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ORIGINAL RESEARCH

Life-cycle impacts of pumped hydropower storage and battery storage

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Abstract Energy storage is currently a key focus of the energy debate. In Germany, in particular, the increasing share of power generation from intermittent renewables within the grid requires solutions for dealing with surpluses and shortfalls at various temporal scales. Covering these requirements with the traditional centralised power plants and imports and exports will become increasingly difficult as the share of intermittent generators rises across Europe. Pumped hydropower storage plants have traditionally played a role in providing balancing and ancillary services, and continue to do so. However, the construction of new plants often requires substantial interventions into virgin landscape and bio-habitats; this is often fiercely opposed by local citizens. Utility-scale lithium ion batteries have recently entered the energy scene. Albeit much smaller than most pumped hydropower plants, they can also provide the required balancing and ancillary services. They can be constructed on brownfield sites as and where needed, to support the move towards increasingly decentralised energy systems. Although they are seen by some as a more environmentally friendly option, they do cause impacts relating to the consumption of limited natural resources during the production stage. Addressing initially technological capacity of pumped hydropower storage and utility-scale battery to meet the required services, a simplified LCA will be performed to examine the environmental impacts throughout their life cycles. This includes two sensitivity analyses. Issues addressed in this paper include also methodological issues relating to comparability and those parameters that are pivotal to the LCA result.

Keywords Pumped hydropower · Utility-scale batteries · LCA · Balancing and ancillary services

Introduction

Following the Fukushima disaster in 2011, the German federal government decided on an accelerated energy transition, involving the retirement of all nuclear power stations by 2022 at the latest, while aiming for a share of at least 80% of electricity generation from renewable sources by 2050 [1]. Due to the intermittent nature of many of these renewables, requirements for balancing in the widest sense will increase. However, those technologies currently providing most of the balancing energy, i.e., conventional power stations, will decrease [2]. At the same time, new players such as energy stores and virtual power stations have entered the market recently [3].

Pumped hydropower storage systems use excess power to pump water uphill into storage basins and release it at times of low renewables output or peak demand and thus are well suited to complement intermittent renewables. The technology is well proven and reliable. It is, however, constrained by the limited availability of sites. Often sites that are suitable on technical grounds are within mountainous landscapes of great natural beauty or within important bio-habitats. Hence new projects often attract fierce local opposition [4]. The question that arises is whether these impacts can be justified, considering the importance of pumped hydropower storage for a more sustainable energy system.

At the same time, battery technologies have been developing at a fast pace in recent years. Utility-scale batteries, while not new in principle, are now using modern lithium ion technology and are now being used to provide a range of balancing services. In contrast to pumped

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hydropower stores, utility-scale batteries do not have to be expansive centralised installations with capacities in the order of magnitude of several GWhs. The required capacity can be broken down into smaller units and distributed across a number of sites. Hence, they are not impacting on the local landscape to the same degree. They do, however, have particular requirements with regard to the materials that they are made from, how they can be operated, and how they are decommissioned at their end of life.

Hence, the question arises which technology is preferable on environmental grounds, if not only local impacts but also those relating to production and extraction of raw materials in other countries are considered, and if impacts in all stages of the life cycle are considered.

Research question and methodology

There are three questions that have guided the work underlying this paper:

- To what extent are pumped hydropower stores and battery stores comparable on technical grounds and in the way they serve the grid?
- Which storage technology performs better environmentally if a range of global environmental impacts are considered over the entire life cycle?
- To what extent do changes to key parameters such as life span influence the results?

Initially, both technologies have to be matched as closely as possible in terms of their ability to provide balancing and ancillary services. This requires an analysis based on a literature review.

On this basis, the environmental impacts over the whole life cycle are calculated using a simplified life cycle analysis (LCA) based on the ecoinvent data sets, but also incorporating real-life data as and where available. Finally, two sensitivity analyses are being undertaken.

As the first question has been discussed in [5] in greater detail, findings will be summarised here. The focus of the paper at hand lies primarily on the detailed discussion of the LCA results including sensitivity analyses and the impact of key parameters, complemented by an outlook to future developments.

Background—energy in Germany

In Germany, low carbon nuclear power is being phased out gradually since the Fukushima disaster. It is being replaced in parts by renewable power, but also in parts with power generation from CO_2-intensive lignite. This has led to a rise of the CO_2 emissions factor of German electricity generation between 2011 and 2013 to 622 g CO_2/kWh [6]. Emissions have since started to decline again somewhat [7]. In 2015, the German electricity mix contained 32.5% of electricity from renewable sources. However, this overall share has contained substantial fluctuations between day and night and also fluctuations dependent on the availability of wind and sun [8]. Official current targets aim for at least 80% renewables in 2050, based on the German Renewable Energy Law of 2012 (EEG 2012, [9]). This date may be brought forward in the wake of the Paris agreement of December 2015 [10], but no new formal targets have been agreed yet at the time of writing.

Nevertheless, as and when such high levels of renewables are achieved, there will be an increased need for balancing and ancillary services at differing temporal scales [2]. Balancing is required at different levels and temporal scales of the energy system, i.e., for frequency containment processes, frequency restoration processes, and reserve replacement processes. Other ancillary services relate to voltage control and emergency and restoration. As the potential providers of these, storage technologies will become more important. Storage technologies are, therefore, the subject of intense research [11, 12]. However, it must be remembered that it takes time to build up sufficient storage capacity. This applies in particular for pumped hydropower stores, which take many years, even decades of planning and construction [13]. Hence, the anticipated storage need has to be addressed early.

Technologies and data to be compared

Two electricity storage options will be compared—a pumped hydropower store and a lithium-ion battery store at utility scale. With comparisons, it is, in general, critical whether the analysed objects are comparable at all. This also applies to the case at hand: even though both technologies are being discussed within political discourses as substitutes, the different economic and technological characteristics of pumped hydropower and battery stores described below show that the emerging battery stores should rather be seen as a complementary technology to the existing hydropower stores than as substitutes.

The pumped hydropower store will provide 1 GW of power and a capacity of 9.6 GWh. The sizing of the battery has to be comparable to undertake a comparative life-cycle analysis—see also the section "Definition of functional unit and time frame".

Pumped hydropower storage has been in use since the early 20th century. It is a technically well-understood, well-proven, economic viable, and reliable technology that can be built at large scale, often having several GWh of storage capacity. Total worldwide capacity is estimated at

127 GW (7 GW in Germany [14]), making it the largest scale technology for electricity storage. Therefore, it can provide large amounts of balancing energy services [15]. Pumped hydropower stores mechanical energy and is being used for load balancing within electric power systems. Energy is being stored in the form of the gravitational energy potential of water, which is pumped from a reservoir at lower level to another reservoir at higher altitude, when there is abundant or cheap energy in the system. At times of high electricity demand, the stored water is released through turbines which produce electric power. Some losses occur in the pumping process, thus making the plant a net consumer of energy [15].

With emerging battery needs for a vast range of applications, including electric vehicles, research and development of batteries are currently evolving at a swift pace [16, 17]. Large utility-scale batteries using lithium ion technologies have only emerged recently. They consist of a large number of battery units on racks filling large halls [18]. They are operated similar to pumped hydropower energy storage, storing energy at times of high availability, and feeding it back into the grid at times of high demand [19]. With efficiencies of over 90% (e.g. [20, 21]), low memory effect and slow aging [22], lithium-ion batteries represent an appropriate choice for large-scale stationary applications [21, 23]. The particular type of lithium-ion technology considered here are lithium–manganese batteries. The fact that lithium-ion batteries can cope well with partial charging cycles makes them well suited for buffering energy requirements in both directions: reducing excesses and feeding into counteract shortfalls in the system [24]. To allow for operation in the low state of charge zone battery arrays should be over-dimensioned [25].

The WEMAG utility-scale battery in Schwerin is currently Germany's largest utility-scale battery with a capacity of 5 MW and able to store 5 MWh. It went online in September 2014. It mainly provides short-term balancing energy and has been the subject of a number of studies [18, 22, 26]. Nevertheless, the economic viability of large utility-scale batteries must be questioned, as, e.g., the WEMAG utility-scale battery was subject to substantial initial funding of 1.3 Mio € [27].

With the use of utility-scale batteries being an emerging field, developments can only partially be anticipated. The assumptions of this study should, therefore, be checked carefully.

Ability to provide balancing and ancillary services

To compare pumped hydropower stores and utility-scale battery storage, the two options have to be sized in a way that allows for comparable functionality. This will be the basis on which the so-called "functional unit" for the life-cycle analysis will be defined [28].

The German Energy Agency (DENA)'s study on balancing and ancillary services [2] was used as a basis for defining functionality. It explores those services likely to increase in importance due to the evolving energy transition. Based on [29–32], an assessment has been made of the ability of the two technologies to provide the services listed (see Table 1).

Both storage technologies are capable of providing an almost identical range of balancing and ancillary services. The technologies do, however, differ in the extent to which they can provide these services. Batteries tend to have an energy-to-power ratio (E2P) of around 1:1 [33, 34]. Hence, they are designed to provide their services on a short-term basis of minutes or a low number of hours. Batteries are particularly well suited to fast-response short-term balancing requirements [35]. Larger storage capacities for long-term services are not currently common [34]. Pumped hydropower storage, on the other hand, tends to hold large volumes, has far higher E2P ratios, and is able to provide long-term services, specifically the compensation of periods of low sun and simultaneously low wind, and to some degree interseasonal fluctuations. The pumped hydropower storage system modelled here could, for example, provide 1000 MWh a day for almost 10 days (information provided by a pumped hydropower storage operating company). This equates to the electrical demand of 120,000 average German households [36]. As pointed out above, it is these longer term services that are expected to be in greater demand as the share of renewable electricity grows [14].

There are other differences in terms of what each technology does best, relating to their inherent technical characteristics and preferred running modes [29]. On one hand, modern batteries will last longer if charging and discharging are done incrementally, thereby avoiding maximum charge and depletion. On the other hand, if pumped hydropower is running on part load, its efficiency is being compromised. However, any storage technology will have to weigh up preferences based on technical characteristics on one hand against grid requirements and related economic impacts on the other. In so far, a trade-off has to be made between maximum operating hours and optimum operational loads.

In summary, also with regard to the provided services, there are limitations as to what extent one technology can be substituted for the other; nonetheless, the ranges of the technical capabilities of both allow for a reasonable comparison to be made.

Table 1 Suitability for balancing and ancillary services (based on [29–32])

	Pumped hydropower Storage	Utility-scale battery
Frequency control		
Frequency response reserve	++	+(+)
Frequency containment reserve (up to 30 s)	+	++
Frequency restoration reserve (FRR) (active in 30 s, up to 5 min)	++	+
Replacement reserves (RR) (active in 5 min)	++	+
Bridging of periods of low sun and wind	+	–
Interseasonal balancing	(+)	–
Loads that can be turned on	+	+
Loads that can be turned off	+	+
High/low frequency response (within 10 s, increase/reduction in active power)	+	+
Load balancing at transmission system level	+	−(+)
Voltage control (keeping voltage in the allowable band, limiting voltage breakdown in case of short circuiting)		
Provision of reactive power	++	+
Reactive power services	+	+
Voltage dependant redispatch	++	+
Fault-ride-through	–	+
Voltage management	+	+
Phase shifting mode	+	+
General voltage stabilisation	+	+
Emergency and restoration (in emergency, blackout, and restoration states)		
Black-start capability	+	+
Decoupling of supply and demand	++	+

Key: ++ very well suitable, + well suitable, (+) only conditionally suitable, − not suitable

Life-cycle assessment (LCA)

Having established that the two technologies have comparable functionality in principle, their potential life-cycle impacts will be examined. An LCA calculates environmental and human health impacts, as well as resource depletion which result from inputs into the necessary processes (materials, energy) and outputs (emissions, waste…) over the whole life cycle of a product or process. Manufacturing with its upstream processes[1] including raw material extraction, operation, and disposal at end of life and all energy requirements throughout the life cycle are included. The methodology is laid down in two ISO standards: ISO 14040 and 14044.

The software Umberto NXT universal in combination with the database ecoinvent v3.2 was chosen for calculating the LCA. The LCA database ecoinvent was relied on for a substantial share of the required data for the life-cycle inventory (LCI[2]) and upstream processes, though it was supplemented with real data wherever possible (see also section "Summary of input data"). In so far, it is a simplified LCA, which is presented here.

Life-cycle stages

A cradle-to-grave analysis will be undertaken. The following life-cycle stages will be considered:

- Productions stage: manufacturing and construction including extraction and all processing of raw materials, transportation processes, construction processes, all energy and water requirements, resulting emissions, wastes, and waste disposal.
- Use stage: operation including management, maintenance, and replacement measures, in particular replacement of battery units, difference between stored and generated energy due to efficiency losses and internal electricity requirements, direct emissions from electricity generation with related upstream processes of power stations, and other generating technologies and

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[1] Upstream processes: processes that happen before those that are directly linked to the item or system to be assessed, such as for example raw material extraction, energy required for extraction as well as environmental impacts resulting from these.

[2] Life cycle inventory (LCI): compilation of the data of all the flows in and out of the product system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance.

infrastructure; for the pumped hydropower storage: lubricating oil consumption and methane developing in reservoirs (according to [37]).
- End-of-life stage: decommissioning and disposal including dismantling, separation, processing and recycling, treatment and safe disposal of hazardous wastes, final disposal of non-recyclables, related transportation processes, energy consumption, and emissions.

Indicator selection

Impact categories have been selected based on a number of considerations relating to the technologies to be assessed, which are set out in the following.

The technologies concerned relate to the energy system and also consume a substantial amount of electricity themselves. The indicators global warming potential and cumulative energy demand were selected to reflect this. The global warming potential (GWP) or greenhouse effect is quantified using global warming potentials (GWP) for substances having the same effect as CO_2 in that they reflect heat radiation (e.g., methane, nitrous oxide…). GWP for greenhouse gases are expressed as CO_2 equivalents (CO_2-eq.), i.e., the effects are expressed relatively to the effect of CO_2. The calculation method used for this indicator is the ReCiPe methodology which complies with IPCC specifications [38]. The indicator cumulative fossil energy demand (CED fossil) measures the primary energy demand required within the life cycle and is measured in MJ [39]. The methodology used is the ecoinvent methodology.

Both technologies require large amounts of minerals and metals in their production and construction, as reflected in the indicators cumulative energy demand of minerals and cumulative energy demand metals. These two indicators represent a way of measuring impacts on natural resources, through the exploitation of mineral and metal resources. These indicators were chosen because of their ability to assess metal and mineral resource needs in two separate indicators but on the same basis of valuation, namely energy. Energy is in principle the share of energy that can be converted into work in relation to a defined reference surrounding. This is dependent on the chemical composition and the concentration. In this case, the indicator considers energy in the chemical conversion of the refining processes, i.e., the embodied energy of the refining processes. It is measured in the unit MJ-equivalent. Both indicators are calculated using the ecoinvent methodology [40].

Pumped hydropower stores constitute substantial interventions into the landscape. The indicator natural land transformation (NLT) according to the ReCiPe methodology [38] has been selected to reflect this. The indicator measures the transformation of virgin land such as forests, rain forests, lakes, and oceans to non-natural land. It includes direct land-use and land-use in upstream chains. The unit of measurement for the indicator is m^2.

The indicators eutrophication potential and human health carcinogenic have been added to reflect impacts on human, animal, and plant life. Eutrophication potential describes the depletion of oxygen in a water body as a response to the addition of excess nutrients, mainly phosphates. This induces an explosive growth of plants and algae, consumes oxygen from the water, and leads to the death of aquatic animals, and more generally to changes in the flora and fauna in rivers and lakes. It is a result of the discharge of phosphate-containing detergents, fertilizers, or sewage into an aquatic system. The unit is phosphate-ions (PO_4^{3-}). The indicator is calculated using the ReCiPe methodology [38]. The indicator human health carcinogenic measures carcinogenic effects of chemical substances, for example those of heavy metals, dioxins, furans, and their effects on the human body. The indicator is calculated using the USEtox methodology and uses the unit "comparative toxic units", (CTU).

Definition of functional unit and time frame

The functional unit defines the performance of the object that is to be assessed. In this case, the functional unit is an entity able to perform a defined set of functions. Both technologies, therefore, have to be sized accordingly to be able to serve these functions, despite their differing technical characteristics. As an initial point of the analysis has been the local opposition to new hydropower projects arguing for an ecologic better performance of battery stores, we generally use rather conservative assumptions for the hydropower stores to justify or falsify this argument.

To define the functional unit, in particular, the aforementioned differences in typical energy-to-power ratios, and also different ways in operation and deployment have to be taken into account. Comparable sizing could either be based on power in MW or on storage capacity in MWh or on the ability to meet a given annual output of electricity stored and fed into the grid (MWh/a). The implications of each approach were discussed in [5] in greater detail.

In summary, the capacity (MWh) of the battery as determining factor takes into account the pumped hydropower store's ability to deliver long-term balancing services, while the other approaches do not. As it is these longer term services which will see an increase in demand [14], this option will be pursued for the base case.

Consequently, the functional unit for the comparison will be defined as the provision of 9.6 GWh stored energy over a time span of 80 years, that is able to provide the balancing and ancillary services defined in Table 1.

Therefore, the data available for the 5 MWh WEMAG battery-store in Schwerin, Germany have to be scaled up initially by a factor of 1920 to 9.6 GWh. The battery may lose 20% of its storage capacity within 20 years (e.g. [41]) due to aging and degradation processes (reflecting its 20-year warrantee [42]). It will, therefore, be over-dimensioned by 10%, over-producing in the beginning, and under-producing towards the end of the life time. Individual battery cells would be replaced gradually, as and when necessary. Hence to provide comparable output on average over the course of its life span, the scaling factor is 2133. It is assumed that the battery solution would be spread over a number of locations, each installation of comparable size to the original installation in Schwerin as it is unlikely that a utility-scale battery 2133 times the size of the installation in Schwerin would be installed in one single location. Therefore, the building housing the battery racks can be scaled up using the same factor as for battery components. Nevertheless, the battery option will be referred to in the singular in the following.

In literature, the life span of pumped hydropower storage ranges from 50 to 150 years with almost no performance deterioration [43, 44]. A period of 80 years was chosen for the base case. There is no long-term evidence yet for life spans of utility-scale batteries, as this is a recent and continuously evolving technology. However, a life span of 20 years can be found in literature [20] and is in line with the warranty for the WEMAG battery in Schwerin. Hence, replacement requirements for the battery units every 20 years have been assumed. Nevertheless, an earlier replacement is possible not only due to higher performance deterioration but also due to technological progress.

System boundaries

The system boundaries of an LCA determine which components and processes are to be included in the assessment. In this case, this includes components of the storage medium, the built structure, and technical components up to the point of hand over to the grid. For the pumped hydropower store, this includes the reservoirs and the water contained within them as storage medium, other built structures such as the underground turbine hall, all necessary services for the turbine hall such as lighting, ventilation, etc., the tunnel penstock and the surge tank. Furthermore, the technical components of the pumps, turbines, cabling, management system, and switchgear and transformers are included. For the utility-scale battery, the battery cells and battery casing make up the storage medium. The built structures include the industrial hall with shelving racks and trays, which house the battery units, as well as building services for heating, cooling, ventilation, and lighting. The technical components of inverters, cabling, a battery management system, switchgears, and transformers are also included.

Building services, management systems, switchgears, cabling, and transformers are, in both the cases, only included up to the point of grid connection.

Summary of input data

For the pumped hydropower, store data could be obtained from a pumped hydropower operator in aggregated form. These data are being complemented by data from ecoinvent and from literature. Technical and operating characteristics are based on real-life data from the operator.

For the utility-scale battery, performance data are being used from the WEMAG store in Schwerin, as found in literature [22, 23]. In particular, the efficiency including all operational losses is based on these sources. However, data regarding material composition and production processes are not based on the WEMAG store, but on ecoinvent data for lithium manganese batteries [45].

Ecoinvent data are depended upon, in both the cases, the upstream processes and their impacts.

Based on the available data and previously discussed considerations, the input data in Table 2 will be used for the life-cycle analysis:

A note on the item “total losses”: these are made up of efficiency losses and internal energy consumption. The pumped hydropower store requires energy for ventilation and lighting in the underground turbine hall. It, furthermore, consumes energy for its back-up generator and a number of ancillary services. The utility-scale battery has very specific requirements regarding its optimal operational conditions. It requires heating, cooling, and ventilation to keep the conditions in the battery environment as stable as possible [46].

Results of the simplified LCA

Figure 1 shows the shares of the different life-cycle stages in the overall impacts, solely for the pumped hydropower store on its own.

Impacts of decommissioning and disposal are barely visible. Impacts of the operational stage (“use stage”) dominate those of the production stage in all categories except for cumulative energy demand. Especially, the categories global warming potential, eutrophication

Table 2 Data and assumptions

	Pumped hydropower storage	Utility-scale battery
Storage capacity	9.6 GWh	9.6 GWh
Power rating	1 GW	9.6 GW (E2P = 1:1)
Efficiency	74.96%	72.5%
Total losses per MWH generated	0.350 $\text{MWh/MWh}_{\text{generated}}$	0.379 $\text{MWh/MWh}_{\text{generated}}$
Life span	80 years	20 years (=current best practice)
Maintenance and replacement cycles	Continuous use of lubricating oil major overhaul of pumps, turbines, and generators for every 25 years	Replacement of battery units every 20 years (no replacements cycles assumed for the building)
Electricity generated per year	1855 GWh/a (based on an existing installation)	1855 GWh/a
Full cycles per year	n/a	194
Deterioration of performance	n/a	20% in 20 years
Main raw materials	Steel: 43.6 Mt	Ecoinvent data for factory building
	Concrete: 2966 Mt	Ecoinvent data for lithium–manganese battery
	Copper: 0.5 Mt	
Direct use of land	98 ha	400 m^2 (estimated) × scaling factor
Type of land-use	Greenfield site	Ecoinvent option for "unspecified land", which assumes 40% greenfield and 60% brownfield
Other data	Electricity use for building services, control and management systems, methane generation in basins as per ecoinvent data for hydropower	Electricity use for building services, control and management systems, Energy density of 114 Wh/kg Low self-discharge rate
Electricity mix	Current German electricity mix used over the whole life cycle (in line with common LCA methodology)	

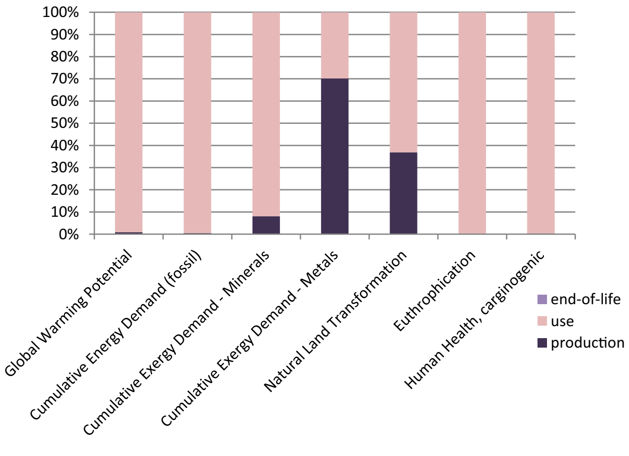


Fig. 1 Environmental impacts of pumped hydropower store according to life-cycle stage

potential, and human health carcinogenic show only a small contribution of the production stage to overall impacts. The use stage is largely made up of the impacts of operational energy losses, i.e., the difference of stored energy and released energy. These losses depend on efficiency losses and internal energy demands of the installations.

Figure 2 shows the equivalent results for the utility-scale battery. In contrast to the pumped hydropower store, impacts from decommissioning and disposal are discernible and impacts from the production stage are larger. This is largely due to the replacement cycles for the battery units every 20 years, which is shown in red.

In Fig. 3, the impacts of both technologies are juxtaposed (utility-scale battery = 100%). The comparison shows that the impacts resulting from the use stage are of similar order of magnitude for both options in most categories, which, in turn, has an equalising effect on overall results. They stem mainly from efficiency losses and internal energy requirements. This, however, does not apply to the categories cumulative energy demand metals and cumulative energy demand minerals. This impact in the use stage is comparatively small. The reason for this is that impacts of the use stage are mainly due to electricity generation making up the electricity mix of the German grid. Metals and minerals do not play a major role in energy generation except for in upstream impacts. The category natural land transformation is the only category in which impacts of the pumped hydropower store exceed those of the utility-scale battery slightly, based on the assumptions stated previously.

A small proportion of impacts, especially in the category global warming potential, results from the potential methane formation in storage basins and the use of lubrication oil for the pumped hydropower store. If these were to be ignored for now, the remaining impacts from the use and end-of-life stage show higher impacts for the utility-

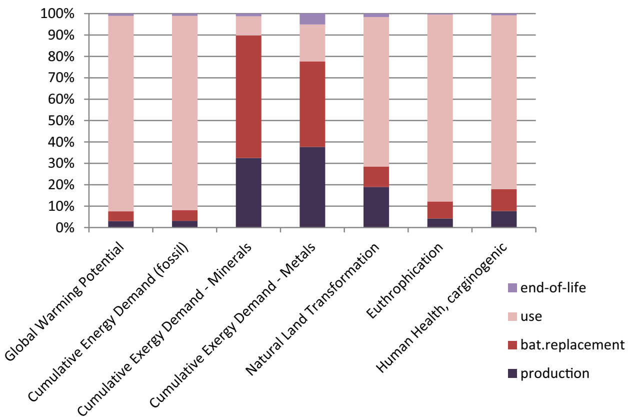


Fig. 2 Environmental impacts of utility-scale battery according to life-cycle stage

scale battery in all categories except natural land transformation.

The role of efficiency losses, internal energy requirements, and assumptions underlying land-use will be discussed in detail later on.

Sensitivity analysis

In general, LCA results harbour always a number of uncertainties and are dependent on the particular assumptions made. Sensitivity analyses, therefore, have to be undertaken to understand the importance and influences of key parameters.

Assumptions deemed to be pivotal in this case are those relating to the life span of the pumped hydropower store, on one hand, and the scaling of the utility-scale battery on the other. Variations of these parameters will, therefore, be tested by way of two sensitivity analyses.

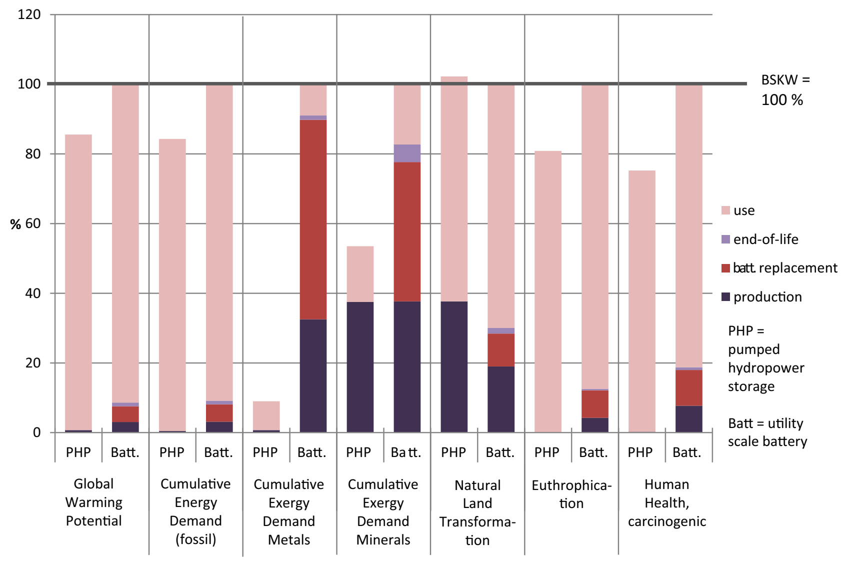
While the reference scenario assumes a life span of 80 years for the pumped hydropower store, this is a conservative assumption. The ecoinvent database for example assumes a life span of 150 years as a default for pumped hydropower, where this occurs within the ecoinvent data for the German electricity mix. This life span has been confirmed as realistic by an operator of pumped hydropower storage.

Alternative approaches to scaling the battery are also possible, as explained previously. The chosen approach of scaling to equal capacity ensures that the battery can provide the same amount of work as the pumped hydropower station, thus allowing for longer term balancing and ancillary service provision. However, this is at odds with typical sizing of battery storage. A utility-scale battery with a storage capacity of 9.6 GWh would, according to common E2P rules, have a much higher capacity than the pumped hydropower storage. It would, therefore, be able to provide short-term balancing services to a far greater extent than assumed for the pumped hydropower storage. It was, therefore, decided to investigate a utility-scale battery sized to generate merely the same annual output (MWh/a) as the pumped hydropower store. In this case, the number of annual full charging cycles for the battery is the decisive parameter. This implies, however, that longer term balancing and ancillary services would have to be excluded from the comparison in this case.

Sensitivity analysis I: lifespan of pumped hydropower storage

The first sensitivity analysis uses a life span of 150 years for the pumped hydro store, in line with the ecoinvent assumption. The assessment period, however, remains at 80 years. This approach leads to the impacts of the

Fig. 3 Comparison of environmental impacts according to life-cycle stage in the reference scenario



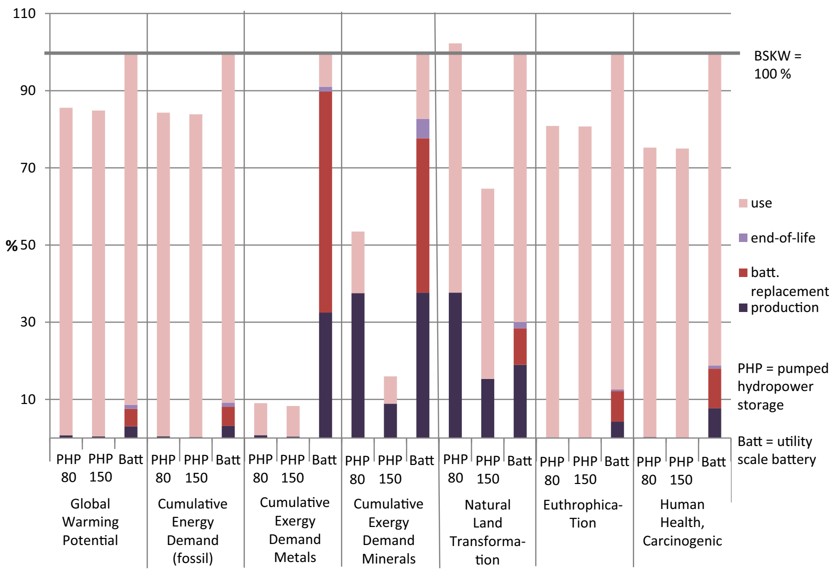


Fig. 4 Comparison of environmental impacts in sensitivity analysis 1—life span of pumped hydropower store = 150 years

production and end-of-life stage being distributed over a greater number of years. As these impacts are proportionally attributed to the assessment period, results for all indicators score lower for the version with the 150-year life span than the pumped hydropower option in the base case. The difference to the utility-scale battery is amplified (Fig. 4).

Notably, the impact of the pumped hydropower store in the category natural land transformation is reduced, no longer exceeding the result of the utility-scale battery. Natural land transformation impacts are now approximately a third lower than those of the battery option. Therefore, in this scenario, all environmental impacts are now without exception lower than those of the utility-scale battery.

The only other indicator showing a visible difference is cumulative energy minerals. In particular, the high mineral requirements for the construction of storage basins and other infrastructure are only taken into account proportionally for 80 years of the 150-year lifespan. The other differences between the two versions of the pumped hydropower station are hardly visible for the indicators global warming potential, cumulative energy demand metals, eutrophication potential, and human health carcinogenic, as impacts are dominated by the impacts of the operational stage, which remain the same as in the base case. For this reason, the impacts resulting from efficiency losses and internal energy consumption have been omitted in Fig. 5. The graph shows, in particular, that it is the lower impacts in production that lead to a better performance in terms of natural land transformation. Remaining impacts in the operational stage relate to lubricating oil and methane development in the reservoir.

Sensitivity analysis II: charging cycles of utility-scale battery

The assumptions made regarding the running of both technologies in the reference scenario would result in 194 charging cycles per year for the utility-scale battery. However, for such a battery to be economically viable, 300–360 cycles per year would need to be achieved [22, 34]. In other words, sizing the battery based on equal capacity in GWh, while allowing for the same long-term services, results in the utility-scale battery being under-used or over-sized for the assumed use, expressed in GWh/a.

The cycle life of best available technology is currently 10,000 cycles. Scientists assume that batteries with a cycle life of up to 20,000 cycles are feasible [17]. This would equate to 1000 full cycles over 20 years. Sensitivity scenario 2 assumes that the battery would complete 1000 cycles per year, still generating the same 1855 GWh of short-term balancing services per year. It is not currently known what chemical composition such a battery would have nor what the production processes involved would be. The same lithium–manganese composition as used in the base case will, therefore, be assumed. Putting it another way, it is assumed that the same batteries would be improved to be much more resilient to withstand the additional charging cycles. The battery would only need to have a capacity of 2.06 GWh (instead of 9.6 GWh) in this scenario. The example installation in Schwerin only needs to be scaled up by 413, rather than 2133. It has to be stated though that in this case, the maximum power available from the battery store in case of grid emergencies would be significantly lower than in the base case. In this way, the scenario is to be seen as representative for unknown future developments in battery technology.

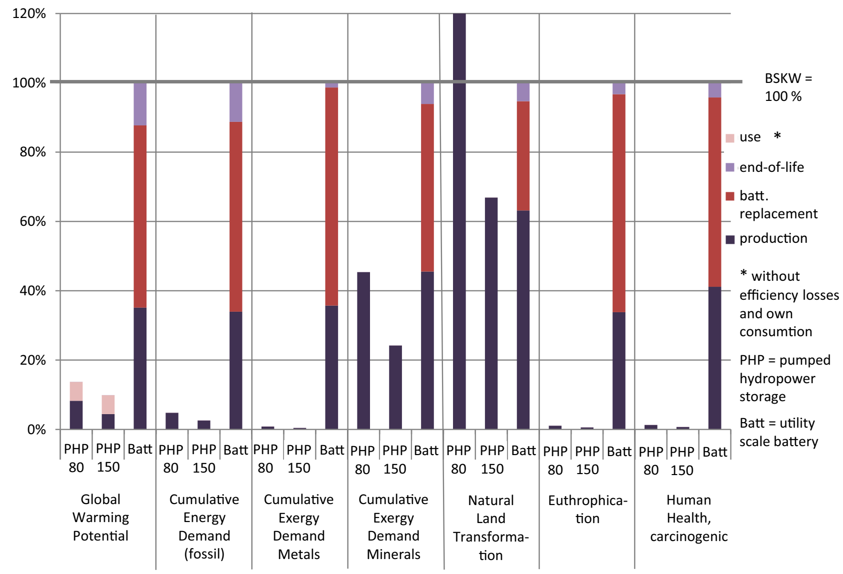


Fig. 5 Comparison of environmental impacts according to life-cycle stage without efficiency losses and internal energy consumption in sensitivity analysis 1—life span of pumped hydropower store = 150 years

The results for the reduced size utility-scale battery presented in Fig. 6 are lower than in the base case. For the indicator natural land transformation, the battery option now clearly shows lower impact than the pumped hydropower option. Furthermore, the relationship between results for the indicator cumulative energy demand minerals is now reversed. Whereas previously impacts were almost twice as high, they are now more than a third lower than those of the pumped hydropower store. This reflects the reduced requirements for minerals, which in the case of the battery option related mostly to the building to house the batteries. The impacts of the much smaller utility-scale battery is well reflected in the much reduced score for the indicator cumulative energy demand metals, though impacts are still almost three times as high as those of the pumped hydropower option. Impacts for the indicators global warming potential, cumulative energy demand fossil, eutrophication potential, and human health carcinogenic are also lower than in the base case, albeit only by a small percentage. This is again due to the dominating impacts of the use stage. Omitting impacts from efficiency losses and internal energy consumption in Fig. 7 shows that impacts in production and end-of-life stage for the aforementioned 4 indicators are reduced by around 80%.

Discussion of results

Pumped hydropower storage is typically designed to serve longer term requirements, including the bridging of longer periods of low sun and simultaneously low wind, while utility-scale batteries are particularly well suited to fulfil

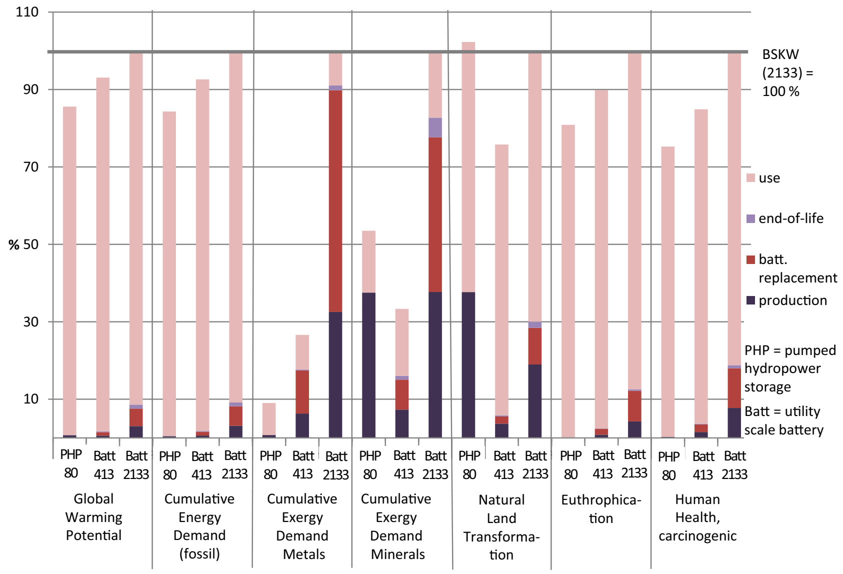


Fig. 6 Comparison of environmental impacts according to life-cycle stage in sensitivity scenario 2—scaling of battery

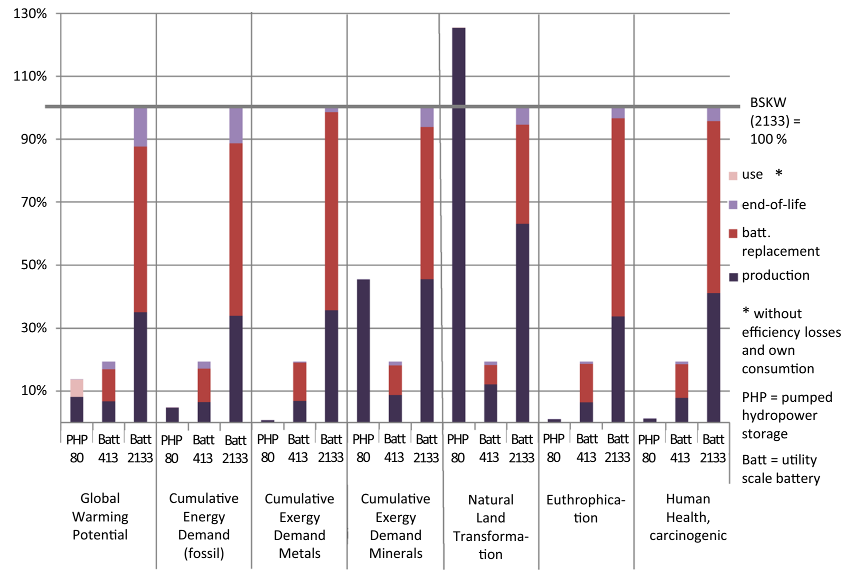


Fig. 7 Comparison of environmental impacts according to life-cycle stage without efficiency losses and internal energy consumption in sensitivity scenario 2—scaling

short-term incremental balancing requirements. Hence, the two technologies are not unconditionally comparable nor are they interchangeable, even though they are capable in principle of providing largely similar balancing and ancillary services. The demand for balancing and ancillary services is expected to increase in line with the increase of intermittent renewables. Rather than one technology substituting the other, they should be employed to complement each other in providing for this increased demand.

In the base case, lower impacts for the pumped hydropower store are shown in all impact categories except for natural land transformation. The two sensitivity analyses by and large confirm the results of the base case. Regarding sensitivity scenario 2—scaling of the battery, it should be remembered that achieving the assumed amount of full cycles within 1 year is not only dependent on battery technology but also on the network requiring services of the battery that frequently. In so far, this scenario makes very favourable assumption for the battery and is taken to be representative for future developments.

Variations in the results for natural land transformation between the base case and both sensitivity analyses deserve particular attention. If a longer life span is assumed for the pumped hydropower store, impacts in this category are a third lower than those of the utility-scale battery. However, impacts of the battery option also drop, if a smaller battery is used, as in the second sensitivity scenario. In this context, it should be remembered that the difference in results stems from differences in land qualities assumed. The pumped hydropower store would be sited on virgin natural land of high ecological quality. For the utility-scale battery, the category "unspecified land" was chosen, which is made up from 40% greenfield and 60% brownfield land. This is deemed appropriate, as utility-scale batteries are more likely to be sited on brownfield sites, such as industrial areas and wastelands. In some cases, though, they may be sited near large renewables installations such as wind farms or PV farms on greenfield land. The area in m^2 that has been assumed for accommodating both installations is only marginally lower for the battery solution. The assumptions regarding the conversion of virgin natural land of high ecology quality by pumped hydropower and "unspecified land" by battery stores apply for Germany. For other countries, these assumptions need to be examined closely as the characteristics of possible sites for large hydropower stores differ significantly between countries. In addition, the feasibility of smaller hydropower stores, e.g., on landfills is being currently analysed which would also change the land quality being changed and thus the results for the indicator natural land transformation.

Other indicators showing notable differences in the two sensitivity scenarios are cumulative energy demand metals and cumulative energy demand minerals, reflecting, respectively, the pumped hydropower store's high mineral requirements for constructing basins and the utility-scale battery's high requirements for metals in production.

Overall results, and, in particular, those of the indicators global warming potentials, eutrophication potential and human health carcinogenic, are being dominated by those environmental impacts relating to the use stage. These are caused by the impacts of the share of electricity, which is stored, but not being fed back because of efficiency losses and internal energy requirements of the installations. This means that the system efficiency and internal energy requirement of the examined technologies are crucial for the overall result, as they define electricity 'lost' in the 80 year use stage.

While pumped hydropower storage has typically an efficiency of 75–80% [29] over the whole lifetime, [32], efficiencies of up to 90–98% can be found for lithium-ion batteries (e.g. [21]). However, these figures exclude losses for inverters, management system, and transformers. With these, included overall-efficiency for batteries is around 80–88% [44] with a significant deterioration over the lifetime depending on the operating modes. In addition, the utility-scale battery's very specific requirements for heating as well as cooling have to be remembered, if optimal operational conditions are to be safeguarded [46]. The pumped hydropower store's internal consumption is relatively moderate, mostly relating to ventilation and lighting in the underground turbine hall as well as periodic testing and use of back-up generators. For both technologies, sub-optimal operation at times in response to requirements of the grid has to be assumed. Realistic figures for losses resulting from efficiency losses and internal energy demand have been used for this study, obtained from an operator of pumped hydropower storage and in the case of the battery from literature [22].[3] Both losses taken together lead to similar overall losses for both technologies. Consequently, impacts in the use stage are similar for both technologies. This, in turn, has an equalising effect on the overall results of the two technologies. For example, results for global warming potential and cumulative energy demand differ by only around 10%. This overall result could, however, be swayed in favour of one technology or the other, if actual losses of one of the technologies were to change considerably, be it due to technical developments or optimised deployment.

Another important parameter relating to the same aspect is the electricity mix, which is used for the LCA model. Since there are EU targets and national targets in place for emission reductions leading up to 2050, it can be reasonably expected that the electricity mix will substantially change over the course of the next 80 years. An extreme scenario is imaginable, in which all electricity would come from zero-emission sources and all generating technologies would be produced from recycled materials using also zero-emission energy for raw material extraction (from recycling) and production processes. This would lead to the emissions arising in the use stage being negligible. Consequently, the overall results would be akin to those shown in the variations "without efficiency losses and internal energy demand" (Figs. 5, 7). The equalising effect of the use stage would no longer be there. Hence, the percentage of difference between the options over the whole life cycle would no longer be just a few percentage points, but be largely amplified. For example, it would be more than ten times larger for the utility-scale battery in the category cumulative energy demand and around 100 times larger in the category cumulative energy demand metals.

However, the energy generation technologies for such a scenario do not yet exist. Even the current zero-emission electricity generation technologies carry many uncertainties regarding their upstream processes. Modelling these would be an extensive LCA exercise in itself. The standard approach in LCA is to use the same electricity mix throughout the life cycle, which is why the current German electricity mix with its currently high emissions and its upstream processes has been assumed (as in Fig. 3).

Ultimately, part of the motivation for this piece of work was the opposition towards new pumped hydropower storage plants encountered whenever new installations are being planned. Given the clearly lower overall impacts for pumped hydropower storage, it appears advisable that these results and others like these are being fed into the public debate. Nevertheless, it has to be also recognised that the somewhat abstract nature of the numerical results for LCA indicators will have to compete against the concern for visible, tangible, and well-loved local flora, fauna, and landscapes. The challenge, therefore, is to present LCA results in a way which shows that impacts elsewhere in the world or in the future are just as important and as painfully felt as those in the present time and place.

Outlook

The limitations of this study lie in the exclusion of the future developments of battery technologies and in the electricity mix used to calculate impacts in the use stage. Substantial developments are to be expected in both areas given current trends and given the long assessment period of 80 years. Impacts of a developing electricity mix have been addressed in the preceding paragraph.

Battery developments are currently moving at a fast pace and are certain to be considerable within the very long life cycle of this study. For example, some suggest that with electric vehicles taking off, there will be a large supply of waste batteries, which may have degraded beyond the 80% capacity currently stated as limiting factor for use in cars (on the basis of current battery guarantees). While no longer considered viable for use in vehicles, these are still suitable for storing and releasing frequent small amounts of energy as part of grid balancing [47]. Two aspects have to be considered: on one hand, these batteries could be viewed as waste products of the product life cycle of the electric car. A view could be taken that the considerable impacts of the production stage must be attributed to the car, not to the utility-scale battery, thus largely reducing the impacts of both the production and

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[3] N.B. life cycle inventory data for the battery is not relating to the example installation in Schwerin, but generic data from ecoinvent.

replacement stage. On the other hand, a greater number of these less powerful batteries would be needed to make up the same storage capacity, compared to virgin batteries. These would need to be housed in larger buildings with greater building services requirements.

In addition, there are suggestions that energy density of batteries could increase tenfold [48]. The composition of such batteries and consequent environmental impacts are as of yet entirely unknown. The same applies to their heating and cooling requirements. However, they would require smaller buildings to be housed in. With the great research effort in the field of batteries and the issue of global limitations on resources likely to become more pressing within the next 80–150 years, it is reasonable to expect that environmental impacts of battery production will be driven down eventually.

A wider question is whether batteries are the technology that pumped hydropower storage should be compared against over such a long time span, given the limitations on their comparability. In general, power-to-gas and power-to-X are considered as likely and necessary technologies for bridging the fluctuations occurring in a renewable-dominated energy scenario [30]. However, power-to-gas-to-electricity systems currently operate at efficiencies of around or below 40% [49]. Whereas the so-called “wind-gas” has moved beyond demonstration stage, the type and scale of storage used in renewable-dominated scenarios are far from mature. The whole current knowledge on such long-term storage alternatives to utility-scale batteries or pumped hydropower storage is too limited to undertake a comparable LCA-analysis.

Summary and conclusions

Pumped hydropower storage is typically designed to serve longer term requirements, including the bridging of longer periods of low sun and simultaneously low wind, while utility-scale batteries are particularly well suited to fulfil short-term incremental balancing requirements. Hence, the two technologies are not unconditionally comparable and nor interchangeable, even though they are capable in principle of providing largely similar balancing and ancillary services. The demand for balancing and ancillary services is expected to increase in line with the increase of intermittent renewables.

To assess the global impacts along the entire life cycle, a simplified LCA has been undertaken calculating global warming potential, cumulative energy demand minerals and metals, natural land transformation, eutrophication, and human health (carcinogenic). Sensitivity analyses have been undertaken regarding the life span of the pumped hydropower station and the sizing of the utility-scale battery.

Lower impacts for the pumped hydropower store are shown in all impact categories except natural land transformation. The two sensitivity analyses by and large confirm the results of the base case.

The limitations of this study lie in the exclusion of future developments of battery technologies. Developments in this field are currently moving at a fast pace and are certain to be considerable within the very long life cycle of 80–150 years considered here.

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