Global Energy Perspectives

funded from chapter 2302, title 687 01

BMZ Final Report / Basic Document

Global Energy Solutions e.V.

Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-3

Status August 8th 2023

Team of authors:	
Siddhant Bane	Joern Becker
Ulrich Begemann	Leon Berks
Christof von Branconi	Simon Göss
Prof. Dr. Estelle Herlyn	Dr. Wilfried Lyhs
Dr. Tobias Orthen	Dr. Ludolf Plass
Dr. Jens Wagner	Dr. Hans Jürgen Wernicke

Ulm, June 2023
Global Energy Solutions e.V.
Lise-Meitnerstr. 9
89081 Ulm
Chairman: Christof von Branconi (Christof.Branconi@Global-Energy-Solutions.org)

2.3 Electricity storage

This chapter refers to the consideration of various forms of green electricity storage. On the one hand, the functionality of their forms is described, including lithium-ion batteries, redox flow batteries, hydrogen and CAES (Compressed Air Energy Storage).

On the other hand, the electricity storage costs are presented, and the last subchapter deals with the carbon footprint and raw material requirements of these forms of electricity storage.

2.3.1 Forms of electricity storage

2.3.1.1 Lithium-ion batteries

A lithium-ion battery (Li-ion) is a battery technology that uses lithium ions as the key component of its electrochemistry. During discharge, the lithium atoms in the anode are ionised and separated from their electrons. The lithium ions leave the anode and travel through the electrolyte to the cathode, where they recombine with their electrons and electrically neutralise. The lithium ions are small enough to flow through the micro-permeable separator between the anode and cathode.

Reactions for a lithium-cobalt battery

- Cathode: $CoO_2 + Li^+ + e^- \rightarrow LiCoO_2$
- Anode: $LiC_6 \rightarrow C_6 + Li^+ + e^-$
- Net reaction (Left to right: discharging. Right to left: charging):
$$LiC_6 + CoO_2 \leftrightarrow C_6 + LiCoO_2$$

Currently, the most common type of lithium battery is the one with lithium cobalt oxide (cathode) and graphite (anode), which is installed in devices such as mobile phones and laptops. Other cathode materials include lithium manganese oxide (used in hybrid and electric cars) and lithium iron phosphate. Lithium-ion batteries typically use ether[136] as electrolytes.[137]

Compared to the other rechargeable battery technologies such as nickel-cadmium or nickel-metal hydride, Li-ion batteries have several advantages. They have one of the highest energy densities of all current battery technologies (see Figure 47). Li-ion batteries also require comparatively little maintenance and do not need to be replaced regularly to maintain their lifespan.

[136] Or also ethers form a class of organic compounds in which two radicals are bonded via an oxygen bridge
[137] Cf. Clean Energy Institute: University of Washington, (2020).

Li-ion batteries do not have a memory effect, a detrimental process whereby repeated partial discharge/charge cycles can cause a battery to 'remember' a lower capacity. This is an advantage over Ni-Cd and Ni-metal hydride batteries, which have this effect. Li-ion batteries also have a low self-discharge rate of about 1.5-2 % per month.

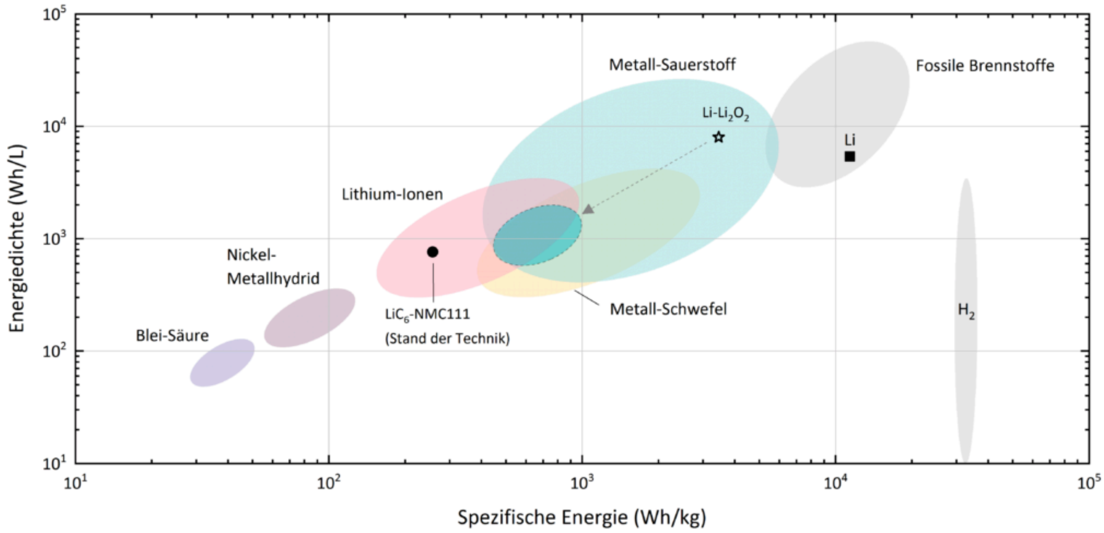


Figure 47: Energy density of different battery types.

Source: Wunderlich, (2020).

The aim of research on batteries is on the one hand to increase the specific charge (in Ah/kg) as well as the specific energy of the cell (in Wh/kg) and on the other hand to maintain its rechargeability after an increased number of charging cycles. Lithium-sulphur cells, for example, have a significantly higher specific energy density than Li-ion cells (450-500 Wh/kg), but are still being developed by e.g. FhG IWS or Lawrence National Lab in Berkeley with regard to the reduction of the charging capacity with increasing number of cycles. The most powerful Li-S cell to date was developed in Australia in 2020.[138] Since the theoretical maximum energy density for Li-S cells is 2.6 kWh/kg, there is a high potential for further development in the period 5-10 years.[139]

2.3.1.2 Alternatives to the lithium battery: metal ions

Promising alternatives to the lithium-ion battery are the metal-ion batteries with sulphur or oxygen, where the critical raw material is replaced by more readily available metals such as sodium, magnesium or aluminium and the cells can therefore be produced more cheaply, partly on the same production lines as lithium-ion batteries.[140] The larger diameter of the metal ions

138 Cf. Wikipedia,.(2022a).
139 Cf. Battery Forum, (2015).
140 Cf. Battery Forum, (2015); Battery Forum, n.d.

compared to lithium, for example, still leads to problems at the electrodes, where the ions have to be reliably stored and removed during operation. There is also still a lack of suitable electrolytes, additives and binders. The Pacific Northwest National Laboratory (PNNL) of the US DoE issued a report in July 2022 that the instability of sodium-ion batteries (NIB) could be reduced.[141] However, there are no signs of this type of battery being ready for series production in the short term, i.e. within the next 5 - 10 years.

Metal-air or metal-oxygen batteries are also being developed (cathode made of pure metal, anode porous with air contact), whose energy density is reduced to about 800 Wh/kg when the entire periphery is taken into account. The lifetimes of these systems are still very short and their rechargeability is limited or even impossible, as is the case with zinc-air batteries.

2.3.1.3 Redox Flow Battery

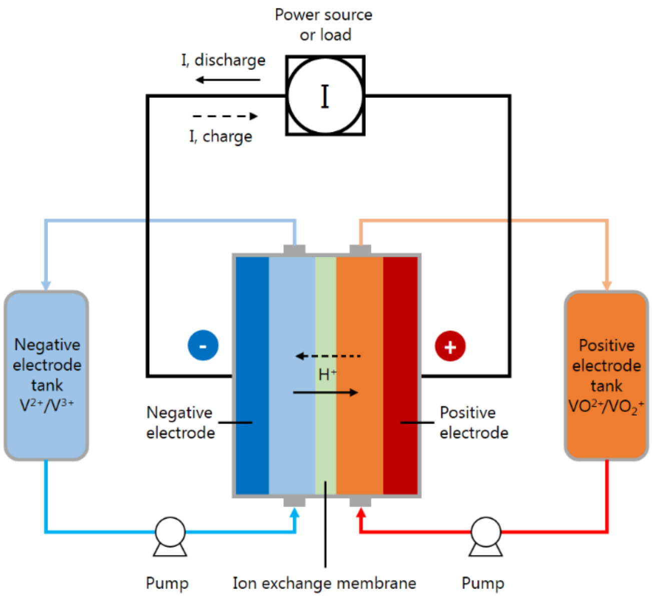


Figure 48: Energy density of different battery types.

Source: Energy Storage News & Potter, (2021).

A redox flow battery is an electrochemical storage medium that stores electrical energy into chemical energy when charging as well as could convert the chemical energy into electrical energy when discharging. These batteries work like a fuel cell, where the chemical energy is stored in two different types of liquids, which are stored in two containers. The chemical reactions take place in a cell that is constantly supplied with these two liquids (anolyte and catholyte) with the help of two pumps. The volume of the electrolytes corresponds to the battery capacity and the number of cells corresponds to the power, i.e. redox-flow batteries are easily

[141] Cf. Efahrer, 2022, also Jin, (2022).

scalable and have a longer life than lithium-ion batteries, but have a relatively low energy density.

2.3.1.4 Hydrogen and hydrogen derivatives

The application of hydrogen as a storage medium is one of the popular solutions, especially for seasonal storage of the surplus green electricity. The storage of green electricity in hydrogen is done in three steps - firstly splitting water into hydrogen and oxygen using electrolysers powered by green electricity, secondly compressing and storing the generated and thirdly converting the stored hydrogen into electricity using fuel cells to generate the electricity when electricity is required. Because of these three steps, the efficiency of the entire storage and reconversion process is lower than lithium-ion battery storage. Nevertheless, hydrogen storage can be advantageous because the loss-free storage period is longer than with lithium-ion batteries (see Table 5).

The production of hydrogen with green electricity is done via electrolysers and here polymer electrolyte membrane,[142] alkali and anion exchange membrane electrolysers are used.[143] The hydrogen production costs, according to Lazard,[144] can vary greatly depending on the electrolyser full load hours, CAPEX and the electricity production costs. The lower the project CAPEX and electricity costs, the lower the hydrogen production costs. Furthermore, the more full load hours the electrolysers are in operation, the more the hydrogen costs are reduced (see Figure 49:). For alkaline electrolysers, the hydrogen production costs are lower than for PEM.

[142] PEM
[143] AEM
[144] See Lazard, (2021b).

Sensitivity to Electricity Cost and Electrolyzer Capex(2)

Alkaline (100 MW) — Electrolyzer Capex ($/kW); Energy Cost ($/MWh)

$/kg	$510	$570	$630	$690	$760
$20	$1.75	$1.76	$1.78	$1.79	$1.80
$30	$2.49	$2.50	$2.52	$2.53	$2.54
$40	$3.23	$3.24	$3.26	$3.27	$3.28
$50	$3.97	$3.98	$4.00	$4.01	$4.02
$60	$4.71	$4.72	$4.74	$4.75	$4.76

PEM (100 MW) — Electrolyzer Capex ($/kW); Energy Cost ($/MWh)

$/kg	$680	$760	$840	$920	$1,010
$20	$2.16	$2.18	$2.20	$2.21	$2.24
$30	$3.01	$3.03	$3.04	$3.06	$3.08
$40	$3.86	$3.87	$3.89	$3.91	$3.93
$50	$4.70	$4.72	$4.74	$4.76	$4.78
$60	$5.55	$5.57	$5.59	$5.61	$5.63

Sensitivity to Electricity Cost and Utilization Rate(3)

Alkaline (100 MW) — Electrolyzer Utilization; Energy Cost ($/MWh)

$/kg	90%	75%	60%	45%	30%
$20	$1.78	$1.77	$1.81	$1.84	$1.93
$30	$2.52	$2.51	$2.55	$2.58	$2.67
$40	$3.26	$3.25	$3.29	$3.32	$3.41
$50	$4.00	$3.99	$4.03	$4.06	$4.15
$60	$4.74	$4.73	$4.77	$4.80	$4.89

PEM (100 MW) — Electrolyzer Utilization; Energy Cost ($/MWh)

$/kg	90%	75%	60%	45%	30%
$20	$2.18	$2.18	$2.22	$2.28	$2.37
$30	$3.03	$3.03	$3.06	$3.13	$3.22
$40	$3.88	$3.87	$3.91	$3.98	$4.06
$50	$4.72	$4.72	$4.76	$4.83	$4.91
$60	$5.57	$5.57	$5.61	$5.68	$5.76

Figure 49: Hydrogen production costs.

Source: Lazard, 2021a.

For stationary storage applications, such as hydrogen as electricity storage, high volumetric density is preferable as weight is not a dominant factor affecting the efficiency of the system. There are two established methods of storing hydrogen:

- Physical storage as a compressed gas: Hydrogen can be compressed and stored as a gas in bottles, containers or even underground caverns, with pressures of up to 700 bar in suitable bottles. The storage of gaseous hydrogen under high pressure is currently the most popular and widely used method.[145]
- Physical storage as cryogenic liquid hydrogen: When storing hydrogen in liquid form, a higher density can be achieved compared to the storage of compressed hydrogen gas. Therefore, more energy can be stored per unit volume. However, there is widespread criticism of the high costs and high energy consumption for liquefaction. For example, the hydrogen has to be cooled down to 21 K for liquefaction, that more than 30 % of the lower heating value of hydrogen is consumed for this process, which is much higher compared to the energy consumption for compression.[146][147] The "boil-off" phenomenon is another factor that further reduces efficiency. Due to the unavoidable heat input into the storage tank, 2 - 3 % of the vaporised hydrogen is lost per day.[148]

---

[145] See Zhang et al., (2016).
[146] about 15 % Case
[147] Cf. Klell et al., (2009).
[148] See Zhang et al., (2016).

As part of the HYPOS research initiative, a pilot project for the underground storage of hydrogen as gas will start in Central Germany in 2019. The storage facility was built at the Bad Lauchstädt site of the gas storage operator VNG Gasspeicher GmbH and will subsequently be transferred to research operations. The facility would be the first hydrogen cavern storage facility in continental Europe and the first cavern storage facility worldwide to store green hydrogen as a gas from renewable energies.[149]

Hydrogen power generation could technically pursue either from direct combustion in gas-fired power plants or by converting hydrogen to electricity through fuel cells. One example is the EU-funded HYFLEXPOWER project, where excess electricity is converted to hydrogen with electrolysers and then compressed and stored. The hydrogen could be mixed with natural gas and burned in gas-fired power plants to generate the electricity and heat (see Figure 50). Siemens Energy will upgrade an existing SGT-400 industrial gas turbine to generate electricity and thermal energy with stored hydrogen and demonstrate a power-to-H_2 -to-power solution on an industrial scale.[150]

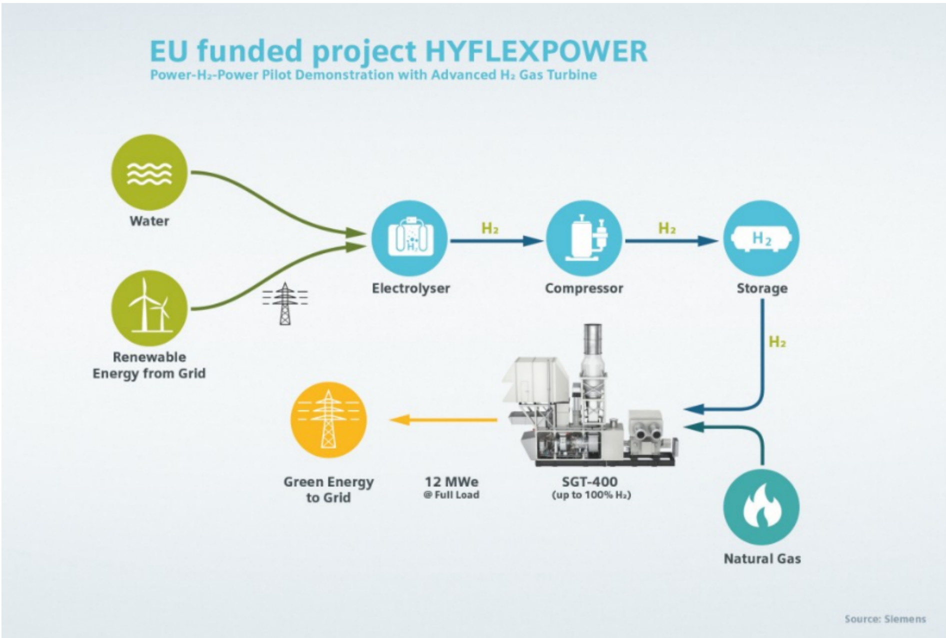


Figure 50: Power-to-Hydrogen-to-Power Model.

Source: Siemens, (2022).

In order to significantly reduce emissions from gas-fired power plants by blending hydrogen with natural gas, higher proportions of hydrogen volume flows would have to be added to the natural gas (see Figure 51), since the lower heating value (LHV) of hydrogen is 10.8 MJ/Nm^3

[149] Cf. Thamm, (2019).
[150] Cf. Siemens, (2022).

and in comparison the LHV of methane is 35.8 MJ/Nm^3 . Therefore, a three times larger volume flow of hydrogen is required to obtain the same heat production as with methane.

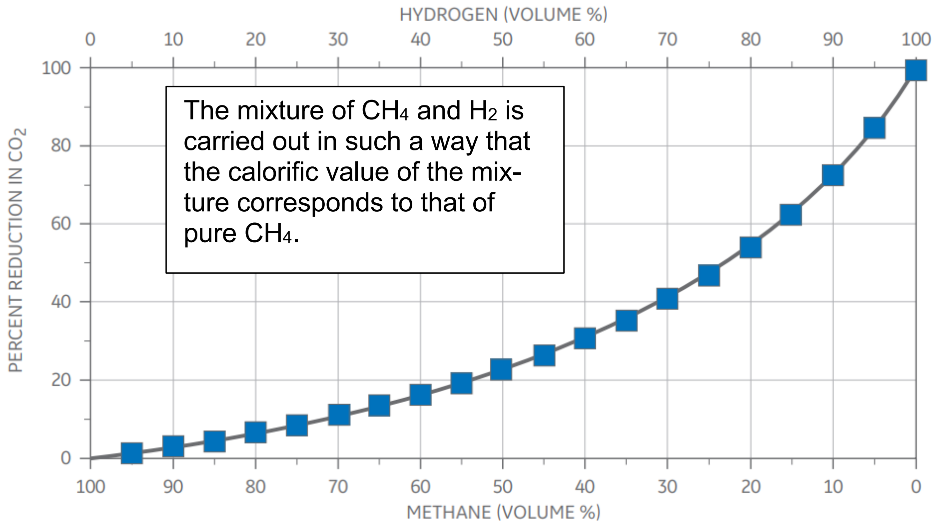


Figure 51: Ratio of carbon dioxide emissions and volume flow for a fuel mixture of methane and hydrogen for the same calorific value

Source: Gold Sea, (2021).

Operating a gas turbine with 100 % hydrogen requires other control systems that could deliver and regulate such higher volumetric flow rates. [151]

Due to the significant difference in flame speeds between methane and hydrogen, combustion systems designed to operate on methane (or natural gas) may not be suitable for operation on a hydrogen-rich fuel. In many cases, the gas power plant powered by a hydrogen-rich fuel requires a combustion chamber specifically designed for the different combustion conditions.

There are other operational problems with hydrogen that affect general safety. Firstly, a hydrogen flame has a low luminosity in the visible light range and is therefore difficult to detect visually. This requires flame detection systems specifically designed for hydrogen flames. Secondly, hydrogen can escape through seals that are considered airtight or impermeable to other gases. Therefore, conventional sealing systems used with natural gas must be replaced with welded joints or other suitable components.[152]

Alkaline electrolysis is a mature technology for large plants, while PEM (proton exchange membrane) electrolysers are more flexible and can be used for small decentralised solutions. The conversion efficiency for both technologies is around 65 % to 70 % (lower calorific value).[153] High temperature electrolysers are currently under development and could be a very efficient alternative to PEM and alkaline systems with efficiencies of up to 90 %. Hydrogen can be re-

[151] Cf. Goldmeer, (2021).
[152] Cf. Goldmeer, (2021).
[153] Cf. ESA, (2021).

electrified in fuel cells with an efficiency of up to 50 % or alternatively burned in gas-fired combined cycle power plants (efficiency up to 60 %). This results in a round-trip efficiency of between 32 % and 42 % for hydrogen storage.

The green hydrogen could also be used to synthesise derivatives such as methane, methanol or ammonia and possibly to convert it back into electricity; this is known in English as "power-to-X-to-power". The storage of e-methane has the advantage that the existing natural gas infrastructure could continue to operate. But this requires an expansion of carbon capture facilities so that the green hydrogen generated with surplus electricity and the captured CO_2 can be processed into methane.

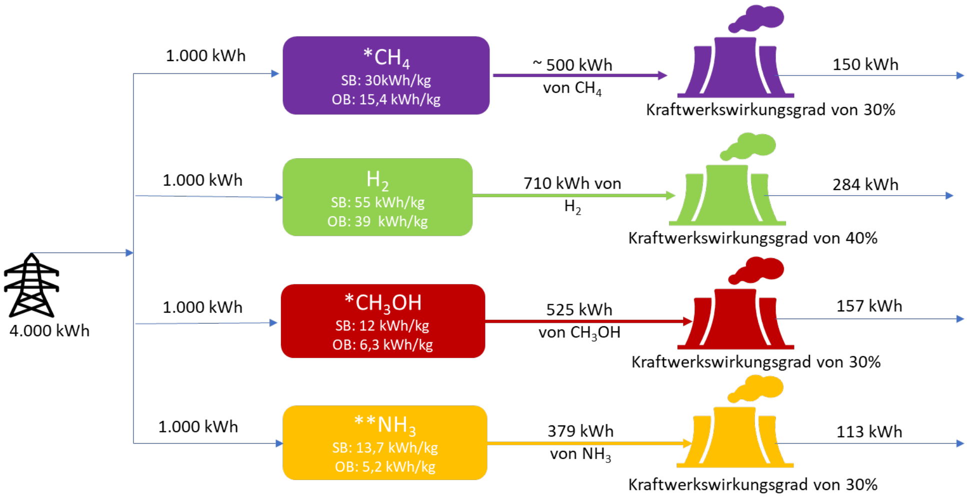


Figure 52: Various power-to-X-to-power solutions;

Source: Prognos 2020

The synthesis of ammonia eliminates the need for the expansion of carbon capture plants but for the Haber-Bosch process the nitrogen in the air has to be removed by pressure swing absorption processes. The use of hydrogen derivatives for storage and re-conversion into electricity means a higher energy input and therefore the round-trip efficiencies of these methods are lower than that for the hydrogen rail (see Figure 52). Here, a surplus of 4,000 kWh of electric power is evenly distributed between the production of hydrogen and the production of its derivatives. The fuels are consumed in the corresponding power plants when there is a shortage of electricity. The energy requirements for storage and transport of hydrogen and derivatives are not taken into account in the model.

2.3.1.5 Compressed air

A CAES system stores energy in the form of compressed air (pressure energy) in a reservoir. Large-volume air reservoirs are essential for large CAES systems. To find suitable storage caverns for compressed air, old, natural salt deposits or depleted gas fields can be used. The electricity storage CAPEX (see glossary) are significantly lower if a suitable cavern is available. Building a purpose-built cavern to hold the compressed air drastically increases the cost of energy storage. Metal containers as reservoirs are technically feasible, but in most cases too expensive to be economically viable.

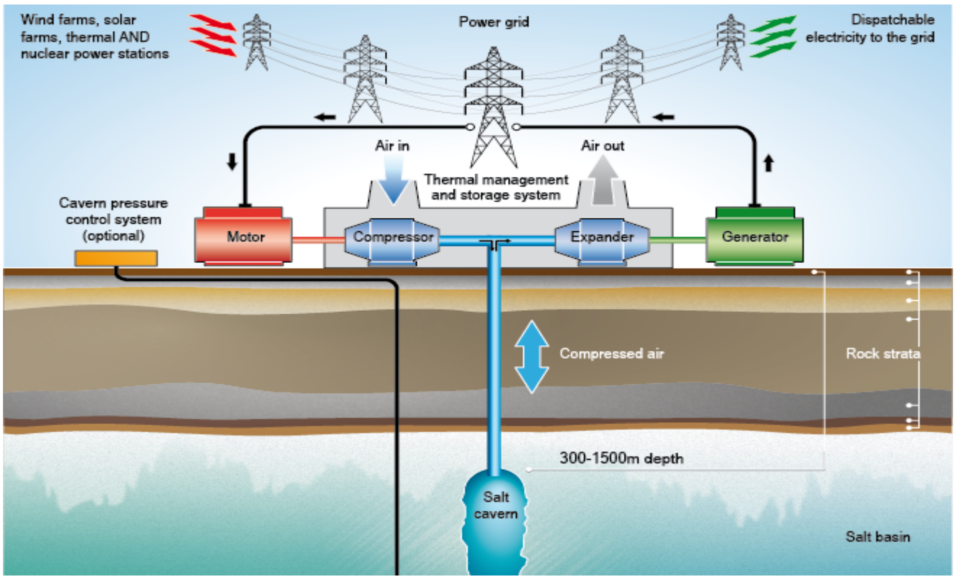


Figure 53: Compressed air storage system.

Source: Oil Free Air, (2021).

CAES systems operate on similar principles to conventional gas turbines, although in CAES systems the compression and expansion phases are decoupled and do not run simultaneously. During charging, excess electricity or electricity from off-peak periods is fed into a motor that drives a chain of compressors that store air in the reservoir. During this process, the air heats up. In a classic (adiabatic) CAES system, this heat is released to the atmosphere by an air cooler and is lost. When discharging, when the energy demand is high, the stored air is usually used to run a gas-fired turbine generator. When the compressed air escapes from the storage (i.e. expands), it consequently cools down and needs to be heated to improve process efficiency. This is achieved by mixing compressed air with fuel (e.g. natural gas) in a combustion chamber to drive the turbine. Often the combustion exhaust gases are recuperated to improve efficiency. In advanced adiabatic compressed energy storage (AA-CAES) systems, the heat that would normally be released to the atmosphere during the compression phase is stored in a thermal storage system and reused during unloading, i.e. expansion, to increase process efficiency.

There are several types of CAES projects in development and construction worldwide, for example a 350 MW and 1.4 GWh storage capacity "Adiabatic-CAES" project will be in operation in Shandong region of China by 2024.[154] The Canadian company Hydrostor uses isobaric CAES technology to store surplus electricity. Hydrostor built such plants in 2022 with a storage capacity of 1.6 GWh and a capacity of about 200 MW.[155] The company also received support from well-known institutions such as Goldman Sachs Assests Management. Energy Dome, an Italian company, is developing energy storage using CO_2 as the storage medium instead of using air. According to company communication, this storage could deliver a round-trip efficiency of up to 70 %.

2.3.1.6 Pumped storage power plants

Pumped storage power plants are an established form of hydropower energy storage used in electricity grids for load balancing. In this method, energy is stored in the form of potential gravitational energy of water pumped from a lower reservoir to a higher reservoir. Low-cost, surplus electricity from off-peak periods is usually used to operate the pumps. During periods of high electricity consumption, the stored water is released via turbines to generate electricity. Although the power plant is a net energy consumer overall due to pumping losses, the system increases revenue by selling more electricity at times of highest demand when electricity prices are highest. The round trip efficiency is based on a literature review from a study that gives a range of 75-85 % in various sources. [156]

Pumped storage currently dominates the total installed storage capacity with 96 % of the total 176 GW of pumped storage installed worldwide in 2017.[157] Total installed battery storage capacity was 17 GW worldwide at the end of 2020. An additional 5 GW of storage capacity was installed globally in 2020, led by China and the United States.

2.3.2 Costs of storing electricity

Lazard (2021b) has analysed in its annual report the electricity storage costs of lithium iron phosphate, lithium nickel manganese cobalt oxide, vanadium redox flow batteries and zinc bromide redox flow batteries for various purposes in the electricity grid. In electricity markets, these types of electricity storage could be implemented to balance the fluctuations in load and frequency, or to avoid substation reconstruction, as well as to minimise the curtailment of electricity from renewable energy plants. In addition, the lithium-ion and redox-flow batteries mentioned above could be used on a relatively smaller scale in commercial, household or

[154] Cf. Energy Storage News, (2022).
[155] Cf. Hydrostor, (2022).
[156] Cf. Mongird, et al., (2020).
[157] Cf. Center for Climate and Energy Solutions, (2020).

residential neighbourhoods to store green power or replace generators for peak loads. Two parameters are crucial for the selection of a suitable storage technology:[158]

- Electricity storage cost: The cost per unit of energy kWh or MWh of storing electricity in a storage facility, taking into account all costs incurred during the lifetime of the storage facility.
- Annuitised capacity cost: The cost of providing electrical power in a storage facility for a given period of time (e.g. one week, one year), taking into account all lifetime costs. The unit of this factor is e.g. USD/MW-a.

For the aforementioned purposes in the electricity grid, the electricity storage costs in Figure 54 is shown. The lowest electricity storage costs are for solar PV + storage and range from 85 to 160 USD/MWh for a capacity of 50 MW and storage capacity of 200 MWh. The highest costs are for small solar PV systems with electricity storage for about 600 kW peak capacity and 250 kWh storage capacity. For large-scale electricity storage applications, the costs are between 130 and 280 USD/MWh.

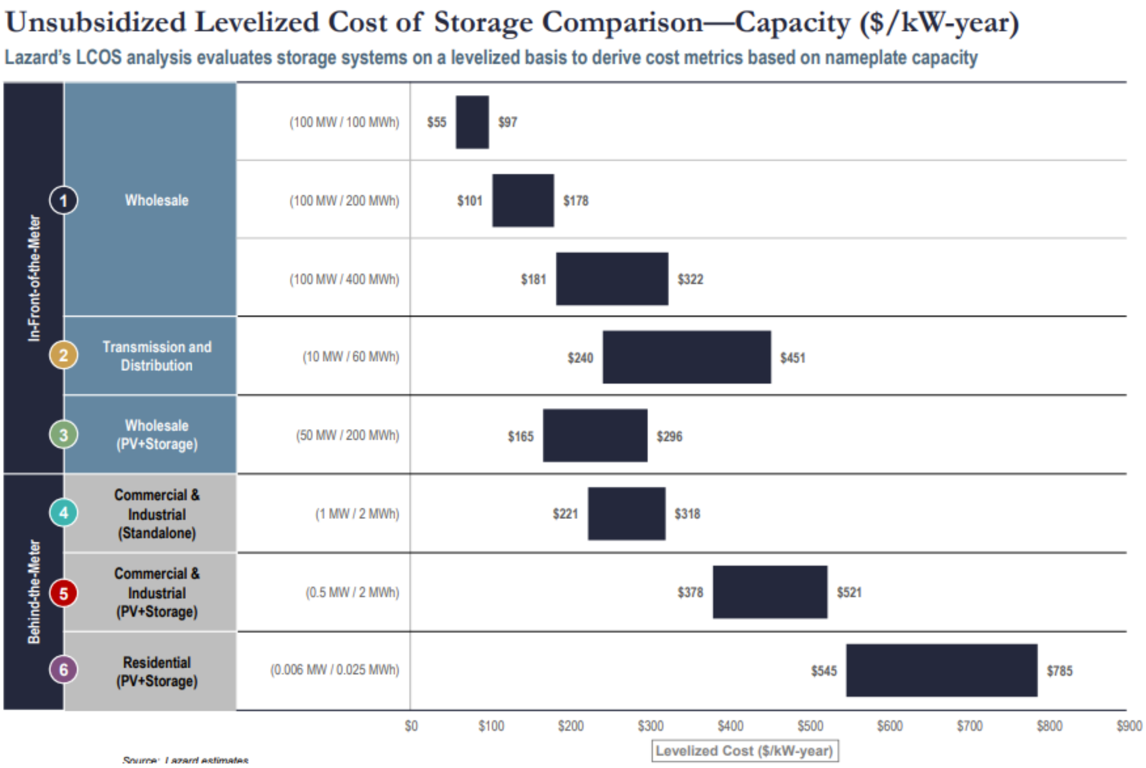


Figure 54: Electricity storage cost (LCOS) of lithium batteries and redox flow batteries for different applications and based on storage capacity.

Source: Lazard, (2021b).

[158] Cf. Storage Labs, (2021).

Based on the ACC parameter, electricity storage costs are lowest at 100 MW peak capacity and 100 MWh storage capacity (see Figure 55). For large-scale solar photovoltaic and storage systems, the costs are between approx. 180 USD/kW-a and 450 USD/kW-a and for small systems, e.g. single-family houses, the costs are much higher and range between 550 USD/kW-a and 790 USD/kW-a.

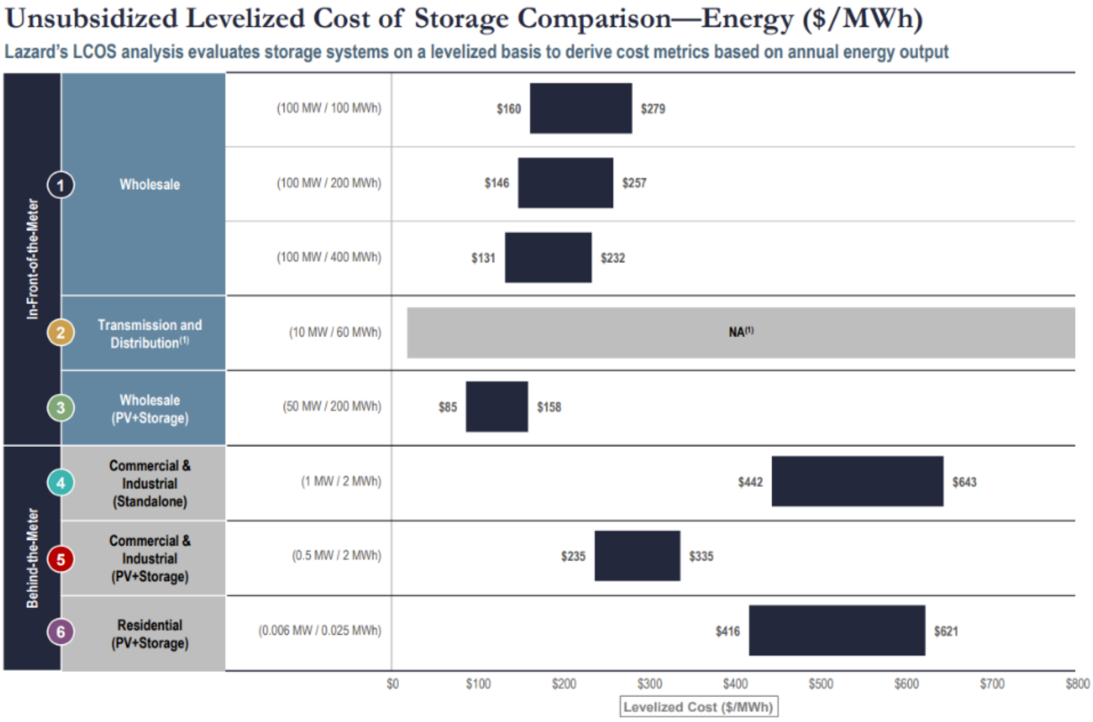


Figure 55: Annuitised capacity cost (ACC) of lithium batteries and redox flow batteries for different applications and based on power.

Source: Lazard, (2021b).

For long-term storage, redox flow batteries, thermal storage, pumped hydro storage, hydrogen storage and CAES are suitable. CAES costs between 116 USD/MWh and 140 USD/MWh and therefore CAES is the most cost-effective solution based on electricity storage costs, followed by established pumped storage technology (see Figure 56). The electricity storage costs of redox flow storage range from 315 USD/MWh to about 700 USD/MWh. According to one study, CAES is estimated to be the lowest cost storage technology (119 USD/kWh) in the United States, but is highly dependent on location near naturally occurring caverns, which significantly lowers the overall project cost. [159]

[159] Cf. Mongird, et al., (2020).

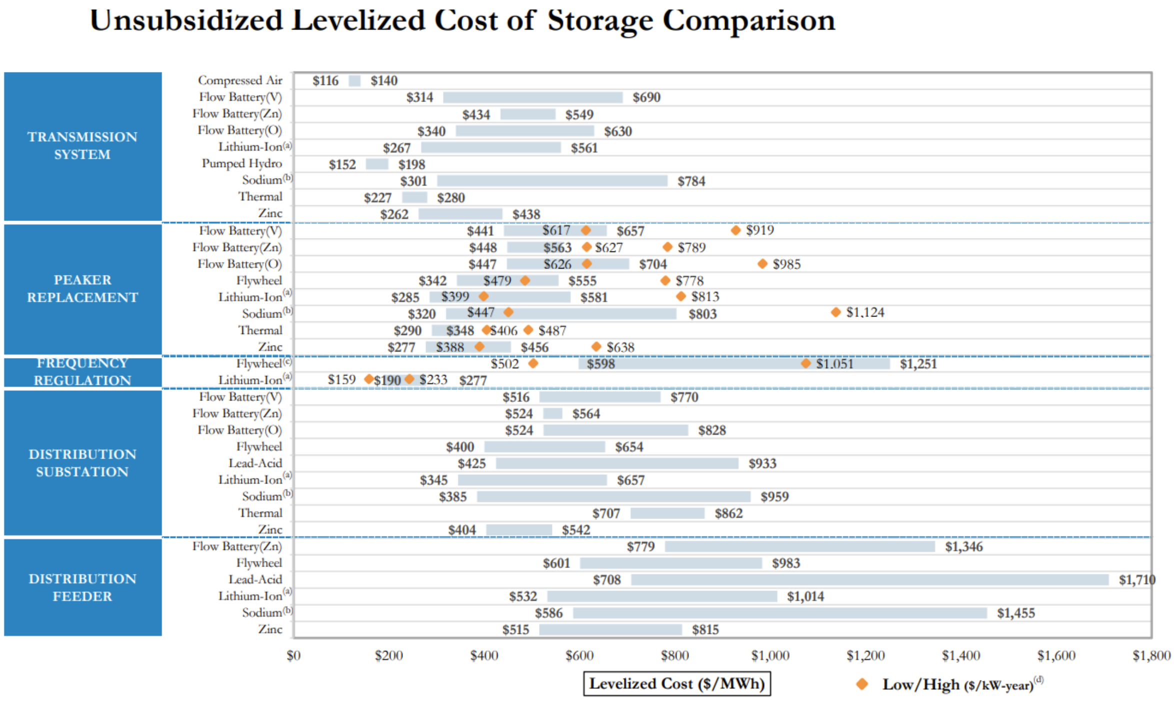


Figure 56: Electricity storage costs (LCOS) of CAES, pumped storage power plant for various purposes in the electricity grid (ordered by storage capacity).

Source: Lazard, (2016).

Although new policies and projects will accelerate the growth of the battery market, an even faster increase is needed to reach the "Net Zero Emissions by 2050" scenario, in which nearly 600 GW of battery storage capacity would need to be installed by 2030, according to the IEA.[160] Lithium-ion battery storage remains the most widespread and accounts for the majority of all newly installed capacity.

Mauler et al. (2021) identified 53 studies providing time- or technology-specific estimates for lithium-ion, solid-state, lithium-sulphur and lithium-air batteries among more than 2000 publications on the topic. The relevant publications are clustered in Mauler et al. (2021) according to four applied forecasting methods: technological learning, literature-based forecasting, expert surveys and bottom-up modelling. trajectory of costs, reaching a level of about 70 USD/kWh in 2050, as well as to 12 technology-specific forecast ranges indicating cost potentials below 90 USD/kWh for advanced lithium-ion and 70 USD/kWh for lithium-metal batteries.

[160] Cf. IEA, 2021a.

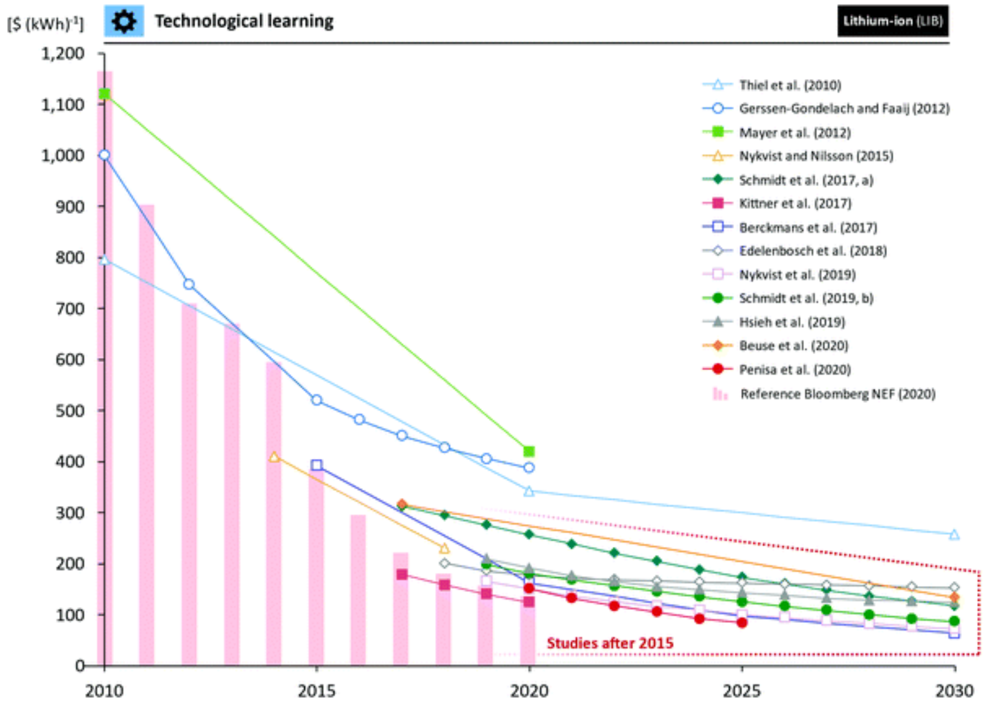


Figure 57: Lithium-ion battery LCOS forecasts from various published studies.

Source: Mauler et al., (2021).

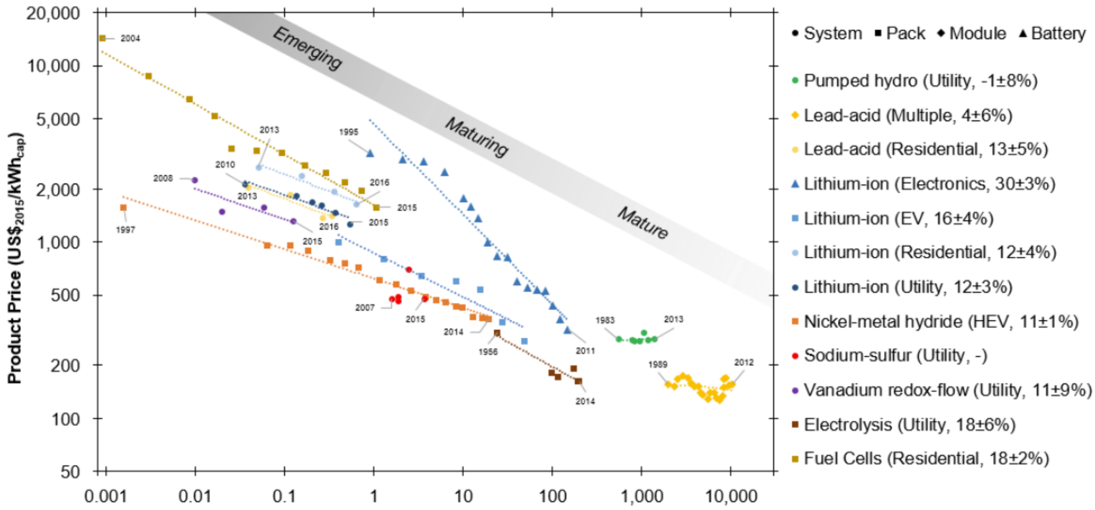


Figure 58: Product price development of various types of electricity storage.

Source: Schmidt et al., (2017).

Schmidt et al. (2017) derive experience curves from historical product prices and cumulative installed capacities based on data from technical literature, research and industry reports, news, energy storage databases and interviews with manufacturers. The Figure 58 shows that product prices decrease with increasing cumulative installed capacity for most electrical energy storage technologies. Pumped storage (system), lead-acid storage (module), alkaline electrolyzers and lithium-ion storage (Li-ion) for consumer electronics (battery) currently have prices below US$300/kWh for over 100 GWh of installed capacity. The relatively low experience rate

(ER) of the experience curve below 5 % for the first two compares to 18 % for electrolyzers (pack) and 30 % for Li-ion. Technologies with a cumulative installed capacity between 1 GWh and 100 GWh, such as Li-ion for e-vehicles, nickel-metal hydride (pack) or sodium-sulphur (system), have current prices below US$500/kWh and experience rates of 11 % and 16 %. Those below 1 GWh such as stationary Li-ion, lead-acid, redox flow and fuel cells cost more than US$1,000/kWh with experience rates between 11 % and 18 %.[161] For lithium-ion battery technologies, the cost of battery packs, which account for a lion's share of total storage costs, is projected to drop from US$160/kWh to about US$100/kWh in 2030.[162]

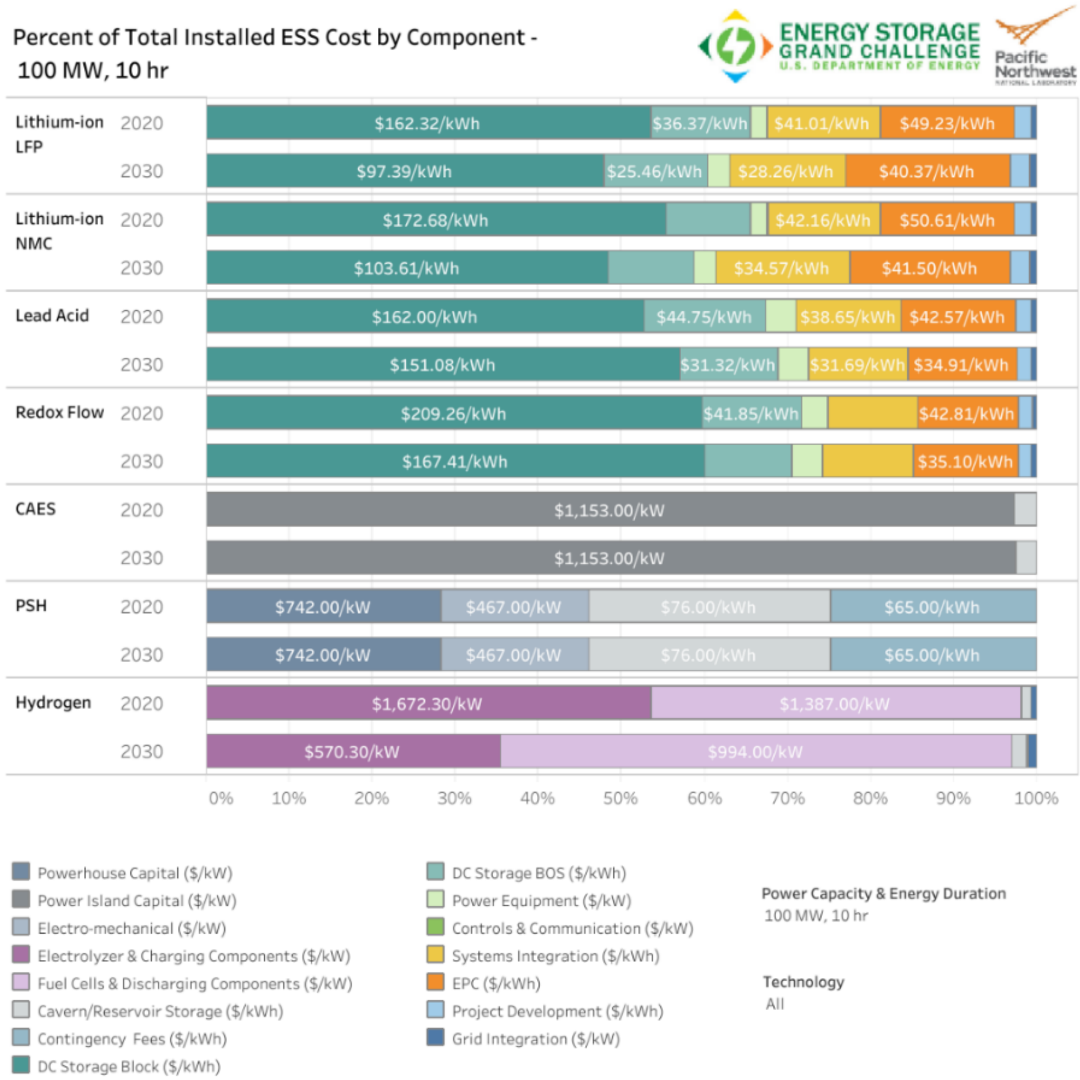


Figure 59: The percentage of total installed electricity storage costs by cost component for each technology.[163] This illustrates the breakdown of cost components within each storage technology and how each contributes to the total installed cost.

Source: PNNL, (2020).

[161] Cf. Schmidt et al., (2017).
[162] Cf. PNNL, (2020).
[163] For an installed capacity of 100 MW and 10 hours storage time

The cost of expanders and compressors for CAES storage is not expected to decrease further as these technologies mature (see Figure 59). The cost of CAES storage also depends on the availability of salt caverns. Salt dome caverns are generally the least expensive option for CAES as they are both deep and wide, while stratified caverns, which have a shallower depth, are more expensive. The pressure of compressed air storage increases with depth, leading to a decrease in the price per kilowatt hour.[164] For example, at a depth of 3,500 feet, 3,000 psi is reached. With the right depth and width of salt domes, cavern costs can be as low as $2/kWh, but this always depends on the geology and region.[165] For high energy demand and long-term solutions, CAES, pumped storage and hydrogen are feasible and more economical (see Figure 60 and Figure 61), as the potential power capacities and storage duration are more significant than lithium-ion and redox flow batteries.

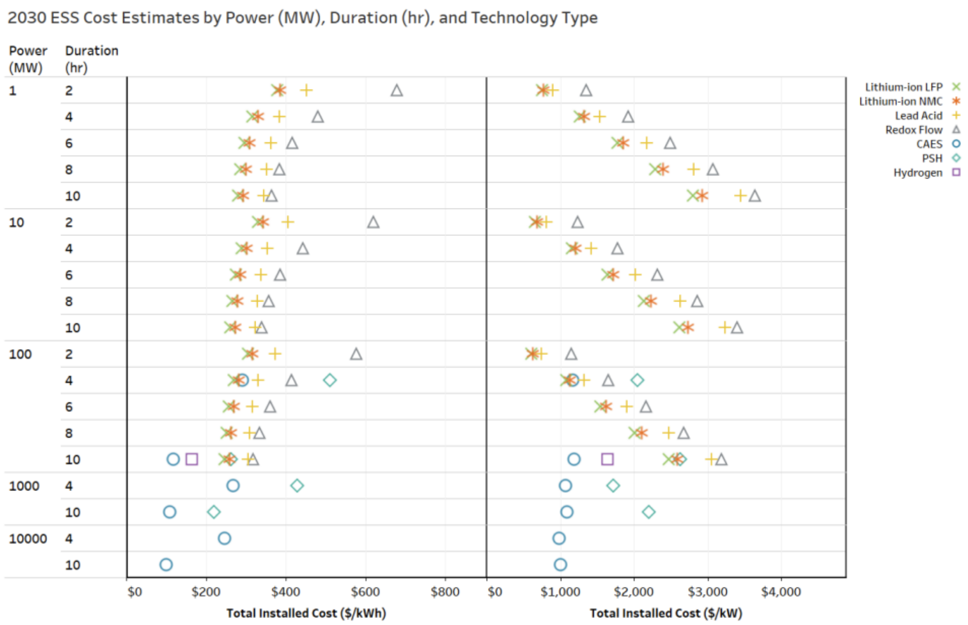


Figure 60:Installation costs (USD/kW) and storage costs by storage capacity (USD/kWh) of various types of electricity storage. [166]

Source: Mongird et al., (2020).

Figure 60 and Figure 61 show that lithium-ion batteries are suitable for a maximum storage time of about 8 hours and a power of about 100 MW. These systems can be used to compensate for daily power fluctuations due to their fast response time. Such systems can be used in locations where the seasonality of solar or wind energy is lower. Very similar storage

[164] Cf. Farley, (2020).
[165] Cf. Mongird et al., (2020).
[166] In Mongird et al, 2020, for battery energy storage systems (BESS), the analysis was carried out for systems in the USA with a nominal capacity of 1, 10 and 100 MW and a duration of 2, 4, 6, 8 and 10 hours. For pumped storage, 100 and 1,000 MW systems with durations of 4 and 10 hours were considered. For CAES, 10,000 MW were also considered in addition to these output and duration levels. For HESS, only 100 MW were evaluated at a duration of 10 hours.

requirements can be met by flow batteries. Their energy density is lower than that of lithium-ion batteries, but this does not play a major role in stationary applications, where their power-to-weight ratio is not as important as in electromobility. Capacitors, flywheels and lithium-ion batteries can be used for fine-tuning and frequency control in the grid. For power in the GW range, pumped storage has long offered robust and efficient electricity storage. CAES, while not as widespread as pumped storage and not as popular as lithium-ion batteries, can provide cost-effective storage solutions in locations that have underground caverns for storage. Hydrogen and its derivatives produced by power-to-X processes can be used for seasonal storage. As outlined in chapter 2.1 on power generation, there is no blanket solution for energy storage. The optimal solution depends on the location where the renewables are deployed, the duration of storage, the maximum energy demand and the response time to manage fluctuations in the grid.

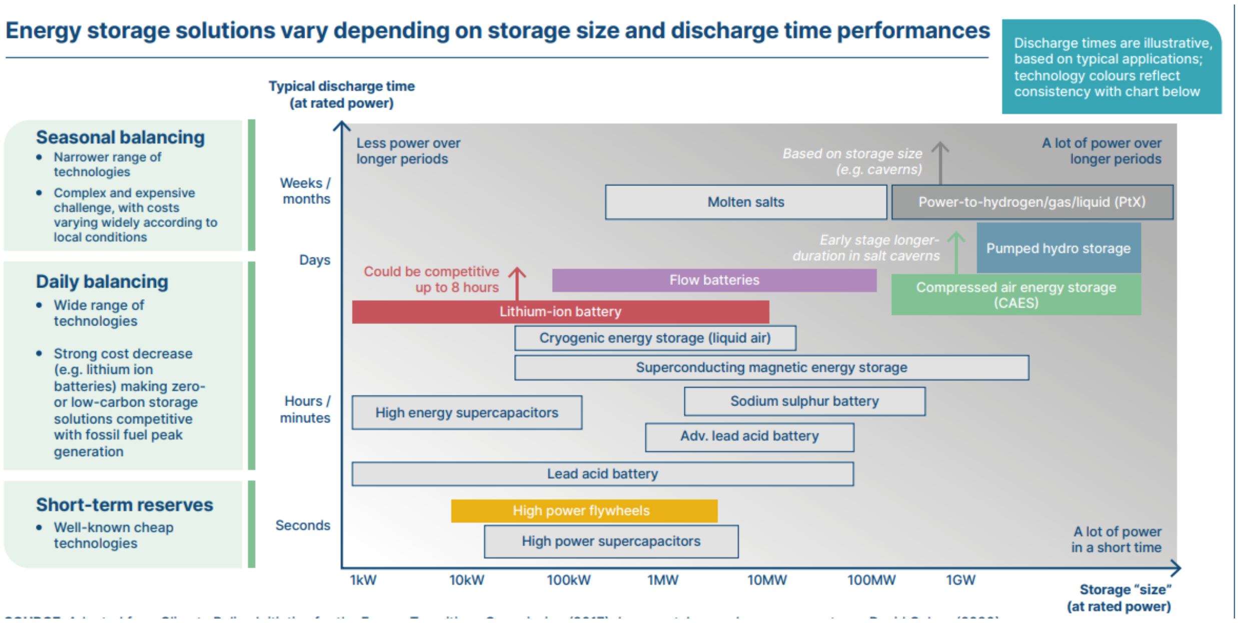


Figure 61: Summary of storage duration and performance of various types of electricity storage.

Source: Energy Transition Commission, (2021).

2.3.3 Raw material requirements, emissions and environmental impact of electricity storage

According to the IEA (2021), lithium demand in the lithium battery industry in 2040 could increase just over tenfold in the Stated Policies Scenario (see chapter 2.2.1) and about fortyfold in the Sustainable Energy Scenario (see also Glossary) compared to consumption in 2020. Consumption for other metals such as manganese, cobalt and nickel will also increase at the same time, as shown in Figure 62 is shown.

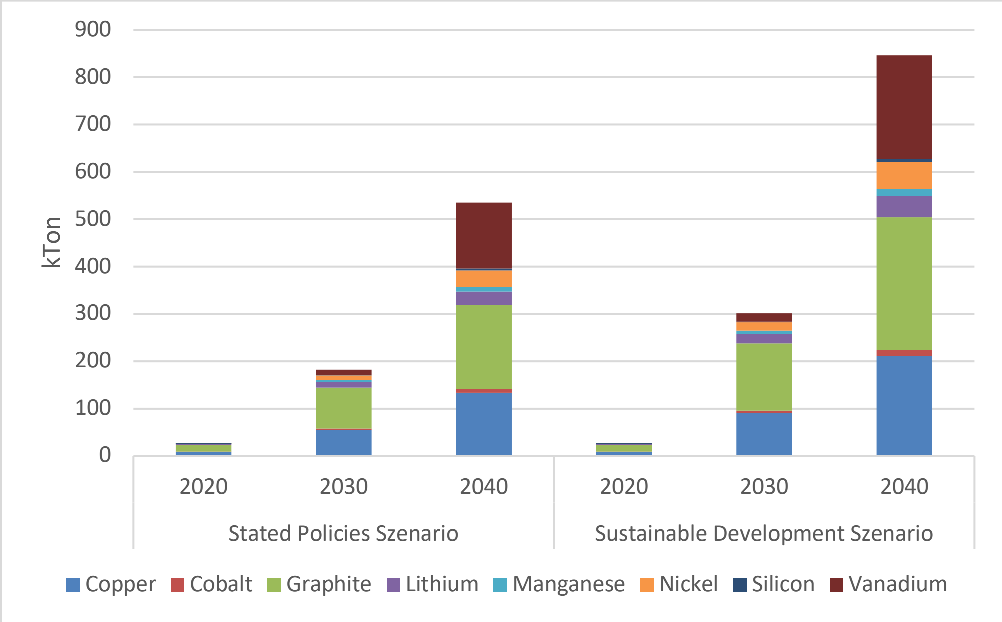


Figure 62: Raw material demand forecasts in the battery industry at STEP & SDS.

Source: IEA, 2021b.

Kurland (2019) has summarised that these lithium-ion batteries consume about 50 - 65 kWh of electricity per kWh of lithium-ion battery capacity during production, not taking into account other steps in the supply chain, such as mining and processing of materials.

Lithium is generally extracted from brine or hard rock (spodumene). Extracting lithium from brine involves drilling and pumping fluids from underground salar brines into evaporation ponds. Extraction of lithium from hard rock consists of extracting lithium from the ore. In 2019, most spodumene reserves were concentrated in Australia, while most lithium brine reserves were concentrated in Chile, Argentina, Bolivia and China.[167] The supply chain mining (from brine or hard rock) typically involves processing and refining into lithium carbonate. The refined lithium carbonate is then purified into battery precursors that are used by manufacturers to produce active cathode materials and electrolytes.

[167] Cf. USGS, (2021).

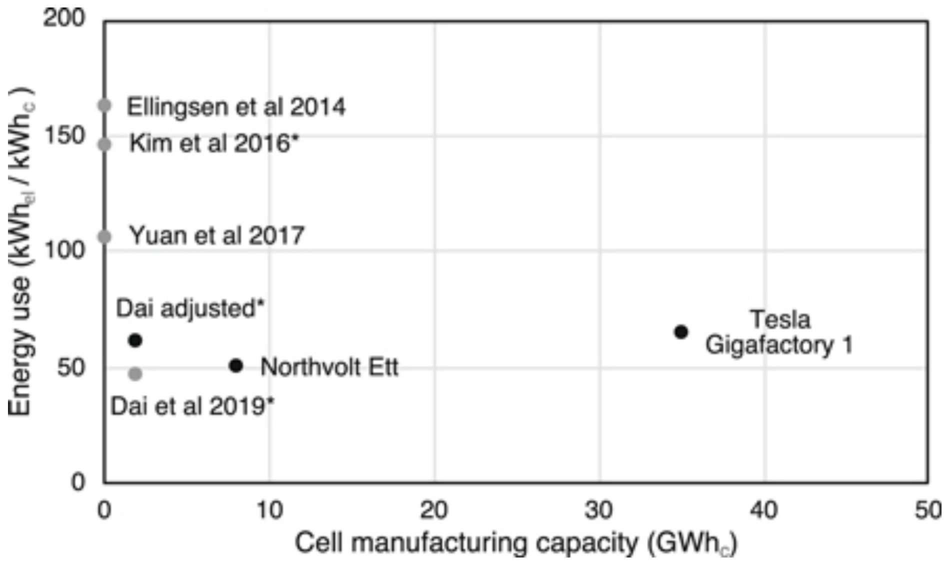


Figure 63: Electricity demand per kWh of lithium-ion electricity storage capacity.

Source: Kurland, (2019).

The Altiplano-Puna Plateau is home to the "Lithium Triangle", salt plains that stretch across Chile, Argentina and Bolivia and contain over 75 % of the world's known lithium reserves. Bolivia's Salar de Uyuni alone is estimated to contain 17 % of the world's lithium deposits.[168] Lithium mining in South America has negative impacts on water, indigenous rights and the traditional livelihoods of local communities. In Chile, lithium mining has affected the rights and livelihoods of indigenous communities (including the Lickanantay people of Chile) with violations of the right to self-determination, freedom of expression, land and water rights.

According to Gonzales (2020) in his report "Battery Paradox", Albemarle extracts brine at a rate of 442 litres/s and 23 litres/s of freshwater for lithium production in Chile. While SQM (Sociedad Química y Minera) extracts brine at 1,700 litres/s and freshwater at 450 litres/s. These two lithium mining companies together with two copper mining companies (Minera Escondida owned by BHP Billiton and Compañía Minera Zaldívar) together extract 4,230 litres of freshwater per second from the groundwater, causing hydrological stress to the Atacama salt plains. The report points out that 70 % of the water is used for mining and 17 % for agriculture, leaving only 13 % for human consumption.[169] The Bolivian government is accused of plundering the country's vast lithium deposits, which are concentrated in areas inhabited by the indigenous Aymara people.

As the popularity of electric vehicles and lithium-ion battery storage systems for households and grid balancing grows, so does the pile of used lithium-ion batteries that once powered these vehicles. Industry analysts predict that by 2020, China alone will have around

[168] Cf. Baxter, (2021).
[169] Cf. Gonzales, (2020).

500,000 tonnes of used lithium-ion batteries and that by 2030, the global amount will reach 2 Mt per year.[170] This means that batteries will be recycled, put to a second use and lithium resources will be used more efficiently. With the continued global growth of electric vehicles (EVs), a new opportunity for the energy sector is emerging: the stationary storage of electricity from used EV batteries, which could exceed 200 GWh by 2030.[171] The global lithium-ion battery recycling market, estimated at US$3.6 billion in 2020, is expected to reach a revised size of US$10.7 billion by 2026, growing at a CAGR of 19.4 % during the analysis period. Lithium nickel manganese cobalt (Li-NMC), one of the segments analysed in the report, is expected to grow at a CAGR of 20.6 %, reaching US$7.7 billion by the end of the analysis period.[172]

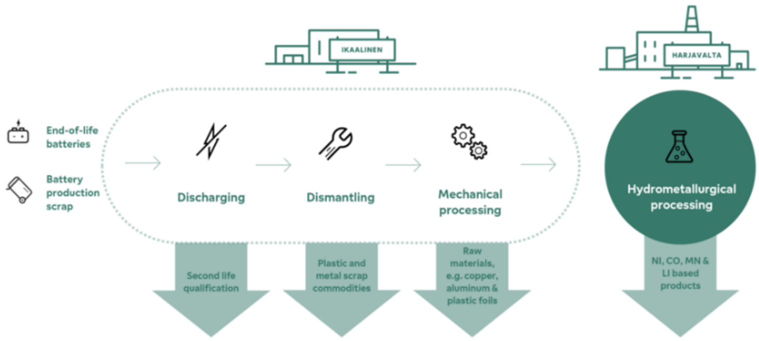


Figure 64: The lithium-ion battery recycling process.

Source: Fortum, (2022).

Lithium-ion batteries are made of metals such as lithium, manganese, cobalt and nickel. When a battery reaches the end of its useful life, the battery pack can be collected, discharged, disassembled and shredded. The shredded material is then processed into so-called "black mass" (see Figure 64). According to Fortum, 80 % of the battery parts can be recycled using a combination of mechanical and hydrometallurgical recycling processes, and 95 % of the metals are recovered from the battery black mass.[173] Companies like Duesenfeld GmbH achieve a recycling rate of 72 % in mechanical recycling, and with the processing of the black mass from the batteries in hydrometallurgy, the material recycling rate rises to 91 %.[174] Only the separator membrane and the high-boiling portion of the electrolyte in the battery are currently not recycled.

Lander et al. (2021) provided a global and comprehensive techno-economic framework that includes the assignment of a $/kWh value for the net recycling gain of different battery chemistries (LiMn2O4 (LMO), LiFePO4 (LFP), LiNiCoAlO2 (NCA) and LiNiMnCoO2 (NMC)),

[170] Cf. Jacoby, (2019).
[171] Cf. Engel et al., (2019).
[172] Cf. Research and Markets, (2022).
[173] Cf. Fortum, (2022).
[174] Cf. Duesenfeld GmbH, (2021).

recycling processes (Pyrometallurgical, Hydrometallurgical, direct recycling) and recycling sites (South Korea, China, USA, Belgium and the UK). The UK, as the country of origin of the lithium battery, and the recycling sites in Belgium, China, South Korea and the USA were chosen to be representative of the current global battery economy, where battery use and recycling often take place in different parts of the world.

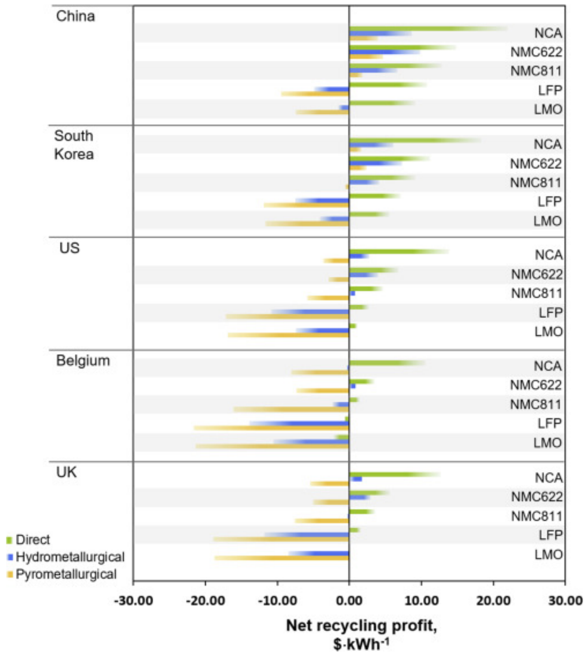


Figure 65: Net recycling gains in $/kWh, compared for five countries, using the transport costs reported in the study. Bars pointing to the left show a total loss, bars pointing to the right show a total gain.

Source: Lander et al., (2021).

The UK as a recycling location was selected as an example of in-country recycling. Figure 65 summarises the net recycling profit (NRP) for a 240 Wh/kg battery pack. Different chemicals, recycling methods and locations are compared. The highest NRP are obtained for recycling in China, direct recycling and NCA batteries. The lowest profits are achieved for recycling in Belgium, pyrometallurgy and LMO and LFP chemistry Lander et al. (2021).

Table 6: Increase in raw material demand for the construction of electrolysers for 8,100PJ of green hydrogen in the EU.

Source: Wieclawska, (2020).

Stack	CRM	Amount required for green hydrogen in 2050, as % of current global annual production	Also used in
PEM	Iridium	122%	Electronics (43%), electrochemistry (27%), chemical industry (7%)
PEM&AEL	Platinum	25%	Car catalysts (80%), jewelry (10%), chemical industry (5%)
AEL	Raney-Ni	0.4%	Ni: stainless steel, magnets, batteries, coinage, alloys, chemical industry
AEL	Nickel (class 1)	2%	Same as described for Ni above
AEL	Cobalt	0.1%	Batteries (42%), alloys (23%), materials (10%)

AEL electrolysers contain platinum, cobalt and nickel. The main advantages of AEL electrolysers are that the technology is established, they are relatively inexpensive, the number of electrolyser stacks can be easily increased and they contain fewer critical materials compared to PEM. Disadvantages of AELs are the lower current densities, the lower efficiency and the fact that the electrolyte liquid is corrosive. PEM electrolyses use a membrane (a solid polymer electrolyte) between the cathode and anode instead of a liquid. They contain iridium, platinum and tantalum. The main advantages of PEM are the high current densities and efficiencies, the fast system response that makes it suitable for dynamic operation, and the fact that the system is more compact than AEL.

In Figure 66 one can see the over 100 % increase in annual iridium demand in various industries relative to 2021. According to Wieclawska (2020), the availability of materials for the production of PEM electrolyses cannot be taken for granted, so plans for the energy transition that do not take these materials into account may be unrealizable. More details on Iridium can be found in chapter 2.13.2.8.

As countries step up their efforts to reduce emissions, they must also ensure that energy systems remain resilient and secure. Today's international energy security mechanisms are designed to provide insurance against the risks of interruptions or price spikes in the supply of hydrocarbons, especially oil. Minerals present a very different challenge, but their increasing importance in a decarbonized energy system requires energy policy makers to broaden their horizons and consider potential new vulnerabilities. Concerns about price volatility and security of supply will not go away in an electrified, renewable-rich energy system.

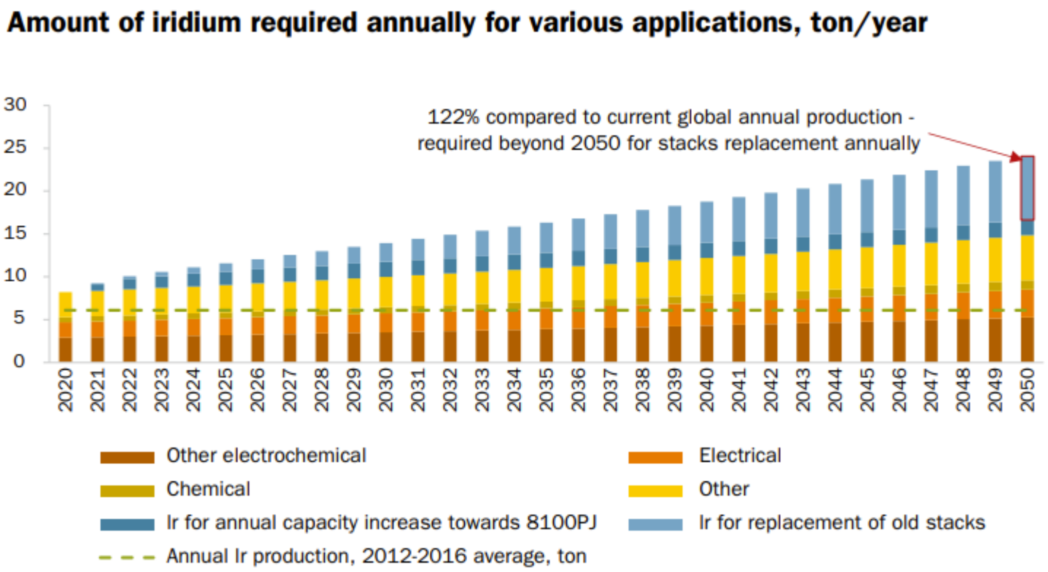


Figure 66: Iridium demand forecasts in various industries.

Source: Wieclawska, (2020).

2.3.4 Example data from Ghana, Kenya and Spain

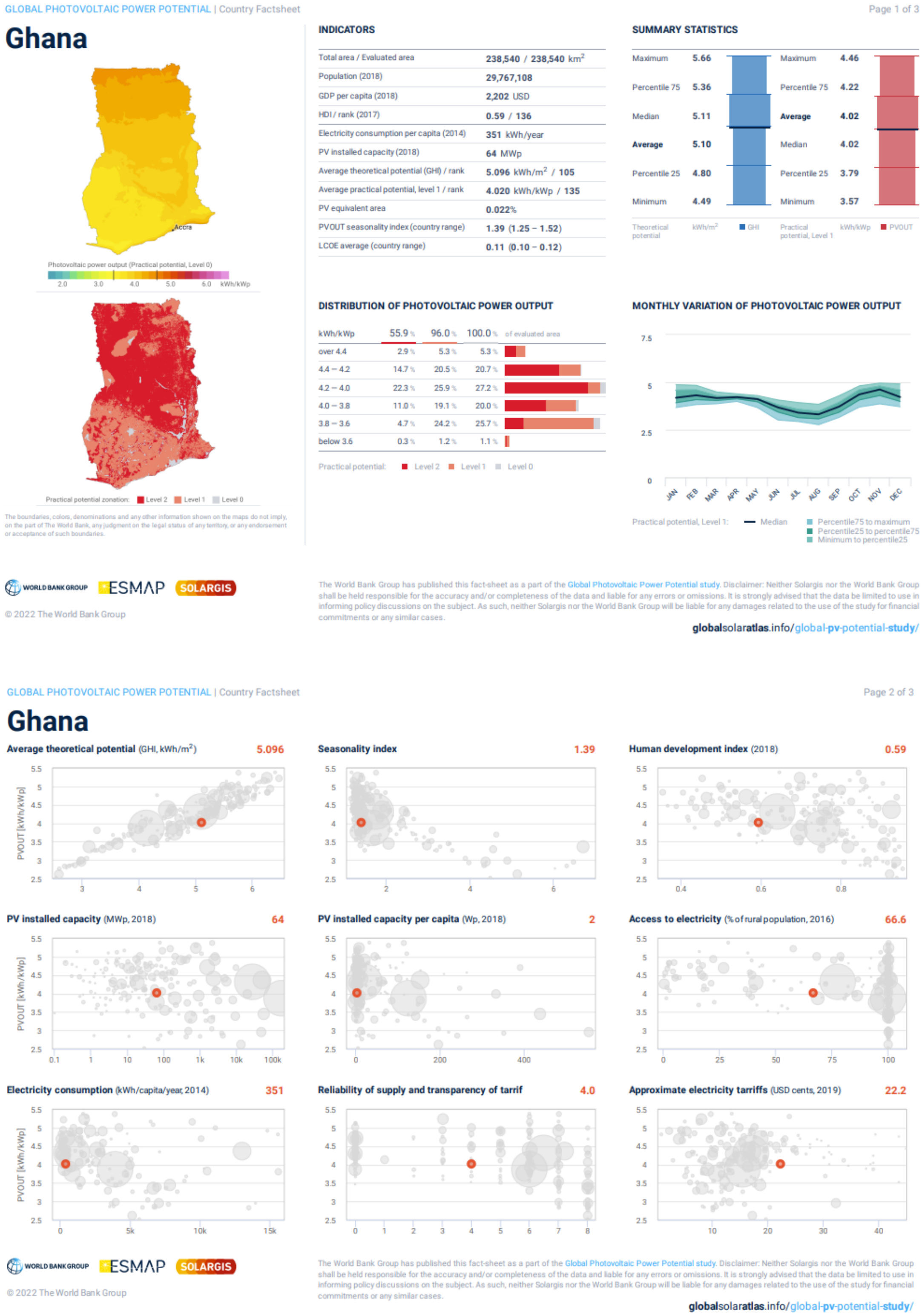
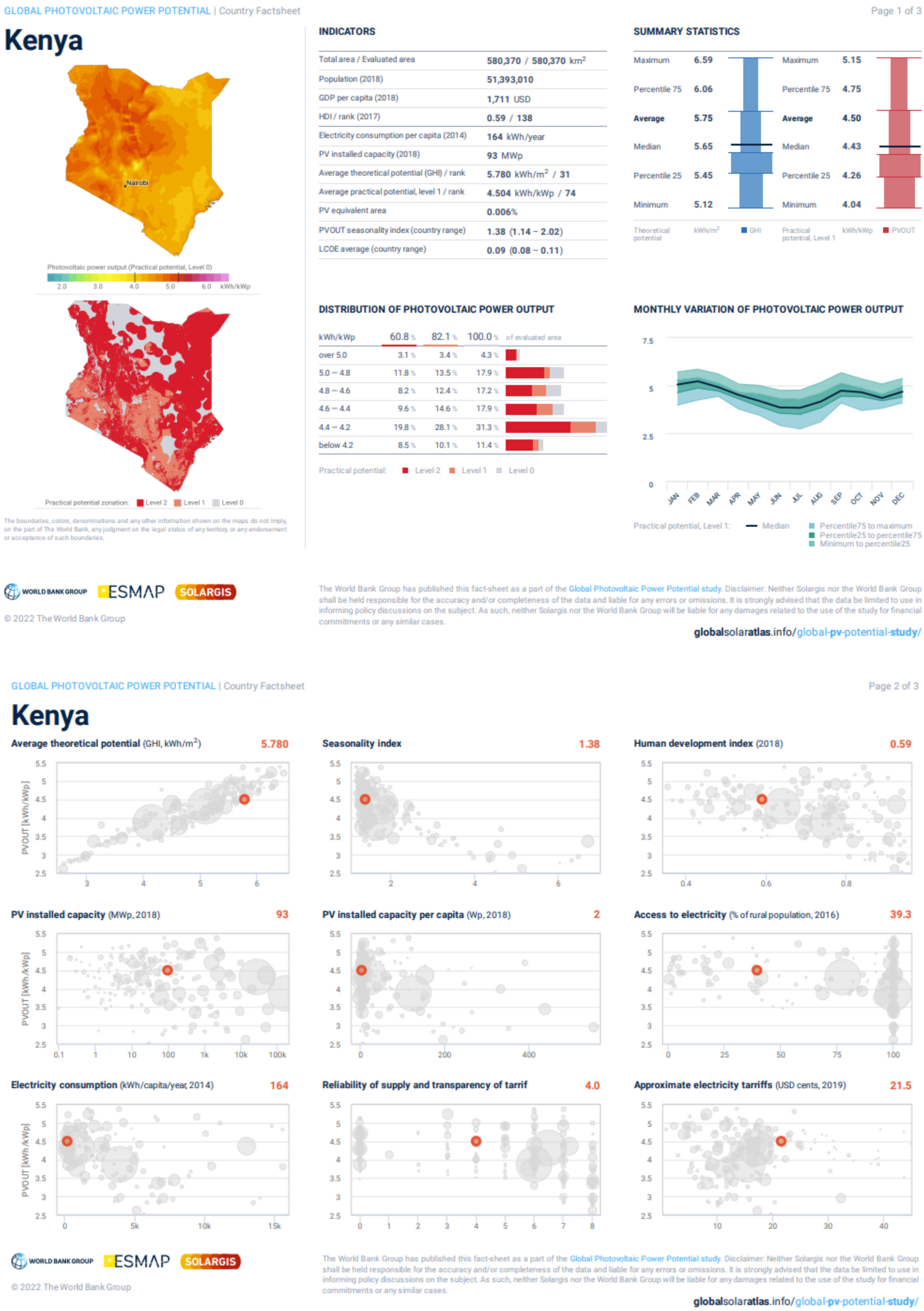


Figure 67: Data from Ghana on solar power potential and -production



GLOBAL PHOTOVOLTAIC POWER POTENTIAL | Country Factsheet

Page 1 of 3

Kenya

INDICATORS

Total area / Evaluated area	580,370 / 580,370 km^2
Population (2018)	51,393,010
GDP per capita (2018)	1,711 USD
HDI / rank (2017)	0.59 / 138
Electricity consumption per capita (2014)	164 kWh/year
PV installed capacity (2018)	93 MWp
Average theoretical potential (GHI) / rank	5.780 kWh/m^2 / 31
Average practical potential, level 1 / rank	4.504 kWh/kWp / 74
PV equivalent area	0.006%
PVOUT seasonality index (country range)	1.38 (1.14 – 2.02)
LCOE average (country range)	0.09 (0.08 – 0.11)

SUMMARY STATISTICS

	Theoretical potential (GHI, kWh/m^2)	Practical potential, Level 1 (PVOUT, kWh/kWp)
Maximum	6.59	5.15
Percentile 75	6.06	4.75
Average	5.75	4.50
Median	5.65	4.43
Percentile 25	5.45	4.26
Minimum	5.12	4.04

DISTRIBUTION OF PHOTOVOLTAIC POWER OUTPUT

kWh/kWp	60.8 %	82.1 %	100.0 % (of evaluated area)
over 5.0	3.1 %	3.4 %	4.3 %
5.0 – 4.8	11.8 %	13.5 %	17.9 %
4.8 – 4.6	8.2 %	12.4 %	17.2 %
4.6 – 4.4	9.6 %	14.6 %	17.9 %
4.4 – 4.2	19.8 %	28.1 %	31.3 %
below 4.2	8.5 %	10.1 %	11.4 %

Practical potential: Level 2 Level 1 Level 0

The boundaries, colors, denominations and any other information shown on the maps do not imply, on the part of The World Bank, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

WORLD BANK GROUP ESMAP SOLARGIS

The World Bank Group has published this fact-sheet as a part of the Global Photovoltaic Power Potential study. Disclaimer: Neither Solargis nor the World Bank Group shall be held responsible for the accuracy and/or completeness of the data and liable for any errors or omissions. It is strongly advised that the data be limited to use in informing policy discussions on the subject. As such, neither Solargis nor the World Bank Group will be liable for any damages related to the use of the study for financial commitments or any similar cases.

globalsolaratlas.info/global-pv-potential-study/

GLOBAL PHOTOVOLTAIC POWER POTENTIAL | Country Factsheet

Page 2 of 3

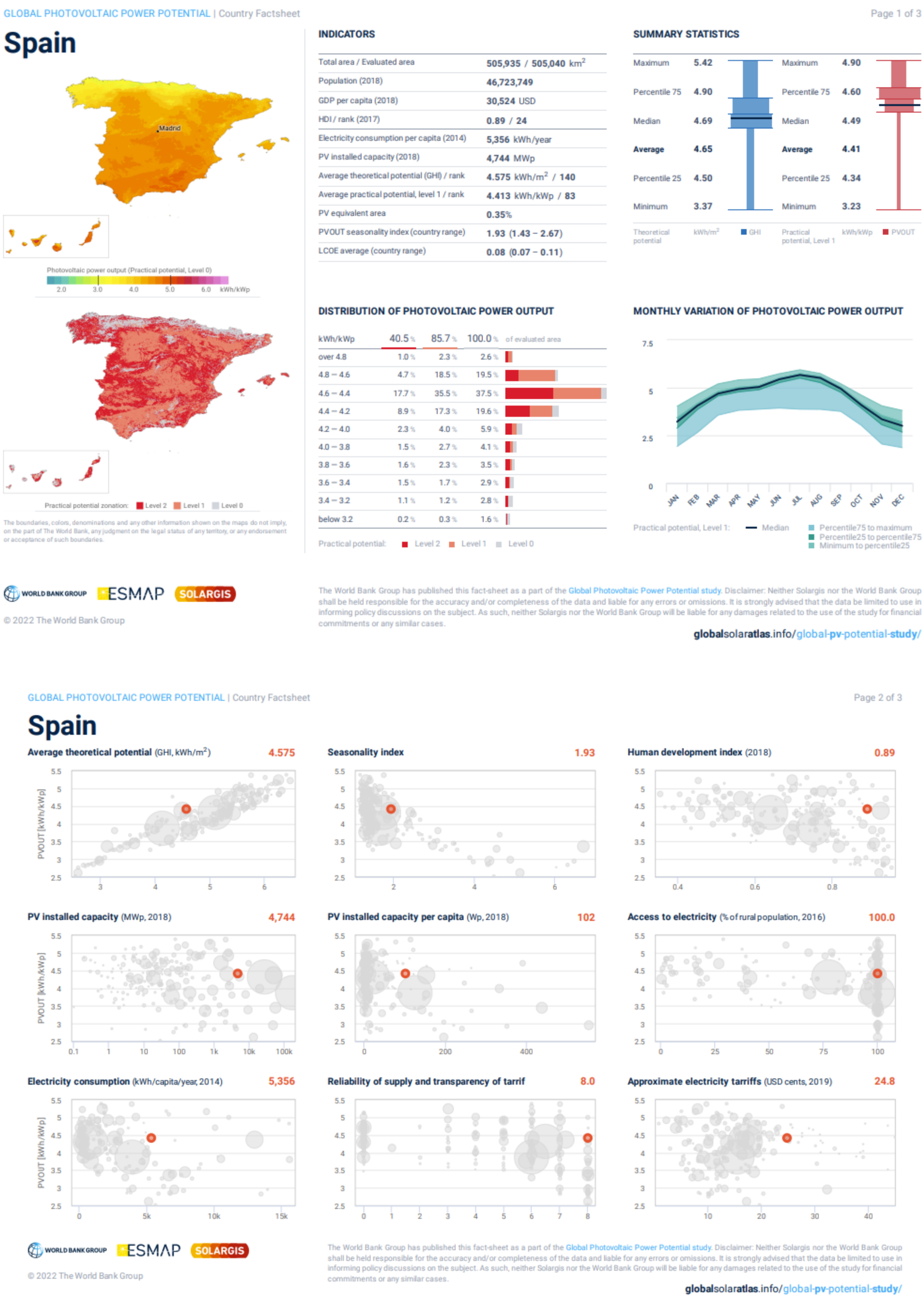
Kenya

WORLD BANK GROUP ESMAP SOLARGIS

The World Bank Group has published this fact-sheet as a part of the Global Photovoltaic Power Potential study. Disclaimer: Neither Solargis nor the World Bank Group shall be held responsible for the accuracy and/or completeness of the data and liable for any errors or omissions. It is strongly advised that the data be limited to use in informing policy discussions on the subject. As such, neither Solargis nor the World Bank Group will be liable for any damages related to the use of the study for financial commitments or any similar cases.

globalsolaratlas.info/global-pv-potential-study/

Figure 68: Data from Kenya on solar power potential and -production



GLOBAL PHOTOVOLTAIC POWER POTENTIAL | Country Factsheet

Page 1 of 3

Spain

The boundaries, colors, denominations and any other information shown on the maps do not imply, on the part of The World Bank, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

INDICATORS

Total area / Evaluated area	505,935 / 505,040 km^2
Population (2018)	46,723,749
GDP per capita (2018)	30,524 USD
HDI / rank (2017)	0.89 / 24
Electricity consumption per capita (2014)	5,356 kWh/year
PV installed capacity (2018)	4,744 MWp
Average theoretical potential (GHI) / rank	4.575 kWh/m^2 / 140
Average practical potential, level 1 / rank	4.413 kWh/kWp / 83
PV equivalent area	0.35%
PVOUT seasonality index (country range)	1.93 (1.43 – 2.67)
LCOE average (country range)	0.08 (0.07 – 0.11)

SUMMARY STATISTICS

Theoretical potential (GHI, kWh/m^2)		Practical potential, Level 1 (PVOUT, kWh/kWp)	
Maximum	5.42	Maximum	4.90
Percentile 75	4.90	Percentile 75	4.60
Median	4.69	Median	4.49
Average	4.65	**Average**	4.41
Percentile 25	4.50	Percentile 25	4.34
Minimum	3.37	Minimum	3.23

DISTRIBUTION OF PHOTOVOLTAIC POWER OUTPUT

kWh/kWp	40.5 %	85.7 %	100.0 % of evaluated area
over 4.8	1.0 %	2.3 %	2.6 %
4.8 – 4.6	4.7 %	18.5 %	19.5 %
4.6 – 4.4	17.7 %	35.5 %	37.5 %
4.4 – 4.2	8.9 %	17.3 %	19.6 %
4.2 – 4.0	2.3 %	4.0 %	5.9 %
4.0 – 3.8	1.5 %	2.7 %	4.1 %
3.8 – 3.6	1.6 %	2.3 %	3.5 %
3.6 – 3.4	1.5 %	1.7 %	2.9 %
3.4 – 3.2	1.1 %	1.2 %	2.8 %
below 3.2	0.2 %	0.3 %	1.6 %

Practical potential: Level 2 Level 1 Level 0

MONTHLY VARIATION OF PHOTOVOLTAIC POWER OUTPUT

WORLD BANK GROUP ESMAP SOLARGIS

The World Bank Group has published this fact-sheet as a part of the Global Photovoltaic Power Potential study. Disclaimer: Neither Solargis nor the World Bank Group shall be held responsible for the accuracy and/or completeness of the data and liable for any errors or omissions. It is strongly advised that the data be limited to use in informing policy discussions on the subject. As such, neither Solargis nor the World Bank Group will be liable for any damages related to the use of the study for financial commitments or any similar cases.

globalsolaratlas.info/global-pv-potential-study/

GLOBAL PHOTOVOLTAIC POWER POTENTIAL | Country Factsheet

Page 2 of 3

Spain

WORLD BANK GROUP ESMAP SOLARGIS

© 2022 The World Bank Group

The World Bank Group has published this fact-sheet as a part of the Global Photovoltaic Power Potential study. Disclaimer: Neither Solargis nor the World Bank Group shall be held responsible for the accuracy and/or completeness of the data and liable for any errors or omissions. It is strongly advised that the data be limited to use in informing policy discussions on the subject. As such, neither Solargis nor the World Bank Group will be liable for any damages related to the use of the study for financial commitments or any similar cases.

globalsolaratlas.info/global-pv-potential-study/

Figure 69: Data from Spain on solar power potential and production