Comparing pumped hydropower storage and battery storage –
Applicability and impacts

Prof. Dr. Ingela Tietze
Chair for Sustainable Energy Economics – Pforzheim University, Germany

Mrs. Andrea Immendoerfer, MSc. (corresponding author)
Research Associate Institute for Industrial Ecology – Pforzheim University, Germany
Tiefenbronner Str. 65, 75175 Pforzheim, Germany,
Tel: +49 (0) 72 31/ 28-6139, E-Mail: andrea.immendoerfer@hs-pforzheim.de

Prof. Dr. Tobias Viere
Chair for Energy and Material Flow Analysis – Pforzheim University, Germany

Mrs. Heidi Hottenroth, Dipl. Ing.
Research Associate Institute for Industrial Ecology – Pforzheim University, Germany

Abstract
As the share of intermittent renewable energy generation rises within the German grid, solutions are required to deal with temporary overproduction of electricity as well as shortfalls. Other changes to energy infrastructure and balancing and ancillary service requirements are expected, due to a changing composition of generating capacity. Pumped hydropower storage systems are natural partners of wind and solar power, using excess power to pump water uphill into storage basins and releasing it at times of low renewables output or peak demand. This is a well-proven, reliable technology, which has traditionally always played a role in providing balancing and ancillary services. However, suitable sites are limited in most countries and where they exist, opposition towards new plants is often high, due to the disruption to landscape and bio-habitats. There are recent developments in battery storage technology, which may be better suited to a largely decentralised energy system. Utility scale batteries using Lithium Ion technology are now emerging.

These could potentially be integrated into the existing built environment, sparing virgin landscape. Nevertheless, battery stores cause also environmental impacts, albeit in different impact categories (e.g. use of scarce natural resources). This paper outlines consequences of increasing renewables on the grid as contextual information, taking Germany as an example. Based on a scientific study for a provider of pumped hydropower storage, the paper clarifies initially the role of pumped hydropower storage and utility scale batteries. It compares their respective technical potentials and limitations in providing certain services. In addition, the paper explores environmental impacts of both technologies over their respective life cycles, drawing on Life-Cycle-Assessment-data.

Keywords
Pumped hydropower, utility scale batteries, balancing and ancillary services.
1. Introduction

In the wake of the Fukushima disaster the German federal government decided on an accelerated energy transition, entailing a shut-down of all nuclear power stations by 2022 at the latest and generating at least 80% of power from renewables by 2050 (Decision of German Cabinet, 2011). Conventional power stations currently cover most of the balancing service requirements of the Transmission Systems Operators (TSOs) involved. However, with their share in the electricity market diminishing, they will no longer be available to cover these requirements to the current degree. At the same time, the need for balancing in the widest sense will increase due to the intermittent nature of much of the prospective 80% renewables making up the energy mix, i.e. wind and solar energy. (Völker et al., 2013, p. 91).

Pumped hydropower storage systems complement wind and solar power well. They use excess power to pump water uphill into storage basins and release it at times of low renewables output or peak demand. Where suitable sites are available, locals often oppose new plants fiercely, due to the disruption to landscape and bio-habitats.

At the same time, battery technologies are developing at a fast pace. Utility-scale batteries have recently emerged, now able to provide a range of balancing services. These can be sited on brownfield sites, thus not impacting on the local landscape to the same degree. However, they have particular requirements as to the materials they are made from, how they can be operated and how they are decommissioned at their end of life. Hence the question arises, how the two storage technologies compare, if considering important environmental impacts over the entire life-cycle.

2. Research Question and Methodology

The three questions to be addressed in this paper are:

- Can utility scale batteries provide an adequate substitute for pumped hydropower storage?
- Given their different technical characteristics, how do they have to be sized to be comparable?
- Which technology performs better, if important environmental impacts are considered over the entire life cycle?

As point of departure, the paper examines the need for storage in the energy system of the evolving German energy transition.

In the second step, 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.

As a third step of analysis environmental impacts over the whole life cycle are calculated using a simplified Life Cycle Assessment (LCA) based on the ecoinvent database version 3 (Werner et al., 2016), but also incorporating real-life data as and where available.

3. The German Energy Landscape and its Balancing Requirements

A share of 32.5% of renewable electricity could be achieved within the German electricity mix in 2015. At times of peak renewable electricity output, such as a sunny day around mid-day, over 80% of energy demand can be met by renewables, while at times of low irradiation and low wind there can be next to none (Agora Energiewende, 2016). The influx of high levels of solar energy in particular into the grid have led to a drop in energy wholesale prices, even leading to negative prices, when total energy supply surpasses demand. Due to this drop in prices and an ill-functioning EU-ETS (Agora Energiewende, 2016), other conventional energy technologies, namely flexible gas turbines can no longer compete, even though they would complement renewables well, due to their ability to modulate (Beck et al., 2013). The only fuels able to compete are CO₂-intensive coal and lignite. This has led to an altogether unsatisfactory development of CO₂ factors rising between 2011 and 2013 to 622g CO₂/kWh (Icha, 2015), though this is now expected to level off. Furthermore, due to the inflexibility of lignite power stations and intermittent renewables, excess electricity has to be exported into
neighbouring grids, such as that of the Netherlands, where gas-generation is now also being displaced, as a result of the low, even negative prices for excess electricity (Agora Energiewende, 2016b; Müller, 2013).

There are therefore many reasons for finding a lower carbon solution for balancing out fluctuations in supply as well as demand, such as storage technologies. Indeed, the market for balancing and ancillary services is expected to change, with conventional generating capacity gradually diminishing and increasing renewables imposing strains on energy infrastructure (Deutsche Energie-Agentur, 2014). Storage technologies are playing an increasing role in providing these services, in particular pumped hydropower storage and large scale batteries. Other storage technologies are being researched intensively (Taylor, 2009; Luo et al., 2015), with high hopes for example placed on compressed air storage, even though this technology is still at pilot stage (Völker et al., 2013).

4. Technologies and Data to be Compared

Two electricity storage options shall be compared – a pumped hydropower store and a large scale lithium-ion store. 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 – see 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 and reliable technology that can be built at large scale, often having several GWh of storage capacity. Total world wide capacity is estimated at 127 GW (7 GW in Germany; Völker et al., 2013), making it the largest scale technology for electricity storage. It can provide large amounts of balancing energy services (Moseley, 2015). Pumped hydropower storage does work on 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 and 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 making the plant a net consumer of energy (Moseley, 2015; Lowry, 2017).

With emerging battery needs for a vast range of applications, including electric mobility, research and development of battery development is currently a dynamic, swiftly evolving field (Wang, 2015). With efficiencies of over 90% (e.g. Hiremath et al., 2015; Korthauer, 2013), low memory effect and slow aging charging cycles (Stenzel et al., 2015), lithium-ion batteries are the technology of choice for large scale stationary applications (Korthauer, 2013; Younicos AG, 2016). The particular type of Lithium-Ion technology considered here are Lithium-Manganese batteries. Utility-scale batteries have only emerged recently. They consist of a large number of battery units on racks filling large halls (Koj et al., 2014). Large scale battery stores are operated similarly to pumped hydropower energy storage, storing energy at times of high availability and feeding it back into the grid at times of high demand (Sterner et al., 2015a).

The WEMAG utility-scale battery in the city of 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 subject to a number of studies (Koj et al., 2015; Koj et al., 2014; Stenzel et al., 2015).

With the use of utility-scale batteries being an emerging field, developments can only partially be anticipated. The assumptions of this study would therefore have to be reconsidered, as and when battery technology evolves.

5. Ability to Provide Balancing and Ancillary Services

In order to compare pumped hydropower stores and utility scale battery storage, it has to be established in how far their technical properties allow for them to be employed in comparable applications. Hence this section explores the role and capacity of
the two storage technologies with regard to their suitability for providing balancing and ancillary services.

A study of the German Energy Agency (DENA) on balancing and ancillary services was used as a basis for defining the relevant fields of application (Deutsche Energie-Agentur, 2014). Balancing and ancillary services include frequency control, voltage control as well as emergency and restoration services in the case of blackouts or total system break-down.

Based on the German grid development plan of 2013 (also known as “NEP; (Bundesnetzagentur, 2013), the study assumes a scenario with tripled renewable energy capacity compared to 2013, an increase in gas generating capacity, a completed nuclear energy phase-out and a much reduced share of large scale conventional power stations in the mix. The study comes to the conclusion that, regardless of when such a scenario may happen, it would result in an increased need for decentralised energy generators and energy stores to provide for short falls in balancing energy left by reduced capacity and reduced running hours of large conventional power stations. The increasing level of geographic disparity between power generation and consumption poses strains on the extra-high voltage transmission network leading to increasing requirements for reactive power at that level. With limitations on expanding network capacities in line with growing renewable capacity, the need for redispatch services will also increase. The role of pumped hydropower stations as a possible solution is emphasized (Deutsche Energie-Agentur, 2014).

Mainly but not exclusively based on (Beck et al., 2013; Sterner et al. 2015a; Ulbig, 2015; Höflich et al., 2010) an assessment has been made of the ability of the two types of energy storage to provide the various balancing and ancillary services. The definitions between different kinds of balancing services differ between countries, in particular with regards to the time band covered by different levels of balancing (E- BRIDGE CONSULTING and IAEW, 2016). In Germany there is a distinction between instantaneous frequency response, frequency containment reserve (up to 30 s), frequency restoration reserve (FRR, active in 30s, lasts up to 5 min), replacement reserves (RR, active in 5 min) and longer term operating reserves. Beck et al. (2013) state that both batteries and pumped hydropower storage are able to provide the different types of balancing services. They find that pumped hydropower storage is better suited than batteries to frequency response. This is contrasted by Sterner et al. (2015a), who point out the ability of batteries to respond within milliseconds. Beck et al (2013) and Deutsche Energie-Agentur (2014) see batteries as preferable to pumped hydropower storage for frequency containment reserve, whereas pumped hydropower is certainly suitable as well (Höflich et al., 2010). Both batteries and pumped hydropower storage can provide frequency restoration and replacement reserves, but there is agreement that the pumped hydropower storage is the better option (Beck et al., 2013; Höflich et al., 2010). Sterner et al. (2015a), and Höflich et al. (2010) point out that the issue for batteries is their economic viability. Batteries are not suited to balancing longer periods of low wind and sun or even interseasonal balancing and opinions as to the suitability of pumped hydro-power storage are divided. Generally, power-to-gas or power-to-X is referred to for longer term balancing (Agora Energiewende, 2014; Sterner 2015b). However, due to their typically high energy-to-power ratio (E2P) pumped hydropower stores contribute to longterm balancing, providing power for several days, if fully charged. For example the 9,6 GWh store considered here could supply the electricity demand of 50 000 homes for 20 days (based on figures supplied by a German operator of pumped hydropower stations and Lang et al., 2015). It should be remembered in this context that batteries commonly have an E2P of 1:1 (Krüger et al., 2015), (Wandelt et al., 2015). This is partly due to the fact that the suitability of Lithium Ion batteries for longer term storage is constraint by the fact that they self-discharge over time (about 2-3% per months; Electropedia, 2016). It is also partly due to their cost. All in all the sizing of utility scale batteries is based on economic considerations to provide maximum use and hence maximum return through their application in short term balancing service markets.
A further difference lies in the two technologies’ suitability for peak-shaving, which, similar to load levelling, reduces peak demand in order to avoid the need for additional capacity to supply peaks (Corson et al., 2014). Energy storage generally provides fast response and emission-free operation. It is hence well suited for this application. Batteries however are constraint by their particular technical properties. A battery has a set cycle life, after which it needs replacing. A cycle equates to one round of charging and discharging to the full storage capacity, but could be made up of many part cycles. Charging or depleting batteries to maximum capacity strains the battery. Part-cycles are preferable and prolong its lifespan (Arcus, 2016). Hence peak-shaving with frequent larger cycles would be damaging to battery-life (Kohler et al., 2010). Battery arrays should also be over-dimensionalized in order to allow for operation in the low state of charge zone (TEC-Institut, 2012).

Reactive power is another service provided to date primarily by conventional power stations. Deutsche Energie-Agentur (2014) identified the need to develop and adapt grid connection rules and technologies, especially for larger decentralised generators to provide reactive power. Both storage technologies are able to provide it, too. Furthermore, they are able to provide the following voltage control services: fault-ride-through, voltage management, phase shifting mode and general voltage stabilisation (Höflich et al., 2010; Sterner et al. 2015a; Agricola, 2015). Equally, emergency and restauration services such as black-start capability and decoupling of supply and demand can be provided by both technologies (Höflich et al., 2010; Sterner et al. 2015a). A summary of this analysis has been compiled in Table 1.

In summary it can be said that suitability for both storage technologies is similar enough to allow for a comparison. It must be remembered, however, that they differ in the extent to which they can provide the services. Batteries are particularly well suited to fast response short term balancing requirements (Agora Energiewende, 2014). Larger storage capacities for longer term services are not currently common (Wandelt et al., 2015). Pumped hydropower energy stores on the other hand tend to hold large volumes, have far higher E2P ratios and thus are able to provide longer term services, even bridging prolonged periods of low renewable energy output at times of low sun and at low wind.

It is these longer term services that are expected to be in greater demand as the share of renewable electricity grows (Völker et al., 2013, p. 91). There are also differences in their preferred running modes. On the one hand, modern batteries will last longer if charging and discharging is done incrementally, avoiding maximum charge and depletion. On the other hand, if pumped hydropower power is running on part-load its efficiency is being compromised. However, any storage technology will have to weigh up their technically preferred running mode against grid requirements and related economic impacts. Thus a trade-off has to be made between maximum operating ours and optimum operational loads.

6. Life Cycle Assessment

Having established that the two technologies have comparable functionality in principle, their global life-cycle impacts will be examined. A simplified Life Cycle Assessment (LCA) has been undertaken using the Umberto NXT software, which accesses the database ecoinvent (Wernet et al., 2016). Umberto NXT universal has been chosen due to its flexibility concerning the modelling and modification of life cycle systems in conjunction with using common LCI databases such as ecoinvent or GaBi2.

An LCA calculates environmental and human health impacts that result from inputs into the necessary processes (materials, energy) and outputs (emissions, waste…) over the whole life cycle of a product, including manufacturing with upstream processes, operation and disposal at end of life. The

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2 Due to the standardization of LCA the use of other software leads to identical results if the same data is considered.
LCA-Method used complies with ISO14040 and ISO14044 (ISO 14040, 2009-11). The impact categories have been selected based on the following considerations:

- The technologies concerned consume a substantial amount of electricity in their operation, as reflected in the indicators “Global Warming Potential” and “Cumulated Energy Demand” (Goedkoop et al., 2013; Hischier et al., 2010).
- Both technologies require large amounts of minerals and metals in their production and construction, as reflected in the indicators “Cumulated Exergy Demand of Minerals and Metals” (Bösch, Hellweg, Huijbregts, & Frischknecht, 2006).

Table 1. Suitability for Balancing and Ancillary Services (based on Beck et al., 2013, p. 112; Sterner et al., 2015a; Ulbig, 2015; Höflich et al., 2010).

<table>
<thead>
<tr>
<th>Frequency Control</th>
<th>Pumped hydro-electric Storage</th>
<th>Utility-scale battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency response reserve</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Frequency containment reserve (up to 30 s)</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Frequency restoration reserve (FRR) (active in 30s, up to 5 min)</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Replacement reserves (RR) (active in 5 min)</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Bridging of periods of low sun and wind</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Interseasonal balancing</td>
<td>(+)</td>
<td>-</td>
</tr>
<tr>
<td>Loads that can be turned on</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Loads that can be turned off</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>High/ low frequency response (within 10s, increase/ reduction in active power)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Load balancing at transmission system level</td>
<td>+</td>
<td>-(+)</td>
</tr>
</tbody>
</table>

Voltage Control (keeping voltage in the allowable band, limiting voltage break-down in case of short circuiting)

| Voltage dependant redispacth | ++ | + |
| 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
- Pumped hydropower stores constitute substantial interventions into the landscape, as reflected in the indicator “Natural Land Transformation” (Goedkoop et al., 2013).

- The indicators “Eutrophication Potential” and “Human Toxicity (carcinogenic)” have been added in order to reflect impacts on human, animal and plant life (Goedkoop et al., 2013).

The definitions of the impact categories will not be given in detail here – the references given for each should be consulted for further information.

7. Definition of Functional Unit and Time Frame

In order to compare the impact of the two options, they have to be sized in a way that allows for comparable functionality in order to define the so-called “functional unit” (quantified performance of a product system for use as a reference unit as defined by ISO 14040).

Bearing in mind the aforementioned differences in typical energy-to-power ratios, the question arises how to size the two technologies with their different technical characteristics and also slightly different ways in operating and deployment. There are a number of approaches to comparability:

- If both systems are to deliver the same amount of power (MW), both are able to serve short-term balancing service requirements. However, longer term balancing service provision would have to be excluded from the comparison, as the battery’s lower E2P will only allow it to operate for minutes up to a few hours.

- If both systems are designed with the same storage capacity (MWh), both can provide the same amount of work, thus allowing for longer term balancing service provision. However, this is not in line with typical sizing of battery storage. A battery store with such a high storage capacity would, according to common E2P rules, have a much higher capacity than the pumped hydropower storage, hence would be able to provide short-term balancing services to a far greater extend than assumed for the pumped hydropower storage.

- If sizing the battery so as to generate merely the same annual output (MWh/a) as the pumped hydropower store, the number of annual full charging cycles for the battery is a decisive parameter. A charging cycle would be taken to be equivalent to the useful storage capacity. The required annual output would thus be divided by typical cycles performed by batteries in a balance energy setting (e.g. according to Stenzel et al., 2015). The result would be the dimension of useful storage capacity of the battery. This would result in a smaller size battery than the previous option. Longer balancing services will however have to be excluded from the comparison in this case as well.

Choosing the capacity (MWh) of the battery as determining factor takes into account the pumped hydropower store’s ability to deliver long-term balancing services. As it is these longer term services which will see an increase in demand, this option will be pursued. Consequently, the functional unit for the comparison will be defined as the provision of 9.6 GWh stored energy, that is able to provide the balancing services defined in Table 1.

Therefore the 5 MWh WEMAG-Battery-store in Schwerin has to be scaled up initially by a factor of 1,920 to meet the requirements of 9.6 GWh. It is assumed that the battery may lose 20% of its storage capacity within 20 years (e.g. Wolfs, 2010) due to aging and degradation processes (reflecting its 20-year warrantee Struck & Broichmann, 2015, p. 6).

It therefore has to be over-dimensioned by 10%, over-producing in the beginning by 10% and under-producing towards the end of life time by 10%, also bearing in mind that the individual battery cells would be replaced gradually, as and when necessary.

Hence in order to provide comparable output on average over the course of its life span, the scaling factor is 2,133. It is unlikely that a utility scale battery 2,133 times the size of the installation in Schwerin would be installed in a single location. More likely it
would be spread over a number of locations, each installation of comparable size to the original installation in Schwerin. This allows for the scaling up of a suitable building using the same factor as for battery components. Nevertheless, the battery option will be referred to in the singular in the following.

The life-span of pumped hydropower storage ranges in literature from 50-150 years (Bauer et al., 2007; VISPIRON, 2015). A life-span of 80 years was chosen which is also the time frame over which the two technologies were compared. 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, e.g. (Hiremath et al., 2015) and is in line with the warranty for the WEMAG-Battery in Schwerin. Hence replacement of the battery units every 20 years has been assumed.

8. System Boundaries

Table 2 shows the components that are included for each technology, reflecting data-availability. Items in brackets will only be accounted for in the LCA up to the point of grid connection.

9. Life Cycle Stages

A cradle to grave analysis will be undertaken. It accounts for impacts in upstream processes resulting from raw material extraction, production and all energy requirements throughout the life cycle. Hence the following aspects 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, assuming current German electricity mix with current direct emissions and upstream processes of power stations, other generating technologies and infrastructure; for the pumped hydropower storage: lubricating oil consumption and Methane developing in reservoirs (Bauer et al., 2007; Treyer, 2015).

<table>
<thead>
<tr>
<th>Storage medium</th>
<th>Utility-Scale Battery</th>
<th>Pumped Hydropower Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built structures</td>
<td>battery cells and case</td>
<td>reservoir and water</td>
</tr>
<tr>
<td></td>
<td>industrial hall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[(building services (heating, cooling ventilation)]</td>
<td>tunnel penstock,</td>
</tr>
<tr>
<td></td>
<td>racks und trays</td>
<td></td>
</tr>
<tr>
<td>Technical components:</td>
<td>inverter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cabling [partial]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>battery management system [partial]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[switchgear]</td>
<td></td>
</tr>
<tr>
<td>Point of hand-over to grid</td>
<td>[transformers]</td>
<td>[transformers]</td>
</tr>
</tbody>
</table>

Our basic assumptions
Table 3. Data and Assumptions.

<table>
<thead>
<tr>
<th>Storage capacity</th>
<th>Pumped Hydropower Storage</th>
<th>Utility-Scale Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>1 GW</td>
<td>9.6 GW (E2P = 1:1)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>74.96 %</td>
<td>72.5 %</td>
</tr>
<tr>
<td>Total losses per MWH generated</td>
<td>0.350 MWh/MWh\text{generated}</td>
<td>0.379 MWh/MWh\text{generated}</td>
</tr>
<tr>
<td>Life span</td>
<td>80 years</td>
<td>20 years (= current best practice)</td>
</tr>
<tr>
<td>Maintenance and replacement cycles</td>
<td>continuous use of lubricating oil major overhaul of pumps, turbines and generators every 25 years</td>
<td>Replacement of battery units every 20 years (no replacements cycles assumed for the building)</td>
</tr>
<tr>
<td>Electricity generated per year</td>
<td>1,855 GWh/a (based on an existing installation)</td>
<td>1,855 GWh/a</td>
</tr>
<tr>
<td>Full cycles per year</td>
<td>n/a</td>
<td>194</td>
</tr>
<tr>
<td>Deterioration of performance</td>
<td>n/a</td>
<td>20 % in 20 years</td>
</tr>
<tr>
<td>Main raw materials</td>
<td>steel: 43.6 Mt concrete: 2966 Mt copper: 0.5 Mt</td>
<td>ecoinvent – data for factory building ecoinvent-Data for lithium-manganese battery</td>
</tr>
<tr>
<td>Direct use of land</td>
<td>98 ha</td>
<td>400 m\text{2} (estimated) x scaling factor</td>
</tr>
<tr>
<td>Type of land use</td>
<td>greenfield site</td>
<td>ecoinvent-option for „unspecified land“, which assumes 40% greenfield and 60% brownfield</td>
</tr>
<tr>
<td>Other Data</td>
<td>electricity use for building services, control and management systems, methane generation in basins as per ecoinvent data for hydro-power</td>
<td>electricity use for building services, control and management systems, Energy density of 114 Wh/kg, Low self-discharge rate</td>
</tr>
<tr>
<td>Electricity mix</td>
<td>current German electricity mix used over the whole life cycle (in line with common LCA methodology)</td>
<td></td>
</tr>
</tbody>
</table>

- End-of Life phase: 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.

10. Input Data Including Critical Data
For the pumped hydropower store data could be obtained from a pumped hydro-power operator in aggregated form. This data is being complemented by data from ecoinvent and from literature. Technical and operating characteristics will be based on real-life data from the operator.

For the utility-scale battery data is being used from the WEMAG-store in Schwerin, as found in literature (Stenzel et al., 2015; Younicos AG, 2016). Data is being checked against ecoinvent data for Lithium–
Manganese batteries. Quantities in particular stem from ecoinvent. The actual efficiency including all operational losses is based on the utility scale battery in Schwerin.

Upstream processes and their impacts, such as for example those relating to the construction of power stations, which provide the electricity for the use stage of the two storage options, are based on ecoinvent-data.

Based on the available data and previously discussed considerations the following input data is to be used for the Life-Cycle Assessment (Table 3).

11. Environmental Impacts

In Fig. 1 the impacts of both technologies are juxtaposed (utility scale battery = 100%). The different colours indicate shares of the different life-cycle stages in the over-all impacts.

For the pumped hydropower store impacts of the end-of-life stage are barely visible. For the utility scale battery, impacts of the end-of-life stage 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 Fig. 1 (black and white hatched).

Impacts of the operational stage (“use stage”) generally dominate those of the production stage in all categories except cumulated exergy demand. Especially the categories, GWP, eutrophication and impacts on human health show only a small contribution of the production stage to over-all 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. The impacts of this lost energy in turn depend on the impacts of the current German energy mix, its direct emissions from combustion plants and upstream processes (i.e. impacts from constructing power stations and renewables installations and infrastructure).

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 equalizing effect on over-all results. This however does not apply to the categories Cumulated Exergy Demand Metals and Cumulated Exergy 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 energy generation, as previously explained. Metals and minerals do not play a major role in energy generation (except for impacts in in upstream chains, i.e. the production stage of power plants within the electricity mix). 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. The short lines on the bars for natural land transformation indicate how much of these impacts relate to the direct land use of the technologies and how much relates to transformation in upstream processes.

Since impacts from electricity losses in the use stage of both technologies outweighs in most categories those in other stages by far and is similar for both technologies, an analysis was undertaken that excludes these (see Fig. 2). The remaining operational impacts result from construction, battery unit replacements, end-of-life and for the pumped hydropower store lubricating oil and methane development in the reservoirs.

The remaining impacts show higher impacts for the utility scale battery in all categories except natural land transformation, even though direct land-use does not differ much. This is a result of the different types of land assumed for the sites – the pumped hydropower store would be built entirely on greenfield land, while utility scale batteries are more likely to be sited on brownfield sites, such as industrial areas and wastelands. Though in some cases they may be sited near large renewables installations such as wind farms or PV-farms on greenfield land.
Fig. 1. Comparison of environmental impacts according to life-cycle stage.

Fig. 2. Comparison of environmental impacts according to life-cycle stage without efficiency losses and internal energy requirements.
12. Discussion of Results

Pumped hydropower stores and utility scale batteries are only conditionally comparable. They can in principle provide the same range of balancing services. However, due to their respective technical characteristics and economic considerations they are deployed differently in practice. Pumped hydropower stores are designed to serve longer term balancing requirements, provide large volumes of energy and can operate at extra-high voltage transmission level. They are also able to bridge periods of low renewable energy output to a certain extend. Utility scale batteries are particularly well suited to short term incremental services and would be part of decentralised generation, usually connected to the distribution system and, due to their different E2P ratios, providing much lower volumes of energy. In so far both technologies can complement each other.

The pumped hydropower store shows lower environmental impacts than the utility scale battery in almost all impact categories, the exception being “natural land transformation”.

Environmental impacts during the use stage dominate the overall result. These depend on the impacts of electricity, which is not fed back due to efficiency losses and internal energy requirements. 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.

High efficiencies of 90-98 % (e.g. Korthauer, 2013) can be found for lithium-ion batteries as opposed to only around 75-80 % for pumped hydropower storage (Beck et al., 2013; Höflich et al., 2010). However, losses for inverters, management system and transformers have to be added, leading to an overall-efficiency of 80-88 % for batteries (VISPIRON, 2015). Furthermore, the utility scale battery has very specific requirements regarding its optimal operational conditions. It requires heating, cooling and ventilation (Santhanagopalan et al., 2014, p. 67). The pumped hydro-electric 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. For both technologies sub-optimal operation at times in response to balancing-requirements have to be assumed. Real-life figures for losses resulting from efficiency losses and internal energy demand have been used and are similar for both technologies. This leads to similar impacts in the use stage for both technologies, which in turn equalise the over-all results of the two technologies. If actual losses of one of the technologies were to change considerably, be it due to technical developments or optimised deployment, this could sway the over-all result in favour of one technology or the other.

Another important parameter to consider is the electricity mix to be used in the LCA-models. It can be treated as a given that the electricity mix will substantially change over the course of the next 80 years, as there are EU-targets and national targets in place, largely relating to emissions reduction leading up to 2050. In an extreme scenario all electricity would come from zero-emission sources and all generating technologies would be produced from recycled materials using zero-emission production energy. In this case emissions arising in the use stage would be negligible. Consequently, the overall result would be similar to that shown in the variation “without efficiency losses and internal energy demand” (Fig. 2). Consequently the equalising effect of the use stage would no longer be there and 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 “cumulated energy demand” and around 100 times larger in the category cumulated exergy demand for metals.

However, the energy generation technologies for this extreme scenario do not yet exist. Even current zero-emission electricity generation technologies carry many uncertainties regarding their upstream processes. Modelling these would be an extensive LCA-exercise in itself. Therefore, the current German electricity mix with its currently high emissions and its upstream processes has been assumed for the whole life cycle (as in Fig. 1). This approach is in line
with common LCA-conventions.

Whereas the starting point for this study was a specific case study, the only site specific data used where the quantities of materials for the pumped storage (which are rough ball-park figures, as the project has not entered yet specification stage). The methodology of LCA provides aggregated results for global, non-site specific impacts. Within the constraints of the simplifications made (reliance on ecoinvent data - see table 2), the results can be seen as a general, non-site specific comparison of the two technologies.

13. Summary and Conclusions

Pumped hydropower storage and utility scale batteries can provide largely similar balancing and ancillary services, but are only conditionally comparable and are not interchangeable, one for the other.

The pumped hydropower store is typically designed to provide longer term services, including the bridging of longer periods of low sun and simultaneously low wind. The batteries are particularly well suited to short term incremental balancing. Both take part in the short term balancing markets. The demand for balancing and ancillary services is expected to increase.

The utility scale battery has been sized to have the same storage capacity as the pumped hydropower store in order to match it as closely as possible to the pumped hydropower store in terms of the ability to provide the full range of balancing and ancillary services. The implication that, due to different E2P ratio, it could then provide short-term balancing services exceeding those of the pumped hydropower store was neglected for this study.

A simplified LCA has been calculated in order to assess global impacts along the entire life cycle, calculating the following impacts: Global Warming Potential, Cumulated Exergy Demand Minerals and Metals, Natural Land Transformation, Eutrophication, Human Health (carcinogenic).

The analysis shows lower impacts for the pumped hydropower store in all impact categories except transformation of natural land.

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