of the anode while the oxidant reduction reaction, which is most often air, on the cathode surface. By definition, the electrolyte acts as an electrical insulator that allows free flow of ions. During operation of the cell, electrical voltage is generated provided that there is continuous access to fuel and oxidant. The disappearance of any of the reactant streams stops the electrochemical reaction and can additionally cause anode oxidation or cathode reduction during fuel decay or oxidant decay, respectively. The work of the fuel cell is accompanied by losses that can be divided into electrochemical reaction activation losses, ohm losses and losses associated with transport (supply) of reagents to the electrochemical reaction area. The location of these processes in the fuel cell is schematically illustrated in Fig. 20.

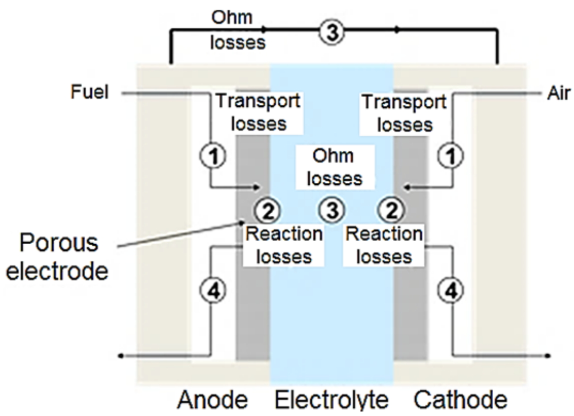


Fig. 20. A simplified diagram of the fuel cell, together with an indication of the location of characteristic losses occurring during its operation[142]

The resulting fuel cell voltage (real cell voltage) is therefore the ideal cell voltage minus activation losses, ohm losses and losses due to concentration differences, respectively.

Fuel cells belong to the group of energy conversion technologies with the greatest potential for construction of co- and polygeneration systems on a micro to large scale. Installations with a capacity of less than 1 kW as well as stationary installations with power of tens of megawatts are known, including the flagship power plant with a capacity of 59 MW, based on carbonate cells (*MCFC – molten carbonate fuel cell*) built by POSCO Energy at Gyeonggi Green Energy Park in South Korea. Among fuel cells, particularly high hopes are placed on SOFC high temperature cells, which have a number of advantages

[138] Japanese group unveils SOFC Ene-Farm residential cogen unit, *Fuel Cells Bulletin*, 4, 2012, 4.

[139] Kulkarni A., Giddey S., Materials issues and recent developments in molten carbonate fuel cells, *Journal of Solid State Electrochemistry*, 16(10), 2012, 3123–3146.

[140] Promising perovskite cathode for low-temperature SOFCs, *Fuel Cells Bulletin*, 2, 2017, 15.

[141] Singhal S.C., Kendall K., High Temperature Solid Oxide Fuel Cells: Fundamentals, Design and Applications, Elsevier, 2003.

[142] Kupecki J. (ed.), Selected aspects of mathematical modeling of SOFC stacks during dynamic operation [in Polish], Wydawnictwo Naukowe Instytutu Technologii Eksploatacji – PIB, 2018, ISBN 978-83-7789-501-6.

over low temperature cells. However, it should be noted that PEM cells are widely used in transport applications, while energy installations are built mainly on the basis of MCFC and SOFC cells. Also known are micro-cogeneration systems with PEM (over 100,000 installations installed as part of the Japanese ENE-FARM program), as well as installations with increased power PEM, which are presented later in this section. Recent years (2010-2018) have resulted in establishment of many demonstration installations in Europe, including the first Polish micro-cogeneration system (*micro-CHP – micro-combined heat and power*) with fuel cells[143], The first installation using sewage sludge to generate electricity with the help of SOFC cells[144] and launched in 2017 as part of the DEMOSOFC project, the largest European installation with 174 kW SOFC cells[145].

The potential of fuel cells is also evidenced by the fact that they have been classified as one of the energy sources that can be at the heart of high-efficiency cogeneration installations operating in a distributed energy system. The EU directive on support for high-efficiency cogeneration[146] lists fuel cells together with other micro and small scale electricity generation technologies, including: gas turbines, back pressure steam turbines, condensation steam turbines, internal combustion engines, microturbines, Stirling engines, fuel cells, steam engines, and steam circuits with low boiling media (ORC – organic Rankine cycle).

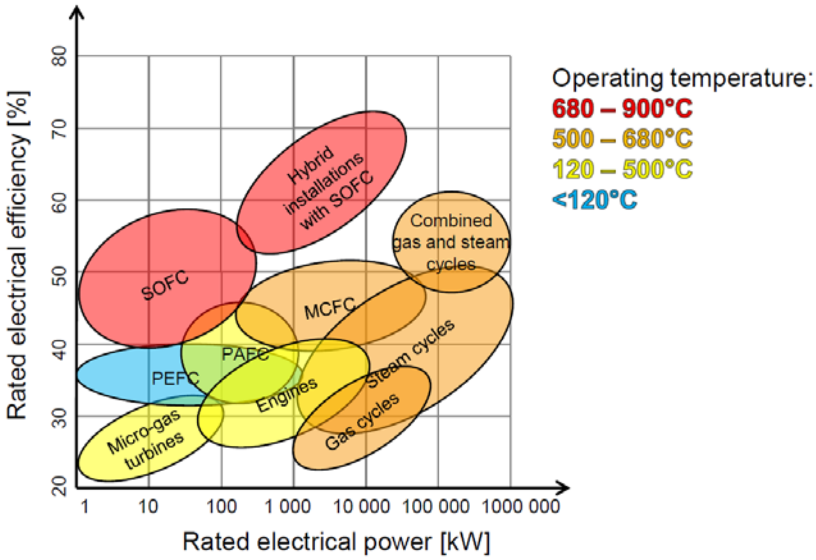


Fig. 21. Graphic presentation of the range of applicability of selected power systems, including rated electrical power, efficiency and operating temperature[147]

A graphic illustration of the performance of installations based on SOFC cells can be a comparison of their performance with selected technologies for generating electricity on a micro to large scale (Fig. 21). In addition, as an extension of the rated power and electrical efficiency, the specification of rated temperature of the energy conversion process in each of the included technologies was introduced. The

[143] Kupecki J., Skrzypkiewicz M., Stefanski M., Stepien M., Wierzbicki M., Golec T., Selected aspects of the design and operation of the first Polish residential micro-CHP unit based on solid oxide fuel cells, *Journal of Power Technologies*, 96(4), 2016, 270–275.

[144] Santarelli M., Briesemeister L., Gandiglio M., Hermann S., Kuczynski P., Kupecki J., Lanzini A., Llovell F., Papurello D., Spliethoff H., Swiatkowski B., Torres-Sanglas J., Vega L.F., Carbon recovery and re-utilization (CRR) from the exhaust of a solid oxide fuel cell (SOFC): analysis through a proof-of-concept, *Journal of CO2 Utilization*, 18, 2017, 206–221.

[145] Strona www projektu DEMOSOFC, http://cordis.europa.eu/project/rcn/197931_en.html [accessed: 13.07.2019].

[146] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC.

data presented in Figure 21 are based on actual efficiency reported for installations with PEFC, MCFC, SOFC cells and specifications of conventional power plant circuits and thermodynamic calculations carried out under strict assumptions[147].

PEM cells are the only ones that have been used in transport and are widely available from each of the leading vehicle manufacturers. For the flagship vehicle – Toyota Mirai – a stack consisting of 370 cells with a total maximum power of 114 kW is used[148].

6.2. DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

PtG hydrogen production

Three basic types of electrolysers can be used in power-to-gas installations:

1. PEM electrolysers.
2. Alkaline electrolysers.
3. SOE electrolysers.

As mentioned in the introduction, solid oxide electrolysers (SOEs) are the only ones that can be freely switched between hydrogen generation mode and electricity generation mode, consuming the previously generated hydrogen. The design and principle of operation of PEM and alkaline electrolysers significantly impedes operation in this mode, called reverse operation or operation as a reversible cell. The potential of PtG installations, particularly in the context of efficiency of the energy storage process and installation costs, is strongly correlated with the electrolyser's performance. To compare the energy expenditure of energy storage, attention should be paid to power density and voltage characteristic of the three types of electrolysers. These parameters are summarized in Fig. 22. Currently, commercial alkaline and PEM electrolysers allow for production of hydrogen with an energy input of 4.9 kWh/Nm^3 of hydrogen[149], which corresponds to approx. 54.52 kWh/kg hydrogen produced (conversion ratio Nm^3 to kg for hydrogen is 11.126). When using SOE cells, energy expenditure can be reduced to 45, and in the case of the most advanced installations, nearly 40 kWh/kg[150]. In case of using the so-called reversible SOC cells (rSOC) operating alternately in SOE electrolyser and SOFC fuel cell mode, it is possible to obtain a value of 45 kWh /kg H_2. This value is marked in Fig. 22.

[147] Kupecki J. (ed.), Selected aspects of mathematical modeling of SOFC stacks during dynamic operation [in Polish], ITE – PIB, 2018 ISBN 978-83-7789-501-6.

[148] Toyota Mirai technical data, https://media.toyota.co.uk/wp-content/files_mf/1444919532151015MToyotaMiraiTechSpecFinal.pdf [accessed: 14.07.2019].

[149] Hydrogenics catalogue data, https://www.hydrogenics.com/wp-content/uploads/2-1-1-industrial-brochure_english.pdf?sfvrsn=2, [accessed: 29.07.2019].

[150] Sunfire catalogue data with SOE electrolysers, https://www.sunfire.de/en/products-and-technology/sunfire-hylink [accessed: 29.07.2019].

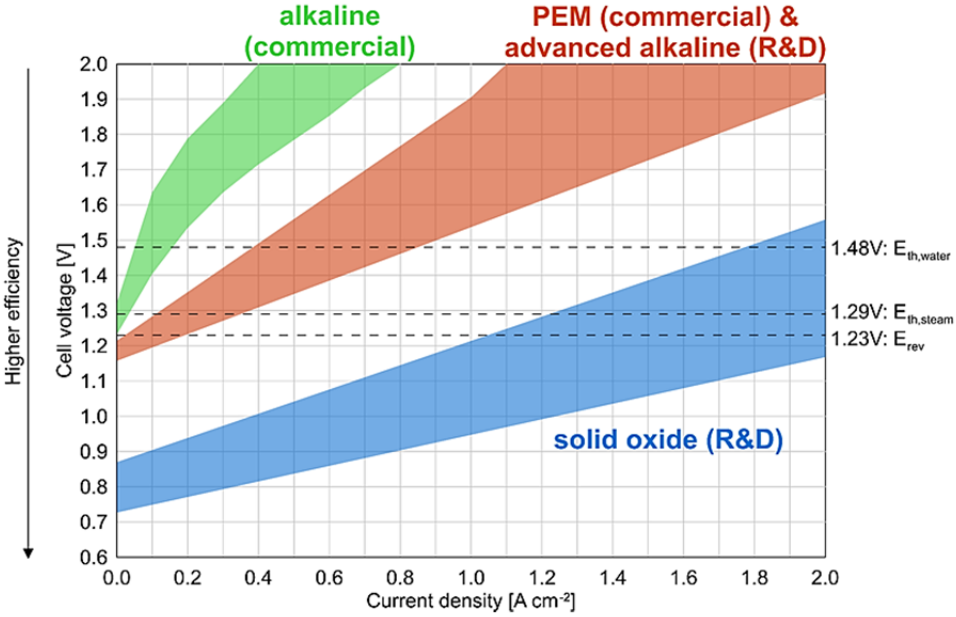


Fig. 22. Comparison of parameters: alkaline, PEM and solid oxide electrolysers. Based on[151], supplemented with unpublished data from Institute of Power Engineering

The environmental impact analysis of PtG installations mainly includes the benefits of:

- Possibilities of managing electricity from renewable energy sources. Depending on the source of electricity, the environmental impact of the installation will be different.
- The possibility of waste heat management (in the case of high-temperature electrolysers), which eliminates the use of electricity to evaporate water in the electrolyser, which directly translates into efficiency of hydrogen production.
- Integration of electrolysers with steam circuits is possible. In this regard, it is particularly advantageous to use SOE electrolysers integrated with steam and gas-steam power systems. Thanks to this combination, the flexibility of power installations increases significantly. Produced hydrogen can be used directly in the power plant cycle or extracted as a commercial product – a substrate in chemical processes, energy fuel or transport fuel. The integration of SOE electrolysers with steam circuits of power plants or combined heat and power plants saves significant amounts of CO_2 generated during the operation of these installations outside the rated operating point, as well as reduces carbon dioxide emissions associated with the start-up of generating units centrally disposed of using kindling fuel.
- Replacement of steam reforming hydrocarbons with systems for generating hydrogen from renewable energy sources. In the case of using electricity from renewable energy sources, PtG installations offer the possibility of producing hydrogen without a carbon footprint, however, however at a price 2-3 times higher than current .
- In the context of PtG system design, PEM cells require noble metals as catalysts. Alkaline electrolysers require replacement of the KOH solution (typically 30% by weight in water). In case of SOE, there are no moving parts or catalysts that will be difficult to recycle or dispose.

[151] Graves C., Sune D., Ebbesen S.D., Mogensen M., Lackner K.S., Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy, Renewable and Sustainable Energy Reviews 2011;15(1):1-23.

Materials used in cells are similar to those in fuel cells, PEM, alkaline cells and SOFC cells, respectively.

- Power-to-gas systems producing high-efficiency hydrogen are currently considered as a technology that can simultaneously perform several basic functions. The use of gas system as a hydrogen storage and distribution system can connect several sectors, in line with concept presented in Figure 23.

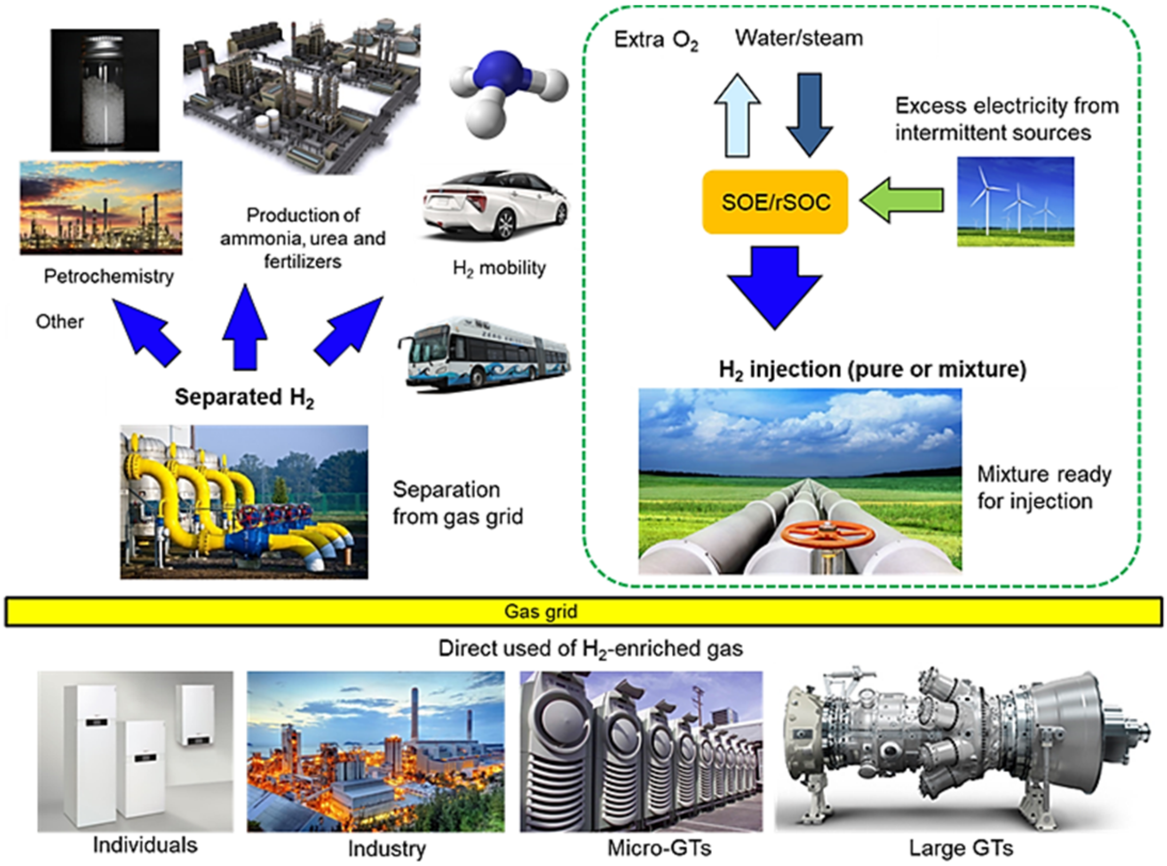


Fig. 23. The possibility of utilizing gas network as a hydrogen storage and distribution system for various industries

Hydrogen storage

The choice of hydrogen storage technology determines the choice of materials and agents that can affect the environment. Compression storage, which is the most common, requires energy expenditure for compressing hydrogen or possibly condensation, as well as for the construction of high-pressure hydrogen tanks. If renewable energy sources are used to compress hydrogen, the environmental impact of this technology will be neutral.

The use of hydrogen storage systems that require complicated regeneration or re-fabrication (such as hydrogen-rich chemicals) will entail additional costs and the potential need for the use or emission of harmful substances.

Fuel cells

The use of fuel cells allows for drastic reduction of emission factors. For transport applications, almost exclusively PEM cells are used[152]. There are no other products in form of impurities or oxides typical for combustion processes, but the potential effect of increasing the content of water vapor in the atmosphere and significantly accelerating the circulation of water in nature on the climate is not known. The impact on the environment, however, depends on the method of obtaining hydrogen. If gas is produced using steam reforming of hydrocarbons, in case of conventional methane reforming, the amount of carbon dioxide emitted is in range from 8.9 to 12.9 kg CO_2/kg H_2[153]. In case of coupling methane steam reforming with carbon dioxide separation and sequestration system, this figure may be reduced to 3.4 kg CO_2/ kg H_2. Further reduction of carbon footprint is possible through use of coal gasification as a source of hydrogen. In this case, the reported values are between 0.91[154] and 4.08[155] kg CO_2/kg H_2. The hydrogen produced in electrolysers coupled with renewable sources has a carbon footprint of nearly zero. If the electricity used in the cells comes from coal combustion process, the carbon footprint analysis becomes complex, but the indicators are within the range defined above by coal-fired power plants and hydrogen generation systems in the process of coal gasification. **Hydrogen extraction in RES-coupled cells is the most clean.**

In stationary applications, the emission indicators for hydrogen powered PEM cells are similar. However, if an installation with PEM cells is fed with network gas, the analysis of the environmental impact takes into account the need for continuous desulphurisation of the gas fed to the fuel cell system. In addition, the lean fuel post-combustion system behind a stack of PEM cells generates nitrogen oxides as well as carbon dioxide.

MCFC and SOFC cells allow the use of a wide range of fuels. The use of biogas and hydrocarbons is particularly preferred. In case of fuels of this type, the installation with MCFC / SOFC is equipped with a so-called fuel processor, which is usually a compact steam reformer. This device converts hydrocarbons to a hydrogen-rich gas, which is then directed to the fuel portion of the cell stack. Behind the stack a depleted fuel afterburner for the fuel leaving that part of the cell stack is located. In this case, emissions of nitrogen oxides and carbon dioxide should be expected in the exhaust stream leaving the MCFC / SOFC cell system. Emission of sulfur compounds is practically eliminated thanks to use of a deep fuel desulphurisation system[156] before the steam reformer and the MCFC or SOFC stack. In this case, when analyzing the environmental impact of installations with MCFC / SOFC cells, replacement of the sorbent bed used in fuel desulphurisation system should be considered. This deposit is based on coal or active coke and is replaced every few months. In power installations, PEM, MCFC and SOFC cell stacks are expected to last for several years, typically 50,000 – 80,000 hours, while in transport applications, the expected lifetime of PEM cells is between 5,000 and 10,000 operating hours. Work is currently underway to extend this time to 40,000 hours[157]. At the end of their life, entire stacks (in case of PEM) or their ceramic components (MCFC and SOFC stacks) are replaced. Noble metals are

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[152] An exception is the work of the American Delphi company on auxiliary power systems with SOFC cells for trucks and the e-Bio Fuel-Cell system developed by Nissan based on a SOFC cell powered with bioethanol, whose operation was demonstrated on the example of the NV200 model, https://newsroom.nissan-global.com/releases/160614-01-e [accessed: 14.01.2020].

[153] Bhandari R., Trudewind C.A., Zapp P., Life cycle assessment of hydrogen production via electrolysis – A review. *J. Clean. Prod.*, 85, 2014, 151–163.

[154] Verma A., Kumar A., Life cycle assessment of hydrogen production from underground coal gasification, *Appl. Energy*, 147, 2015, 556–568.

[155] GREET Model, http://greet.es.anl.gov [accessed: 10.06.2019].

[156] Określenie *głębokie odsiarczania* stosuje się zwyczajowo do określenia systemów usuwania związków siarki, w których paliwo po oczyszczeniu zawiera do 1 ppm. W przypadku paliw takich jak biogaz pochodzenia rolniczego, początkowa zawartość związków siarki w paliwie nieoczyszczonym może wynosić nawet do 20 000 ppm.

[157] EU project repository – STAYERS project, https://cordis.europa.eu/project/rcn/97935/factsheet/en [accessed: 13.07.2019].

recovered from PEM cells [158]. In the case of MCFC / SOFC, it is possible to separate most materials, in particular nickel, from which the next series of cells is then made.

6.3. RESOURCE RESTRICTIONS

PtG hydrogen production

Materials used in hydrogen production systems based on electrochemical processes are simillar to those in the case of fuel cells (e.g. PEM, MCFC, SOFC etc.). In addition, it should be noted that the full implementation of the concept of the so-called green hydrogen requires several basic criteria to be met. Firstly, fuel without a carbon footprint, i.e. hydrogen produced only from renewable energy sources, can be generated if wind, solar or other renewable energy is used. Generation units of this type are characterized by high variability of operation over a weekly or monthly perspective, therefore it is not possible to assume that they will operate continuously in a long time perspective, for example several months. Therefore, as a raw material limitation of PtG systems, the limited possibility of supplying electrolysers only from renewable energy sources should be considered. The gradual increase in the share of renewable energy in national power system creates possibility of building high-power PtG systems that produce a storage medium without a carbon footprint.

The electrolysis process requires continuous water supply (for PEM and alkaline and SOE cells) or steam (SOE only). The specifics of electrolyser operation requires ensuring proper water and steam purity, which is subjected to demineralization or demineralization combined with deionization. This is to reduce the accumulation of impurities on electrode surface (PEM and SOE) or in the electrolyte solution (alkaline electrolysers). Demineralization and deionization processes require use of carbon cartridges and an ion exchanger, respectively. They are mostly made on the basis of natural materials – zolites, cellulose or activated carbon. Therefore, there are no restrictions on raw materials in this respect.

It is also possible to use a closed water cycle, but only if the produced hydrogen would be stored and consumed in the same plant. However, this solution is not technically feasible if the hydrogen produced would be used in another location, e.g. in vehicles or in enriched natural gas installations.

The design of PtG systems is different for low-temperature (PEM and alkaline) and high-temperature (SOE) installations. In both cases, dedicated, commercially available steels or plastics are used. Key elements, i.e. electrolyser components, are made of materials commonly used in other industries. It should only be noted that in PEM, a noble metal catalyst is needed, which determines the price of this technology, however it is not a material restriction.

Hydrogen storage

The possibility of efficient storage of hydrogen in high-pressure containers is not limited by the availability of raw materials. They are made of widely available materials, such as aluminum, steel, glass and carbon fibers, polymeric materials and other carbon materials. However, the limitation may be the degree of development and availability of technology related to production of specialized hydrogen tanks.

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[158] Cooper J.S., Grot S., Hartnig C., 5 – Recycling and life cycle assessment of fuel cell materials [in] Hartnig C., Roth C. (eds), Polymer Electrolyte Membrane and Direct Methanol Fuel Cell Technology, *Woodhead Publishing*, 1, 2012, 117–134.

Fuel cells

The materials used in fuel cells depend on type of cell and its operating parameters. In the case of low-temperature cells, i.e. operating at temperatures below 100°C, which mainly form cells with a proton conductive membrane, materials significantly different than in the case of high-temperature cells (600–1000°C), which include MCFC and SOFC. The materials used to build each layer are different, depending on the type of cells. A summary of the specifics of raw materials used for PEM, MCFC and SOFC is presented in Table 14.

Table 14. List of raw materials used to build fuel cells

Component	PEM	MCFC	SOFC
Anode	Graphite paper coated with Teflon from the outside of the electrode	Sintered nickel with the addition of chromium	Nickel cermet[159] (Ni-YSZ) or cobalt cermet (Co-YSZ) with porous structure. Also used: cermets Cu/CeO_2, $Cu/CeO_2/YSZ$, Perovskites $La_{1-x}Sr_xCrO_3$, Perovskites $La_{1-x}SrxCr_{1-y}MyO_3$
Electrolyte	Polymer coated with a precious metal catalyst (platinum). The dominant electrolyte material is Nafion®[160] manufactured by DuPont	Lithium carbonate (Li_2CO_3) or potassium carbonate (K_2CO_3) placed in a ceramic matrix in the form of $LiAlO_2$	Zirconia (ZrO_2) doped with yttrium oxide (Y_2O_3), which occurs under the abbreviated name YSZ (Yttia stabilized zirconia)
Cathode	Graphite paper coated with Teflon from the outside of the electrode	Sintered nickel and lithium oxide	Perovskit $(La,Sr)MnO_3$, oxides from the $Ln_{1-x}A_xCo_{1-y}Fe_yO_{3-\delta}$ lub $Ln_{1-x}A_xMnO_{3\pm\delta}$ groups are also used

The high operating temperature of MCFC and SOFC cells eliminates the use of noble metals. In their place, common and cheap nickel is used. When using cobalt-based materials, problems related to its availability, geographical distribution of resources (mainly Democratic Republic of Congo) and mining methods should be indicated. In addition, it should be noted that the price of cobalt has changed rapidly over the last three years, from 30,000 USD/ton, to nearly 100,000 USD/ton[161] (Fig. 24).

[159] The cermet is a composite of dispersed metal particles in a solid electrolyte matrix (CER – ceramics / MET – metal).

[160] Synthetic copolymer of teflon monomer and perfluorinated oligovinyl ether terminated with a sulfone residue.

[161] Cobalt price, http://www.infomine.com/investment/metal-prices/cobalt/5-year/ [accessed: 14.01.2020].

Fig. 24. Change in the cobalt price over the last 5 years (as of August 1, 2019)

In construction of fuel cell stacks, materials dedicated to PEM, MCFC and SOFC are used. For low-temperature cells, these are basic plastics or typical steels, for MCFCs, heat-resistant steels (containing chromium, silicon, aluminum and other alloy additives, including nickel and manganese) or martensitic stainless steels, including AISI 410 or 414 steel (additionally enriched with nickel). In the case of SOFC cells, whose operating temperature exceeds the typical operating parameters of stainless steels, it is necessary to use dedicated alloys. These are high-chromium alloys, in particular Crofer® 22H and Crofer APU [162]. It contains between 20 and 24% chromium, silicon, carbon, manganese, copper, aluminum, sulfur, phosphorus, titanium, lanthanum and iron.

In turn, fuel cell stack seals are made of commonly used materials. For PEM, a wide range of plastic seals can be used. For MCFC and SOFC cells glass, ceramic or glass-ceramic composites are used, based on standard materials used in other industries and market sectors.

6.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

PtG hydrogen production

PEM and alkaline electrolysers have an established position on the market. They are offered by recognized global companies, such as NEL Hydrogen[163], HYDROGENICS[164], McPhy[165], ITM Power[166] or SIEMENS[167]. SOE electrolysers are developed by the German company Sunfire[168] and several research

[162] Crofer is the protected trade name of the product offered by ThyssenKrup / VDM Metals.
[163] https://nelhydrogen.com/ [accessed: 29.07.2019].
[164] https://www.hydrogenics.com/technology-resources/hydrogen-technology/electrolysis/
[165] https://mcphy.com/en/our-products-and-solutions/electrolyzers/ [accessed: 29.07.2019].
[166] http://www.itm-power.com/ [accessed: 29.07.2019].
[167] https://new.siemens.com/global/en/products/energy/renewable-energy/hydrogen-solutions.html [accessed: 29.07.2019].
[168] https://www.sunfire.de/en/products-and-technology [accessed: 29.07.2019].

centers, including EIFER[169], Julich Research Center[170], IKTF Fraunhofer[171] and the Institute of Power Engineering [172]. Each of the mentioned types of electrolysers is built in a modular form. The smallest units occur in case of SOE technology, in which, so far, the largest of the constructed installations had a power of 120 kW[173] and was created for the needs of the US Navy. In the case of PEM and alkaline cells, 10-20 MW class installations are offered, while production capacity of technology suppliers allow for producing systems with a total capacity of up to 360 MW per year in one factory[174]. In terms of scalability, there are no restrictions typical for conventional energy technologies. Electrolysers, thanks to the modular design, are easy to replicate, thanks to being based on series of smaller units. A certain limitation in the construction of high power PtG installations is the common equipment used in hydrogen production systems. For 2-5 MW class systems, a common hydrogen compressor is used, which is produced in 5-15 smaller PEM or alkaline electrolyser modules. The scale increase, due to the limited availability of hydrogen compression machines, requires the use of several separate units. This is a process limitation for the largest installations and adversely affects the cost effect of scale. In addition, the economic analysis of hydrogen production systems should take into account issues related to availability of electrical connection to the power grid, with adequate power supply for the cells and discharge of hydrogen – the possibility of its injection into the gas network or local compression and storage in tanks. The decisive factor in determining the scale of PtG installations is the overall analysis of the value chain of produced hydrogen, taking into account the availability of utilities, area occupied by the installation, availability of the distribution network for generated hydrogen and possible storage at the electrolyser location. In case of SOE, limitations in scalability result from significant costs of CAPEX installations, which at an early stage of technology development are assumed to be smaller than systems based on proven PEM and alkaline cells.

The technological barrier associated with operation of PEM electrolysers is the sensitivity of it's proton conductive membrane to impurities. The membrane is a polymer with a complex structure that is subject to degradation, in particular when working under high electrical load conditions. A detailed discussion of the technological problems of PEM cells is presented in study[175].

Hydrogen storage

Industrial hydrogen storage is currently using metal high volume and high pressure tanks, as in industrial storage of other gases. There is no scalability problem in this case.

Storage of hydrogen for mobile applications can be one of the key problems delaying or suspending introduction of the so-called hydrogen economics. Due to the need to minimize the weight of hydrogen tanks, modern, lightweight composite materials are used, production of which is time consuming and expensive. It is estimated that producing one hydrogen tank costs about 2,000 USD[176], so the cost barrier to the possible introduction of widespread hydrogen storage is significant compared to a fuel

[169] http://www.eco-soec-project.eu/partners#eifer [accessed: 29.07.2019].

[170] https://www.fz-juelich.de/iek/iek-1/EN/Research/FestoxidBrennstoff_Elektrolysezellen/_node.html [accessed: 29.07.2019].

[171] https://www.ikts.fraunhofer.de/en/departments/energy_bio-medical_technology/materials_and_components/ceramic_ energy _converters.html [accessed: 29.07.2019].

[172] HITEP, https://ien.com.pl/informacja-ogolna-2424 [accessed: 29.07.2019].

[173] Sunfire supplies Boeing with largest reversible solid oxide electrolyser/fuel cell system, *Fuel Cells Bulletin*, 2, 2016, 1.

[174] NEL information about the construction of the largest electrolyser factory, https://nelhydrogen.com/press-release/constructing-the-worlds-largest-electrolyzer-manufacturing-plant/ [accessed: 29.07.2019].

[175] Shiva Kumar S., Himabindu V., Hydrogen production by PEM water electrolysis – A review, *Materials Science for Energy Technologies*, 2(3), 2019, 442–454.

[176] B.D. James, C. Houchins, J.M. Huya-Kouadio, D.A. DeSantis, „Final Report: Hydrogen Storage. System Cost Analysis", *Strategic Analysis*, 2016.

tank in vehicles with an internal combustion engine, whose manufacturing cost does not exceed 300 USD.

Fuel cells

The advantage of fuel cells is their scalability, understood both as a modular design, that allows the construction of units with higher power, as well as minor impact of electrical power on efficiency of the installation. In professional and industrial power engineering, the global trend is construction of high power systems, typically above 500 MW. The scale effect allows for increase of efficiency, thereby improving economic indicators. In case of fuel cells, the efficiency characteristics are relatively flat, which means that both low power installations (0.3- 10 kW) and high power installations (25 – 200 kW and larger) achieve comparable efficiency. The electrical efficiency of PEM, MCFC and SOFC fuel cells, which is defined as the electrical voltage obtained in relation to the chemical energy supplied in the fuel, exceeds 40% at the current stage of development. In case of hybrid installations, including coupling cells with a gas turbine set, the efficiency may exceed 70%. Table 15 summarizes the scope of applicability and the electrical efficiency of installations with PEM, MCFC and SOFC cells.

Table 15. The scope of applicability and electrical efficiency of fuel cell systems in question.

Fuel type	Application range (electric power)	Electric efficiency
PEM	20 W – 2 MW[177]	do 52%[178]
MCFC	1,4-59 MW[179]	do 47%[180]
SOFC	400 W – 200 kW[181] [182]	25-70%[183] [184]

The basic limitation of MCFC and SOFC cells scalabilitys is the construction of fuel cell stacks, based in large installations with thousands of connected individual cells. In case of PEM, these restrictions are not present, mainly due to low operating temperature of these cells, which allows for use of relatively simple design solutions and non-advanced materials. For this reason, cells with power of hundreds of kW (e.g. maneuver hydrogen locomotives) and megawatt scale (e.g. 2 MW installation, which was created as part of the DEMCOPEM project) are already used in energy and mobile applications. From the point of view of real restrictions, technological barriers are of secondary importance due to considerable costs of building the installation, as well as limited experience in high power PEM, MCFC and SOFC installations operation. The modularity of fuel cell systems is confirmed by the largest constructed fuel cell installation (59 MW, MCFC technology), located at Gyeonggi Green Energy Fuel

177 DEMCOPEM 2 MW, http://www.demcopem-2mw.eu/ [accessed: 07.07.2019].

178 G. Guandalini, S. Foresti, S. Campanari, J. Coolegemb, J. ten Have, Simulation of a 2 MW PEM Fuel Cell Plant for Hydrogen Recovery from Chlor-Alkali Industry, *Energy Procedia*, 105, 2017, 1839–1846.

179 A. Kulkarni, S. Giddey, Materials issues and recent developments in molten carbonate fuel cells, *Journal of Solid State Electrochemistry*, 16(10), 2012, 3123–3146.

180 Status of POSCO ENERGY's, http://eng.poscoenergy.com/_ui/down/posco_2011sr_eng.pdf [accessed: 13.07.2019].

181 Promising perovskite cathode for low-temperature SOFCs, *Fuel Cells Bulletin*, 2, 2017, 15.

182 J. Kupecki, Introduction, [in:] J. Kupecki (ed.), Modeling, Design, Construction, and Operation of Power Generators with Solid Oxide Fuel Cells – From single cell to complete power system, Springer, Cham, 2018.

183 T. Pfeifer, L. Nousch, D. Lieftink, S. Modena, System design and process layout for a SOFC micro-CHP unit with reduced operating temperatures, *International Journal of Hydrogen Energy*, 38, 2013, 431–439.

184 Strona projektu DEMOSOFC, http://www.demosofc.eu/ [accessed: 13.07.2019].

Cell Park in Hwasung, South Korea. It consists of 21 modules, with capacity of 2.8 MW each and total area of just above 20000 m^2 [185].

6.5. ENERGY STORAGE COSTS

PtG hydrogen production

Hydrogen production in power-to-gas systems enables for use of electricity to produce fuel from water or steam. In perspective of systematical rise of electricity prices, costs of hydrogen production show a similar trend. PEM, alkaline and SOE electrolysers technologies are developing together, with progress in material improvement, shaping their electrochemical properties and effective implementation, aimed at improvement of cell life. Alkaline and PEM electrolysers have reached their technological maturity in the 20th century. The last two decades have resulted in electrolysers scaling up to production volumes, corresponding to capacity of several tonnes of hydrogen per day. For example, the NEL A Series modular electrolyser produces up to 8 tons of hydrogen per day, drawing 2.2 MW of electrical power[186]. On a large scale, alkaline and PEM electrolysers allow for production of hydrogen with an energy input between 3.8 and 5.5 kWh/kg H_2. Taking into account the lifetime and investment costs, hydrogen produced in PEM and alkaline cells can cost less than 5 EUR/ kg of hydrogen produced. According to the United States Department of Energy (DOE) analyzes for large scale hydrogen production (measured in tens of tons per day), the cost goal is to reach USD 3.10/kg for central hydrogen production installations[187]. For systems working in distributed energy system, this value is slightly higher and estimated at 3.70 USD/kg. These values have remained unchanged for several years, which results from the mutual correlation of increase in energy prices with the simultaneous reduction of electrolyser costs. It should be noted that costs of hydrogen conditioning (compression and distribution) in PtG systems cooperating with hydrogen infrastructure may reach 2 USD/kg. In low-power installations operating for the needs of distributed hydrogen production systems for transport purposes (gas with purity 99.999%), costs can be as high as 8.8-10.45 USD/kg[188] (EUR / USD exchange rate = 1.1). It should be noted that hydrogen production systems in installations based on methane steam reforming may be at the level of USD 1.5/ kg[189,190]. The structure of hydrogen production costs in PtG systems, however, strongly depends on the systems' operation characteristics and the hourly, daily and seasonal variability of electricity prices[191].

The investment costs of PtG systems depend strongly on the type of electrolyser used. For well-established alkaline electrolyser technology, CAPEX costs for the electrolyser and power-to-gas installation

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[185] FuelCell Energy in 20 MW project with Korea Southern Power, *Fuel Cells Bulletin*, 10, 2017, 5–6.

[186] NEL electrolysers specification, https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/ [accessed: 29.07.2019].

[187] Analysis of US Department of Energy, Multi-Year Research, Development and Demonstration Plan (Hydrogen Production), https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22 [accessed: 29.07.2019].

[188] Weidner S., Faltenbacher M., François I., Thomas D., Skùlason J.B., Maggi C., Feasibility study of large scale hydrogen power-to-gas applications and cost of the systems evolving with scaling up in Germany, Belgium and Iceland, *International Journal of Hydrogen Energy*, 43(33), 2018, 15625-15638.

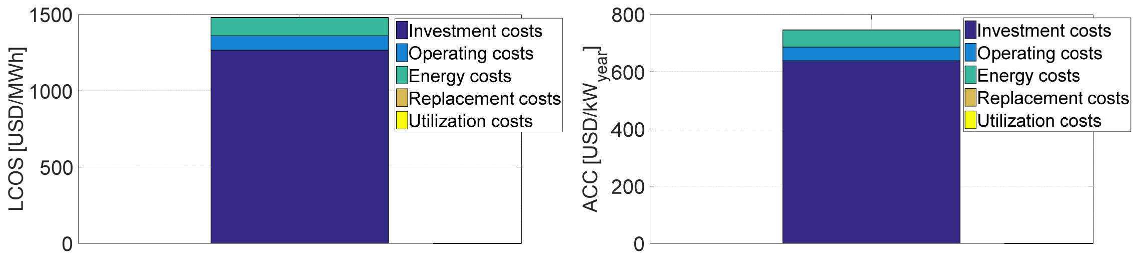
[189] Shaner M., Atwater H.A., Lewis N.S., McFarland E.W., A comparative technoeconomic analysis of renewable hydrogen production using solar energy, *Energy and Environmental Science*, 9, 2016, 2354–2370.

[190] Lück L., Larscheid P., Maaz A., Moser A., Economic potential of water electrolysis within future electricity markets. In: 14th International conference on the European Energy Market (EEM) 2017, doi: 10.1109/EEM.2017.7981950.

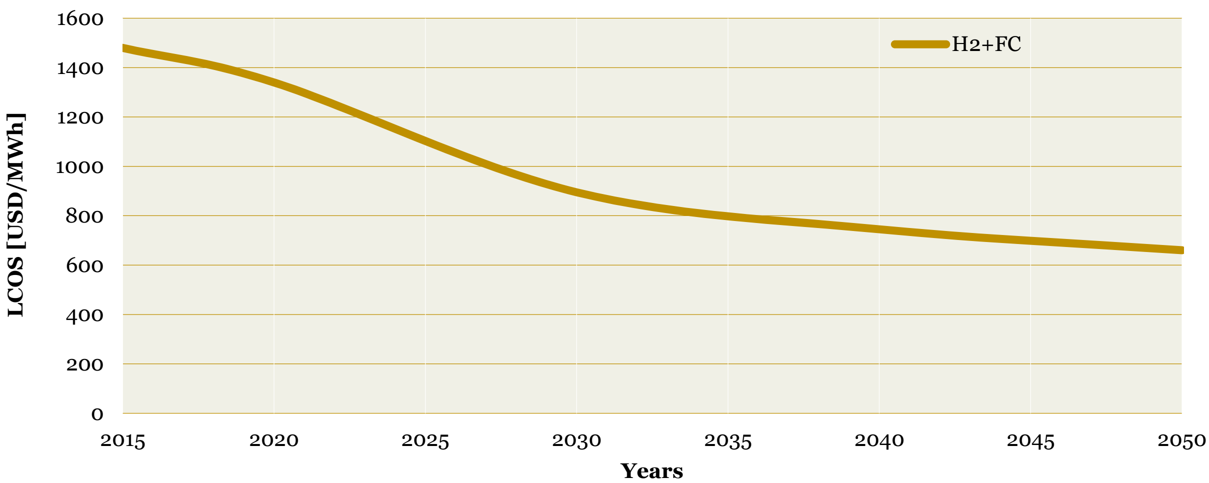
[191] van Leeuwen C., Mulder M., Power-to-gas in electricity markets dominated by renewables, *Applied Energy*, 232, 2018, 258–272.

auxiliaries are between EUR 1,000 and 1,500 per kilowatt of installed capacity[192]. SOE electrolysers are the phase of intensive development and significant cost reduction. Therefore, it is expected that currently estimated values of 2,200-3,300 USD/ kW will decrease to a level below 1,650 USD/kW in the 2030 perspective[193].

Figure 25a shows LCOS for reliable power systems based on hydrogen fuel cells, broken down into, among others, investment, O&M (operation and maintenance), electricity, repair and decommissioning costs. Figure 25b shows LCOS in the 2015-2050 perspective (its value does not exceed USD 1,500/MWh for hydrogen used in *energy arbitration* application). In the 2050 perspective, a greater than 50% drop in LCOS can be observed, below 700 USD/MWh.

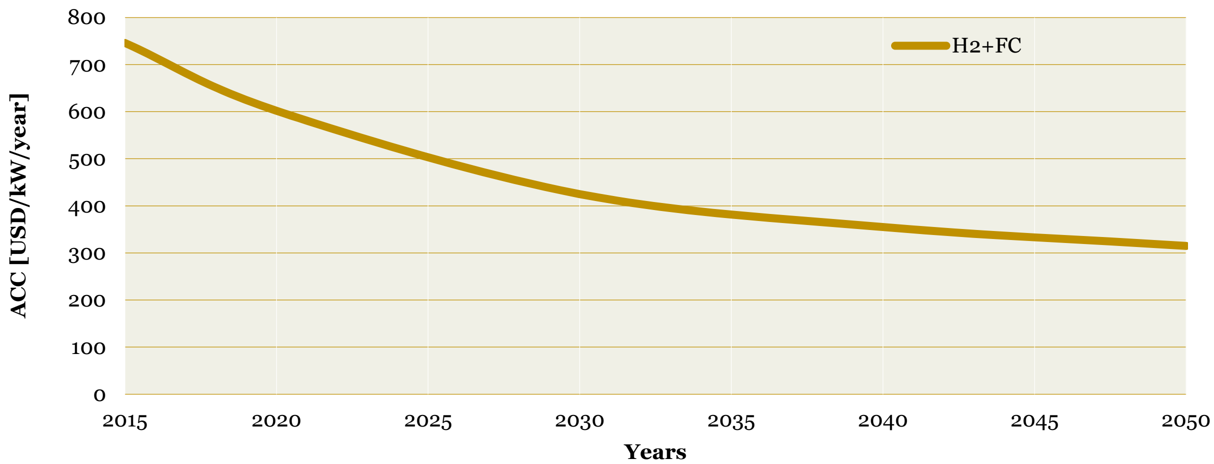


(a)



[192] Götz M., Lefebvre J., Mörs F., McDaniel Koch A., Graf F., Bajohr S., Reimert R., Kolb T., Renewable power-to-gas: a technological and economic review, *Renewable Energy*, 85, 2016, 1371-1390.

[193] E&E Consultant, Etude portant sur l'hydrogene et la m ethanation comme proced e de valorisation de l 'electricit e exc edentaire, Cassel, France, 2014, http://www.grtgaz.com/fileadmin/engagements/documents/fr/Power-to-Gas-etude-ADEME-GRTgaz-GrDF-complete.pdf [accessed: 29.07.2019].



(b)

Fig. 25. a) LCOS & ACC for reliable power supply systems based on hydrogen fuel cells broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective for reliable power systems based on hydrogen fuel cells

Hydrogen storage

The main costs associated with hydrogen storage relate to the provision of suitable tanks, hydrogen compression, and in mobile applications also the common infrastructure for filling tanks. Currently, the unit cost of producing one mobile high-pressure tank is approx. USD 2,000/unit[194], the cost of compressing hydrogen is approx. 1.5 USD/kg H_2[195], and the cost of infrastructure for filling the tanks is comparable with the current costs of infrastructure of petrol stations and filling points for LPG tanks. This means that investment costs for mobile applications are a major contribution to total storage costs, significantly greater than operating costs. In turn, the production costs of stationary high-pressure hydrogen tanks, due to the relative simplicity of their construction and greater availability of materials (iron, aluminum) is definitely lower, compared to the production costs of technically advanced mobile tanks, however they still constitute the main operating cost.

Fuel cells

Fuel cells are not a direct energy storage system. In case of solutions using PEM, MCFC or SOFC cells connected to hydrogen generation systems (electrolysers powered by renewable energy sources), the cost calculation is analogous to that in PtG systems, which are discussed in the next section.

In case of installations with fuel cells without hydrogen storage, which is a particularly costly technology in terms of fixed costs, the cost structure depends on the scale used and the locations considered. For this reason, the three most important studies that provide detailed analysis of investment costs for reference markets should be recalled. The key element of unit cost analysis for fuel cell installations is the scale of production of the considered units. Therefore, most analyzes take into account number of installations from several hundred to several thousand units, or (optionally) relate costs to the total power installed in energy installations with cells, with reference power. The first of the documents

[194] B.D. James, C. Houchins, J.M. Huya-Kouadio, D.A. DeSantis, „Final Report: Hydrogen Storage. System Cost Analysis", Strategic Analysis, 2016.

[195] „Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs", Independent Review of National Renewable Energy Laboratory, U.S. Department of Energy, 2014.

analyzing costs of manufacturing installations with cells is the Battelle Memorial Institute (BMI) report, prepared separately for low[196] and medium power installations[197]. In the study, a price was determined for systems with installed nominal power in the range of 1 – 250 kW, assuming production of 100 to 50,000 installations per year. A summary of the costs is presented in Table 16.

Table 16. Costs of fuel cell systems depending on power capacity of the installation and the scale of production. Based on data [196,197] (USD/PLN exchange rate = 3.89)

System power [kW]	Installation costs [USD] depending on production input in pcs / year. The costs in parentheses are given for one kilowatt of installed capacity			
	100	1 000	100	50 000
1	30 052,18 (30 052,18)	15 493,32 (15 493,32)	12 991 (12 991)	12 256,81 (12 256,81)
5	39 421,34 (7 884,27)	23 615,17 (4 723,03)	19 800,77 (3 960,15)	18 804,88 (3 760,98)
10	50 629,82 (5 062,98)	31 883,80 (3 188,38)	27 709,25 (2 770,92)	26 407,71 (2 640,77)
25	90 171,72 (3 606,87)	64 949,61 (2 597,98)	57 909,25 (2 316,37)	55 344,21 (2 213,77)
100	275 128,79 (2 751,29)	229 192,54 (2 291,92)	207 770,69 (2 077,71)	196 167,61 (1 961,68)
250	557 373,01 (2 229,49)	478 904,11 (1 915,62)	437 646,27 (1 750,59)	412 809,51 (1 651,24)

Table 17. Costs of fuel cell systems depending on power capacity of the installation and the scale of production. Based on data[198] (USD/PLN exchange rate = 3.89)

System power [kWe]	Installation cost [USD] depending on production input in pcs / year. Costs are given in brackets for one kilowatt of installed capacity			
	100	1 000	10 000	50 000
1	27 784,06 (27 784,06)	15 731,36 (15 731,36)	12 308,74 (12 308,74)	10 881,23 (10 881,23)
10	50 664,01 (5 066,40)	29 975,32 (2 997,53)	23 155,01 (2 315,50)	20 878,41 (2 087,84)
50	140 011,31 (2 800,23)	89 024,93 (1 780,50)	74 558,87 (1 491,18)	66 875,32 (1 337,51)
100	221 684,57 (2 216,84)	143 615,94 (1 436,16)	123 031,62 (1 230,32)	111 553,73 (1 115,54)
250	445 598,46 (1 782,39)	316 353,47 (1 265,41)	277 461,44 (1 109,84)	250 901,03 (1 003,60)

[196] Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications, Battelle Memorial Institute 505 King Avenue Columbus, OH 43201, 2017.

[197] Manufacturing Cost Analysis of 100 and 250 Fuel Cell Systems for Primary Power and Combined Heat and Power Applications, Battelle Memorial Institute 505 King Avenue Columbus, OH 43201, 2016, 94–95.

An alternative document, referring specifically to the American market, is a study that was created at Ernest Orlando Lawrence Berkeley National Laboratory[198]. The costs, presented in an analogous manner as based on the Batelle study, are included in Table 17.

The cost assessment in European conditions was carried out by Roland Berger at the request of the Fuel Cell and Hydrogen Joint Undertaking (FCH-JU)[199]. Taking into account the conditions of EU member states, an attempt was made to determine the unit price, even for production of a single system of a given type. Data summary is presented in Table 18. However, installations larger than 50 kW were not included in the study prepared for FCH-JU. Estimates for this type of system are currently not available. This is mainly due to specifics of the systems.

Table 18. Costs of fuel cell systems depending on power capacity of the installation and the scale of production. Based on data[199] (USD/PLN exchange rate = 3.89)

System power [kWe]	Installation cost [USD] depending on production input in pcs / year					
	1	100	500	1 000	5 000	10 000
1	43 638,56	brak danych	20 156,30	15 214,39	10 244,73	8 051,41
5	116 717,74	69 186,63	48 630,59	27 919,02	19 767,61	18 101,80
50	994 377,38	461 029,56	314 078,41	185 791	129 171,21	115 315,17

Analysis of data resulting from the three cited reports allows for determination of cost limits in the case of conservative, i.e. strict assumptions – which correspond to the European report.

6.6. MAIN APPLICATIONS

PtG hydrogen production

The use of power-to-gas installations is of particular importance for the concept of connecting electricity and gas systems implementation, the so-called sector coupling. PtG systems are used only in stationary installations, designed to be connected only to electric or both electric and gas networks. Basic applications:

- hydrogen production for transport, which is stored in a way that allows injection into a tank with storage pressure of 350 or 700 bar,
- hydrogen production, which is stored directly near the PtG installation, and serves as fuel during the electrolyser's operation in fuel cell mode. Storage pressure is from several to several dozen bar,
- hydrogen production as a substrate for chemical processes or as a substrate in production of synthetic fuels (discussed in detail in section on SNG production),

[198] Scataglini R., Mayyas A., Wei M., Han Chan Sh., Lipman T., Gosselin D., D'Alessio A., Breunig H., Colella W.G., James B.D., A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and PowerOnly Applications; Ernest Orlando Lawrence Berkeley National Laboratory, 2015.

[199] Roland Berger elaboration commissioned by Fuel Cells and Hydrogen Joint Undertaking; Advancing Europe's Energy systems: Stationary fuel cells in distributed generation, 2015.

- stabilization of the grid power system, through the production of hydrogen and its injection into the gas network – management of surplus electricity from renewable energy sources or from commercial and industrial power generation units.

Hydrogen storage

Hydrogen storage is applicable wherever gaseous hydrogen is used. Basic applications:

- large industrial plants
- small tanks for mobile applications, i.e. in vehicles,
- science laboratories.

Fuel cells

Fuel cells are used in transport sector, including:

- small individual vehicles (scooters, bicycles, motorbikes),
- individual transport,
- special-purpose vehicles, in particular: forklifts for indoor use and light transport vehicles,
- public transport vehicles, in particular: buses in which fuel cells are used as a basic electricity generator or in which the cell is used as a so-called range extender
- locomotives (engines)
- auxiliary power sources, in particular: installations enabling production of electricity when the vehicle is stationary – to eliminate engine idling, only for the purposes of generating electricity to power the sleeping part of transport trucks cabin.
- Low-temperature cells, i.e. PEM, fed with 99.999% pure hydrogen (so-called hydrogen 5.0).
- In power applications, PEM, MCFC and SOFC, fuel cells are used in following systems:
    - electricity generation,
    - cogeneration installations, i.e. systems in which electricity and heat are generated at the same time,
    - polygeneration systems in which, apart from electricity and heat, other media are also generated, for example cold or purified water (in case of coupling of fuel cells with desalination plants),
- cells powered by hydrogen generated using electrolysers powered by renewable energy sources work in the power system, or simultaneously in power and heating systems, as part of energy storage systems. The considered storage cycle ranges from hourly to daily. This is significantly limited by the difficulty of storing hydrogen, which is typically stored in dedicated tanks at pressure of 350 or 700 bar,
- installations with cells can be used in power range corresponding to micro-cogeneration installations (rated electrical power up to 50 kW), low power installations (up to 1 MW) or larger. Regardless of the scale, systems with PEM, MCFC and SOFC fit into the concept of distributed energy generation, while improving the balance of supply and demand in the grid power system by using locally available or locally stored fuels. In the case of low-power installations, they can cooperate with micro-renewable energy sources and provide dynamic adaptation to market conditions, ensuring a quick response on the demand side. PEM, MCFC and SOFC cells allow to ensure high efficiency of electricity generation and generation of other utilities, therefore their potential includes the possibility of replacing a certain part of conventional generation capacities of professional and industrial power generation. When used as fuel for hydrogen from the electrolizers, cell installations allow for continuous power supply to meet peak energy demand. In this mode of operation, their power will require sufficiently large amounts of stored hydrogen, produced in the night demand valleys from renewable sources.

6.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR HYDROGEN

Advantages of the technology:

- Possibility to replace fossil fuel technologies
- The possibility of storing and producing energy without a carbon footprint (in the case of hydrogen production using only renewable energy sources).
- The highest efficiency of energy generation, exceeding the efficiency of other energy installations that implement the Carnot thermal cycle (the operation of fuel cells, which are electrochemical devices, is not limited by the theoretical efficiency of the thermal cycle).
- Modular design, allowing for multiplication of solutions and construction of systems in a wide power range.

Disadvantages of the technology:

- Social fear of hydrogen, which is a flammable gas, reaction of hydrogen with oxygen is violent. The lower flammability limit for hydrogen is only 4%, which means that even a small concentration of gas in the air can lead to ignition.
- Storage in mobile tanks is an expensive technology that has not been fully commercialized.
- Lack of many years of operational experience of hydrogen energy storage systems.

PtG hydrogen production

Advantages of the technology:

- The possibility of hydrogen production without the use of hydrocarbons (subjected to steam reforming), i.e. the production of green hydrogen.
- Possibility of stabilizing the grid power system, rich in generating units classified as renewable energy sources, with unstable and unpredictable nature of work.
- The implementation of the sector coupling concept, integrating the power system with the gas system, which increases the security of energy supply, enables diversification of electricity production technology or combined heat and power.
- The highest efficiency of hydrogen production can be above 80%, in case of solid oxide electrolysers (SOE).
- Broad development prospects and significant progress in increasing life time.
- The possibility of using waste steam or waste heat, which in case of solid oxide electrolysers eliminates the need for water evaporation with the help of electricity – improving process efficiency by over 20%.

The main challenges of PtG technology include: currently high level of CAPEX costs and service intervals for PEM, alkaline and SOE electrolysers, which are several times shorter than in production process of the so-called black hydrogen in installations based on methane steam reforming.

Disadvantages of the technology:

- Relatively low operational experience of PtG systems, which results from relatively young age of electrochemical hydrogen production technology,
- There is currently no installation with a capacity comparable to methane steam reforming process hydrogen generation systems for petrochemicals.

Hydrogen storage

Advantages of the technology:

- The possibility of utilizing hydrogen fuel for specific energy and industrial purposes,
- Increasing the importance of low-emission gas systems, based on hydrogen and/or hydrogen mixtures.
- Popularization of fuel, which can be used in stationary and transport solutions in an identical form.

Disadvantages of the technology:

- Large cost barrier of purchasing a storage installation.
- Restrictions related to the lack of legal regulations regarding transport safety, determining the quality and storage of hydrogen.
- No safety procedures have been developed for, for example, hydrogen fire extinguishing or fire fighting in the event of hydrogen vehicle accidents.

Fuel cells

Advantages of the technology:

- The main advantage of fuel cells is the direct conversion of chemical energy contained in fuel into electricity. For this reason, the efficiency of fuel cells is particularly high – the conversion of heat into mechanical energy (fuel combustion and turbine propulsion) and then mechanical work into electricity (operation of a turbine coupled with an electric generator) does not occur.
- Modular design allows for construction of systems with scalable power – by replicating stacks, depending on the required power rating,
- For MCFC and SOFC cells it is possible to use a wide range of fuels,
- Possibility of construction of co- and polygeneration systems, in which the efficiency of electricity generation may exceed 65%,
- No moving parts in PEM, MCFC and SOFC stacks.

Disadvantages of the technology:

- For PEM cells, very high hydrogen purity (99.999%) is required,
- Compounds such as carbon monoxide (CO) or ammonia (NH_3), which can be fuels for MCFC and SOFC, lead to rapid contamination and damage to PEM cells,
- Very high sensitivity of PEM cells to contaminants in fuel (sulfur and chlorine compounds),
- High sensitivity of MCFC and SOFC cells to contaminates in fuel. The need to filter fuel from sulfur compounds, to a level below 1 ppm, and from chlorine compounds below 10 ppm,
- High CAPEX cost, compared to other technologies, among others: BES, PHS, CAES, VRFB.
- Relatively low cumulative operational experience compared to classic transport solutions or energy technologies,
- The use of noble metals as catalysts in PEM cells,
- The need to use dedicated and therefore expensive steels in SOFC cell stacks, which is due to the high operating temperature,
- Low power density of MCFC cells requiring a large active surface.
- Complex manufacturing process for SOFC and MCFC cells, requiring dedicated furnaces.

However, it should be noted that PEM, MCFC and SOFC cells are a young technology that has been particularly developed since the 1980s. Therefore, a continuous increase in performance, reduction of production costs and durability increase is observed. National and regional subsidies are a mechanism to improve the economics of investment in fuel cell systems, while research funding programs enable continuous improvement of technology. Providing further support for research and development works is the basis for bringing the technology to a state that allows commercialization in the absence of subsidies or dedicated concessions.

In a longer perspective, hydrogen is an alternative to currently used fossil fuels. The production of hydrogen by PtG electrolysis using excess energy from renewable sources makes it possible to efficiently store this energy, which can then be used on site or in remote locations, after its transport in mobile tanks or pipelines. Hydrogen can be used to enrich natural gas, increasing its calorific value and reducing carbon dioxide emissions per unit of released energy. Hydrogen compression in high-pressure tanks, although requiring large investments, is the cheapest and most reliable method of its storage. Conversion of hydrogen to electricity and heat in fuel cells allows for obtaining almost zero greenhouse gas emissions and significantly increases the efficiency of electricity generation, even on a scale of few kilowatts. Due to the costs, in the first phase of fuel cell installations implementation, it is necessary to apply financial support mechanisms, which will allow for break the entry barriers to the market.

In case of hydrogen production and its injection into the gas network, such solution may be used, however, it requires an appropriate legislative framework, particularly in scope of testing the quality of hydrogen before connecting it to gas transmission or distribution pipelines.

Storage of hydrogen (H2) is recommended for use in the transport sector, seasonal energy storage, making operation of the network more flexible, as well as for the integration of the power grid with the gas network in accordance with the concept of sector coupling. High development potential in Poland, given that Poland is the world's fifth largest producer of hydrogen used in industry.

Potential stakeholders include gas companies, energy companies, and the petrochemical industry. Poland has the appropriate technical facilities and R&D to develop this type of solution.

7. CHEMICAL ENERGY STORAGE – other PtG products

Technical characteristics of **chemical energy storage systems (PtG)**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
PtG (Power to gas)	500-3 000	0-50	h – months	5-20	1 s – 24+ h	1 000+	~25–70	In development/ TRL-9

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **chemical energy storage systems (PtG)**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
PtG	500-3 000	2-15	0,0019–0,0153 USD/kW

7.1. INTRODUCTION

One of the promising energy storage technologies are power-to-gas (PtG or P2G) systems. They can use excess electricity generated by renewable sources to separate water molecules into hydrogen and oxygen. In this way, it is possible to convert electricity into chemical energy for gaseous fuels, which can be easily stored. Such fuels can then be used to power classic energy installations (internal combustion engines, external combustion engines, gas turbines) as well as in fuel cell systems. Additionally, hydrogen produced in electrolysers, using electricity from renewable energy sources, is a commodity that can be processed further. Aside from direct conversion to electricity, hydrogen can be treated as a substrate in chemical processes, for example in the production of gaseous fuels (methanation reaction, i.e. the Sabatier reaction), liquid fuels (Fischer-Tropsch synthesis), ammonia (Haber-Bosch synthesis). Each of the products manufactured has energy values and is a form of energy storage. A list of main technologies considered in the P2X group is shown in Figure 26. It should be noted that the electrolyzer is a basic element of hydrogen generation systems (power-to-hydrogen, P2H), the production of gaseous fuels (power-to-gas, P2G), liquid fuels (power-to-liquid, P2L) and ammonia (power-to-ammonia, P2A), which is supplemented with a reactor or synthesis systems.

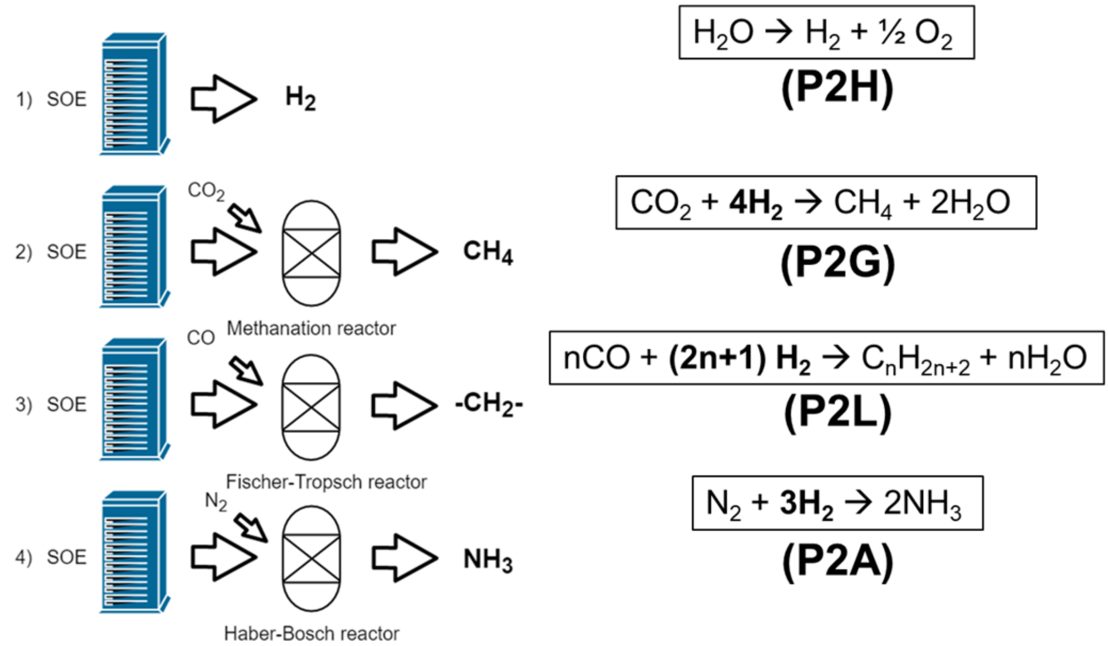


Fig. 26. A list of the four most important technologies under the common name of P2X

According to the possible ways of using hydrogen, which are shown in Figure 27, the electrolyser can operate in installations for production of liquid fuels and chemicals (e.g. ammonia). It should be noted that in this case, production of liquid fuels requires supply of carbon monoxide (CO), which may come from conventional chemical installations or in electrochemical reduction installations from CO_2 to CO (so-called CO_2 co-electrolysis). In this case, the electrolyzer is integrated with a Fischer-Tropsch synthesis system, which was introduced in 1926[200], and later developed in the context of production of other hydrocarbons[201]. An alternative possibility of using an electrolyser is in power-to-ammonia installations (PtA or P2A), which allows production of ammonia in reaction of hydrogen with nitrogen. With this technology, hydrogen stream from the electrolyser must be supplied with nitrogen, for example separated from the air.

Among the four possible options included in the group of power-to-X technologies, the most popular are solutions that allow production of gaseous fuel, most often in the form of SNG (Synthetic Natural Gas). Combining hydrogen production using renewable energy sources with a system for separating carbon dioxide from exhaust fumes or other process gases is particularly advantageous. The combined CO_2 and H_2 streams are directed to a methanation reactor, to produce fuel that can be used in stationary systems or as a fuel for motor vehicles.

SNG production installations are a special class of PtG systems, in which the electrolyser works with a methanation reactor, i.e. a Sabatier reactor. The concept of methanation, involving the reaction of hydrogen with carbon dioxide in the presence of a catalyst, was first presented in 1897 by Paul Sabatier and Jean-Baptiste Senderens and later described in detail in the context of its possibilities in the 1911 Sabatier study[202]. In the reaction according to the $CO_2 + 4H_2$ $CH_4 + 2H_2O$ scheme, each mole of carbon

[200] F. Fischer, H. Tropsch, Über die direkte Synthese von Erdöl-Kohlenwasserstoffen bei gewöhnlichem, *Druck*, 59, 1926, 830.

[201] S.R. Craxford, The Fischer-Tropsch synthesis of hydrocarbons and some related reactions, *T Faraday Soc*, 35, 1939, 946.

[202] P. Sabatier, Hydrogénations et déshydrogénations par catalyse, *Eur J Inorg Chem*, 44, 1911.

monoxide reacts with four moles of hydrogen. This determines the proportion of substrates involved in the reaction. The potential of SNG production technology is considered in two aspects – production of easy-to-store fuel (methane) and the possibility of utilizing carbon dioxide separated from power plants or other industrial processes.

7.2. DEVELOPMENT PERSPECTIVE FOR SNG MANUFACTURING INSTALLATIONS AND ENVIRONMENTAL IMPACT

The perspective of SNG production system development includes the conversion of carbon dioxide to commercial products – transport fuel or SNG, which can be an energy carrier for professional, industrial and distributed energy systems.

The development of systems includes both improving the technology of electrolysers, which are a source of hydrogen, as well as developing new techniques for separating carbon dioxide from power plant flue gas streams or waste gases. In this regard, attention should be paid to systems integrating electrolysers with amine installations for separating CO_2 from the exhaust stream. Amine installations are a key element of CCS systems, the gas separated as a result of their operation is not compressed and stored (underground or underwater sequestration), but rather converted to transport fuel[203].

Table 19. The most important projects regarding the production of SNG in electrolysis based systems

Project	Period of implementation	General characteristics
2SynFuel	2017-2021	Development and demonstration of SNG and green hydrogen production using organic waste biomass[204].
STORE&GO	2016-2020	Development and demonstration of three different SNG production systems in Germany, Italy and Switzerland along with gas injection into the network[205].
Jupiter 1000	2018-	Development of a high-efficiency 1 MW class installation generating 200 m^3/h hydrogen and 25 m^3/h methane, intended for injection into the network[206].
HySynGas	2019-	50 MW class installation generating SNG using photovoltaic electricity and wind farms[207].
TENNESSEE	2017-2022	A unique installation for the production of SNG in the process of SOE electrolyser for the production of hydrogen and a stack of carbonate fuel cells (MCFC) for CO_2 separation[208].
CO_2-SNG	2018-2021	Methanation system, in a process using CO_2 separated from the flue gas of a coal power plant[209].

203 Lucyna Wieclaw-Solny L., Wilk A., Chwola T., Krotki A., Tatarczuk A., Zdeb J., Catalytic carbon dioxide hydrogenation as a prospective method for energy storage and utilization of captured CO2, Journal of Power Technologies, 96(4), 2016, 213–218.

204 2SynFuel project website, http://www.tosynfuel.eu/#home [accessed: 10.07.2019].

205 STORE&GO project website, https://www.storeandgo.info/ [accessed: 10.07.2019].

206 Jupiter 1000 project website, https://www.jupiter1000.eu/english [accessed: 10.07.2019].

207 HySynGas project website, https://www.hysyngas.de/ [accessed: 10.07.2019].

208 TENNESEE project website, en.raport2017.tauron.pl/innowacje/innowacje-w-2017-roku [accessed: 31.07.2019].

209 CO2-SNG project website, www.tauron-wytwarzanie.pl/innowacje/co2-sng [accessed: 31.07.2019].

Currently, there are several installations in Europe that have been launched as part of national and European projects. The most important include the projects listed in Table 19, along with their general characteristics. A comprehensive overview of other PtG projects, including PtG-SNG, can be found in the review article[210].

The environmental impact of SNG production installations related to the system design is analogous to that for PtG systems for hydrogen production. One additional consideration is the presence of a methanation reactor, which is based on a nickel catalyst, and additional heat exchanger system and a gas drying system. According to the methanation reaction scheme, the SNG production process simultaneously produces water. Its presence adversely affects the kinetics of the reaction, therefore the methanation reactors are built in a system of serially connected modules with interstage gas drying. In aspects of installation operation, environmental effects are better than in the case of PtG installations. This is due to the fact that, in addition to the possibility of producing hydrogen in the electrolyser using electricity, carbon dioxide, converted from exhaust gases or waste gases of technological processes, is additionally converted. This allows the production of liquid fuels, needed where use hydrogen fuel is not possible, the combustion of which does not emit additional portions of carbon dioxide to the atmosphere over those from the previous combustion process, and emissions from energy needed in the process of fuel production.

7.3. RESOURCE RESTRICTIONS

The raw material restrictions in SNG production systems are analogous to those in the case of PtG installations meant for hydrogen production.

7.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

In the case of SNG generation systems, there are no restrictions typical for conventional power technology. Thanks to the modular design, the PtG systems are easy to replicate, thanks to being based on series of smaller units. A certain limitation in the construction of high power PtG installations is the common equipment used in SNG production systems. For 2-5 MW class systems, a common hydrogen compressor is used, which is produced in 5-15 smaller PEM or alkaline electrolyser modules. The scale increase, due to the limited availability of hydrogen compression machines, requires the use of several separate units. This is a process limitation for the largest installations and adversely affects the cost effect of scale. The decisive factor in determining the scale of SNG manufacturing installations is the overall analysis of the value chain of produced hydrogen, taking into account the availability of utilities, i.e. electricity, area occupied by the installation, availability of the distribution network for generated hydrogen and possible storage at the electrolyser location. Additionally, the economics of systems with methanation reactors also take into account the fact that carbon dioxide is subject to environmental fees. In this case, the production of SNG allows for conversion of greenhouse gas, the emission of which is a cost, into fuel, which is a commercial product.

[210] Eveloy V., Gebreegziabher T., A Review of Projected Power-to-Gas Deployment Scenarios, *Energies*, 11, 2018, 1824, doi:10.3390/en11071824.

7.5. ENERGY STORAGE COSTS

The costs of producing SNG as a storage medium are in direct correlation with the electrolyser's operation time. In the profitability analyzes of the PtG-SNG installation, the electrolyser's operation time is assumed to be between 2,000 and 3,000 hours (in the renewable energy only option)[211]. This corresponds to a period of 83-125 days in continuous work, i.e. approx. 22-34% of the year. These values result from the possibility of continuous supply of energy directly from renewable energy sources, or energy with certificates of origin – produced in photovoltaic or wind systems in the same power grid, but outside the direct location of PtG-SNG. In case of the electricity market, calculations directly indicate that the profitability of SNG production using electricity is significantly reduced, and the use of PtG-SNG installations should be analyzed in the context of network services – the possibilities of energy storage in flow systems. The cost of using SNG as a storage medium is estimated at 165-220 USD/MWh[212].

7.6. MAIN APPLICATIONS

The main area of SNG production systems application is energy, gas and transport sectors. In case of the first two, installations using only electricity from renewable energy sources are of particular interest. However, it is possible to use energy from coal or gas blocks. In this case, the substitute for natural gas cannot be considered a carbonless fuel. In the transport sector, SNG production installations are additionally equipped with compressors, which enables the generation of CNG with parameters analogous to those currently offered on the market. In case of integration with industrial facilities, the potential of PtG-SNG systems also includes production of SNG, which is a high-calorie addition to refining of low-quality gas fuels. It can be added, for example, to agricultural biogas to increase its calorific value. The key element of PtG-SNG installation is a carbon dioxide supply system necessary to conduct the methanation reaction. If this gas comes from waste – for example, it is produced in the process of sewage sludge management, combustion of other organic matter or is separated from waste gases or flue gas, the potential of SNG production installations also includes the reduction of greenhouse gases emission. In the case of large-scale systems (1 MW+), it should be expected that PtG-SNG installations will also be considered in the context mitigating CO_2 emissions.

7.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS

Advantages of the technology:

- Production of natural gas substitute – synthetic methane, utilizing renewable energy.
- Possibility to convert greenhouse gas (CO_2) into transport fuel or energy fuel
- The possibility of using electrochemical processes for both hydrogen production (PEM, alkaline or SOE electrolysers) as well as carbon dioxide separation (carbonate fuel cells – MCFC)
- Cooperation of SNG production systems with the gas network and possibility of SNG compression, which allows for obtaining CNG.

[211] Schürle M., Business models for power to gas – focus on short term power trading, Energieforschungsgesprache Disentis, 25.01.2018, www.alpenforce.com/media/EFGD18_Schürle.pdf [accessed: 31.07.2019].

[212] The Oxford Institute for Energy Studies, october 2018, www.oxfordenergy.org/wpcms/wp-content/uploads/2018/10/Powert-to-Gas-Linking-Electricity-and-Gas-in-a-Decarbonising-World-Insight-39.pdf [accessed: 31.07.2019].

- In the case of using high-temperature electrolysers (SOE), SNG generation systems can be thermally integrated with power plant heat circuits or technological / chemical processes, which allows for obtaining particularly high efficiency of natural gas production.

Disadvantages of the technology:

- the need to use high power electrolysers (regardless of technology). Despite the supply of carbon dioxide, SNG production is limited by green hydrogen production capacity.
- The need to cooperate with sources of carbon dioxide, which imposes location restrictions – SNG installations must be located close to energy facilities or other industrial facilities.
- Relatively new technology with little operational experience.
- The possibility of low-cost SNG production is limited by the costs of hydrogen production in the cells, which was discussed in detail in an earlier chapter.

The cost of the SNG production installation is largely determined by the cost of the electrolyser, which is between 40 and 65% of the CAPEX of the PtG system connected to the Sabatier reactor.

Power to gas / Power to X (PtG / PtX) is recommended for use in SNG production systems, in sectors such as energy, gas and transport.

Potential stakeholders include gas and energy companies. Poland has the appropriate technical facilities and R&D to create and implement such solutions. Currently, the first small research demonstration installations are being created, which in the next step will require scaling to size of 1 or 10 MW.

8. GALVANIC CELLS – BATTERY ENERGY STORAGE (BES)

Technical characteristics of **galvanic cell systems (BES)**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
Li-ion (Lithium ion)	150-500	0-100	min – d	5-15	min – h+	1 000-10 000	~75–97	In development / TRL-9 (implemented and commercialized)
Pb-A (Lead-acid batteries)	50-90	0-40	min – d	5-15	min – h+	500-1 300	~70–84	Mature / implemented – NA
NiCd (Nickel-cadmium batteries)	60–150	~0-0.5	min – d	10-20	min – h+	20 000-25 000	~60–83	Mature / implemented – NA
Na-S (Sodium sulphur batteries)	150–250	0.5-35	min – d	10-15	min – h+	4 500-25 000	~75–90	Mature / NA

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **galvanic cell systems (BES)**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
Li-ion	200-900	176-900	~9-10 USD/kW/year, ~0,003-0,004 USD/kWh
Pb-A	300-700	75-500	~8-20 USD/kW/year, ~0,001-0,002 USD/kWh
Ni-Cd	500-1 500	400-1 500	~12-20 USD/kW/year, ~0,0012-0,002 USD/kWh
Na-S	350-3 000	300-800	~20-80 USD/kW/year, ~0,0035 USD/kWh

8.1. INTRODUCTION

Galvanic cells are electricity stores where energy is accumulated in the form of two electrodes (half cells) made of different materials, showing a mutual potential difference. The reason behind the potential difference lays in properties of metals used to build the electrodes and specificity of chemical reactions that occur between the electrodes and the electrolyte. Depending on the selection of electrode materials, it is possible to obtain a cell with specific operating parameters.

The galvanic cell retains its properties while idle. It is only by closing the electrical circuit – closing the electrode short circuit, allows the flow of charge between the electrodes and the conduct of electrode reactions. During operation, the cell discharges – the electrode material is consumed for electrode reactions, and the chemical energy stored in the cell is converted into electricity. In a discharged cell, when the electrode reactions have gone completely, there is no flow of current since there is no longer a potential difference between the electrodes.

There are two main types of cells: primary cells (first type cells, so-called non-rechargeable batteries), which cannot be recharged after discharging, and secondary cells (second type cells, so-called rechargeable batteries), which can be charged and discharged many times.

Batteries (primary cells) of the first type are used in low-power mobile devices, where one battery is able to power this device for a period of a few to several months without the need for replacement. Then the cost of using batteries is relatively small in the assumed time and the of much more expensive rechargeable batteries is unjustified.

In turn, rechargeable batteries (secondary cells), i.e. cells of the second type, are used to power mobile devices that require high power consumption, such as flash lamps and cameras, cell phones, scooters, electric bicycles, vehicles, etc., as well as stationary backup power sources. The possible use of disposable batteries to power these devices would require their frequent replacement, which would involve significant costs of maintaining them. Therefore, it is justified to use relatively expensive batteries and their regular charging with electricity from the mains power, which requires the use of a power converter, converting alternating current into direct current. The use of batteries for emergency power supply of stationary devices also requires a converter, since the powered devices require AC power. In turn, mobile devices are powered with direct current and do not require a converter.

Currently on the market there are three main types of batteries: lead-acid (Pb-A), nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion), and until recently – nickel-cadmium (Ni-Cd) batteries, which are withdrawn due to high toxicity of cadmium. The market is supplemented by three main types: zinc-carbon, alkaline and lithium. Each of the types of galvanic cells listed here has advantages that allow their specific use.

Lead-acid batteries (Pb-A) are the oldest of currently used battery types, developed as early as the mid-nineteenth century, but still the most reliable and cheap electrochemical energy source. Individual LA cells have an operating voltage in range of 2.0-2.2 V, but usually lead-acid batteries are composed of 6 cells with a total voltage of 12 V. Lead-acid batteries have an energy density of 25-40 Wh/kg. Pb-A cells consist of a negative plate made of metallic lead, a positive plate made of lead oxide, separator and electrolyte, which is concentrated sulfuric acid. The battery plates have an active mass deposited on current collectors, made of solid lead. During discharge (Fig. 27 the process of lead oxidation and reduction of lead oxide occurs, accordingly with the following reaction equations:

Negative plate (–): $$Pb^0 + SO_4^{2-} \rightleftarrows Pb^{II}SO_4 + 2e^- \qquad E^\circ = 0{,}356\ V \qquad (8.1)$$

Positive plate (+): $$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightleftarrows Pb^{II}SO_4 + 2H_2O \qquad E^\circ = 1{,}685\ V \qquad (8.2)$$

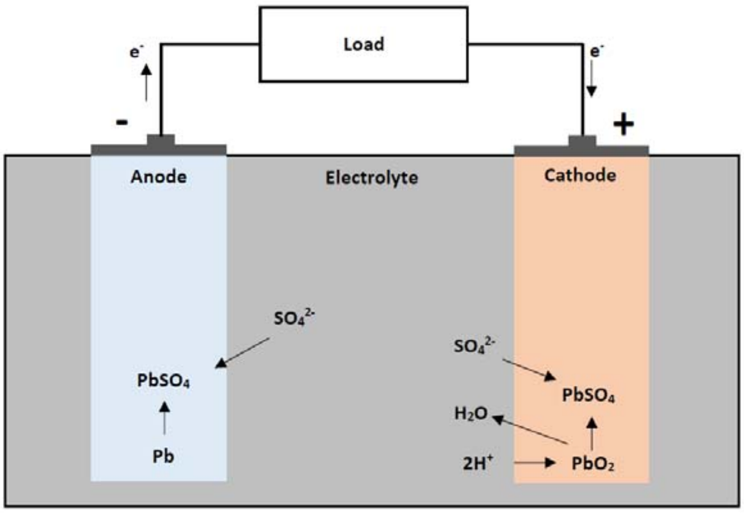


Fig. 27. Functional diagram of the Pb-A battery during discharge – own study

The biggest limitation of lead-acid batteries is their large mass, resulting from the large amounts of lead inside them. Lead is one of the heaviest elements. In turn, their biggest advantage is work safety, low production cost, high recyclability, and the possibility of obtaining high-density currents. Production of lead-acid batteries is currently conducted in Poland.

A composite lead-acid battery (CLAB) has been developed in recent years[213,214]. CLAB is a new type of Pb-A battery with composite lead-carbon current collectors instead of solid lead collectors, while the electrode reactions in the CLAB battery being the same as in classic Pb-A batteries. The use of composite collectors reduces the total battery weight and reduces lead use by approx. 30%. As a result, the battery capacity is doubled while maintaining a constant weight. Thanks to this, the capacity of CLAB batteries is approx. 50 Wh/kg, and is comparable to the capacity of Ni-MH batteries, that are commercially used to power hybrid vehicles. At the same time, CLAB batteries show better tolerance to charging and discharging with high density current, as well as longer life and storage life (so-called *shelf life*) while maintaining 72% capacity after 12 months of storage. CLAB batteries are currently at the stage of pre-implementation tests and have not yet been used commercially due to their limited lifetime, production costs are comparable with PbA batteries.

Nickel-cadmium (Ni-Cd) batteries (Fig. 28) were developed at the end of the 19th century as an alternative to Pb-A cells. Ni-Cd batteries have a rated voltage of 1.2 V and an energy density of 40-60 Wh/kg. The cell voltage is not significantly reduced during discharge, they can be used as replacements for 1.5 V batteries in most applications. Ni-Cd batteries have the negative plate made of metallic cadmium, the positive plate made of nickel (III) hydroxide, separator and an alkaline electrolyte based on concentrated potassium hydroxide. During discharge, cadmium oxidizes to cadmium (II) hydroxide, and NiO (OH) is reduced to nickel (II) hydroxide, accordingly to the following reaction equations:

Negative plate (–):	$Cd + 2OH^- \rightleftarrows Cd(OH)_2 + 2e^-$	$E^\circ = 0{,}40$ V	(8.3)
Positive plate (+):	$NiO(OH) + H_2O + e^- \rightleftarrows Ni(OH)_2 + OH^-$	$E^\circ = 0{,}49$ V	(8.4)

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[213] A. Czerwinski, P. Podsadni, Z. Rogulski, J. Lach, K. Wrobel, „Composite lead-acid battery", national patent application no. P.423253 (2017); international patent application no. PCT/PL2018/000100 (2018).

[214] A. Czerwinski, J. Wrobel, J. Lach, K. Wrobel, P. Podsadni, The charging-discharging behavior of the lead-acid cell with electrodes based on carbon matrix, *J. Solid State Electrochem.*, 22, 2018, 2703.

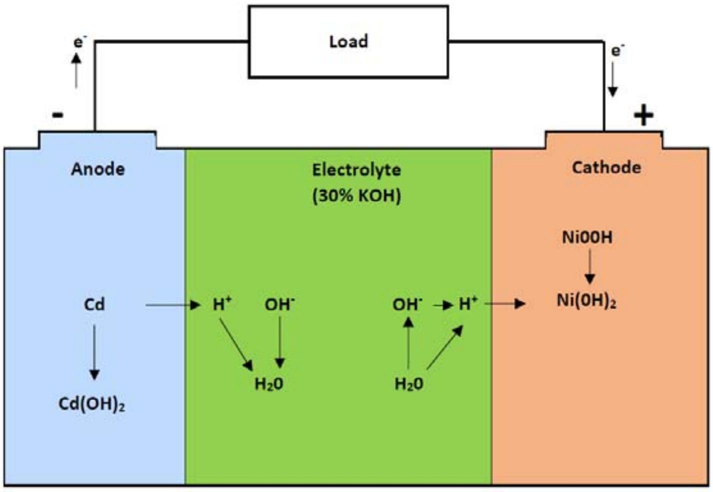

Fig. 28. Functional diagram of the Ni-Cd battery during discharge – own study

Ni-Cd batteries have a very long life (approx. 20 years) and reliability over a wide temperature range from –40° C to +70° C. The main disadvantage in their use is the need for careful charging, otherwise they quickly lose capacity due to the so-called memory effect. Until the 1990s, many Ni-Cd batteries were the most popular source of power for mobile devices, but were later forced out of the market by lighter, but more expensive, Ni-MH batteries. In addition, in the European Union, due to the current directive on non-rechargeable an rechargeable batteries and waste disposal of said batteries[215], the use of batteries containing toxic cadmium has been legally restricted and is possible only if there are no alternative solutions with similar parameters.

Nickel-metal hydride (Ni-MH) batteries were developed in the 1960s. Their electromotive force is 1.2-1.3 V and energy density 55-90 Wh/kg. Ni-MH batteries have negative plates made of water-absorbent alloys ($LaNi_5$ type), positive plates made of nickel (II) oxide (similar as in Ni-Cd batteries), separator and alkaline electrolyte based on concentrated potassium hydroxide. When the cells charging, protons from the electrolyte are reduced to hydrogen, which is stored as a hydride in the hydrophilic alloy. In turn, during the discharge, the reverse process takes place, i.e. the oxidation of hydrogen stored in the negative plate absorbing alloy, according to the following reaction equations:

Negative plate (–): $MH + OH^- \rightleftarrows M + H_2O + e^-$ $E^o = 0{,}83\ V$ (8.5)

Positive plate (+): $NiO(OH) + H_2O + e^- \rightleftarrows Ni(OH)_2 + OH^-$ $E^o = 0{,}49\ V$ (8.6)

Ni-MH batteries (Fig. 29) are characterized by good power parameters, their weight is not an obstacle for use in mobile devices that require high instantaneous current densities. The biggest limitation of nickel-metal hydride batteries is their relatively low resistance to successive charging and discharging cycles, when the process of degradation (excessive grinding) of a hydrophilic alloy occurs, which systematically loses its absorption capacity.

[215] Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC.

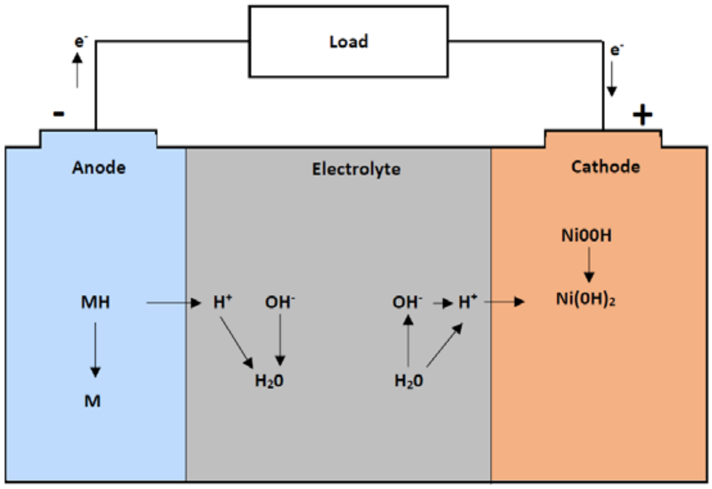

Fig. 29. Diagram of NiMH battery operation during the discharge process – own study

Lithium-ion (Li-ion) batteries were developed in the 1970s and are currently the solution with the largest gravimetric electrochemical capacity due to use of lithium – the lightest metal – as a charge carrier. Li-ion batteries have an operating voltage of 3.2–4.0 V and an energy density of up to 250 Wh/kg based on the weight of the entire cell[216]. Many variants of Li-ion batteries are known, differing in construction and composition of positive and negative electrodes. Li-ion batteries use liquid organic electrolytes, for example containing $LiPF_6$ dissolved in a mixture of ethylene carbonate and dimethyl carbonate ($LiPF_6$@EC/DMC).

The negative electrode (anode during discharge) is usually made of lithium metal alloys, conversion materials and intercalation materials. The materials forming lithium AyLix alloys with variable structure (e.g. aluminum and silicon) are characterized by a very high specific capacity (up to 3590 mAh/g, for silicon), but have little tolerance for subsequent charging and discharging cycles, due to large changes material volume (up to 300%) while receiving lithium ions, which results in mechanical degradation. Conversion materials made of metal oxides (e.g. SnO_2), reach a high specific capacity (approx. 1200 mAh/g), however during operation an uncontrolled reaction of Li2O formation occurs and a simultaneous reduction of conversion material, which results in a rapid decrease in their capacity. Intercalation materials (carbon and graphite) have the ability to absorb lithium in their volume and achieve a relatively high specific capacity (approx. 300 mAh/g), which is stable during successive charging and discharging cycles. Due to the high resistance of intercalation materials based on carbon and graphite, they are most often used in commercial lithium-ion cells.

Positive electrode (cathode during discharge – Fig. 30) is usually made of materials containing transition metals, capable of absorbing lithium in a redox reaction (reduction and oxidation), for example: lithium cobalt oxide (LCO) CoO_2, lithium manganese oxide (LMO) $LiMn_2O_4$, lithium nickel-manganese oxide cobalt (NMC) $Li(NiMnCo)O_2$, or lithium iron phosphate (LFP) $LiFePO_4$. Electrode reactions occurring during discharge of Li-ion cells (Fig. 29) are shown in the equations below.

Negative plate (–): $LiC_6 \rightleftarrows C_6 + Li^+ + 2e^-$ $\quad E^o = 2{,}84\ V$[217] (8.7)

$Li_{4+x}Ti_5O_{12} \rightleftarrows Li_4Ti_5O_{12} + xLi^+ + xe^-$ $\quad E^o = 1{,}55\ V\ vs.\ Li/Li^+$ [218] (8.8)

[216] K. Liu, Y. Liu, D. Lin, A. Pei, Y. Cui, Materials for lithium-ion battery safety, *Science Advances*, 4, 2018, 9820.

[217] P. Vanýsek. “Electrochemical Series”, in: Handbook of Chemistry and Physics: 92nd Edition, Chemical Rubber Company, 2011.

$Li \rightleftarrows Li^+ + e^-$
Positive plate (+): $FePO_4 + Li^+ + e^- \rightleftarrows LiFePO_4$ $E^\circ = 3{,}5$ V vs. Li/Li^+ [219] (7.9)
$CoO_2 + Li^+ + e^- \rightleftarrows LiCoO_2$
$Li_2Mn_2O_4 \rightleftarrows Li_2MnO_3 + MnO$

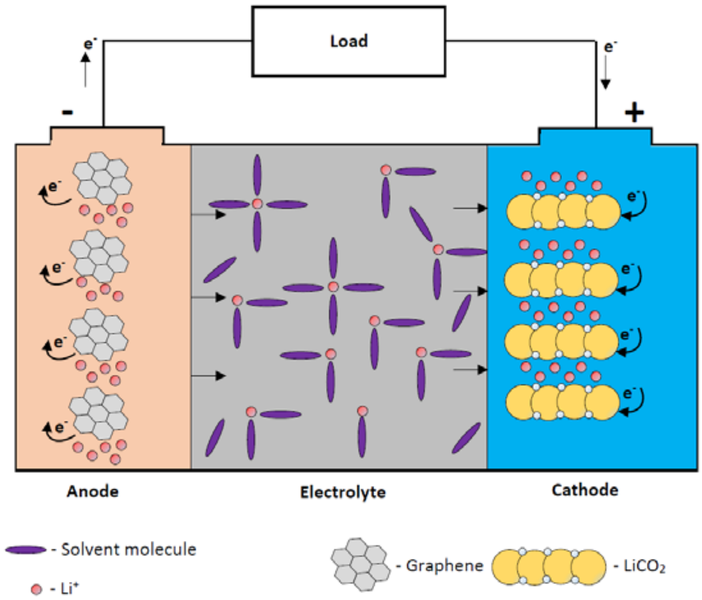

Fig. 30. Diagram of operation of lithium battery works – own study

Lithium-ion cells have the highest energy density among all known galvanic cells, but the main limitation of applicability is the relatively low current density obtained. The systems that obtain the highest power have capacities comparable to Ni-MH batteries.

Sodium-sulfur (Na-S) batteries are still being developed, a new type of electrochemical cells with a rated voltage of approx. 2 V and a relatively high energy density (150 Wh/kg), which uses the reaction of sodium oxidation and sulfur reduction – two cheap and easily available elements. The discharge reaction follows the equations:

Negative plate (–): $Na \rightleftarrows Na^+ + e^-$ $E^\circ = +2{,}71$ V (8.10)

Positive plate (+): $S + 2e^- \rightleftarrows S_2^-$ $E^\circ = -0.48$ V (8.11)

Sodium-sulfur cells, due to the relatively low mobility of sodium ions in a solid, usually require high temperatures to achieve full efficiency. The most common are high-temperature sodium-sulfur cells operating 300-350°C, in which the chamber with molten sodium is separated by an alumina membrane from the chamber with molten sulfur. After the discovery of low-temperature solid sodium electrolytes (e.g. NASICON) there was a chance to develop Na-S cells operating at temperatures below 100°C, but development work in this direction is still ongoing.

[218] Koohi-Fayegh, S., Rosen, M. A., Optimization of seasonal storage for community-level energy systems: status and needs. *Energy, Ecology and Environment*, 2(3), 2017, 169-181.

[219] Cold storage and thermal energy storage technologies – CRYOGEL, www.airclima-research.com/cold-storage-technologies – [accessed: 31.07.2019].

8.2. BES DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Regardless of the type of galvanic cell, attempts to increase their electrochemical capacity are the main direction of electrochemical energy storage development. For many systems, the problem of excessive weight is a key factor limiting their applicability in certain types of devices. No less important are the issues of safety of use and life time of non-rechargeable and rechargeable batteries.

The development of Pb-A batteries in recent years has mainly been related to ensuring trouble-free and maintenance-free operation. Batteries with gel electrolyte were developed, which did not require systematic replenishment of electrolyte. In recent years, however, the main direction of development was the reduction of weight of batteries by reducing the amount of lead used and the introduction of composite, carbon-lead current collectors in place of solid lead grilles, which resulted in, among others, the CLAB battery design.

Research work on Ni-MH batteries mainly focuses on the development of new hydrophilic alloys with greater capacity and resistance to successive charging and discharging cycles, that would show minimal volume differences between charged and discharged conditions. At the same time, work is underway to optimize composition of the electrolyte, which would allow efficient operation at low temperatures.

Li-ion batteries currently require further research and development to optimize the composition and construction of the electrodes. In addition, lithium-ion cells with solid electrolyte are being tested, which will show increased electrochemical capacity and increased levels of safety.

Li-ion batteries are widely used in the electric and hybrid vehicle market, including:

- BMW i3 (22–33,2 kWh)[222,220] – akumulatory LMO/NMC[221, 222].
- Nissan Leaf (40–62 kWh)[223] – akumulatory LMO/NMC[221,222].
- Chevrolet Volt (15–16 kWh)[222,224] – akumulatory LMO/NMC[221,222].
- Tesla X (75–100 kWh)[225] – akumulatory Li-ion.
- TESLA S (70–90kWh)[222] – akumulatory NCA Li-ion.
- Toyota Prius Plug in Hybrid (4,4–8,8 kWh)[222,226] – akumulatory Li-ion.

Li-ion batteries have also been used in OFF-GRID installations, cooperating with prosumer solar photovoltaic installations, like Powerwall, produced by Tesla (13.5kWh)[227].

Currently, legal acts are being prepared in Poland regarding support (supplement for purchases) of, among others: M_1 category vehicles (vehicles featuring more than 8 seats besides the driver's seat) for individuals from the funds of the Low-Emission Transport Fund (for a vehicle that uses only electricity to propel it, support up to 30% of the purchase price is proposed, however no more than PLN 37 500zł[228,229]). In Poland, the National Fund for Environmental Protection and Water

220 BMW i3, https://insideevs.com/news/338067/bmw-i3-samsung-sdi-94-ah-battery-rated-for-524000-miles/ [accessed: 08.08.2019].

221 Electric Vehicles, https://www.sail-cg.com/electric-vehicles.html [accessed: 08.08.2019].

222 Electric Vehicle requirements, https://www.sail-cg.com/electric-vehicles.html [accessed: 08.08.2019].

223 Nissan Leaf, https://www.nissan.pl/oferty.html#category=SAMOCHODY+OSOBOWE&model=LEAFZE1A [In Polish] [accessed: 08.08.2019].

224 Chevrolet Volt, https://formula-hybrid.org/wp-content/uploads/Chevrolet-Volt-Battery_101.pdf [accessed: 08.08.2019].

225 TESLA X, https://www.tesla.com/sites/default/files/model_x_owners_manual_europe_en_gb.pdf [accessed: 08.08.2019].

226 Toyota Prius, https://www.toyota.com/content/ebrochure/2020/priusprime_ebrochure.pdf [accessed: 08.08.2019].

227 TESLA Powerwall, https://www.tesla.com/en_GB/powerwall?redirect=no [accessed: 08.08.2019].

228 Draft regulation of the Ministry of Energy, July 4, 2019, http://n-22-7.dcs.redcdn.pl/file/o2/tvn/web-content/m/p121/f/139f0874f2ded2e41b0393c4ac5644f7/0af1909c-ef55-43d0-a7e8-6987f02ed9ee.pdf [accessed: 08.08.2019].

Management also runs the „GEPARD – low-emission transport" program, which aims to support the development of electromobility in Poland by local government units[230].

Li-ion batteries have also been used in [231]:

- Stationary systems, among others: in UPS systems, monitoring systems, speed cameras, street lamps, systems for energy storage from wind farms, portable power supplies for electrical devices.
- Maritime shipping, among others: passenger ships,
- Machinery, among others: loaders, forklifts,
- Autonomous robots, including: weeding crops,
- Zero-emission public transport, incl. on city buses ..

Pb-A lead batteries are mainly used to drive vehicles and machinery with internal combustion engines. They have also been used in OFF-grid prosumer installations and emergency power supply systems[232] e.g. in hospitals. In order to extend the life of lead batteries, they are connected in parallel with supercapacitors (one of the batteries in the system is replaced by the ESM module – which has a stabilizing function). These types of systems have been used in heavy goods vehicles in, among others, Australia.[239] VRLA battery system *Valve Regulated Lead Acid*) a 3MW lead-ultracapacitor also found application in the eastern US in Lyon, Pennsylvania. The purpose of this system is grid frequency regulation[232].

Sodium sulfur (NaS) batteries are mainly used to make the power grid more flexible. An example of application is Xcel Energy from Japan, which built a 50kW NaS cell in 2010[233] which cooperate with a wind farm to stabilize the power grid.

Electrochemical energy sources are neutral to the environment when used correctly and allow reversible energy storage with an efficiency of 70-90%. Additional energy expenditure is needed for their production and utilization, which is associated with carbon dioxide emissions, if this energy does not come from renewable sources.

Extraction of raw materials needed to produce electrochemical cells can also have a significant impact on the environment. For example, cobalt ore is extracted mainly in poor regions of Africa (Congo: 60% of global extraction). Mining is carried out manually, without safety precautions, often in the open-pit method, in catastrophic conditions, causing numerous diseases of the local population, water pollution and landscape degradation[234]. Lithium salt extraction is often carried out by washing the deposits with fresh water and allowing it to evaporate naturally, which leads to crystallization of lithium carbonate (n. Bolivia, Tibet). The extraction of one ton of lithium by this method requires approx. 2 million liters of water. It is estimated that 65% of drinking water resources in lithium mining sites are used for mining operations, and huge areas used as lithium settlers are degraded[235]. On the other hand, lead mining is

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[229] Government Legislation Center, https://legislacja.rcl.gov.pl/projekt/12322752/katalog/12609459#12609459 [In Polish] [accessed: 08.08.2019].

[230] NFEP&WM, http://nfosigw.gov.pl/oferta-finansowania/srodki-krajowe/programy-priorytetowe/ [In Polish] [accessed: 08.08. 2019].

[231] Li-ion applications, https://www.powertechsystems.eu/ [accessed: 08.08.2019].

[232] G.J. Maya, A. Davidson, B. Monahov, Lead batteries for utility energy storage: A review, *Journal of Energy Storage*, 15, 2018, 145–157.

[233] D. Kumara, S.K. Rajouria, S.B. Kuhar, D.K. Kanchan, Progress and prospects of sodium-sulfur batteries: A review, *Solid State Ionics*, 312, 2017, 8–16.

[234] L. Mucha, T.C. Frankel, K.D. Sadof, The hidden costs of cobalt mining, The Washington Post, *In Sight, Perspective*, online, 28.02.2018.

[235] A. Katwala, The spiralling environmental cost of our lithium battery addiction, *WIRED on Energy*, online, 5th august 2018.

associated with high pollution of groundwater with sulphides and heavy metals present in ore[236]. Nickel is extracted in the form of sulfate ore, the deposits of which are mainly found in Australia, Canada, Indonesia, Russia and the Philippines. Nickel ore treatment involves emission of sulfur dioxide (IV) into the atmosphere, which can cause acid rain and landscape degradation. It is estimated that annual sulfur dioxide emissions from factories in Norilsk in Russia reach 350,000 tonnes[237].

A separate issue is the possible environmental impact of toxic components of galvanic cells in absence of their proper recycling. Introducing these components into the environment can be dangerous for humans and animals.

Lead is highly toxic when entering the body through the respiratory or digestive systems. Even touching your mouth with lead contaminated hands can be dangerous. Lead disrupts the work of some enzymes and can adversely affect the brain, kidneys, hearing and reproductive system. Lead poisoning can also cause behavioral problems, problems with concentration, nervous problems, hypertension, and muscle and joint pain. Lead can bind trace elements needed for the body to function properly, such as calcium, iron and zinc. Children and pregnant women are particularly susceptible to lead poisoning. It is speculated that one of the reasons for the fall of ancient Rome was the massive lead poisoning of its inhabitants, since water supply and vessels were then commonly made of lead. Furthermore, sulfuric acid (VI) used as electrolyte in Pb-A batteries is a highly irritating substance that is dangerous upon skin contact and after being absorbed by the respiratory and digestive systems.

Cadmium is a more toxic metal than lead when absorbed, which can occur even in contact with skin. Cadmium damages the kidneys, causes anemia, bone diseases, smell disorders and proteinuria. Cadmium accumulates in the placenta and causes severe fetal damage. Cadmium is also a threat to the brain, causing cell death in cortical cells. The alkaline electrolyte of Ni-Cd cells is an irritable substance.

Nickel is not toxic to humans, but has adverse effects on plants. The alkaline electrolyte of Ni-MH cells has similar irritant properties as the cadmium cell electrolyte.

Lithium is not a toxic metal but may ignite when exposed to air and atmospheric moisture. Li-ion cell electrolyte may contain toxic and flammable substances.

Zinc-manganese batteries contain an irritating electrolyte (acid or alkaline) but their other components are not toxic.

Table 20 compares carbon footprint generated in production of electrochemical batteries. The presented data shows that carbon footprint associated with production of lithium-ion batteries (115–170 kg CO_2/kWh) is lower than for flow batteries (VRFB 183 kg CO_2/kWh) but definitely higher than for lead-acid batteries (51,6 kg CO_2/kWh).

Table 20. CO_2 carbon footprint during battery production[238] based on life-cycle inventory (LCI)

Technology / Name	Carbon footprint [kg CO_2/kg]	Energy density [Wh/kg]	Carbon footprint [kg CO_2/kWh]
LFP Li-ion (lithium-iron-phosphate)	13,98–16,11	83–109	147,41–168,56
LTO Li-ion (lithium iron phosphate with lithium titanium anode)	14,19	52	270,99

[236] https://www.worstpolluted.org/projects_reports/display/84?fbclid=IwAR2nGAOo_MSt7hBlLGDKP565INQJ3tZL2ClOAbn7VnGFCtLaevJkG7R6hbQ [accessed: 07.10.2019]

[237] M. Opray Nickel mining: the hidden environmental cost of electric cars, The Guardian, online, 24.08.2017.

[238] M. Baumann, J.F. Peters, M. Weil, A. Grunwald, CO2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications, *Energy Technol.*, 5, 2017, 1071–1083, doi:10.1002/ente.201600622.

Technology / Name	Carbon footprint [kg CO_2/kg]	Energy density [Wh/kg]	Carbon footprint [kg CO_2/kWh]
LMO Li-ion (Lithium-manganese)	13,8	116	118,9
NCM Li-ion (lithium-nickel-cobalt-magnesium)	14,12–16,13	130–139	108,3–115,98
NCA Li-ion (lithium-nickel-cobalt-aluminum)	15,4	133	115,74
Pb-A (lead-acid with reduction valve)	2,33	45	51,6
NaNiCl (Sodium-nickel-chloride)	13,01	112	116
VRFB (redox flow – vanadium)	3,2	17	183

8.3. RESOURCE RESTRICTIONS

Restrictions on raw materials can be a significant problem in the way to a wider use of electrochemical energy storage in everyday life (electric vehicles, home energy storage, etc.). The production of each of the types of electrochemical cells discussed here requires use of specific metals and materials, which are extremely difficult to replace without changing the parameters of the cell. The production of non-rechargeable and rechargeable batteries requires continuous extraction of strategic raw materials, such as lithium, aluminum, manganese, nickel, cobalt, copper, lead. The forecasted scale of production assumes a 4-times increase over the next decade.

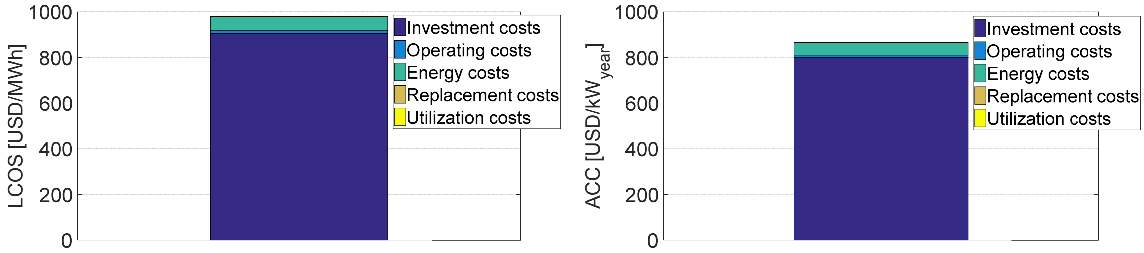
The extraction is supplemented by cell recycling, which allows for recovery of valuable raw materials and their reuse in the electrochemical industry. The Pb-A battery market is an example of the best recycling system for electrochemical cells, where the recovery rate reaches 99%. For other types of cells, the recovery of electrode materials may exceed 90%, but the recycling system is not yet tight enough to capture all used cells from the waste stream. Further education of the public and provision of more collection points for used cells are needed in order to increase the degree of battery recycling.

8.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

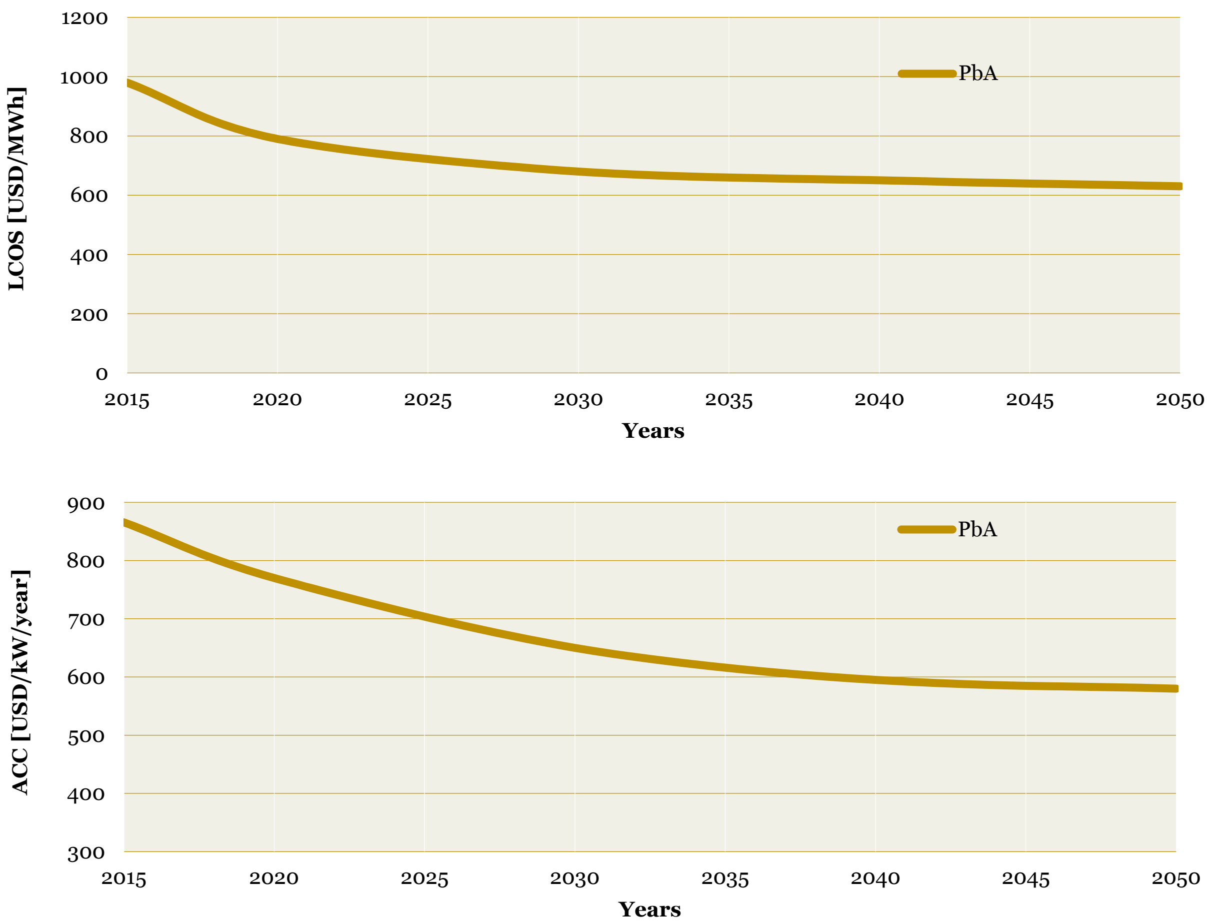
Batteries, as a result of modular design, are easily scalable for mobile applications (e.g. small robots, laptops power supply) as well as for medium-scale applications, e.g. prosumer and large-scale installations, where batteries perform the function of energy arbitration and have a stabilizing role for the operation of the power grid. The main technological barrier is the limited service life, e.g. up to 1000 cycles for Pb-A batteries, and the limited energy density, especially of lithium-ion batteries, which in the case of mobile applications translates directly into the range of an electric vehicle[225]. In addition, it is necessary to use energy management systems and cooling systems with lithium batteries, as if the maximum parameters of charging current or maximum temperature are exceeded, the battery pack may ignite. The development of effective recycling methods that will allow nearly 100% use of recyclable materials in the future is also a technological challenge. It should also be noted that in Poland the battery recycling market is currently not regulated or stimulated for the eventuality of massive appearance of electric vehicles, which will constitute a major challenge.

8.5. BES ENERGY STORAGE COSTS

Figure 31a presents the LCOS for Pb-A with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 31b shows LCOS in the 2015-2050 perspective (its value does not exceed 1000 USD/MWh for Pb-A operating in „*energy arbitration*" application). In case of ACC cost, it does not exceed 870 USD/kW per year. In the 2050 perspective, there is a more than 35% decrease in LCOS to below USD 650/MWh and an over 40% decrease in ACC to below USD 600/kW per year.



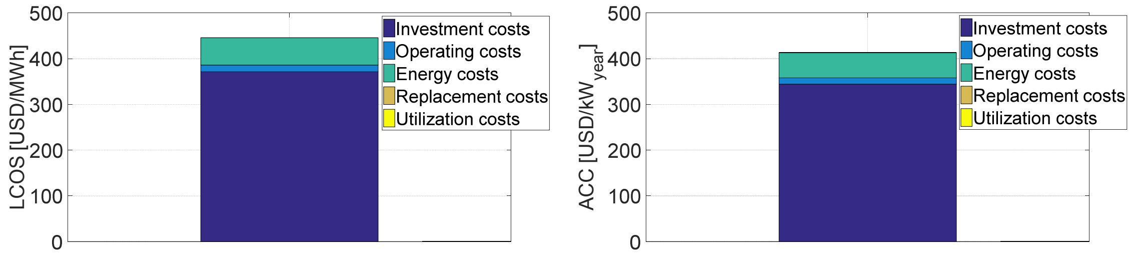
(a)



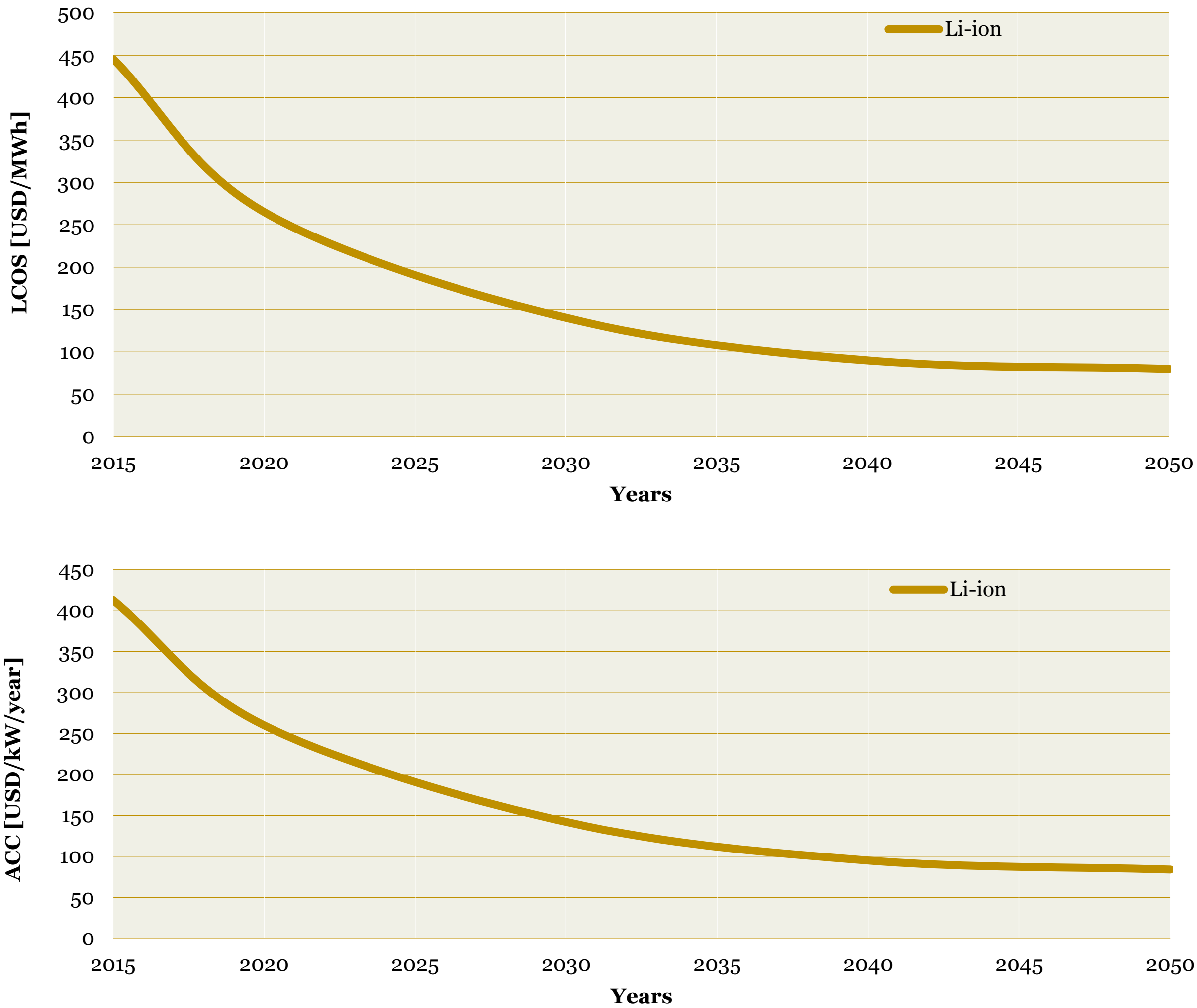
(b)

Fig. 31.) LCOS & ACC of the Pb-A magazine broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective.

Figure 32a presents the LCOS for Li-ion with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 32b shows LCOS in the 2015-2050 perspective (its value does not exceed 450 USD/MWh for Li-ion working in energy arbitration application). In case of ACC cost, it does not exceed 420 USD/kW per year. In the 2050 perspective, a drop of more than 80% in LCOS below 95 USD/MWh can be observed, and over 75% drop in ACC below 100 USD/kW per year. It should be added that the presented data are similar to the estimates made in the work of V.[303] Jüchch both for 2015 and the perspective up to 2030, which justifies the accuracy of the adopted assumptions.



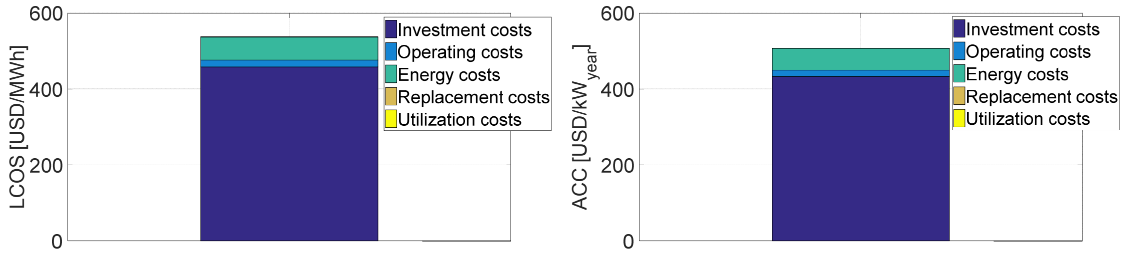
(a)



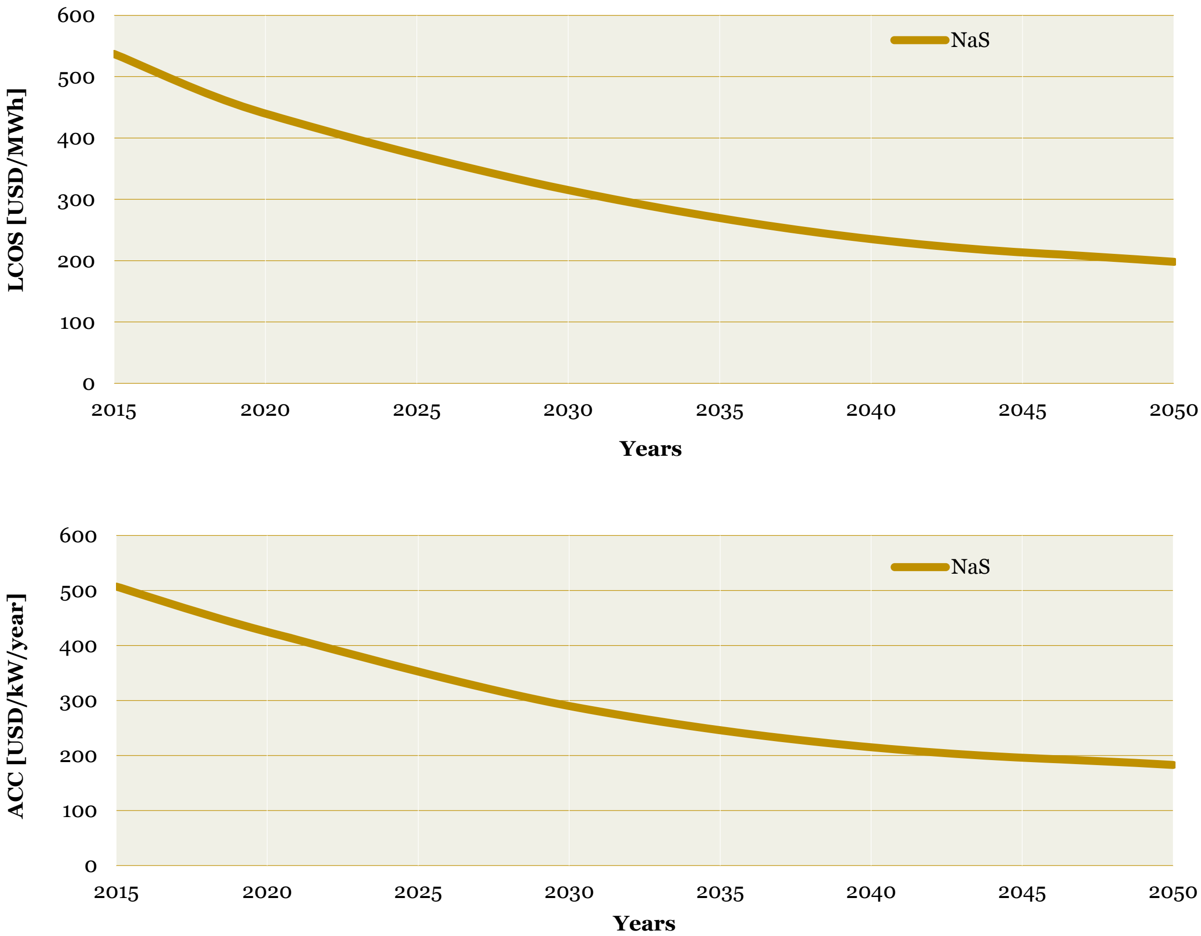
(b)

Fig. 32.a) LCOS & ACC of Li-ion magazine broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

Figure 33a presents the LCOS for NaS with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 33b shows LCOS in the 2015-2050 perspective (its value does not exceed 540 USD/MWh for Li-ion working in energy arbitration application). In case of ACC cost, it does not exceed 510 USD/kW per year. In the 2050 perspective, a drop of more than 60% in LCOS below 200 USD/MWh can be observed, and over 60% drop in ACC below 190 USD/kW per year.



(a)



(b)

Fig. 33. a) LCOS & ACC of NaS storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

8.6. MAIN BES APPLICATIONS

Galvanic cells currently are mainly used to power mobile devices or as emergency power sources, as well as increased utilization network regulation applications and daily or seasonal storage. Depending on the application and thermal conditions of use, specific cell types are selected for specific purposes. Main applications of electrochemical batteries are daily and seasonal energy storage, road transport (hybrid and electric vehicles), network support services (making the network operation more flexible), aviation and shipping.

Pb-A batteries

Due to the high weight of lead elements, lead-acid batteries are used only in devices requiring reliable periodic power supply with high density, as well as in devices for which the use of batteries of relatively high mass causes a negligible increase in the total mass of the system (e.g. some mobile applications: starter batteries in internal combustion vehicles, air transport, shipping, etc.) or is not a significant issue (e.g. stationary applications: prosumer energy storage in households, emergency energy storage). Lead acid batteries have been used for years to power MELEX electric vehicles, and are now also considered as power sources for hybrid and electric cars. Currently this application has been dominated by lithium-ion and nickel-metal hydride cells. Currently the selection of 12 V Pb-A starter batteries on the market is very large (approx. 60-140 Ah) and 12 V emergency Pb-A UPS (approx. 5-10 Ah). These solutions are several times cheaper than other types of batteries.

Ni-Cd batteries

The utilization of these batteries is currently quite narrow, due to development of other types of batteries and legal restrictions in the European Union. Ni-Cd cells are used mainly in medical and military devices, due to their reliability over a wide temperature range.

Ni-MH batteries

The technology of these batteries is mainly used in mobile devices that require high instantaneous current densities, such as cameras, flashlights. Nickel-metal hydride batteries are also used to power hybrid cars equipped with electric motors (e.g. Toyota Prius). A large installation made of nickel metal hydride batteries is an emergency power source in the Tokyo subway (Giga-cell).

Li-ion batteries

are currently used mainly to power lightweight mobile devices, such as cell phones, laptops and cameras, but also to power electric and hybrid vehicles. Due to the operating characteristics of Li-ion cells, high power consumption can lead to overheating and leakage, which may result in a fire. To counteract this, among others: in vehicles, electronic devices, stationary systems, energy flow management systems (Battery Management Systems), which monitor key battery parameters, among others: cell temperature, degree of charge, change of internal resistance or conductance, battery health, temperature increase and voltage.

Main applications of galvanic cells (Li-ion)[11] are: daily storage and seasonal energy storage, road transport – in particular hybrid and electric vehicles, network support services (making the operation of the network more flexible), aviation and shipping. In case of lead-acid cells, the main applications are, among others: seasonal and daily storage, transport – vehicles and working machines with classic drive (internal combustion engines), post-consumer in households, air transport and shipping. They are several times cheaper than lithium-ion batteries.

Sodium-sulfur batteries

These batteries have found[11] application mainly in making operation of the grid network more flexible (network services for over 20 years with a capacity of 1–10 MW) and in daily / daily energy storage. Due to the operating temperature range of 300-350°C, they are not suitable for household applications.

8.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR BES

Advantages of the technology: [11,86]

- Efficient electricity storage,
- A quiet and emission-free energy source,
- It is possible to power devices of various types with the use of appropriately selected cells.

Advantages of technology, divided by cell types:

Pb-A:

- technology implemented on the market with extensive recycling infrastructure,
- reliability and low cost,
- high energy densities are obtainable,
- relatively high resistance to low operating temperatures,
- no risk of fire when unsealed,
- possibility of extending the service life by connection with a ultracapacitor[239,240],

CLAB:

- higher capacity compared to Pb-A,
- greater resistance to self-discharge compared to Pb-A,

Ni-Cd:

- good tolerance of low temperature,

Ni-MH:

- high energy densities are obtainable,
- no risk of fire when unsealed,

Li-ion:

- a rapidly growing production base, leading to a reduction in production costs,
- high energy density (currently up to 250 Wh/kg) and efficiency (up to 97%),
- lifetime up to 10,000 cycles,
- a prospective fall in price due to the development of the electric vehicle market,

Na-S:

- mature, high-temperature technology to support the power grid,
- long service life up to 25,000 cycles (high temperature technology),
- low temperature technology (TRL-1) for smaller scale applications,

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[239] Piorkowski P., Chmielewski A., Bogdzinski K., Mozaryn J., Mydlowski T. Research on Ultracapacitors in Hybrid Systems: Case Study, *Energies*, 11, 2018, 2551; doi:10.3390/en11102551.

[240] Chmielewski A., Piorkowski P., Bogdzinski K., Szulim P., Guminski R. Test bench and model research of hybrid energy storage, *Journal of Power Technologies*, 97(5), 2017, 406–415.

Disadvantages of the technology:

- Relatively low energy density compared to fossil fuels
- A relatively complicated production method
- High demand for raw materials

Disadvantages of technology, divide by cell types:

Pb-A:

- limited ability to operate in a partially charged state (for a charge less than SOC = 0.3),
- relatively low life (up to 1000 cycles) compared to Li-ion (up to 10,000 cycles),
- self-discharge 5-30% per month (depending on the ambient temperature),
- component toxicity,

Ni-Cd:

- memory effect when charging incorrectly
- component toxicity

Ni-MH:

- relatively fast degradation of the electrode material and decreasing capacity

Li-ion:

- limited capacity at low / negative temperatures
- susceptible to explosion if the maximum charging currents are exceeded

Na-S:

- high operating costs
- flammability of high temperature cells
- high cost and lower efficiency (TRL-9) of low-temperature cells

Lithium-ion (Li-ion) cells are recommended primarily for use in daily storage, road transport – in particular hybrid and electric vehicles, network support services (making the grid operation more flexible), aviation and shipping. In order to extend their life, they are connected in parallel with supercapacitors and renewable energy sources, e.g. PV cells (the starting capacity at low / negative temperatures of Li-ion batteries is increased). Very high development potential in Poland, especially in transport sector, network support services and industrial electronics.

Potential stakeholders include: road transport (EV users), freight transport, fuel companies, among others: Lotos, Orlen, BP, Lukoil (autonomous OFF-GRID charging stations based on renewable sources of electric vehicles – supporting the operational infrastructure for EV), prosumers. Poland has the appropriate technical facilities and R&D to develop this type of solution.

Pb-A /**CLAB lead-acid / composite cells are recommended** primarily for seasonal and daily storage, transport – vehicles and machinery with conventional drive (internal combustion engines), prosumer households, air transport and shipping. In order to extend their service life, similarly to Li-ion, they are connected in parallel with supercapacitors and renewable energy sources, e.g. PV cells (the starting capacity at low / negative Pb-A / CLAB temperatures is increased). It should be emphasized that CLABs have a higher energy density than Pb-A and therefore can be used in hybrid vehicles.

Potential stakeholders include: road transport (users of vehicles with combustion engines), freight transport, prosumers. Poland has the appropriate technical facilities and R&D to develop this type of solution.

Sodium-sulfurcells **(NaS) are recommended** for making the power grid more flexible and for daily energy storage.

Potential stakeholders include: distribution network operators, Polish Power Systems (PSE).

In summary, in the 2050 perspective, the cheapest energy storage will be possible in Li-ion cells, LCOS below 80 USD/MWh.

9. FLOW CELLS (VRFB)

Technical characteristics of **flow cell systems (VRFB /ZnBr)**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permanent energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
VRFB ('REDOX' type flow batteries)	16–33	0.02-30	Min.-D.	5-10	Min.-h+	120 000+	~65–85	In development /TRL-9
Zn-Br (Zinc-bromium flow batteries)	30–60	0.05-30	Min.-D.	5-10	Min.-h+	2 000+	~65–80	In development /TRL-9

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **flow cell systems (VRFB /ZnBr)**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
VRFB	600-1 500	150-1 000	~12-15 USD/kW/year, ~0.001-0.002 USD/kWh
Zn-Br	200-2 500	150-500	~12-16 USD/kW/year, ~0.001-0.0015USD/kWh

9.1. INTRODUCTION

Flow cells are a specific type of electrochemical batteries that don't feature classic solid electrodes that undergo oxidation-reduction reactions, but separated electrolytes, whose components undergo oxidation and reduction (redox) reactions as in a conventional electrochemical cell. Electrolytes flow through the electrochemical cell. The electrode reaction can run continuously as long as fresh electrolyte is delivered. Capacity of the cell depends on volume of the electrolyte, power is related to the surface of the electrodes. However, flow cells differ from fuel cells in that the used electrolyte can be reversibly regenerated in the same way as charging discharged batteries. Like other electrochemical cells, flow batteries store and generate direct current, and require the use of a power converter to ensure interoperability with the electrical grid network.

Construction of the flow cells involves storage of the electrolyte, outside of the electrochemical cell, in special containers, the volume of which can be freely selected (Fig. 35). The electrochemical cell has two separated chambers with an electrolyte, one for the cathode electrolyte (catholyte) and the other for the anode electrolyte (anolyte), with an ion exchange membrane separating electrolytes. During cell operation, two types of electrolyte are pumped through the cell, where redox reactions occur. Solid flow electrodes are used in flow systems, most often carbon ones due to low price. As the redox reaction progresses (simultaneous oxidation and reduction), protons flow through the membrane.

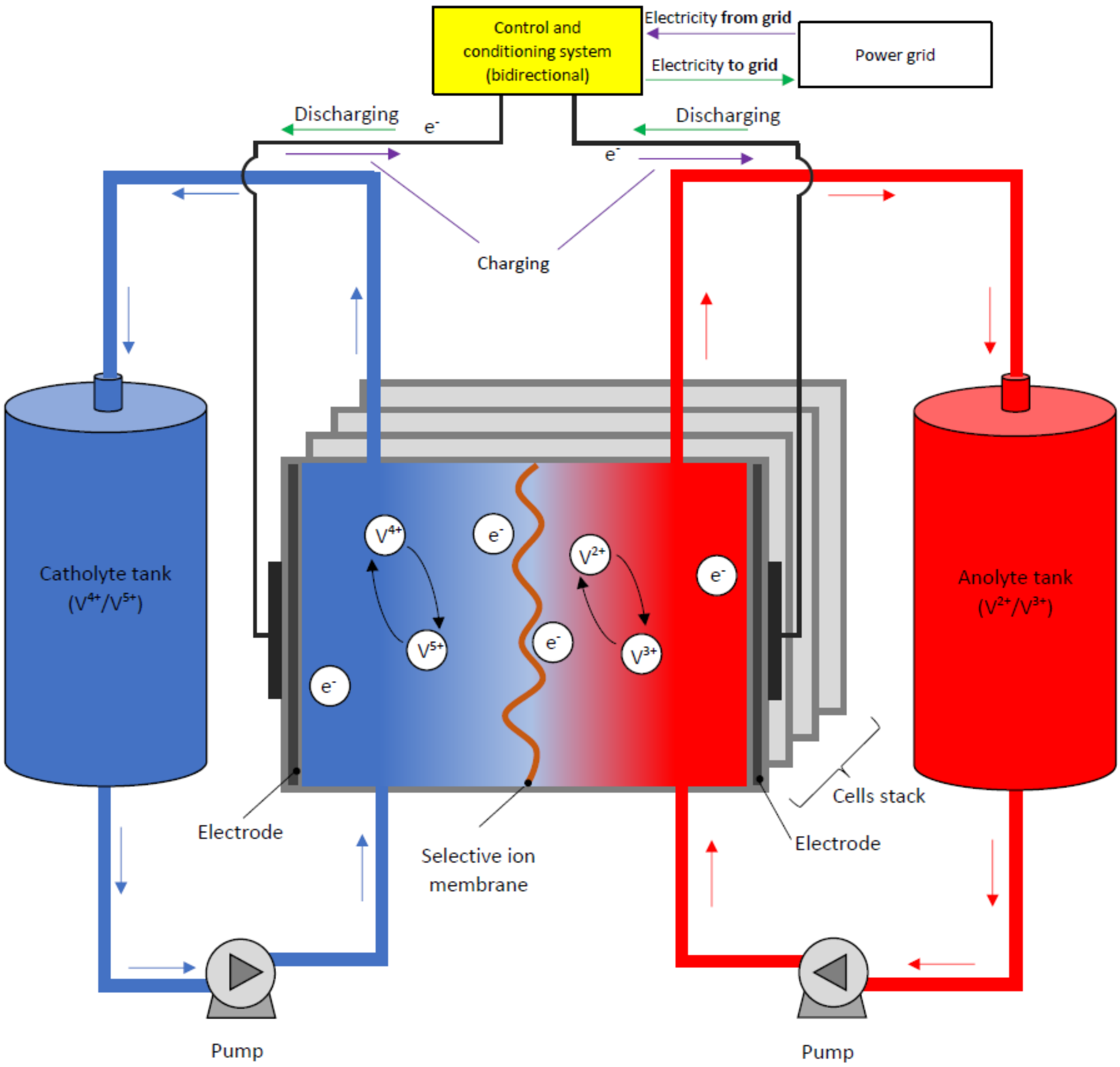

Fig. 34. VRFB flow-through battery operation diagram – own study

Energy is stored in electrolyte solutions. For Redox flow batteries (*Vanadium Redox FlowBattery-VRD*) are used vanadium redox pairs (V^{2+}/V^{3+} oraz VO^{2+}/VO_2^{+}). The efficiency of the charging / discharging process is approx. 85%, with a voltage of 1.4 V. Batteries of this type are used as auxiliary power sources during power load peaks in, among others, state of Utah, USA (250 kW) and Japan (500kW). VRFB batteries have very short response time (below 0.001s), they can operate up to 100,000 charge /

discharge cycles. Vanadium cell electrolytes have a relatively low energy density of approx. 35Wh/L. During discharge, the following redox reactions (simultaneous oxidation and reduction) occur:

Negative plate (–): $V^{2+} \rightarrow V^{3+} + e^-$ $E^o = +0{,}26\ V$ (9.1)

Positive plate (+): $VO_2^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O$ $E^o = +1{,}00\ V$ (9.2)

Zinc-bromine flow cells (ZnBr) operate in a similar way, which have a slightly higher rated voltage of 1.8 V, compared to VRD cells, and their charge / discharge efficiency ranges in the range of 65-75%. The following electrode reactions occur in the cell:

Negative plate (–): $Zn \rightarrow Zn^{2+} + 2e^-$ $E^o = +0{,}76\ V$ (9.3)

Positive plate (+): $Br_2 + 2e^- \rightarrow 2Br^-$ $E^o = +1{,}06\ V$ (9.4)

Flow batteries were designed for large-scale energy storage. To increase storage capacity of the battery, it is possible to add larger amounts of cheaper electrolyte. It should be added that flow batteries have a much longer life, but lower energy density than, for example, lithium-ion batteries.

9.2. VRFB DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Flow cells can be used as stationary energy storage, mainly as components of energy quality improvement systems and emergency power supply systems – UPS. Currently, the use scale of flow cells is negligible. However, intensive work is underway to develop this technology in many research centers around the world. Two projects regarding the use of vanadium batteries undergo research in the United Kingdom. The first project (Scottish Power, University of Southampton) evaluates a 100 kW battery in terms of its usability during stationary energy storage. The second project (C-Tech Innovation Ltd, E.ON UK plc.) concerns the storage of surplus energy from renewable energy sources in flow batteries. A project was carried out at the University of Monash in Australia, in cooperation with RedT Energy storage company from the United Kingdom, where a 900 kWh VRFB battery connected to a 120 kW lithium battery was manufactured and connected to solar cells.[241] RedT company implemented flow accumulators in 14 OFF-GRID installations in Botswana (with a capacity of 40 kWh[242], which operate in continuous mode, connected to a photovoltaic system with a capacity of 11 kWp) and in South Africa in the Thaba Eco Hotel (VRFB installation with a capacity of 15-75 kWh[243] cooperating with 100kW solar cells and diesel generators, reducing pollution). It should be emphasized that redT together with partners has signed an exclusive agreement for a system with total capacity of approximately 700MWh throughout the transmission network throughout Germany[244]. In Great Britain, the world's first Energy Superhub Oxford is being built, where a 2 MW/ 5 MWh flow battery will work with 48 MW/MWh lithium-ion batteries, supplying infrastructure including vehicles, taxis and electric buses, with some of the energy used for supplying heat pumps in buildings.

During the production of VRFB batteries, CO_2 is emitted into the atmosphere. The carbon footprint of their production is 183 kg CO_2/kWh (Table 20).

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[241] RedT Energy storage, https://www.redtenergy.com/vanadium-lithium-hybrid-systems-optimal-power-energy-applications/ – [accessed: 08.08.2019].

[242] RedT Energy storage Botswana, https://redtenergy.com/customers/off-grid-energy/ [accessed: 09.08.2019].

[243] RedT Energy storage Hotel, http://redtenergy.com/story/solar-mini-grid-for-resort-hotel/[accessed: 07.09.2019].

[244] RedT Energy storage Germany, https://redtenergy.com/story/700mwh-germany-grid/ [accessed: 09.08.2019].

NAFION[245] is most commonly used for the membrane material, which is a synthetic copolymer of tetrafluoroethene and perfluorinated oligovinyl etherterminated with a strongly acidic sulfone residue.

9.3. RESOURCE RESTRICTIONS

The main raw materials used in flow batteries are vanadium[246], zinc[247] and bromine. Changes in price of zinc over the last five years, which ranged from 1.5-3.0 USD/kg. In turn, changes in vanadium prices in the last 3 years, where a six-fold increase in prices in the first period can be observed (to approx. USD 130/kg), followed by their equalization to the initial level (approx. 20 USD/kg). Such large fluctuations in raw material prices, as was the case with vanadium, can have a significant impact on the availability and cost of flow cells.

9.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

The technology of flow cells is at a relatively early stage of development, the first commercial installations date back only to 1990s. The design assumptions of flow cells suggest that they will be easily scalable, thanks to their modular structure and separation of tanks with active material (electrolytes) from the electrochemical cell in which redox reactions occur. In addition, the need to ensure precise control of electrolyte flow and the need for components of significant size further increases the cost of flow battery technology.

9.5. VRFB ENERGY STORAGE COSTS

Figure 35a presents the LCOS for VRFB with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 35b presents LCOS in the perspective of 2015–2050 (its value does not exceed USD 645/MWh for VRFB working in the primary reaction application). In case of ACC cost, it does not exceed 570 USD/kW per year. In the 2050 perspective, a drop of more than 70% in LCOS below 190 USD/MWh can be observed, and over 70% drop in ACC below 170 USD/kW per year. These predictions make this technology one of the cheapest.

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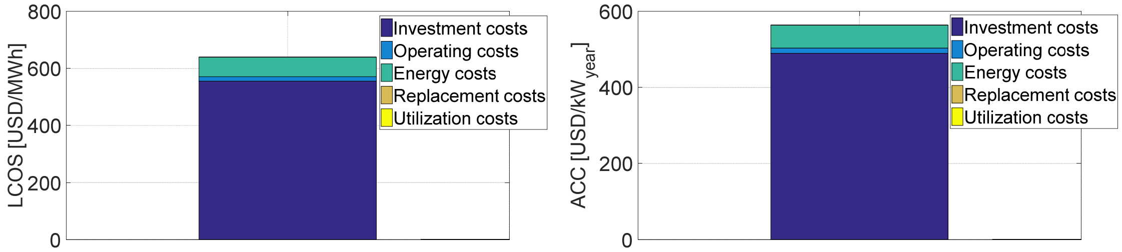
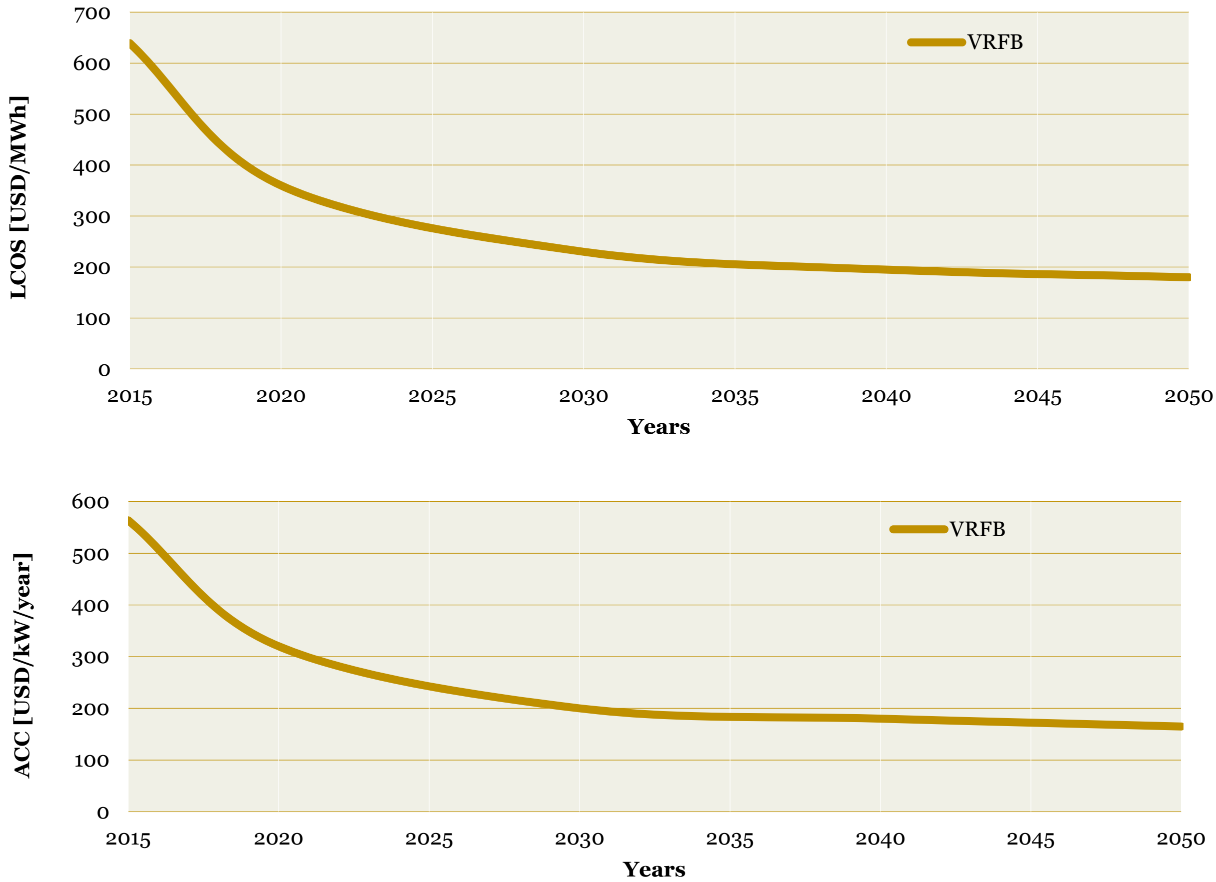
[245] H. Prifti, A. Parasuraman, S. Winardi, T.M. Lim, M. Skyllas-Kazacos, Membranes for Redox Flow Battery Applications, Membranes 2, 2012, 275–306, doi:10.3390/membranes2020275.

[246] Vanadium prices, https://www.vanadiumprice.com/ [accessed: 06.08.2019].

[247] Zinc prices, http://www.infomine.com/investment/metal-price-futures/zinc/3-month/5-year/ [accessed: 06.08.2019].



(a)



(b)

Fig. 35. a) LCOS & ACC of the PCM storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

9.6. MAIN APPLICATIONS OF VRFB

The main applications of flow batteries are network support services and daily electricity storage[11].

9.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR VRFB

Advantages of the technology:

- Longer service life (up to 25 years, up to 120 000 cycles) than for batteries, e.g. Li-ion (up to 10,000 cycles), Pb-A (up to 1,000 cycles), CLAB (up to 1,500 cycles),
- Safe components – no possibility of fire when the system is unsealed,
- Modularity and easily scalable (zinc bromide designed in modular housings),
- Easy scalability of the vanadium system to power demand profile.

Disadvantages of the technology:

- Lower energy density, up to 60Wh/L than in the case of batteries, among others: Li-ion (up to 500 Wh/L), Pb-A (up to 90Wh/L), CLAB (up to 150 Wh/L), NaS (up to 250 Wh/L).
- Acid based electrolyte,
- decrease in efficiency during fast charging,
- Higher operating and operating costs (~ 65-70 USD/kW per year) than for conventional batteries, among others: Pb-A (~ 50 USD/kW per year), CLAB (~ 35 USD/kW per year), Ni-Cd (~ USD 20/kW per year).

Vanadium flow cells (VRFB) are recommended for use in network support services and daily electricity storage in cooperation with renewable energy and infrastructure for charging purely electric vehicles. VRFB has great potential to achieve the assumed zero-emission goals of economies, i.e. in Germany. High development potential in Poland.

Potential stakeholders include: Polish Power Systems (PSE), Distribution Network Operators (OSD), Lotos, Orlen, BP and Lukoil fuel companies (development of autonomous OFF-GRID charging stations based on renewable sources for electric vehicles – support of operational infrastructure for EV). Poland has the appropriate technical facilities and R&D for the development of this type of solutions. Currently research in this field is being carried out in Poland by, among others, Warsaw University of Technology, AGH University of Science and Technology.

10. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

Technical characteristics of **superconducting coil systems (SMES)**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
SMES (Supercondu ctive coils)	0.2-6	0.1-10	mSec.-h.	20-30	≥30Min.	~10 000-~∞	~95–97	In development/ TRL-9

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **superconducting coil systems (SMES)**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
SMES	200-489	5 000-72 000	~0.001USD/kWh, 16-18.5USD/kW/year

10.1. INTRODUCTION

An example of a system that accumulates energy in a magnetic field is a superconducting energy store (*Superconducting Magnetic Energy Storage, SMES*), i.e. a coil made of superconducting material, which during storage at a sufficiently low temperature (below the so-called critical temperature) can losslessly conduct electricity, thereby generating a stable magnetic field. Heating the coil above the critical temperature results in appearance of electrical resistance in the system, generating energy losses. Currently known superconductors require storage in liquid helium (T = 4.2 K) or liquid nitrogen (T = 77 K). A cryogenic system, the so called cryostat, is responsible for maintaining continuous low temperature, using a cryocooler or helium condenser (Fig. 36). The cryostat is connected with a vacuum installation.

In SMES systems, commonly the so-called *low temperature superconductors (LTSC),* requiring liquid helium cooling are used, and not so-called high *temperature superconductors (HTSCs) which require liquid nitrogen cooling,* since they are able to store a significant amount of energy, which compensates for higher cooling costs. The most commonly used superconductor material in SMES systems is niobium-titanium ($NbTi_2$) embedded in a copper or aluminum matrix[248], which becomes a superconductor when cooled below a temperature of 9.2 K[249].

Unfortunately, such solutions are very expensive (over 10 000 USD/kWh). In addition, daily self-discharge is at a level of 5–15%, which results from, among others, increase in temperature of the coil, caused by the current flow, resulting in loss of superconducting properties. The full discharge time lasts about 1 minute. However, the advantage of this storage is a very high service life of up to 30 years. The capacity of SMES stores ranges from 100 kW to 10 MW.

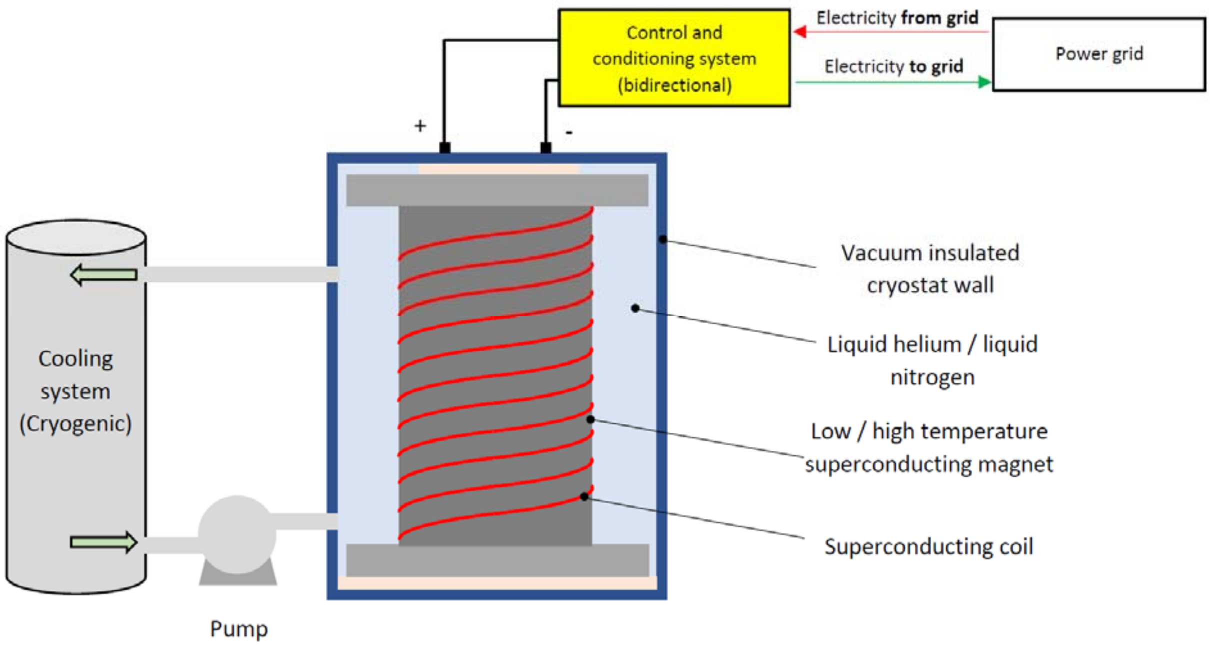


Fig. 36. SMES system diagram – own study

10.2. SMES DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

The first successful SMES systems were constructed in 1971[250] at the US National Laboratory in Los Alamos (Los Almos National Laboratory – LANL). Work began then with the University of Wisconsin on construction of a 30 MJ superconducting energy storage tank[251]. The developed system was to ensure operational stability of the power dispatch center in Bonneville (Bonneville Power Athority – BPA), which managed the strategic Pacific Intertie power line. Based on the prototype, the possibilities and benefits of the SMES technology were presented and commercialized in 1981. Currently, the technology

[248] M. Ghate, P. Raj, A. Singh, S. Pradhan, M.M. Hussain, K.K. Abdulla, Design, development and fabrication of indigenous 30 kA NbTi CICC for fusion relevant superconducting magnet, *Cryogenics*, 63, 2014, 166–173.

[249] X. Luo, J. Wang, M. Dooner, J. Clarke, Overview of current development in electrical energy storage technologies and the application potential in power system operation, *Applied Energy*, 137, 2015, 511–536.

[250] P. Mukherjee, V.V. Rao, Design and development of high temperature superconducting magnetic energy storage for power applications – A review, *Physica C: Superconductivity and its applications*, 563, 2019, 67–73.

[251] Janowski T., Kondratowicz-Kucewicz B., Kozak J., Kozak S., Majka M., Malinowski H., Surdacki P., Wojtasiewicz G., Nadprzewodnikowe zasobniki energii (Superconducting energy storage), ,,LIBER DUO s.c.", Lublin 2007. [In Polish]

is being developed by, among others, Super Power Inc. in the form of an advanced 20 kW HTS SMES system and *ultra high field (UHF),* with a capacity of up to 2 MJ in cooperation with ABB Inc., Brookhaven National Laboratory (BNL) and Texas Center for Superconductivity (TCSUH) at the University in Houston[250]. Currently, China and Japan are also developing SMES systems on a small scale, whose goal is to stabilize operation of a micro network cooperating with a wind farm. Currently in China a 100kJ SMES system is being developed, cooperating with a cooling system operating at 20K, which allows for suppression of voltage oscillations in a 25MW micro grid.

Systems based on SMES don't have a negative impact on the environment during operation (there is no emission of toxic compounds, however, there is an impact of a strong magnetic field, whose impact in terms of SMES has not yet been studied). Superconducting materials used in production of SMES cables are, among others: Nb-Ti (titanium niobium), Nb_3Sn (tinniobium)[252], Nb_3Al (aluminum niobium), V_3Ga (gallium vanadium) and ceramics. Superconductors during use have neutral impact on the environment, however, during their production carbon dioxide is emitted into the atmosphere. Table 21 shows the carbon footprint during production for, among others: aluminum, copper, iron, lead, nickel, tin and zinc, which are used for components of SMES.

Table 21. Carbon footprint during the production of selected primary raw materials [253,254]

Material	Carbon footprint [ktCO_2/100 000 t]
Aluminum	383
Copper	125
Iron	167
Lead	163
Nickel	212
Tin	218
Aluminum	236

10.3. RESOURCE RESTRICTIONS

There are no restrictions for raw materials. Current prices of raw materials have been stable and predictable over the past two years, most often used for SMES components include: niobium[255] (65%) – 39 USD/kg, aluminum – 2000 USD/ton, copper – 7,000 USD/ton and tin[256] – 20,000 USD/ton.

[252] V. Corato et al. Progress in the design of the superconducting magnets for the EU DEMO, *Fusion Engineering and Design*, 136, 2018, 1597–1604.

[253] Report on the Environmental Benefits of Recycling – 2016 edition, Bureau of International Recycling (BIR), BIR-Nominated Commodities: Aluminium, Copper, Ferrous and Paper, https://www.mrai.org.in/site/assets/files/7762/report_on_environmental_benefits_of_recycling_-_2016_edition.pdf [accessed: 08.08.2019].

[254] S. Grimes, J. Donaldson, G.C. Gomez, Report on the Environmental Benefits of Recycling, Bureau of International Recycling (BIR), Imperial College London 2008, https://www.mgg-recycling.com/wp-content/uploads/2013/06/BIR_CO2_report.pdf [accessed: 08.08.2019].

[255] Niobium prices, https://www.niocorp.com/the-fundamentals-of-ferroniobium/ [accessed: 09.08.2019].

[256] Tin prices, http://www.infomine.com/investment/metal-prices/tin/6-month/ [accessed: 09.08.2019].

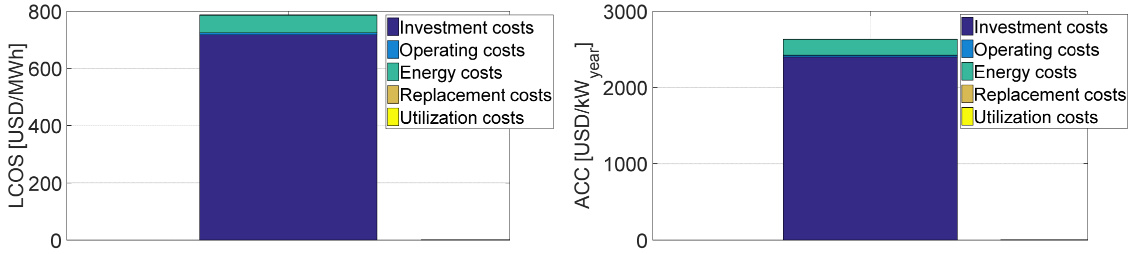
10.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

SMES systems have a modular structure, making them easily scalable[257]. The main technological barrier for the wider use of SMES systems is the lack of superconducting materials that would not require cooling to very low temperatures. In addition, despite the cooling of the coil to a suitable temperature, self-discharge at a level of 10-15%[249] per day is present (caused by electrical resistance that appears in the coil after overheating, as a result of current flowing through the winding), which has a significant impact on loss of stored energy. Additional element that increases the cost of the entire system is utilization of cryogenic refrigerators, e.g. with liquid helium, which provides appropriate temperature conditions for SMES operation.

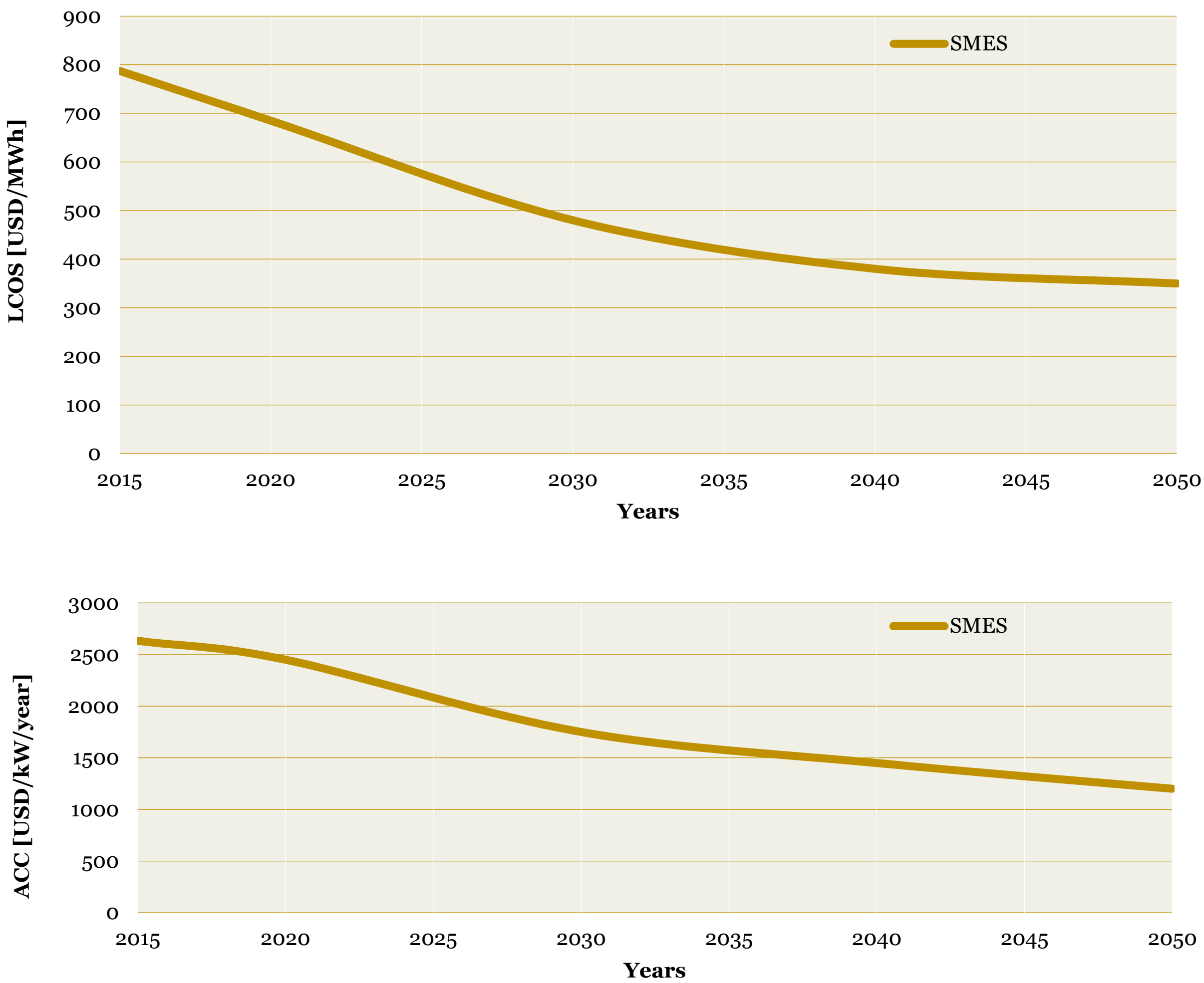
10.5. SMES ENERGY STORAGE COSTS

Figure 37a presents the LCOS for SMES with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 37b shows LCOS in the 2015-2050 perspective (its value does not exceed 800 USD/MWh for SMES operating in „*primary response*" application). In case of ACC cost, it does not exceed 2700 USD/kW per year. In the perspective of 2050, ta decrease of over 60% in LCOS, below 380 USD/MWh and a decrease of over 50% in ACC, below 1,200 USD/kW per year is observed. However, it should be emphasized that LCOS for SMES in the 2050 perspective, despite the decrease in value, will be more than three times higher than for supercapacitors and inertia, whose LCOS will be around 100-115 USD/MWh.

[257] Parchomiuk M., Strzelecki R., Zymmer K., Domino A., Modular Power Converter with Superconducting Magnetic Energy Storage for Electric Power Distribution System – Analysis and Simulation, EPE'17 ECCE Europe, ISBN: 9789075815276 et CFP17850-ART.



(a)



(b)

Fig. 37. a) LCOS & ACC of the SMES storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

10.6. MAIN SMES APPLICATIONS

The main application of SMES systems is increasing flexibility of grid network services, e.g. voltage stabilization. SMES systems can operate during „cold starts" similarly to inertial FES and super-capacitors (UC / EDLC) and emergency power supply systems (UPS). Additionally, they can be used in: lasers (times in the order of micro seconds), induction loads during plasma limitation in fusion reactors and microgrids. SMES systems can cooperate in installations with photovoltaic cells and wind farms to improve power delivery quality[251].

10.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR SMES

Advantages of the technology[249,258,259]*:*

- High efficiency, up to 95-98%,
- High power density,
- No moving mechanical parts,
- Quick response (on the order of milliseconds),

Disadvantages of technology[249]*:*

- High investment costs, up to USD 72,000/kWh and up to USD 500/kW,
- The need for continuous cooling to very low temperatures (e.g. 9.2 K – for the Nb-Ti system), liquid helium and liquid nitrogen used as cooling agents,
- Self discharge (10-15%/day),
- Low energy density (0.2–6 Wh/L),
- Risk to human health – strong magnetic field in the vicinity of the system,
- Influence of magnetic field on operation of nearby electrical and electronic devices.

Superconducting coils (SMES) are recommended for use in voltage stabilization in RES micro-networks, i.e. wind farms. SMES systems can also perform functions in primary response (ensuring network stability in the event of sudden frequency and voltage changes) similarly to inertial systems (FES) and supercapacitors (UC / EDLC), as well as to enable quick recovery of power plant operation after network overload without additional external power supply (cold start). Furthermore, in the future they can act as consumer protection against short-term power loss, change in supply voltage or frequency. A very expensive solution, is in the research phase. Poland has the appropriate technical facilities and R&D to develop this type of solution.

Potential stakeholders include: Polish Power Systems (PSE), Distribution Network Operators (OSD).

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[258] J. Zhu, M. Qiu, B. Wei, H. Zhang, X. Lai, W. Yuan, Design, dynamic simulation and construction of a hybrid HTS SMES (high-temperature superconducting magnetic energy storage systems) for Chinese power grid, *Energy*, 51, 2013, 184–192.

[259] J. Zhu, W. Yuan, T.A. Coombs, Q. Ming, Simulation and experiment of a YBCO SMES prototype in voltage sag compensation, *Physica C*, 471, 2011, 199–204.

11. ULTRACAPACITORS (UC)

Technical characteristics of **ultracapacitors (UC/EDLC)**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
UC/EDLC (Ultracapacitors/double-layer capacitors)	2-6	~0-0.5	Sec.- h.	5-15	mSec.- 1h.	50 000-1 000 000	~ 84–97	Commercialized / implemented – NA

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **ultracapacitors (UC)**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
UC/EDLC	25-450	3000-14 000	<0.001USD/kWh, <0.001USD/kW/year

11.1. INTRODUCTION

Capacitors are electrical components built of two sheets separated by a dielectric, which are able to store electric charge by opposing charging – one sheet receives an excess of positive charge and the other an excess of negative charge. The biggest advantage of capacitors is their fast charging and discharging time, their capacity is proportional to surface of sheets used. Unfortunately, due to the necessity to use macroscopic materials, the capacity of classic capacitors is small and ranges from 16-50μF.

Ultracapacitors are a specific type of capacitors, in which one of the covers is replaced with an electrolyte, and the separation of charges takes place in a double electric layer (the so-called Helmholtz layer) with a thickness of 0.3-0.8 nm, which is formed on the surface of a charged electrode submerged in electrolyte (*Electrochemical Double Layer Capacitors*). Ultracapacitor covers are built of high-porosity materials, such as carbon materials, to increase their surface, which in the solution are covered by an extremely thin double layer. Thanks to this, the capacity of ultracapacitors reache values from hundreds to thousands of Farads, for example 3000 F at a cell voltage of 2.2-2.7 V for ultracapacitors manufactured by Maxwell[268]. As mentioned above, the large capacity of ultracapacitors is associated with the very short distance between the covers and large specific surface area of the covers, which reaches 2500 m^2/g.

Usually the ultracapacitors consists of two electrodes and a separator (Fig. 38). In the electrolyte, charges of ions (anions and cations) balance each other, (ions are distributed evenly in the volume of the solution), but after applying an electric field they diffuse into appropriate electrodes. In a short period of time, ultracapacitors are able to supply the device with high current, up to several kiloamps, which emphasizes their usefulness in peak power demand. The described supercapacitors are used by the TVA company (USA[249]) for, among others, when starting high-power DC electric machines (up to 200 kW).

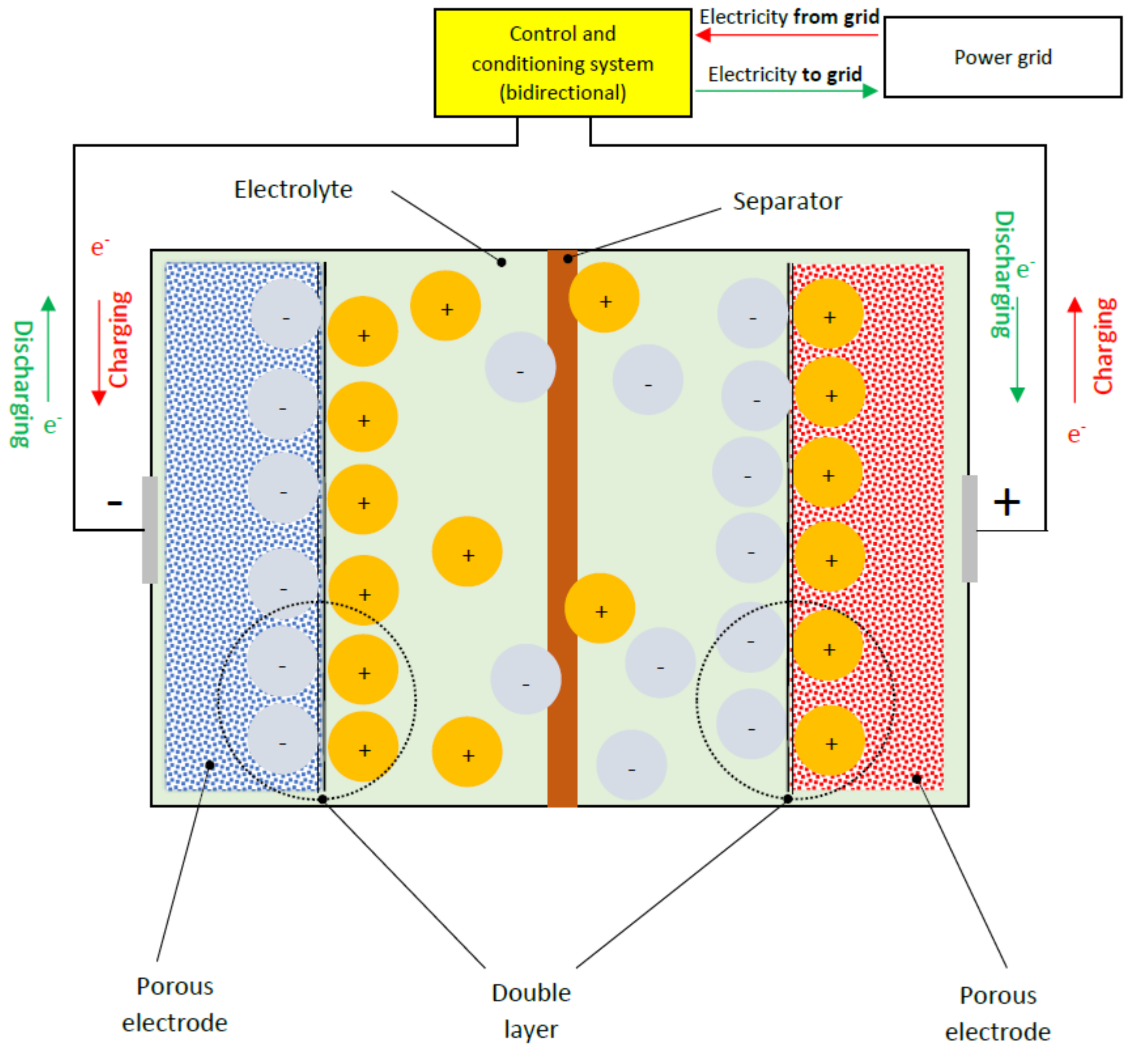

Fig. 38. Double layer supercapacitor diagram (UC / EDLC) – own study

Supercapacitors have high efficiency, reaching up to 97%. It should be emphasized that these values are unattainable for traditional capacitor technologies. The large capacity ultracapacitors are also accompanied by possibility of charging / discharging with high currents (210–2800 A), e.g.for Maxwell 3000F BCAP3400 P300 K04 /[260]05 ultracapacitor, which allows complete charging or discharging in a few seconds. Supercapacitors feature physical and chemical processes, such as connection resistances,

[260] Data sheet: https://www.maxwell.com/images/documents/3V_3400F_datasheet.pdf [accessed: 08/08/2019].

electron effects[261], *charge transfer* processes and associated electrode resistances, trace electrolyte geometrical capacity, electrostatic capacity of the Helmholtz double layer, trace adsorption on electrodes and diffusion (mass transport). They occur with varying intensity. Undoubted advantages are the manufacturers' guaranteed durability of 1 million cycles or 10 years and a very wide range of permissible operating temperatures (from –40°C to +65°C), which makes ultracapacitors useful in many industries.

Currently, supercapacitors can be used as power buffers (during very high current amplitudes). In emergency power supply systems, the main energy source is a battery. By connecting a ultracapacitor in parallel to the battery, the system becomes more flexible for high current peaks (the battery with appropriate control of inverters can work in the most effective range, which directly translates into extending its life[239]).

Ultracapacitors, like inertia FES, are used for short-term energy storage with a very short response time (of milliseconds). Similarly to inertial FES systems and SMES superconducting coils, they are used to protect consumers against short-term power loss, change of supply voltage or frequency and improve power delivery quality. They also ensure stability of the power grid in the event of sudden changes in frequency and voltage (*Primary response*) and allow for quick recovery of power plant operation after network overload, without additional external power supply (so-called „cold start").

11.2. UC DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Currently, UC / EDLC ultracapacitors are used primarily in transport (buses, buses, trucks, trams, trains). A new perspective for the development of ultracapacitors is also opening up in hybrid energy storage applications, where a battery and ultracapacitor are connected in parallel. The use of a ultra-capacitor in parallel with a battery, e.g. Li-ion, can extend the battery life by factor of 2-3 times[262].

In 2019, Tesla (a leader in the electric vehicle market) merged with Maxwell (a leader in the ultra-capacitor industry). The main purpose of the merger is to utilize ultracapacitors in future electric vehicles and to extend the life of currently used Li-ion batteries by 2-3 times[263].

In transport, ultracapacitors are used for the following types of vehicles:

- **Trucks:** starting diesel engines and alternative fuel engines, such as: compressed natural gas (CNG), liquid natural gas (LNG), biodiesel, dimethyl ether (DME) as well as propane-butane or liquefied gas Petroleum (LPG)[268].
- **Buses:** battery support for regenerative braking in hybrid powertrains. As a result of ultra-capacitor utilization, the regenerative braking range is improved (the ultracapacitor supplies and receives energy in a wider voltage range, from 0 to nominal voltage. It should be added that a battery below it's nominal voltage is not able to supply power to the system[239]).
- **Trains and trams:** assuming high current loads during acceleration and stopping, support the battery operation on one hand (extending the service life) and limit its size on the other (through the ultracapacitor, proper power density is provided in the propulsion system).

[261] Buller S., Karden E., Kok D., De Doncker RW, Modeling the dynamic behavior of supercapacitors using impedance spectroscopy. IEEE Transactions on Industry Applications, Vol. 38, No. 6, pp.1622-1626, 2002.

[262] Adrian Chmielewski PhD thesis „The use of the battery-supercapacitor module in distributed generation devices and vehicle drives", OWPW, Waraw 2019.

[263] Merger of Tesla with Maxwell Technologies, https://ir.tesla.com/news-releases/news-release-details/tesla-completes-acquisition-maxwell-technologies [accessed: 08.09.2019].

- **Passenger cars:** to increase efficiency of Start & Stop systems. Supercapacitors are used to start the internal combustion engine. In addition, supercapacitors are used in active vehicle suspension systems, door locks and remote collision notification systems.
- **Military and special vehicles:** increasing combat readiness, starting vehicles in difficult conditions (especially at low temperatures) on military missions in cooperation with renewable energy (e.g. photovoltaic panels) located on roof of the vehicle.

In **machinery,** supercapacitors are used for energy recuperation during typical cyclical work, e.g. cranes/excavators (moving the load / soil – during lifting and lowering, the lost energy is transformed into high current values by an electric machine, which are further taken over by the supercapacitor).

Supercapacitors are also used to **start generators** based on diesel engines, which are turned on during emergency power supply to hospitals, where start up time of few seconds is required, e.g. during operations.

Ultracapacitors are used to postpone modernization of network infrastructure – improvements due to increased efficiency of energy supply at peak of power demand. Supercapacitors allow for greater penetration of the power grid with energy from renewable energy sources[264], and with proper configuration with FES and BES / VRFB can lead to zero-emission micro-networks (especially on islands), which is very important from energy independence point of view.

During operation, it has no negative impact on the environment. Sodium carbonate toned down to the electrolyte occurs naturally. For airgels, the carbon footprint is 4.2 kgCO2 eq./kg[265].

11.3. RESOURCE RESTRICTIONS

There are no resource restrictions. The electrodes are made of activated carbon or carbon aerogels with porous structure. As electrolyte, usually used are[266] potassium hydroxide (KOH), sulfuric acid (H_2SO_4) or sodium carbonate (Na_2CO_3) occur in the natural state. Separators must be chemically inert to protect the stability and conductivity of the electrolyte. As separators, non-woven porous polymer films, such as polyacrylonitrile or Kapton, woven glass fibers or porous woven ceramic fibers are used. Celgard 3501[267] is also used as a separator. Aluminum strips can be used as current collectors.

11.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

Ultracapacitors are easily scalable due to their modular design and there are no technological barriers. Currently, supercapacitors are a mature and forward-looking technique for short-term energy storage.

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[264] L.I. Schultz, N.P. Querques, Tracing the ultracapacitor commercialization pathway, *Renewable and Sustainable Energy Reviews*, 39, 2014, 1119–1126.

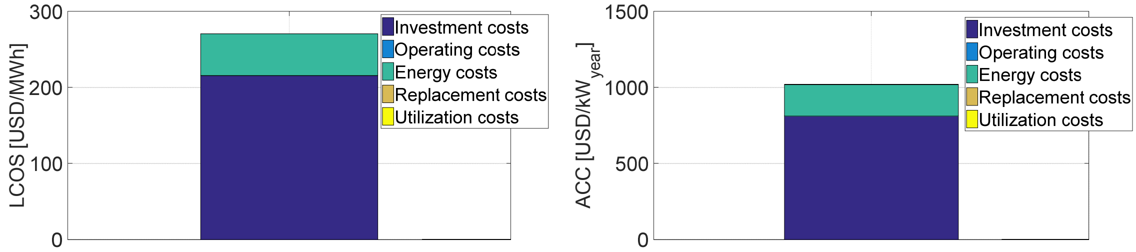
[265] R. Kunič, Carbon footprint of thermal insulation materials in building envelopes, Energy Efficiency, doi:10.1007/s12053-017-9536-1, 2017.

[266] W. Raza, F. Ali, N. Razac, Y. Luo, Ki-Hyun K., J. Yanga, S. Kumare, A. Mehmooda, E.E. Kwon, Recent advancements in supercapacitor technology, *Nano Energy,* 52, 2018, 441–473.

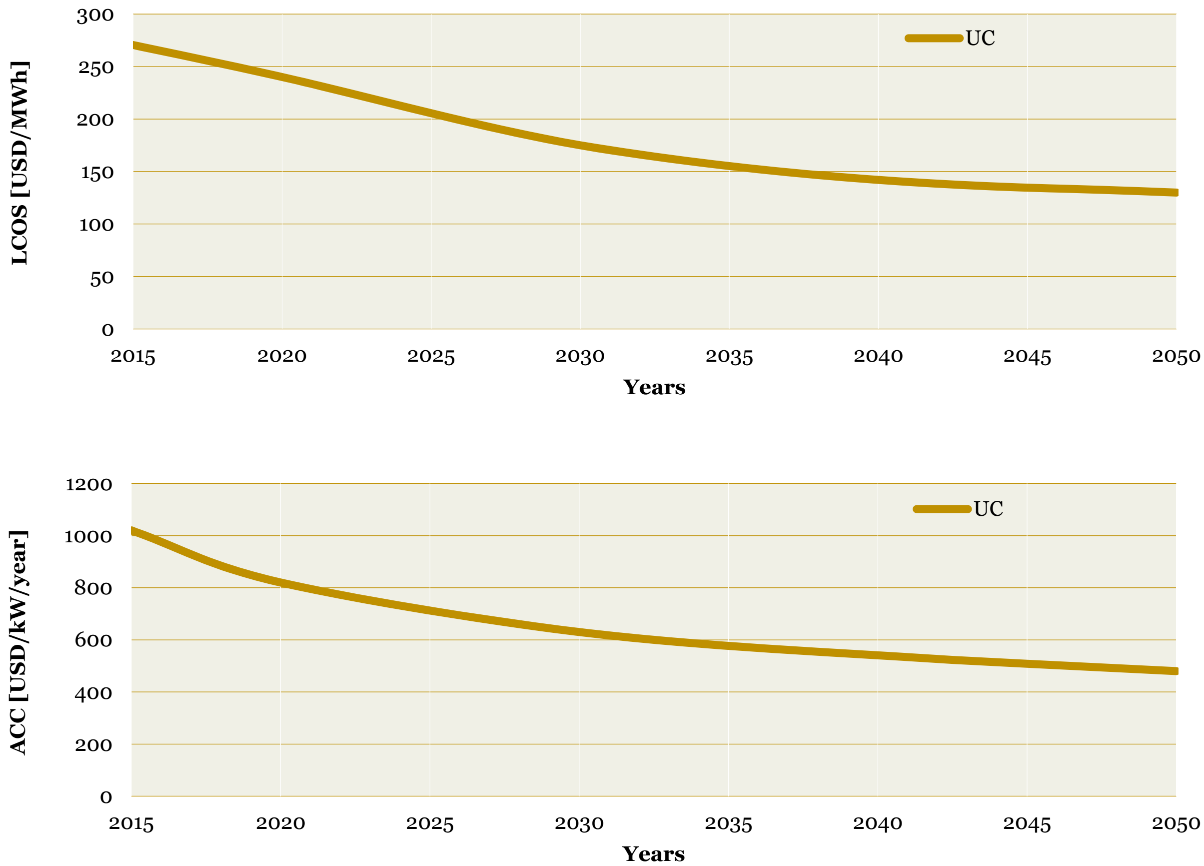
[267] D. DeRosa, S. Higashiya, A. Schulz, M. Rane-Fondacaro, P. Haldar, High performance spiro ammonium electrolyte for Electric Double Layer Capacitors, *Journal of Power Sources*, 360, 2017, 41–47.

11.5. UC ENERGY STORAGE COSTS

Figure 39a presents the LCOS for UC/EDLC with cost breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 39b shows LCOS in the 2015-2050 perspective. Its value does not exceed 270 USD/MWh for UC working in „*primary response*" application. In case of ACC cost, it does not exceed 1050 USD/kW per year. In the 2050 perspective, a drop of more than 45% in LCOS below 140 USD/MWh can be observed, and over 50% drop in ACC below 500 USD/kW per year.



(a)



(b)

Fig. 39. a a) LCOS & ACC of a UC storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

11.6. MAIN UC APPLICATIONS

Ultracapacitors are used primarily in[11] network support services and transport. Ultracapacitors are used in electric vehicle drives, where they are connected in parallel with batteries, e.g. Li-ion, ensuring longer battery life by taking over high current impulses. In this case, the ultrarcapacitor is the first to supply energy to the system, while stabilizing the battery (its current load, for example in cars and other vehicles). Another application is in large trucks in Australia[239], where supercapacitors are connected in parallel with batteries or replace one of the batteries in systems with internal combustion engines.

11.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR UC

Advantages of the technology:

- High power density (maximum load of 2100A per single module)[268],
- Long service life: over a million cycles (up to 15 years)[268],
- Possibility of quick charging from a few to several minutes (linear voltage characteristics in the entire charging range with a constant current value – an advantage compared to electrochemical batteries, e.g. CLAB, Pb-A, Li-ion),
- Reliable operation at low temperatures, from -40^{o}C,
- Modular design, easy scalability of technology,
- High cycle efficiency (up to 97%),
- Resistance to short circuit process, which means that they can be unloaded to zero without damage,
- Low operating and maintenance costs (~ 0.005 USD/kWh, ~ 6 USD/kW/year).

Disadvantages of the technology:

- Much lower amount of stored energy per unit of mass (up to 5 Wh/kg) while for Li-ion batteries is 250 Wh/kg,
- Self-discharge (~ 6.25%/month, 75%/year),
- Exponential change in voltage value at discharge – the need to use power electronics.

Ultracapacitors **(UC / EDLC) are recommended** for use in support of grid services, emergency power systems, in the transport, shipping and aviation sectors. Intensive development of hybrid energy storage is taking place currently, such as: battery-ultracapacitor system used for starting vehicles, or inertial FES-ultracapacitor system used for voltage stabilization in micro networks. High potential for technology development in Poland. Poland has the appropriate technical facilities and R&D to develop this type of solution.

Potential stakeholders include: prosumers, road transport (in particular electromobility) and freight forwarding, local energy clusters, shipping, aviation, and OSD.

[268] Maxwell Technologies, https://www.maxwell.com/products/ultracapacitors/modules [accessed: 06.08.2019].

12. PHASE-CHANGE MATERIALS (PCM / molten salts MS)

Technical characteristics of **PCM based systems / molten salts**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
PCM	147.7-200[273]	Up to 50MW	h.	To 25	h.	>1 000 000[269]	60-97[270]	Early commerce /TRL-9, in development

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **PCM based systems / molten salts**

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
PCM/MS	1000-3800[271]	16-220[272,273]	112USD/kW/year (total constant and various costs calculated to contant costs)[273]

[269] G. Cáceres, K. Fullenkamp, M. Montané, K. Naplocha, A. Dmitruk, Encapsulated Nitrates Phase Change Material Selection for Use as Thermal Storage and Heat Transfer Materials at High Temperature in Concentrated Solar Power Plants, *Energies*, 10, 2017, 1318; doi:10.3390/en10091318.

[270] H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza-Ruiz, X. Xu, K. Vignarooban, P. Phelan, Inamuddin, A.M. Kannan, Recent developments in phase change materials for energy storage applications: A review, *International Journal of Heat and Mass Transfer,* 129, 2019, 491–523.

[271] Z. Wang, S. Sun, X. Lin, C. Liu, N. Tong, Q. Sui, Z. Li, A remote integrated energy system based on cogeneration of a concentrating solar power plant and buildings with phase change materials, *Energy Conversion and Management*, 187, 2019, 472–485.

[272] B.C. Zhao, M.S. Cheng, C. Liu, Z.M. Dai, Thermal performance and cost analysis of a multi-layered solid-PCM thermocline thermal energy storage for CSP tower plants, *Applied Energy*, 178, 2016, 784–799.

[273] J. Lizana, M. de-Borja-Torrejon, A. Barrios-Paduraa, T. Auerb, R. Chacartegui, Passive cooling through phase change materials in buildings. A critical study of implementation alternatives, *Applied Energy,* 254, 2019, 113658.

12.1. INTRODUCTION

Phase change *materials (PCM)* are substances or mixtures of substances showing a phase transition in an assumed temperature range, which are able to reversibly store and release thermal energy while undergoing the phase change. Importantly, the temperature of the phase change material undergoing the phase change remains constant until the change is over. As a general rule, any known substance can be considered as phase change material within a certain temperature range. For example, water shows a solid / liquid phase transition at 0°C, ethanol at -114°C, and hydrogen at -259°C.

For the phase-change material to be functional, it is important that the heat of its phase transformation is as high as possible and that its thermal conductivity is as low as possible. Only then will the phase change material be able to quickly absorb or release a significant amount of heat at its phase transition temperature.

The function of phase-change material may vary depending on the application, but its basic role is to stabilize the temperature of the system and to eliminate thermal effects caused by contact of the system with the environment. The type of phase change material and the type of phase transformation used are selected for the particular application and desired phase transition temperature. For example, in construction it is necessary to use phase-change materials exhibiting a solid / solid phase transition, while the transition temperature may fluctuate in a relatively wide temperature range. In turn the so-called hand warmers must show a phase transition at a temperature slightly above the human body temperature, but solid / liquid phase transition may be used.

Currently, phase-change materials are used in the economies of Western European countries. In[296] the Netherlands, PCM systems in climate floors and climatic ceilings are widely used, reducing energy consumption by the heat pump (up to 50%) in climate controlled rooms, server rooms and data centers. They are also used in the transport sector, especially in mobile cold stores (cooling of the transported food)[274]. Phase-change materials have also been used in solar systems (e.g. widely used in the Middle East – Egypt, Iran and Turkey) for cooling solar energy concentrators[275] as well as cooling photovoltaic modules (efficiency and yield from photovoltaic modules decrease above 50°C, at which point greater losses in the system occur). Phase-change materials have also been used in the pharmaceutical industry, industrial refrigerators and textiles designed for cooling human bodies, especially in areas where the average daily temperature exceeds 30°C (as well as for example Formula 1 racing, to cool the bodies of drivers[276]). Phase-change materials can also be used to cool passenger spaces in electric vehicles and to cool battery packs[277].

Phase-change materials on form of molten salts have also found application in Heliostats, in which high-temperature thermal energy is stored in the form of liquid salt[278] (from 288^{o}C to 566^{o}C). An example of use is the Crescent Dunes Solar Energy Project in the United States. It should be emphasized that molten salts are not toxic. Systems with molten salts have a long lifetime of up to 30 years and can be widely used in zeroemission installations.

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[274] PLUSS Technology for better world, http://pluss.co.in/upload/application/plusa21fab_pluss_cold-chain-transportation.pdf [accessed: 08.08.2019].

[275] CSP Concentrated Solar Power – PLUSS Technology for better world, http://pluss.co.in/upload/application/plus10d82e _Pluss%20PCM%20in%20Solar%20Application.pdf [accessed: 08.08.2019].

[276] PCM product, http://www.pcmproducts.net/Phase_Change_Material_Development.htm [accessed: 08.08.2019].

[277] N.R. Jankowski, F.P. McCluskey, A review of phase change materials for vehicle component thermal buffering, *Applied Energy*, 113, 2014, 1525–1561.

[278] SolarReverse, https://www.solarreserve.com/en/technology/heliostats-and-collector-field-controls.html [accessed: 08.08.2019].

The impact of phase-change materials on the environment is minimal during their standard operation. Production and utilization requires energy expenditure, which is associated with a non-zero carbon footprint. Table 30 shows the carbon footprint using molten salts at a hypothetical concentrated solar plant in Daggett[279] California, USA, whose annual direct normal sunlight is one of the highest in the United States (~ 2700 kWh/m^2). It was assumed in the analyzes that the system will work for 30 years, with power of 103 MW, storage time of 6.33 h (using two tanks in which molten salts are found). Table 22 presents the carbon footprint at various stages of life, including production, construction, operation, dismantling and transport. The total carbon footprint for this installation with wet cooling was 26 gCO2 eq/kWh while with dry cooling 28 gCO2 eq/kWh.

Table 22. Carbon footprint in molten salts during wet and dry cooling[279]

Material	Carbon footprint [gCO_2eq/kWh]	
Molten salts:	Wet cooling	Dry cooling
Manufacturing	12	13
Construction	1,7	1,8
Operation	10	11
Decomission	0,12	0,12
Transport	2,1	2,1
Total:	26	28

The operation of phase-change materials can be carried out in a zero-emission mode, especially when they are used as admixtures for building materials to increase their heat capacity, or as protective elements of clothing fabrics. In turn, the use of thermal inserts or hand warmers containing appropriately selected phase-change materials requires their prior preparation (cooling or heating), which may be associated with carbon dioxide emissions if the energy originates from fossil fuels.

12.3. RESOURCE RESTRICTIONS

There are no resource restrictions for phase-change materials[277]. Examples of materials used as PCM include: ternary molten salts, e.g. potassium perchlorate ($KClO_4$)with a phase transition temperature of 527 ° C. Currently, there are several hundred chemical compounds that can be used as phase-change materials, including as inorganic salt hydrates and salts, and organic such as paraffins, fatty acids, eutectics and other mixtures. For heliostat applications, eutectic materials with a relatively low phase transition temperatureare best e.g. two-component carbonate mixtures (43% Li_2CO_3 + 57% Na_2CO_3, melting temperature 500°C), three-component carbonate mixtures (32.1% Li_2CO_3 + 33.4% Na_2CO_3 + 34.5% K_2CO_3, phase change temperature 401°C)[280]. Another example is inorganic lithium fluoride (LiF), whose phase transition temperature is 850°C.

[279] J.J. Burkhardt, G.A. Heath, C.S. Turch, Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives, *Environmental Science & Technology*, 45, 2011, 2457–2464.

[280] L.F. Cabeza et al. Lithium in thermal energy storage: A state-of-the-art review, *Renewable and Sustainable Energy Reviews*, 42, 2015, 1106–1112.

12.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

Phase-change materials are a very uneven group of functional materials that differ in heat capacity and phase change temperature. Main technological barrier related to the implementation of new solutions concerns the development of the phase-change material itself, whose parameters will be optimally adapted to the specific application.

The phase transition temperature and the accompanying thermal effect are characteristic parameters for a given material. However, they can be modified to a limited extent by changing the composition of materials and creating their mixtures, just like the addition of table salt to water reduces its freezing point and raises the boiling point. However, developing a stable material with specific parameters requires a considerable amount of work, which is a limiting stage for the introduction of new technology.

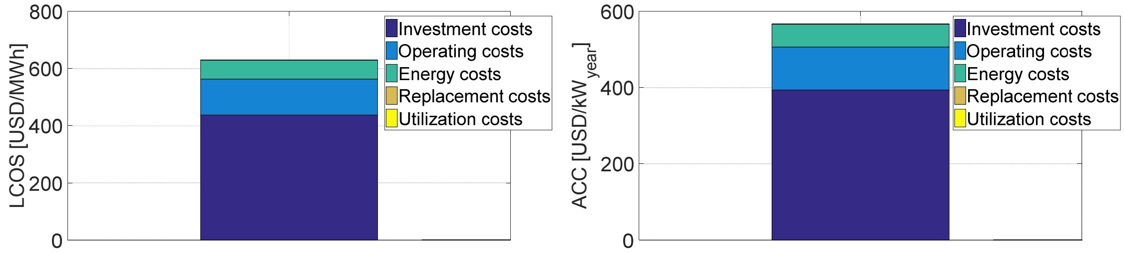
Problems associated with the production scalability of variable phase materials do not differ from the problems characteristic of large-scale production of other materials in the chemical, textile or construction industries.

12.5. PCM/MS ENERGY STORAGE COSTS

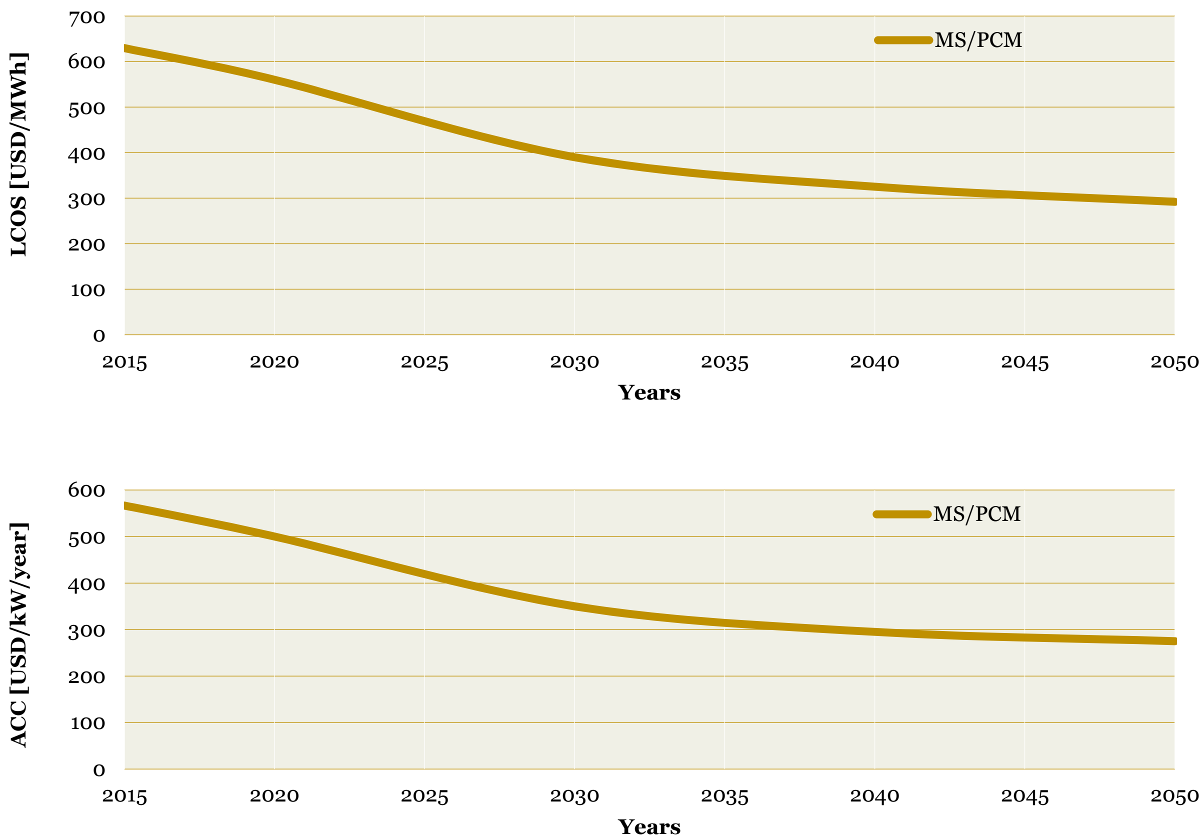
The average cost of PCM materials is 6 EUR/kg[273]. To obtain a temperature difference of up to 6–8°C, about 10 kg of PCM material per 1 m^2 of a standard room has to be used (for PCM material in the form of microcapsules, the latent heat capacity is 110 kJ/kg[281], 30 kg of PCM material corresponds to about 1 kWh which is 216 USD/kWh (180 EUR/kWh at the EUR/USD exchange rate = 1.2).

Figure 40a presents the LCOS for PCM/MS with cost breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. Figure 40b shows LCOS in the 2015-2050 perspective (its value does not exceed USD 630/MWh for a PCM system operating in „heat arbitration" application). In case of ACC cost, it does not exceed 570 USD/kW per year. In the 2050 perspective, a drop of more than 45% in LCOS below 300 USD/MWh can be observed, and over 45% drop in ACC below 280 USD/kW per year.

[281] Micronal PCM, https://www.maisonpassive.be/IMG/pdf/Micronal_EN.pdf [accessed: 07.08.2019].



(a)



(b)

Fig. 40. a) LCOS & ACC of a UC storage broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective

12.6. MAIN APPLICATIONS OF PCM / MS

Construction – phase-change materials are used as construction materials in form of panels or additives for concrete or cement. The task of phase-change materials is to increase the building's insulation parameters and to mitigate thermal effects associated with daily weather cycles by absorbing some of the heat during the day high sunlight and emitting heat at night. Use of phase-change materials makes allows for reduction of temperature amplitude inside the building by 6–8°C without additional energy expenditure related to the use of air conditioning and heating systems. In recent years, an increase in use of phase-change materials in construction has been observed, for example in the construction of office buildings and the so-called passive buildings.

Transport – Phase-change materials are used for production of thermal inserts that stabilize the temperature inside containers used for transport of substances sensitive to temperature changes. Cooling cartridges are used to transport substances such as food, chemicals, medicines, etc., preventing rapid heating of transported products. In turn, heating cartridges are used to transport freshly prepared meals such as pizza. Inserts from phase-change materials are able to maintain a constant temperature even up to several hours.

Industry and electronics – phase-change materials are used to construct enclosures that ensure system temperature stabilization in the event of unforeseen events, such as apparatus overheating or an unexpected exothermic process. Housing containing the phase change material is able to absorb some of the heat generated and minimize possible losses.

Tourism and sport – phase-change materials are used as filling for small thermal inserts for local heating of the human body. The process of crystallizing supercooled phase change materials, for example sodium acetate, is used here. After initiating the crystallization process, the insert spontaneously warms to 65° C using the heat of crystallization and maintains it until the process is completed.

Each application requires a material with an appropriate phase transition temperature, which can be controlled by appropriate design of the PCM material composition.

- Phase transition temperature range from -20°C to 5°C: domestic refrigerators[282] and commercial refrigeration products, incl. industrial cold stores [283],
- Phase transition temperature range from 5° C to 40°C: in free-cooling systems [284] (installations producing chilled water), in buildings with passive heating and cooling, in air-conditioning systems, in solar absorption coolers (very often used, among others, in: Africa and the Middle East to increase the efficiency of photovoltaic modules by lowering the module temperature from 20°C[285] to over 30°C[286] (- very high temperature above 50°C has negative impact on energy yield and efficiency of solar panels[285]), air conditioning systems, evaporative and radiation cooling[287] (including: solar panels),
- Phase transition temperature approx. 18°C: body cooling (textiles)[288], among others: nextek18d,
- Phase transition temperature approx. 28°C: building materials, improvement of energy efficiency of residential buildings, improvement of human thermal comfort – mattresses, pillows, interior (passenger space) cooling in electric vehicles,
- Phase transition temperature in range from 40°C to 80°C: solar air heaters[289], hot utility water from solar collectors (tanks lined with PCM materials)[290], for cooling electrical / electronic equipment, passive cooling systems in battery packs for electric vehicles [291],[292],

[282] R. Elarem, S. Mellouli, E. Abhilash, A. Jemni, Performance analysis of a household refrigerator integrating a PCM heat exchanger, *Applied Thermal Engineering*, 125, 2017, 1320–1333.

[283] S. Rosiek, M.S. Romero-Cano, A.M. Puertas, F.J. Batlles, Industrial food chamber cooling and power system integrated with renewable energy as an example of power grid sustainability improvement, *Renewable Energy*, 138, 2019, 697–708.

[284] Thermix Service, http://www.thermix.pl/klimatyzacja-precyzyjna/free-cooling-lodz-thermix-service [accessed: 08.08.2019].

[285] S.A. Nadaa, D.H. El-Nagar, H.M.S. Hussein, Improving the thermal regulation and efficiency enhancement of PCMIntegrated PV modules using nano particles, *Energy Conversion and Management*, 166, 2018, 735–743.

[286] R. Stropnik, U. Stritih, Increasing the efficiency of PV panel with the use of PCM, *Renewable Energy*, 97, 2016, 671–679.

[287] D. Satoa, N. Yamada, Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method, *Renewable and Sustainable Energy Reviews*, 104, 2019, 151–166.

[288] Microtek, https://cdn2.hubspot.net/hubfs/4153344/Microtek%20Laboratories%20December2017/PDF/MPDS3300-0050%20Product%20Data%20Sheet%20-%20nextek18D%20Rev%200.pdf?__hstc=144617194.0dc4234c2bbf4e99b51667c448163bd8.1565546280443.1565546280443.1565771364318.2&__hssc=144617194.10.1565771364318&t=1530493736469&submissionGuid=5d333077-3742-4d37-8dd0-d264d7124f9b [accessed: 08.08.2019].

[289] M. Abuşkaa, S. Şevikb, A. Kayapunar, A comparative investigation of the effect of honeycomb core on the latent heat storage with PCM in solar air heater, *Applied Thermal Engineering*, 148, 2019, 684–693.

- Phase transition temperature range from 80°C to 200°C: solar absorption cooling systems[293], increasing the efficiency of energy recovery systems, among others: ORC (limitation of operation in low efficiency ranges [294]),

12.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR PCM / MS

Advantages of the technology[295]:

- Construction[296] – passive technology that does not require additional work and energy expenditure during use, including: offices, housing, passive houses, data centers and server rooms, cooperation with heat pumps (improvement of heat balance),
- For paraffins: non-corrosive, non-toxic, commercially available on a large scale, easily scalable, low costs from 4 USD/kg – on a large scale, high melting heat up to 259 kJ/kg, low thermal conductivity ~ 0.25 W/mK, chemically inert to 5000C, no intensive cooling,
- Salt hydrates: high melting heat, up to 296 kJ/kg, low cost from USD 0.17/kg,
- Organic PCM – fatty acids: High melting heat – up to 259 kJ/kg, no intensive cooling, applicability in a wide melting range from 7.8°C to 127.2°C, low thermal conductivity, transition from solid to solid phase.
- Low melting metals: non-flammable, high boiling point (above 2000°C), small volume increase with phase change.

Disadvantages of the technology:

- Paraffins[297]: flammable, cannot be used with plastic containers, lower flash point (108–170°C) in the phase change / melting range at 6–37°C,
- For salt hydrates: there is intensive cooling, corrosive to metals, toxic, higher thermal conductivity than paraffin 0.4-0.7 W/mK (higher thermal conductivity in a warmer climate),
- Organic PCM – fatty acids: flammable, some toxic, produce harmful fumes when burned.
- Low melting metals: high cost, supercooling effect, high thermal and electrical conductivity, can corrode when used with building materials.

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[290] J. Denga, S. Furbo, W. Kong, J. Fan, Thermal performance assessment and improvement of a solar domestic hot water tank with PCM in the mantle, *Energy & Buildings*, 172, 2018, 10–21.

[291] K.S. Kshetrimayum, Young-Gak Y., Hye-Ri G., Chul-Jin L., Preventing heat propagation and thermal runaway in electric vehicle battery modules using integrated PCM and micro-channel plate cooling system, *Applied Thermal Engineering*, 159, 2019, 113797.

[292] R. Koyama, Y. Arai, Y. Yamauchi, S. Takeya, F. Endo, A. Hotta, R. Ohmura, Thermophysical properties of trimethylolethane (TME) hydrate as phase change material for cooling lithium-ion battery in electric vehicle, *Journal of Power Sources*, 427, 2019, 70–76.

[293] A. Aliane, S. Abboudi, C. Seladji, B. Guendouz, An illustrated review on solar absorption cooling experimental studies, *Renewable and Sustainable Energy Reviews*, 65, 2016, 443–458.

[294] F. Dal Magro, M. Jimenez-Arreola, A. Romagnoli, Improving energy recovery efficiency by retrofitting a PCM-based technology to an ORC system operating under thermal power fluctuations, *Applied Energy*, 208, 2017, 972–985.

[295] K. Du, J. Calautit, Z. Wang, Y. Wu, H. Liu, A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges, *Applied Energy*, 220, 2018, 242–273.

[296] PCM Technology, http://www.pcmtechnology.eu/applications/_385____GB [accessed: 08.08.2019].

[297] A. Hassan, M. Shakeel Laghari, Y. Rashid, Micro-Encapsulated Phase Change Materials: A Review of Encapsulation, *Safety and Thermal Characteristics, Sustainability*, 8, 2016, 1046; doi:10.3390/su8101046.

Phase-change **materials / molten salts (PCM / MS) are recommended** for use in construction (daily energy storage), to support systems with renewable energy sources (improving efficiency of photovoltaic cells that operate at high temperatures), to improve efficiency of cogeneration systems based on i.e. ORC, in transport (cooling of battery packs in electric vehicles), for interior cooling / heating in electric vehicles (heat pump operation support). High development potential in Poland.

Potential stakeholders include: construction (developers), road industry (caravan manufacturers), container buildings, electric vehicles (maintaining thermal comfort of electrochemical cells). Poland has the appropriate technical facilities and R&D to develop this type of solution.

13. HEAT STORAGE (low-medium-high temperature) AND COLD STORAGE (TES)

Technical characteristics of systems based on **TES**

Technology	Energy density per unit of volume [Wh/L]	Power range [MW]	Time of permament energy storage*	Life time [years]	Discharge time*	Number of cycles [cycles]	Efficiency [%]	Technology maturity /Technological readiness level (TRL)[55]
TES (Thermal energy storage)	10-50	0.1-300	Min.-D.	5-30	1-24h+	-	50-90	Commercialized /implemented – NA

* mSec – mili second, s – second, min. – minute, h – hour, d – days, mo. – months

Costs of **TES** based systems

System	Capital costs to power [USD/kW]	Capital cost to energy [USD/kWh]	Operation & Maintenance costs (O&M)
TES	100-400	3-130*	120 USD/kW/year (total constant and various costs calculated to contant costs)

* depending on the technology used – technologies using natural geological conditions are much cheaper than in the case of artificial reservoirs

13.1. INTRODUCTION

The most common heat stores (*Thermal Energy Storage, TES*) are water tanks, which are part of domestic hot water and central heating installations. These installations are most often heated using boilers powered by natural gas, heating oil or wood / coal. In recent years, an increasingly common solution is also the use of solar collectors to power this type of installation.

Another, quite widespread, distributed heat storage method is the use of electric storage stoves. This method, unfortunately, uses electricity to generate heat, which is not justified from a thermodynamic point of view, but can be economically justified (in case of using cheaper electricity produced outside peak hours, or by using photovoltaics).

Most large, water-based TES warehouses use the phenomenon of thermal stratification for their operation. This phenomenon hinders the mixing of hot and cold water. Between the cold and hot water area there a so-called thermocline (mixing zone) occurs. The thinner the thermocline area is, the better the TES storage works. To prevent hot and cold water from mixing, the tank must be high enough, and the storage charging and discharging process cannot be too fast. The operating principle of such a storage is shown in Figure 41.

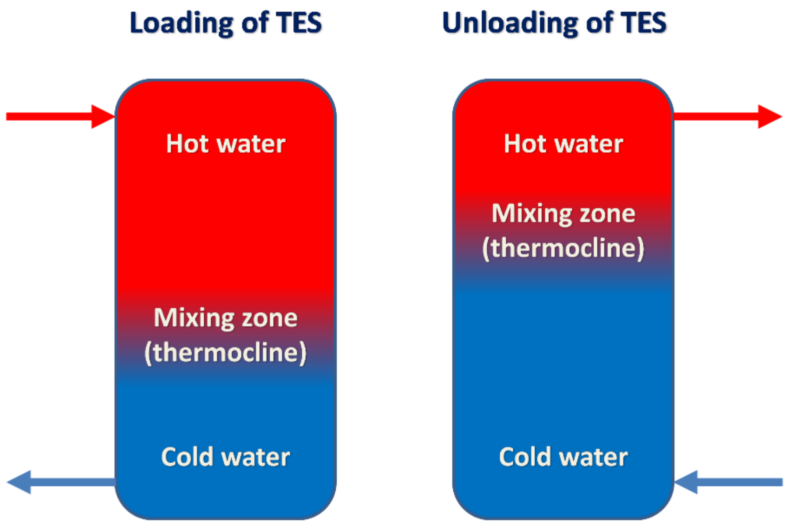

Fig. 41. Principle of operation of the TES magazine – own study.

Depending on the size of the TES storage, as well as the geological structure of the area, we can distinguish four basic types of heat storage[298]:

TTES (Tank Thermal Energy Storage)

Tanks made of steel, compressed concrete or GRP composites (glass fiber reinforced plastics) are used in many cogeneration plants as short-term energy storage. The tanks can be used to store water under pressure, which allows the maximum temperature of the stored medium to be increased. Standard tanks of this type are designed for storage up to 5000 m^3. The maximum storage temperature is between 95°C (atmospheric pressure) and 108°C (increased pressure – 3 bar).

PTES (Pit Thermal Energy Storage

This storage is built the same way as TTES, but with use of a pit, which acts as the bottom surface and walls. The walls are covered with a suitable liner made of, for example, durable polyethylene films. The most commonly used heat storage medium is water.

The most expensive and the most problematic element of the warehouse structure is the floating cover. Appropriate construction, including insulation and a layer protecting against UV radiation and precipitation, is crucial to minimize both construction costs and heat loss.

The cost of building PTES is around 1/4 of TTES cost. The maximum temperature of the heat storage medium is between 80 and 90°C.

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[298] K. Kubinski, Ł. Szablowski, Dynamic model of solar heating plant with seasonal thermal energy storage, *Renewable Energy*, 145, 2020, 2025–2033, https://doi.org/10.1016/j.renene.2019.07.120.

Borehole Thermal Energy Storage

This warehouse does not use a tank filled with a storage medium, but is based on geological formations heated by the flowing working medium. This type of storage has thermal insulation only on top. Insulation of the sides and bottom of the magazine is not feasible. The maximum storage temperature is 90°C.

ATES (Aquifer Thermal Energy Storage)

In case of aquifers closed from above and below by a layer of impermeable rock, in which natural water flows are negligible, it is possible to store energy using at least two wells (similar to geothermal sources), taking into account the possibility of reverse circulation.

The efficiency of TES warehouses using water ranges from 50 to 90%[30].

In turn, the most common way of short-term heat storage in heating networks is to use the accumulative capacity of the heating network itself (storage in the plant)[29]. This solution is very beneficial since it does not require additional investment costs.

In contrast to heat storage described above (using explicit heat – water heating), cold storage usually uses latent heat (phase transformation)[299].

Among the commercially available cold stores, we can distinguish[300]:

- Chilled water tanks – a tank with atmospheric pressure on top for storing chilled water. This technology has the capacity to store 10 kWh of cold for every m^3. The restrictions of this reservoir are soil surface and weight. These tanks use the effect of water temperature stratification.
- Ice on coils – tank filled with water with atmospheric pressure at the top. Tubes in which a mixture of water and glycol (acting as an intermediate medium exchanging heat with water / ice) are immersed in this tank. Storage takes place via freezing of water filling the tank. The energy storage density is 50 kWh /m^3 and the maximum energy stored in a single tank – 5 MWh.
- „Ice Ball" – a pressure tank filled with polymeric coated balls containing water. Inside this tank, a mixture of water and glycol flows as an intermediate medium exchanging heat with water / ice enclosed in polymer spheres. Storage takes place due to water freezing inside the polymer spheres. The energy storage density is 50 kWh /m^3 and the maximum energy stored in a single tank is 5000 kWh. The tank is mounted horizontally and its maximum volume is 100 m^3. Maximum tank diameter – 3 m.
- „Ice Spray" – atmospheric tank, filled with polymeric coated balls filled with water. Storage takes place due to water freezing inside the polymer spheres. The cold is supplied or taken from the spheres by a mixture of water and glycol injected at the top of the tank and collected at its bottom. The energy storage density is 50 kWh /m^3.

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[299] Koohi-Fayegh S., Rosen M.A.. Optimization of seasonal storage for community-level energy systems: status and needs, *Energy, Ecology and Environment*, 2(3), 2017, 169-181.

[300] CRYOGEL, Cold storage technologies, http://www.airclima-research.com/cold-storage-technologies [accessed: 31.07.2019].

13.2. TES DEVELOPMENT PERSPECTIVE AND ENVIRONMENTAL IMPACT

Heat storage is a well-known and well-developed technology that finds application wherever the time of heat production does not match its demand. In the case of heating networks, the central location of the generating source is an additional limitation, which contributes to the loss of transmission. Distributed heat storage could remedy that[301].

An important aspect when considering the possibility of using seasonal heat storage is the storage temperature and network operating temperature. In case of a direct connection, the return temperature is also the minimum storage temperature and at the same time the storage discharge limit. Due to the relatively high temperatures at the entrance and return from the heating network, many currently built seasonal storages have a heat pump-based discharge system, which allows for reduction of the temperature in the store to 10°C[298].

Use of heat and cold storage systems leads to a reduction of CO_2 emissions in many different applications:

a) heat storage systems

- in cooperation with combined heat and power plants enables for production of electricity with reduced heat demand (the greatest demand for heat is at night, while the highest demand for electricity – during the day). In the case of extensive heating systems, the time difference between heat demand by the customer and the supply of heat at the generating source, which significantly complicates the situation presented above[301]. This makes better use of systems producing electric energy in combination with heat possible – which is much more effective than generating electricity and heat separately.
- in cooperation with solar heating plants – zero CO_2 emissions for solar energy.
- distributed installations located at the prosumer – reduction of CO2 emissions due to better use of generation sources (renewable or non-renewable).

b) cold storage systems are used in, among others:

- hotels – allows for use of lower power cooling systems, working closer to its rated efficiency.
- public buildings – allows for use of lower power cooling systems, working closer to its rated efficiency.
- office buildings – allows for use of lower power cooling systems, working closer to its rated efficiency.
- shopping centers – allows for use of lower power cooling systems, working closer to its rated efficiency.
- warehouses requiring storage at low temperature – allows the use of less powerful cooling systems, working closer to its rated efficiency.
- living quarters – TES micro installations could allow the use of a lower power cooling system working closer to its rated efficiency.

13.3. RESOURCE RESTRICTIONS

For the construction of TES systems, no sophisticated and rare raw materials are used.

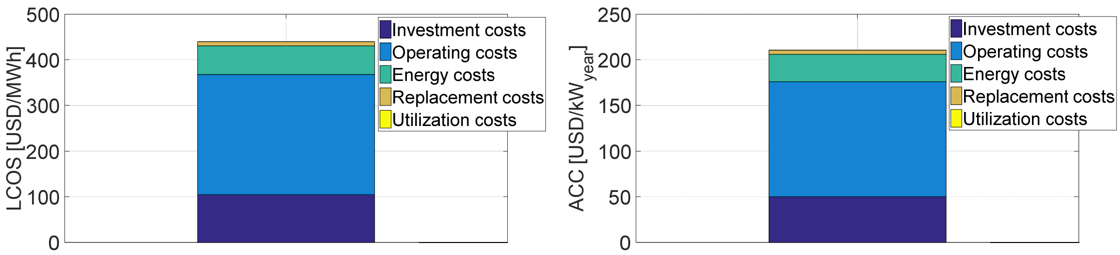
[301] M. Kwestarz, Heat thermal storage, *Nowoczesne Cieplownictwo*, 30.03.2019, [In Polish] www.nowoczesnecieplownictwo.pl/magazynowanie-ciepla-w-zasobnikach/ [accessed: 19.09.2019].

13.4. TECHNOLOGICAL BARRIERS AND SCALABILITY

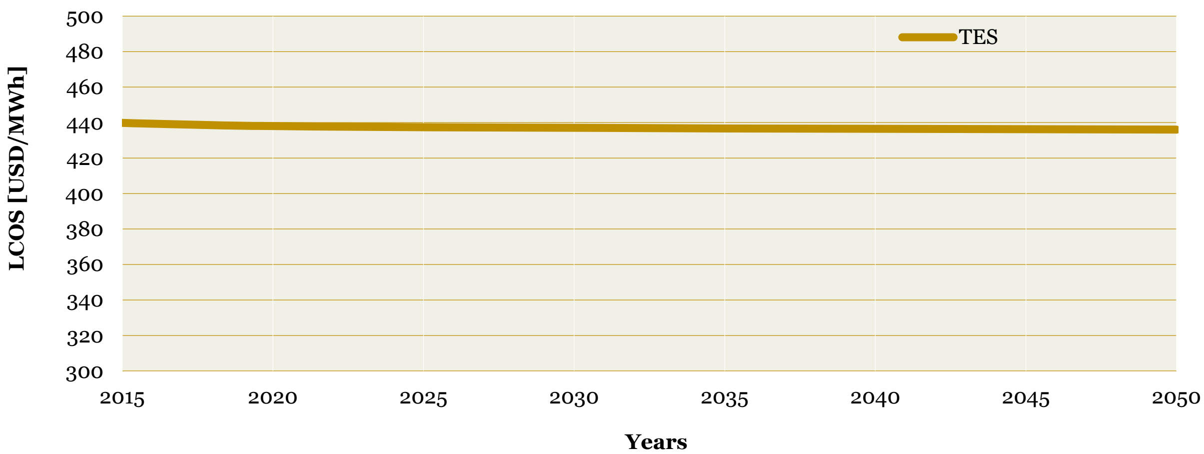
Despite the significant differences in costs of storage construction using the technologies described above, it is not possible to clearly indicate the optimal solution. Depending on the location and size of the installation, storage temperature and system structure, it is necessary to evaluate each project individually. For geological reasons, in many cases only TTES or PTES can be used[298].

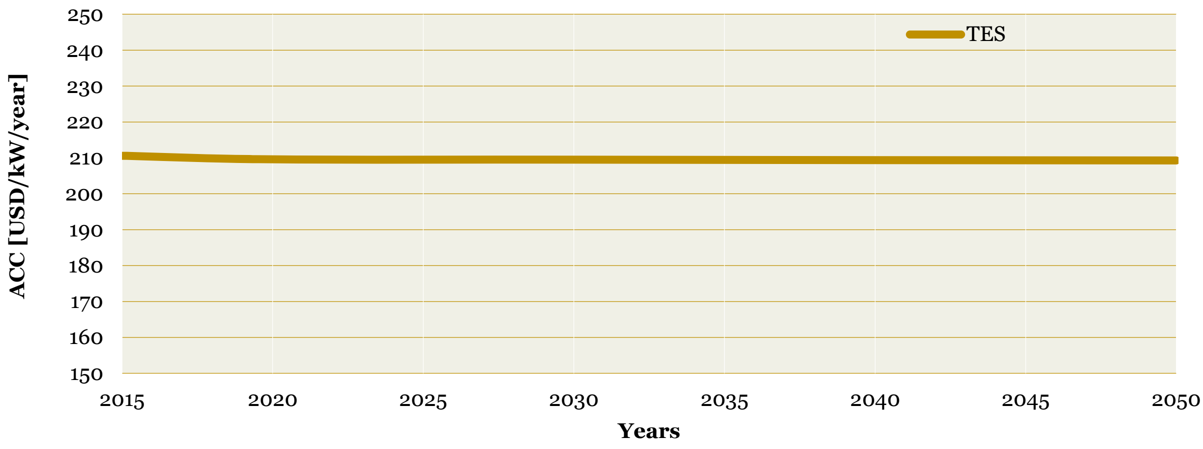
13.5. TES ENERGY STORAGE COSTS

The investment costs for heat storage are between 100-400 USD per kW installed capacity and between 3 and 130 USD per kWh storage capacity[47]. Investment costs were adopted at the level of 250 USD/kW, 68 USD/kWh, fixed FOM costs were adopted at the level of 120 USD/kW (VOM costs were also included in this amount), 70% efficiency for 100MW installations, lifetime 30 years. In Fig. Figure 42a presents the LCOS for TES systems with costs breakdown, including: investment, O&M (operation and maintenance), electricity, repairs and decommission. In Fig. 42b presents LCOS in the 2015-2050 perspective (its value does not exceed USD 450/MWh for TES used for heat arbitration application). In the 2050 perspective, the LCOS value is practically constant, due to the fact that the technique is already mature, change in LCOS depends mainly on changes in prices of raw materials and materials on the markets, including: steel. Also, the ACC value does not exceed 210 USD/kW per year in the 2050 perspective.



(a)





(b)

Fig. 42. a) LCOS & ACC for TES broken down into costs, b) change of LCOS & ACC in the 2015-2050 perspective for TES

13.6. MAIN APPLICATIONS OF TES

Heat storage systems are most often used near conventional cogeneration plants, enabling for production of electricity with reduced heat demand (the greatest demand for heat is at night, while the highest demand for electricity – during the day). In the case of extensive heating systems, the time difference between heat demand by the customer and the supply of heat at the generating source, which significantly complicates the situation presented above[301]. The solution to improve the described situation can be the use of additional distributed TES systems[301].

These systems are also used in connection with solar heating plants, e.g. the system in Vojens (Denmark), Graz (Austria), Drake Landing Solar Community (Okotoks, Canada) and many other smaller systems (e.g. in Ząbki near Warsaw).

In turn, cold storage systems can be used in case of hotels, public buildings, office buildings, shopping centers, and warehouses requiring storage at low temperatures.

13.7. CONCLUSIONS: ADVANTAGES, DISADVANTAGES AND RECOMMENDATIONS FOR TES

Advantages of the technology:

- Allows the use of a heating / cooling system with lower power, working closer to its rated efficiency, which leads to a reduction in energy consumption, and thus – to a reduction in CO_2 emissions (in case of heating / cooling devices powered by non-renewable energy).
- Heat stores working in cooperation with conventional heat & power plants allow for production of electricity with reduced heat demand, which results in better use of cogeneration sources of electricity and heat. This results in lower CO_2 emissions compared to systems that generate electricity and heat separately.
- Heat storage systems can cooperate with solar power plants, allowing for better use of solar (zero-emission) energy.

Disadvantages of the technology:

- In case of warehouses using explicit heat of the medium (increase or decrease in the temperature of the storage medium), a large volume is required (low energy density) compared to heat or cold stores using latent heat (phase change heat solid – liquid).
- Some cold stores use glycol as an intermediate medium, which can be harmful to the environment if it leaks.

Recommendations for TES are primarily for heat storage near conventional heat & power plants, enabling production of electricity with reduced heat demand, combined with solar heat plants (seasonal and daily storage). In the case of cold storage, the main facilities where the technology is used are: hotels, public buildings, office buildings, shopping centers, warehouses for goods requiring storage at low temperatures. In order to activate the prosumers it seems necessary to use distributed TES systems. Thanks to this, they can fully use the potential of their generation sources (renewable or non-renewable). High development potential in Poland – distributed heat storage.

Potential stakeholders include: Combined heat and power plants. Poland has the appropriate technical facilities and R&D to develop this type of solution.

SUMMARY

This report presents 12 forward-looking energy storage techniques, of which 10 described techniques (including: PHS, CAES, LAES, FES, PtG, H_2, BES (PbA, Li-ion, NaS), VRFB, SMES, UC refers to storage of easily convertible electric energy, while PCM and TES techniques relate to heat storage. Table 23 presents a summary description of possible applications of electricity and heat storage technologies and their usefulness in given energy and heat market segments.

Table 23. Summary description of the applications of electricity and heat storage technologies and their usefulness in given energy and heat market segments

Role	Application	Description	PHS	CAES	LAES	FES	Li-ion	PbA	NaS	VRFB	H_2	SMES	UC	PCM	MS	TES
Operation of the energy grid	1. Energy arbitrage	Buying energy at a low price and selling at a high price on the wholesale or retail market	+	+	+		+	+	+	+	+					
	2. Primary response	Ensuring network stability with sudden changes in frequency and voltage				+	+	+	+	+	+	+	+			
	3. Secondary response	Ensuring predictability for unexpected differences between system load and power generation	+	+	+	+	+	+	+	+	+	+	+			
	4. Tertiary response	Replacement of primary and secondary reaction with prolonged system overload	+	+	+		+	+	+	+	+					
	5. Peak shift	Ensuring adequate generation capacity during peak power demand periods	+	+	+		+	+	+	+	+					
	6. Cold start	Quick power plant recovery after network overload without additional external power supply	+	+	+	+	+	+	+	+	+	+	+			
	7. Seasonal storage	Balancing the variability of seasonal electricity supply resulting from energy demand and supply	+	+	+					+	+					

Role	Application	Description	PHS	CAES	LAES	FES	Li-ion	PbA	NaS	VRFB	H_2	SMES	UC	PCM	MS	TES
Grid exploitation	8. Postponement of investment in transmission and distribution network	Postponement of network infrastructure modernization – improvements due to increased efficiency of energy supply at the peak of power demand	+	+	+		+	+	+	+	+					
	9. Restrictions management	Limiting the risks associated with overloading the power grid	+	+	+		+	+	+	+	+					
Consumption	10. Account Management	Optimization of energy purchase by maximizing the use of energy from renewable energy sources (e.g. PV) for own needs and reducing energy bills					+	+	+	+	+					
	11. Power quality	Protection of consumers against short-term power loss, change of supply voltage or frequency				+	+	+	+	+	+	+	+			
	12. Power reliability	Energy supply during temporary interruptions in energy supply (e.g. blackouts)					+	+	+	+	+					
Heat system operation	13. Heat arbitrage	Purchase of electricity for heat production at a low price and sale of heat at a high price on the wholesale or retail market												+	+	+
	14.Seasonal heat storage	Balancing the variability of seasonal electricity supplies that are used to produce heat resulting from heat demand and supply														+

Figure 43 shows the carbon footprint determined by GWI factor[302] (*Global Warming Impact*) for selected energy storage techniques, among others: Li-ion, CAES, H_2, VRFB, SNG, PbA and NaS. It should be emphasized that the most promising energy storage techniques, Li-ion cells, have the lowest GWI index of 11kg CO_2 eq./MWh.

[302] C. Mostert, B. Ostrander, S. Bringezu, T. M. Kneiske, Comparing Electrical Energy Storage Technologies Regarding Their Material and Carbon Footprint, *Energies*, 11, 2018, 3386, doi:10.3390/en11123386.

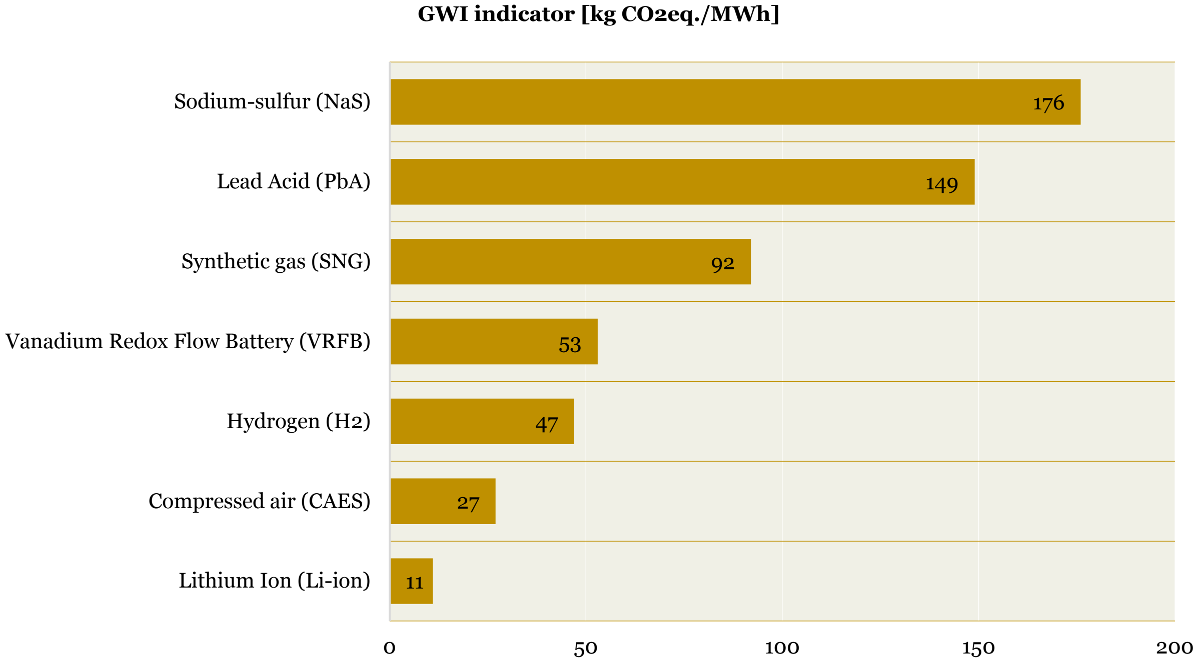
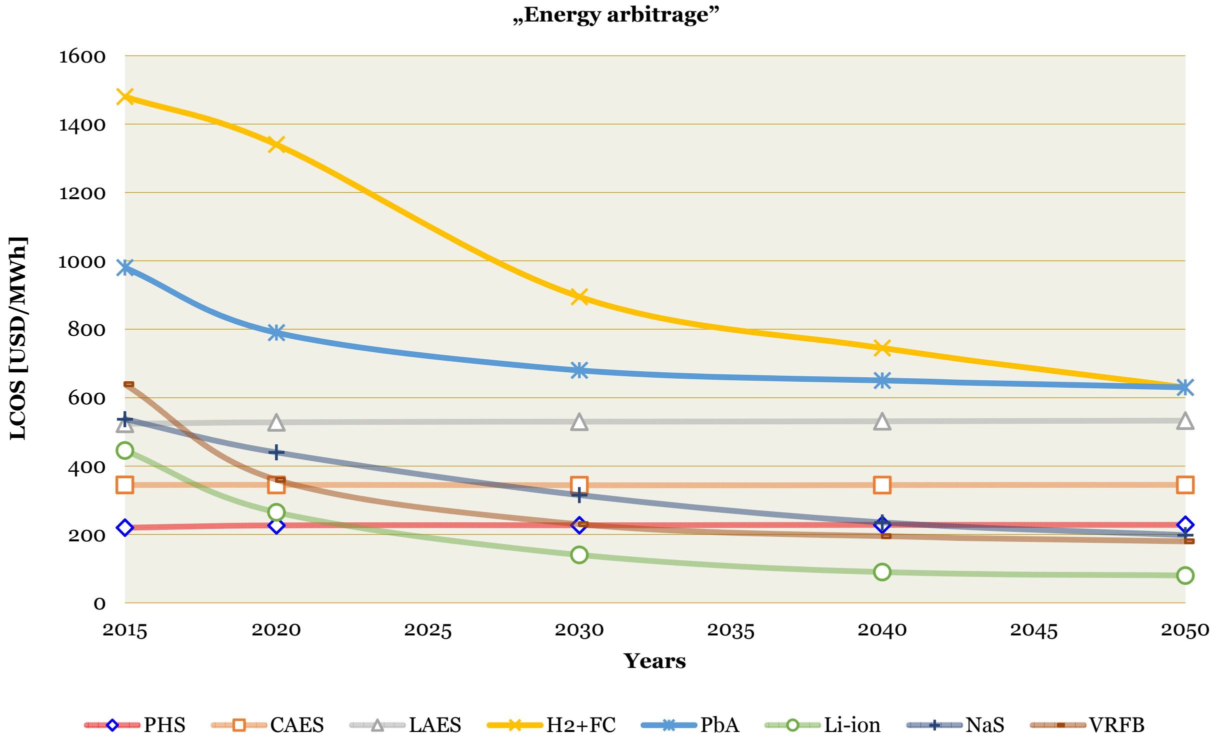
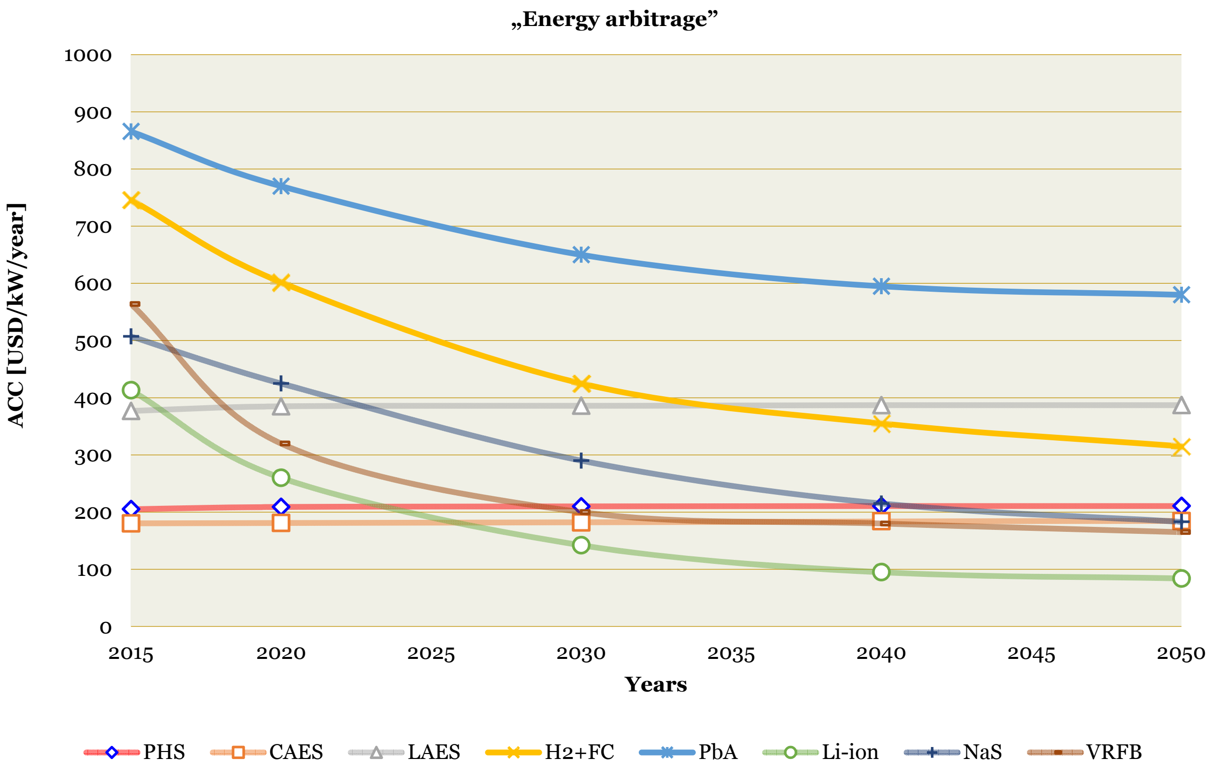


Fig. 43. Carbon footprint determined by the GWI indicator[302].

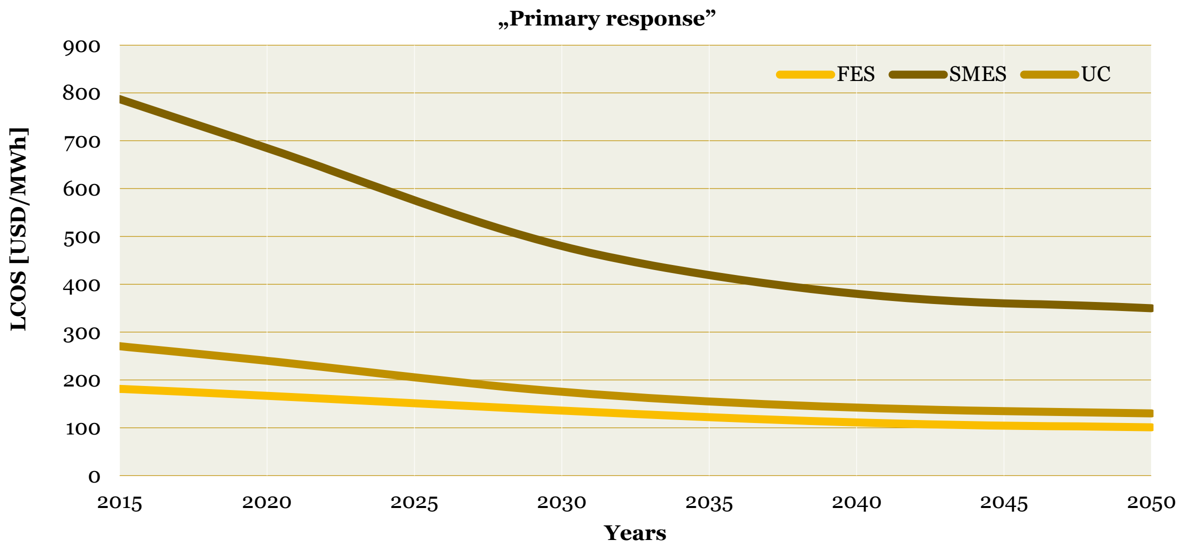
Figure 44 presents collective energy storage cost projection charts (LCOS – Fig. 44a, c, e) and annual energy storage costs (ACC – Fig. 44b, d, f) in perspective from 2020 to 2050. Particularly noteworthy is the estimated decrease in costs for Li-ion batteries (in perspective of 2050 LCOS below 95 USD/MWh and ACC below 90 USD/kW-annually). In addition to PHS, LAES, CAES and TES techniques, a decrease in energy storage costs of other techniques is also forecast in perspective of 2050. Figure 44c shows the discounted costs of energy storage for LCOS, while Figure 44d shows the discounted costs of power in primary response application for FES, UC and SMES. In the 2050 perspective, UC and FES will be competitive on the market (cost reduction by over 50%), however SMES technology is predicted to remain too expensive to be implemented on the market. Figure 44e presents the discounted costs of energy storage LCOS, while Figure 44f shows the discounted power costs in heat arbitration application for PCM / MF and TES. In the case of TES technology, it is competitive on the market and used. No decrease in value of costs is expected in 2050. Considering PCM / MF, in the 2050 perspective, a decrease in LCOS and ACC by over 50% is visible. PCM / MF technology will become market competitive in the 2050 perspective.


„Energy arbitrage”
LCOS [USD/MWh]
1600
1400
1200
1000
800
600
400
200
0
2015
2020
2025
2030
2035
2040
2045
2050
Years
PHS
CAES
LAES
H2+FC
PbA
Li-ion
NaS
VRFB

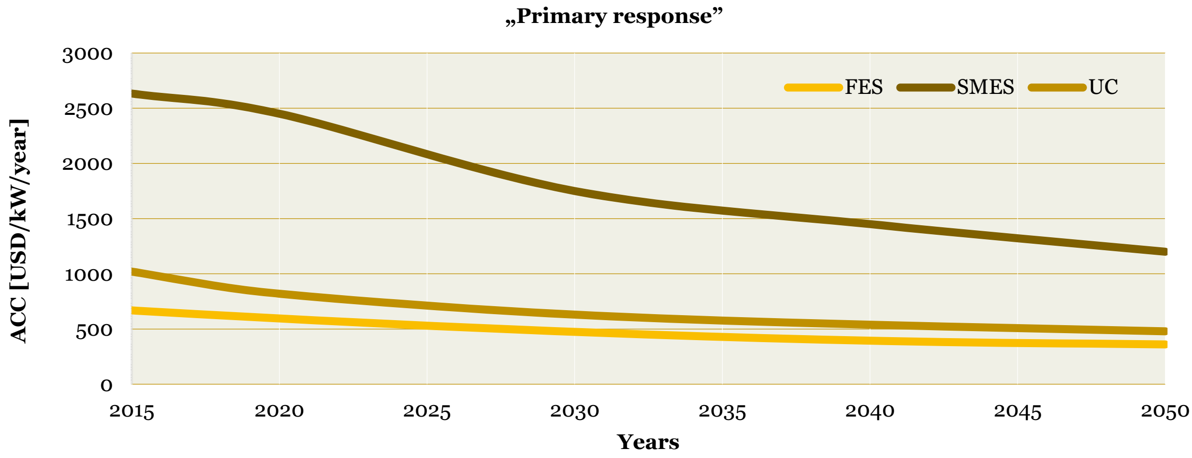
(a)


„Energy arbitrage”
ACC [USD/kW/year]
1000
900
800
700
600
500
400
300
200
100
0
2015
2020
2025
2030
2035
2040
2045
2050
Years
PHS
CAES
LAES
H2+FC
PbA
Li-ion
NaS
VRFB

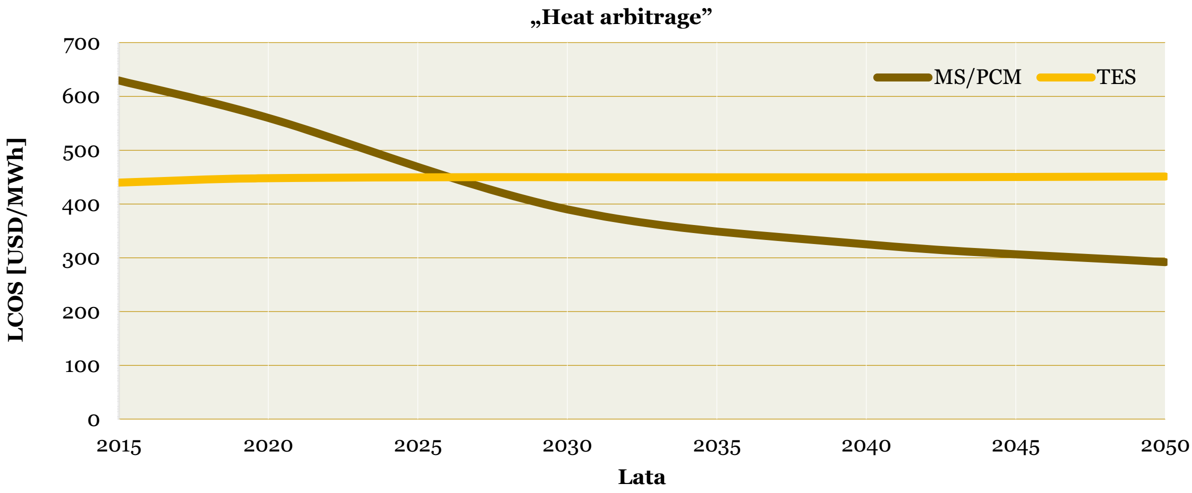
(b)


„Primary response”
FES
SMES
UC
LCOS [USD/MWh]
900
800
700
600
500
400
300
200
100
0
2015
2020
2025
2030
2035
2040
2045
2050
Years

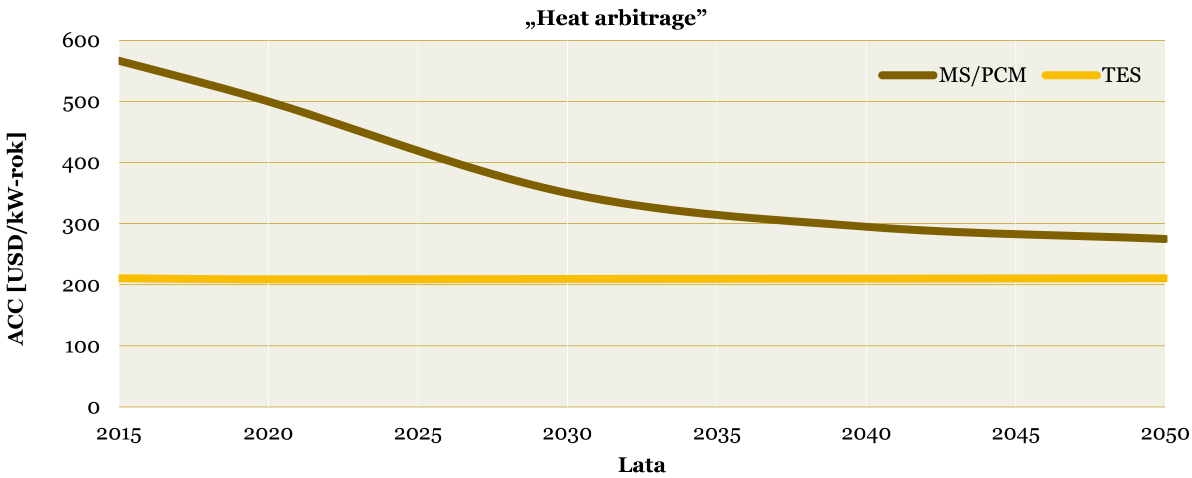
(c)


„Primary response”
FES
SMES
UC
ACC [USD/kW/year]
3000
2500
2000
1500
1000
500
0
2015
2020
2025
2030
2035
2040
2045
2050
Years

(d)


„Heat arbitrage”
MS/PCM
TES
LCOS [USD/MWh]
700
600
500
400
300
200
100
0
2015
2020
2025
2030
2035
2040
2045
2050
Lata

(e)



(f)

Fig. 44. Summary charts a) LCOS – for the analyzed techniques in *energy arbitration* application, b) ACC – for the analyzed techniques in *energy arbitration* application, c) LCOS – for the analyzed techniques in *primary response* application, d) ACC – for the analyzed techniques in *primary response* application, e) LCOS – for the analyzed techniques in *heat arbitration* application, f) ACC – for the analyzed techniques in *heat arbitration* application

BASED ON THIS STUDY, IT IS RECOMMENDED:

- **Pumped storage plants (PHS)** for medium-term, long-term and seasonal energy storage applications, in order to make the power grid more flexible. This technology is already mature and widely used in the world. High potential for underwater development of PHS (StEnSea) in Poland, in the Baltic Sea. **Potential stakeholders** include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solution.
- **Compressed air energy storage (CAES):** for medium and long-term energy storage purposes, to make the power grid more flexible (similar to PHS). High development potential in northern Poland due to presence of significant amount of saltdumps[90]. **Potential stakeholders** include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solution.
- **Liquid air energy storage facilities (LAES):** for medium and long-term energy storage, in order to make the power grid more flexible. Seasonal storage is not recommended here due to relatively high investment costs for LAES system. Expensive solution, currently in research phase. **Potential stakeholders** include: Polish Power Systems (Polskie Sieci Elektroenergetyczne – PSE), Distribution Network Operators (Operatorzy Sieci Dystrybucyjnych – OSD) and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solution.
- **Inertial storage (FES):** for applications in hybrid systems, among others: with fuel cells, electrochemical cells (i.e. Li-ion), flow cells, ultracapacitors, small CAES and low-temperature micro-cogeneration systems. FES systems have also found application in KERS / ERS (*Kinetic*

Energy Recovery System / Energy Recovery System) in: Formula 1 cars, hybrid vehicle propulsion systems, electric vehicle propulsion systems. FES systems can be used for storing energy from renewable sources, particularly wind farms. It should also be noted that currently there are no legal regulations in Poland regarding the use of FES with renewable energy sources, especially in mass-scale prosumer applications, this area requires legal regulations. High development potential in Poland – support for the development of operational infrastructure for hybrid and electric vehicles. **Potential stakeholders** include: prosumers, road transport, construction. Poland has the appropriate technical facilities and R&D to develop this type of solution.

- **Hydrogen storage (H_2):** applications in the transport sector, seasonal energy storage, making the operation of the grid more flexible, sector coupling. High development potential in Poland. **Potential stakeholders** include gas and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solutions.
- **Power to gas / Power to X (PtG / PtX):** for use in SNG production systems, in sectors such as energy, gas and transport. **Potential stakeholders** include gas and energy companies. Poland has the appropriate technical facilities and R&D to develop this type of solutions.
- **Electrochemical Battery Energy Storage (BES):** for electrochemical energy storage:
  - ✓ **Lithium-Ion (Li-ion)** is primarily used for daily storage and seasonal energy storage, road transport, particularly hybrid and electric vehicles, network support services (making the network operation more flexible), aviation and shipping. In order to extend their life, they are connected in parallel with ultracapacitors and renewable energy sources, e.g. PV cells (the starting capacity at low/negative temperatures of Li-ion batteries is increased). Very high development potential in Poland, especially in transport sector, network support services and industrial electronics. **Potential stakeholders** include: road transport (EV users), freight transport, fuel companies, among others: Lotos, Orlen, BP, Lukoil (autonomous OFF-GRID charging stations based on renewable sources of electric vehicles – supporting the operational infrastructure for EV), prosumers. Poland has the appropriate technical facilities and R&D to develop this type of solution.
  - ✓ **Pb-A / CLAB is primarily suitable for** seasonal and daily storage, transport – classic drive vehicles and machinery (internal combustion engines), prosumer households, air transport and shipping. In order to extend their service life, similarly to Li-ion, they are connected in parallel with ultracapacitors and renewable energy sources, e.g. PV cells (the starting capacity at low/negative Pb-A / CLAB temperatures is increased). It should be emphasized that CLABs have a higher energy density than Pb-A and therefore can be used in hybrid vehicles. **Potential stakeholders** include: road transport (users of vehicles with combustion engines), freight transport, prosumers. Poland has the appropriate technical facilities and R&D to develop this type of solution.
  - ✓ **Sodium-sulphur (NaS)** is primarily used for making the power grid more flexible and for daily energy storage. **Potential stakeholders** include: distribution network operators, Polish Power Systems (PSE). Poland has the appropriate technical facilities and R&D to develop this type of solution.
- **Vanadium flow cells (VRFB):** for use in network support services and daily electricity storage, in cooperation with renewable energy and infrastructure for charging purely electric vehicles. VRFB has great potential to achieve the assumed zero-emission goals of economies, i.e. in Germany. High development potential in Poland. **Potential stakeholders** include: Polish Power Systems (PSE), Distribution Network Operators (OSD), Lotos, Orlen, BP and Lukoil fuel companies (development of autonomous OFF-GRID charging stations based on renewable

sources for electric vehicles – support of operational infrastructure for EV). Poland has the appropriate technical facilities and R&D to develop this type of solution.

- **Superconducting coils (SMES):** future applications for voltage stabilization in RES micro-networks, including with wind farms. SMES systems can also perform functions in primary response (ensuring network stability in the event of sudden frequency and voltage changes) similarly to inertial systems (FES) and ultracapacitors (UC / EDLC), as well as to enable quick recovery of power plant operation after network overload without additional external power supply (cold start). Furthermore, in the future they can act as consumer protection against short-term power loss, change in supply voltage or frequency. Expensive solution, currently in research phase. **Potential stakeholders** include: Polish Power Systems (PSE), Distribution Network Operators (OSD). Poland has the appropriate technical facilities and R&D to develop this type of solution.
- **Ultracapacitors (UC / EDLC):** applications in support of network services, emergency power systems, in transport sectors. Currently, hybrid energy stores are under intensive development, based on, among others: battery-ultracapacitor (vehicle start-up), inertia FES-ultracapacitor (voltage stabilization in micro-networks) and increase in renewable energy penetration, with possible zero-emission in local micro-networks. High development potential in Poland. **Potential stakeholders** include: prosumers, road transport (in particular electromobility) and freight forwarding, local energy clusters, shipping and OSD.
- **Phase-change materials / molten salts PCM / MS:** primarily tourism, electronic devices, applications in construction – daily energy storage, to support systems with renewable energy sources (improving the efficiency of photovoltaic cells that operate at high temperatures), improving the efficiency of cogeneration systems based on, among others, ORC, transport (cooling of the battery pack in electric vehicles), cooling / heating of electric vehicles interior – supporting the work of the heat pump. High development potential in Poland. **Potential stakeholders** include: construction (developers), road industry (producers of caravans), container truck bodies, electric vehicles (maintaining thermal comfort of electrochemical cells). Poland has the appropriate technical facilities and R&D to develop this type of solution.
- **Heat storage tanks (TES):** for storing heat near conventional cogeneration plants, enabling for production of electricity with reduced heat demand, in conjunction with solar heating plants (seasonal and daily storage). In case of cold storage, the main applications are: hotels, public buildings, office buildings, shopping centers, warehouses for goods requiring storage at low temperatures. High development potential in Poland – distributed heat storage. High development potential in Poland. **Potential stakeholders** include: Combined heat and power plants. Poland has the appropriate technical facilities and R&D to develop this type of solution.

THE MOST PROMISING TECHNOLOGIES ARE:

- ***pumped hydroelectric storage plants (PHS)***. By 2030, more than a 10-fold increase in PHS systems on the market is expected, increasing to 2.34TGWh. According to IRENA data[12], in 2030 PHS will constitute about 45% to 51% share on the global energy storage market.
- ***lithium-ion (Li-ion) cells***. By 2028, it is estimated that Li-ion cells will account for over 1.2TWh on the global market, of which the use of cells in electric vehicles will be 1TWh, 0.15TWh – electronics while 0.1TWh – stationary energy storage. Nearly 600 million electric vehicles are expected to appear in the world by 2040[17]. It should also be added that the cells used in vehicles after reaching a 30% capacity loss will be reused in stationary storage aftermarket, which in the perspective of 2040 may even amount to 1.3TWh.

- ***FES inertia.*** By 2025, the market share of FES is expected to grow more than twice, to more than 2GW[14].
- ***flow cells (VRFB).*** In 2024 perspective[23] (based on data from Sumitomo Electric, UniEnergy Technologies, Gildemeister, Primus Power, redT Energy Storage, EnSync Energy Systems, China Local Manufacturers Covered, Dalian Rongke Power), an intensive, more than double increase in the share of flow cells on the global market is expected, to a level of over 1GWh. In 2027 perspective, Bushveld Minerals forecasts an increase in share of flow cells on the global market to 27.5 GWh[24].
- ***systems using hydrogen, among others: in fuel cells (H2 + FC).*** According[15] to IRENA, by 2050, 8% of the world's final energy consumption will be hydrogen produced from renewable energy (19 exaJouls (1EJ=10^{18}J)).
- ***ultracapacitors (UC).*** An increase of[25] ultracapacitors on the global market to 0.5GW is expected by 2026.
- ***systems using molten salts (MS) and phase-change materials (PCM).*** In the perspective of 2022[28], an increase to nearly 2.51GW is expected, while for 2024 nearly to 3.3GW of installations, using MS / PCM and concentrated solar energy.
- ***heat accumulators (TES).*** By 2025[32], the TES share is expected to increase on the market by 3 times compared to 2017, to nearly 10GW.

These technologies, in accordance with the estimates of IEA, IRENA, BP EU Commission, will develop most intensively in the near future in the perspective of 2030 and 2050.

Hydrogen storage with fuel cells (H2 + FC) are **the most suitable for seasonal energy storage**. Dedicated to making the power grid more flexible.

Pumped-storage power plants (PHS), compressed air storage (CAES), liquid air storage (LAES) and hydrogen storage (H2 + FC) are best for medium and long-term energy **storage. Dedicated to making the power grid more flexible.**

For daily energy storage, the best are: PHS, BES cells (e.g. VRFB, Li-ion), hydrogen storage with fuel cells. Dedicated to making the power grid more flexible during peak power demand, in the morning and afternoon summits.

For short-term / temporary energy storage the best systems are: ultracapacitors (UC), inertia (FES) and systems with superconducting coils (SMES). These warehouses can work as voltage and frequency stabilizers for the power grid for the purpose of temporary flexibility of power demand. These stores have high power density and long life, up to a million cycles.

For use **in road and air transport**, the best are: Li-ion cells, Li-ion + UC (hybrid warehouses),

For use **in energy storage in shipping** the best are: PbA cells (also ballast), Li-ion cells, hybrid systems: Li-ion-UC, PbA-UC,

For use **in electricity storage in construction**, the most suitable are: Li-ion cells, PbA cells, VRFB cells, and hybrid systems Li-ion-UC, PbA-UC, VRFB-UC, Li-ion-FES, PbA-FES, VRFB-FES.

Phase-change materials / molten salts and heat accumulators are **the most suitable for use in thermal energy storage in construction**.

For application with **prosumer microinstallations** most suitable are: Li-ion cells, PbA cells, VRFB flow cells and hybrid energy storage, e.g. Li-ion-UC, PbA-UC, VRFB-UC, Li-ion- FES, PbA-FES, VRFB-FES.

WHY HYBRID STORES?

Because by connecting them, the life of the cells is extended (FES / UC makes the cells more real, limits the momentary loads of electrochemical cells PbA / Li-ion / VRFB and increases power availability).

PbA/Li-ion/VRFB + FES/UC = times increase of lifetimeBłąd! Nie zdefiniowano zakładki. **of PbA/Li-ion/VRFB cells.**

RECOMMENDATIONS FOR POLAND:

- Including information about **prospective hybrid energy storage techniques in Poland's strategic documents, which have more advantages than each of them separately** (BES-UC, VRFB-UC, BES-VRFB-UC etc.),
- **Determining the support rules** for the aforementioned techniques (including environmental impact, e.g. GHG, GWI) and life cycle, climate neutral economy perspective *in Poland.*
- **Focusing on the autonomy of infrastructure based on storage**, i.e. for the development of electromobility in Poland,
- **Determining the development potential of the domestic market regarding Recycling of energy storage components** in context of closed loop economy,
- **Determining the development potential of the domestic market regarding Recycling of energy storage components** in context of closed loop economy,
- **Stimulation of incentive programs** in form of, i.e., subsidies (NFOŚiGW, ARiMR, BGK, PFR), innovation programs for enterprises, individuals, etc.
- **Obtaining an increase in the country's energy security** through the development of distributed energy storage with respect for natural resources.
- **Defining strategic research and development programs in the field of innovative and forward-looking energy storage technologies**, with an emphasis on hybrid energy storage (e.g. NCBiR, NFOŚiGW, PFR).

By obtaining adequate support for the development of the forward-looking energy storage techniques shown in this report, it is possible to achieve a low-carbon, circular economy in Poland in the near term, while in the long term after 2050 efforts should be made to ensure that local micro-networks reach zero emissions. This is a big challenge, however, taking appropriate actions regarding support for energy storage techniques is necessary now for the assumed goal of „zero emissions" to be achieved.

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Annex 1 – CAPEX AND OPEX IN THE 2030 PERSPECTIVE

Table 24 presents a comparison of CAPEX (*capital expenditure) for* PHS and other energy storage techniques currently and in the perspective of 2030. The data presented in Table 38 shows that the pumped storage plants (PHS) perform best. PHS has the highest financial life span, which can reach up to 80 years, the total adequate CAPEX (taking into account charging and discharging) is 450-1020 EUR/kW, while the cost of capital to energy alone does not exceed 20 EUR/kWh. In the 2030 perspective, it is assumed that these costs will be slightly higher, due to increase in price of electricity. A similar situation will apply to adiabatic and diabatic CAES. The decisive factor behind PHS technology is higher efficiency, up to 85% while for adiabatic compressed air storage it does not exceed 70%.

In perspective of 2030, the most favorable in terms of capital to energy costs is methane CH4 (capital cost to energy 0.14 EUR/kWh[303], while the total appropriate CAPEX ~ high is over 2,000 USD/kW.

Table 24. CAPEX for the considered energy storage technologies – comparison with PHS [303]

	PHS	D-CAES	A-CAES	Li-ion		VRLA/Pb		VRFB		H_2	CH_4
Time scale	Currently	Currently	2030	Currently	2030	Currently	2030	Currently	2030	2030	2030
Appropirate CAPEX:											
Capital cost to power (charging) [EUR/kW]	250-560	220-340	380-620	-	-	-	-	-	-	410-880	790-1360
Capitzl cost to energy [EUR/kWh]	10-20	20-30	20-30	660-1050	230-610	240-320	190-270	930-1040	250-350	0,3-0,6	0,14
Other constant costs [EUR]	-	-	-	-	-	-	-	-	-	-	264-300
Capital cost to power (discharging) [EUR/kW]	220-460	230-380	230-360	80	60-70	80	60-70	-	-	727	727
Finantial life time	80	35	35	Attach-ment to operational value	Attach-ment to operational value	Attach-ment to operational value	Attach-ment to operational value	Attach-ment to operational value	Attach-ment to operational value	30	30
Typical input/output Power ratio	0,95	0,92	0,92	1	1	1	1	1	1	2	2
Total efficiency [%]	76	55	70	95	95	77	78	80	85	41	32

[303] V. Jülch Comparison of electricity storage options using levelized cost of storage (LCOS) method, *Applied Energy* 183 (2016) 1594–1606.

Table 25 presents expenses related to OPEX (*operating expenditures*) maintenance for PHS and other energy storage technologies, currently and in the year 2030 perspective.

Table 25. OPEX for the considered energy storage technologies – comparison with PHS[303]

	PHS	D-CAES	A-CAES	Li-ion		VRLA/Pb		VRFB		H_2	CH_4
Time scale	Currently	Currently	2030	Currently	2030	Currently	2030	Currently	2030	2030	2030
Appropriate OPEX:											
Based on energy [EURcent/kWh]	0,05	0,33	0,26	-	-	-	-	-	-	0,3	0,3
Based on charging power [% z CAPEX]	-	-	-	-	-	-	-	-	-	1,6	1,5-2
Based on charging power [EUR/kW]	-	-	-	-	-	-	-	-	-	-	3,2
Based on discharging power [EUR/kW]	11	9	11	-	-	-	-	-	-	-	3,2
Based on discharging power [% z CAPEX]	-	-	-	2	2	2	2	2	2	0,06	0,06
Startup cost [EUR/kWstart]	0,02	0,016	0,016	-	-	-	-	-	-	-	-
Energy cost [EURct/kWh]	-	-	-	-	-	-	-	-	-	-	5
Natural gas cost	-	3,5	-	-	-	-	-	-	-	-	-
CO_2 certificates costs [EUR/tCO_2]	-	5	-	-	-	-	-	-	-	-	-

Annex 2 – RELATIONSHIPS USED TO ESTIMATE LCOS and ACC

Discounted energy storage costs LCOS [USD/MWh] – life costs related to the annual discharge, expressed in the volume of electricity throughout the entire life cycle, taking into account: investment costs, operating costs (O&M), replacement costs, utilization costs, electricity costs (charging / discharging) can be written as:

$$LCOS\,[USD/MWh] = \frac{IC + \sum_{k}^{i} \frac{O\&M}{(1+W_{DR})^{k}} + \sum_{k}^{i} \frac{Ch_{c}}{(1+W_{DR})^{k}} + \frac{E_{of}}{(1+W_{DR})^{i+1}}}{\sum_{k}^{i} \frac{E_{disch}}{(1+W_{DR})^{k}}} \tag{1}$$

Where: k – running costs in each year, i – system lifetime, W_{DR} – discount rate, Ch_c – charging costs, E_{ol} – decommissioning cost, $O\&M$ – operating costs, E_{disch} – annual electricity in the discharge process. Individual expressions in equation (1) can be represented in the following form:

$$\sum_{k}^{i} \frac{E_{disch}}{(1+W_{DR})^{k}} = R_{cr} \cdot GR \cdot N_{cap} \cdot \eta_{cd} \cdot (1 - S_{oD}) \cdot \sum_{k=1}^{i} \frac{(1-Deg_{C})^{(k-1)\cdot R_{cr}} \cdot (1-Deg_{T})^{(k-1)}}{(1+W_{DR})^{k+C_{time}}} \tag{2}$$

Where: R_{cr} – annual cost for electricity during discharge, GR – discharge depth, N_{capE} – nominal energy capacity, η_{cd} – charge / discharge efficiency, Deg_C degradation in cycles, Deg_T – degradation time, S_{oD} – self-discharge, C_{time} – construction time.

The next expression in equation (1) is *Investment Costs*, which can be described by the following relationship:

$$IC = N_{capP} \cdot C_{power} + N_{capE} \cdot C_{energy} + \sum_{W_{DR}=1}^{W_{DRn}} \frac{C_{Replacement} \cdot N_{capP}}{(1+W_{DR})^{C_{time}+R_{ep}\cdot I_{w}}} \tag{3}$$

Where: N_{capP} – nominal power, C_{power} – investment costs to power, C_{energy} – investment costs to energy, $C_{Replacment}$ – replacement costs, I_w – exchange interval $I_w = C_{int}/R_{cr}$, C_{int} – exchange interwal cycles, R_{ep} – exchange throughout the entire life cycle, $C_{Replacment}$ – replacement cost.

O&M operating costs can be represented as:

$$\sum_{k}^{i} \frac{O\&M}{(1+W_{DR})^{k}} = \sum_{k}^{i} \frac{C_{Power\text{-}OM} \cdot N_{capP} + C_{Energy\text{-}OM} \cdot (R_{cr} \cdot S_{oDi} \cdot N_{capE})^{(k-1)\cdot R_{cr}} (1\text{-}Deg_{T})^{(k-1)}}{(1+W_{DR})^{k+C_{time}}} \tag{4}$$

Where: $C_{Power-OM}$ – operating costs related to power, $C_{Energy-OM}$ – operating costs related to energy.

The value of charging costs for the electricity price $Elec_p$ taking into account the charge / discharge efficiency ηcd can be expressed in the following form:

$$\frac{Elec_p}{\eta_{cd}} = \frac{\sum_k^i \frac{Ch_c}{(1+W_{DR})^k}}{\sum_k^i \frac{E_{disch}}{(1+W_{DR})^k}} \tag{5}$$

The costs of decommissioning E_{oL} can be expressed as:

$$\frac{E_{of}}{(1+W_{DR})^{i+1}} = \frac{(C_{power} \cdot N_{capP} + C_{energy} \cdot N_{capE}) \cdot \delta_{of}}{(1+W_{DR})^{i+1}} \tag{6}$$

Where: δ_{of} – the investment cost.

Self-discharge can be represented by the equation:

$$S_{oD} = S_{oDi} \cdot \frac{8760hrs - 2 \cdot R_{cr} \cdot t_{disch}}{R_{cr}} \tag{7}$$

Where: t_{disch} – duration of discharge, S_{oDi} – self-discharge in idle state.

Discounted power costs (adjusted power cost – ACC or LCOS [USD/kW $_{annually}$]) – life costs related to the annual installed power capacity over the entire life cycle, taking into account: investment costs, operating costs (O&M), replacement costs, disposal costs, costs of nominal power can be described wit the following equation:

$$LCOS\,[USD/kW_{rocznie}] = ACC = \frac{IC + \sum_k^i \frac{O\&M}{(1+W_{DR})^k} + \sum_k^i \frac{Ch_c}{(1+W_{DR})^k} + \frac{E_{of}}{(1+W_{DR})^{i+1}}}{\sum_k^i \frac{N_{capP}}{(1+W_{DR})^k}} \tag{8}$$

The numerical values of parameters from equations (1-8) adopted for LCOS estimation are presented in tables: 27 (energy arbitration), 28 (primary response) and 29 (heat arbitration).

Table 26 presents the requirements for energy storage in the applications presented in Table 23.

Table 26. Requirements for energy storage[69,71]

Application	Capacity [MW]	Opration time [h]	Number of cycles [per year]	Response time [s]
Energy arbitrage	0,001-2 000	1-24	50-400	$>10^5$
Primary response	1-2 000	0,02-1	250-15 000	$<10^2$
Secondary response	10-2 000	0,25-24	20-10 500	$<10^2$
Tertiary response	5-1000	>1,5	20-50	$>10^2$
Peak shift	1-500	2-6	5-100	$>10^5$
Cold start	0,1-400	0,25-4	1-20	$>10^5$
Seasonal storage	500-2 000	24-2000	1-5	$>10^5$
Postponing investments into distribution network	1-500	2-8	10-500	$>10^5$
Limit management	1-500	1-4	50-500	$>10^5$
Bills management	0,001-10	1-6	50-500	$>10^5$

Application	Capacity [MW]	Opration time [h]	Number of cycles [per year]	Response time [s]
Power supply quality	0,05-10	0,003-0,5	10-200	<10^1
Power reliability	0,001-10	2-10	50-400	>10^1
Heat arbitrage	0,001-2 000	1-24	50-400	>10^5
Seasonal heat storage	500-2 000	24-2000	1-5	>10^5

Table 27 presents the adopted input data for 2015 for energy arbitration techniques (including: PHS, CAES, LAES, H_2+FC, BES), which were used in subsequent chapters for the LCOS and ACC projection, in the perspective of 2050.

Table 27. Adopted input data for 2015 for techniques in *energy arbitration* application

Name	Unit	Parameter	PHS	CAES	LAES	H_2+FC	PbA	Li-ion	NaS	VRFB
Investment costs – power	USD/kW	C_{power}	1129,2	870,65	1390	5420	675	675	660	830
Investment costs – energy	USD/kWh	C_{energy}	80	39,15	345	30,5	460	500	700	760
Operation costs – power	USD/kW-annualy	$C_{Power\text{-}OM}$	7,54	4,35	20,85	45,50	8	9,5	12	12
Operation costs – energy	USD/MWh	$C_{Energy\text{-}OM}$	0,0005	0,0038	0,0038	0	0,0015	0,003	0,0035	0,001
Change cost	USD/kW	$C_{Replacement}$	0,103	0,1069	0,1069	0,302	0	0	0	0
Change cycle intervals	Cycles	C_{int}	7300	1460	1460	15000	1225	3250	3250	8300
Decommission costs	%	E_{oL}	0%	0%	0%	0%	0%	0%	0%	0%
Discount rate	%	W_{DR}	8%	8%	8%	8%	8%	8%	8%	8%
Efficiency	%	η_{net}	77,8%	44,25%	60%	42%	80%	89%	82%	73,5%
Self-discharge	%	S_{oDi}	0	0	0	0	0	0	0	0
Life cycle	Cycles	L_{cycle}	33250	16250	16250	15 000	1250	3250	3250	8500
Durability period	Years	T_{life}	55	30	30	15	10	10	14	13
Response time in seconds	Seconds	R	>10	>10	>10	<10	<10	<10	<10	<10
Degradation time	%/year	Deg_T	0,35%	0,65%	0,66%	1,15%	2,2%	1,7%	1,6%	1,2%
Degradation in cycles	%/cycle	Deg_C	0,0006%	0,0012%	0,00125%	0,0011%	0,0182%	0,0069%	0,0054%	0,0027%
Construction time	Years	C_{time}	2,5	1,5	1,5	0,5	0,5	0,5	0,5	0,5
Chaging cost	USD/kWh	Ch_c	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05

Table 28 presents the adopted input data for 2015 for techniques working in primary response application (e.g. FES, SMES and UC / EDLC), which were used in subsequent chapters for the LCOS and ACC projections in the perspective of 2050.

Table 28. Input data for 2015 for *primary response* techniques

Name	Unit	Parameter	FES	SMES	UC/EDLC
Investment costs – power	USD/kW	C_{power}	640	350	80
Investment costs – energy	USD/kWh	C_{energy}	5 400	50 000	14 000
Operation costs – power	USD/kW-annualy	$C_{Power\text{-}OM}$	6,6	18,5	0
Operation costs – energy	USD/MWh	$C_{Energy\text{-}OM}$	0,0015	0,001	0
Change cost	USD/kW	$C_{Replacement}$	0,31	0	0
Change cycle intervals	Cycles	C_{int}	22500	75000	70000
Decommission costs	%	E_{oL}	0%	0%	0%
Discount rate	%	W_{DR}	8%	8%	8%
Efficiency	%	η_{net}	89%	95	91%
Self-discharge	%	S_{oDi}	0	0	0
Life cycle	Cycles	L_{cycle}	145 000	300 000	500 000
Durability period	Years	T_{life}	17,5	25	15
Response time in seconds	Seconds	R	<10	<10	<10
Degradation time	%/year	Deg_T	1,3%	1,9%	1,6%
Degradation in cycles	%/cycle	Deg_C	0,0002%	0,00015%	0,0001%
Construction time	Years	C_{time}	0,5	0,5	0,5
Chaging cost	USD/kWh	Ch_c	0,05	0,05	0,05

Table 29 presents the adopted input data for 2015 for techniques working in heat arbitration application (e.g. PCM / MS and TES), which were used in subsequent chapters for the LCOS and ACC projections, in the perspective of 2050.

Table 29. Adopted input data for 2015 for techniques working in *heat arbitration*

Name	Unit	Parameter	PCM	TES
Investment costs – power	USD/kW	C_{power}	3500	250
Investment costs – energy	USD/kWh	C_{energy}	216	68
Operation costs – power	USD/kW-annualy	$C_{Power\text{-}OM}$	112	120
Operation costs – energy	USD/MWh	$C_{Energy\text{-}OM}$	0	0
Change cost	USD/kW	$C_{Replacement}$	0	0,1069
Change cycle intervals	Cycles	C_{int}	100 000	1 460
Decommission costs	%	E_{oL}	0%	0%
Discount rate	%	W_{DR}	8%	8%
Efficiency	%	η_{net}	75%	70%
Self-discharge	%	S_{oDi}	0	43%
Life cycle	Cycles	L_{cycle}	50 000	100 000
Durability period	Years	T_{life}	25	30
Response time in seconds	Seconds	R	>10	>10
Degradation time	%/year	Deg_T	0,9%	0,9%
Degradation in cycles	%/cycle	Deg_C	0,00015%	0,0001%
Construction time	Years	C_{time}	0,5	1,5
Chaging cost	USD/kWh	Ch_c	0,05	0,025

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