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ABSTRACT

The intermittent nature of renewable energy sources like solar and wind energy stimulates the use of centralised and decentralised energy storage systems. The sustainability of lead acid, lithium-ion and concentration gradient flow batteries, compressed air and pumped hydro energy storage (PHES) systems is investigated by conducting a multi-dimensional life cycle assessment. The environmental, economic and exergetic sustainability are assessed by calculating ReCiPe 2016 indicators, the present worth ratio and the Total Cumulative Exergy Loss, respectively. The multi-dimensional sustainability assessment did not lead to one preferred system. The PHES causes the lowest damage to human health, ecosystem diversity and resource availability and results in the lowest global warming potential. The concentration gradient flow battery system named BBS is preferred from an economic viewpoint, while the PHES is second-best. The lithium-ion battery system causes the lowest exergy losses, followed by the PHES. It is recommended to pay attention to the exergetic sustainability of technological systems as exergy losses are independent of environmental models, weighting factors, market prices, subsidies etc. More research into the specifications of the energy storage systems is needed to be able to draw firm conclusions with regard to which system is preferred.

1. Introduction

The threat of global warming and the depletion of fossil fuels stimulate the use of renewable energy sources like solar and wind energy. However, the intermittent nature of these energy sources requires strengthening of the transmission grid and/or the use of centralised and decentralised systems for energy storage. Many researchers are active in the field of energy storage systems and each type of energy storage has its advantages and disadvantages with regard to e.g. the use of materials, recyclability, size and costs. When assessing the sustainability of technological systems, it is important to take a life cycle point of view, i.e. by conducting a life cycle assessment (LCA), to prevent problem-shifting between the different phases of a life cycle and/or between sustainability aspects [1]. In literature, several publications can be found that use LCA to compare energy storage systems, e.g. large-scale compressed air energy storage (CAES) and pumped hydro energy storage systems (PHES) [2], lead-acid and lithium batteries [3], PHES and lithium batteries [4], several lithium batteries [5,6], large-scale CAES [7] and PHES, CAES, lead-acid, lithium and other types of batteries [8]. The applied environmental indicators include greenhouse gas emissions [2], global warming potential (GWP) [4], ReCiPe midpoints [3,7], cumulative energy demand (CED) [4], IMPACT 2002+ midpoint and endpoint indicators [6] and ReCiPe midpoint and endpoint indicators [8]. According to Peters et al. [5], the indicators that are used most in the environmental impact assessment of lithium batteries are the CED and GWP, mostly calculated by applying the ReCiPe method. This research compares a newer type of energy storage system, i.e. a concentration gradient flow battery, and four more common energy storage systems:

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compressed air energy storage, a lead acid battery, a lithium-ion battery and pumped hydro energy storage. The multi-dimensional LCA of the five energy storage systems considers the following three dimensions: environment, economy and exergy (the quality of energy). The ReCiPe 2016 method [9] is used to calculate the environmental sustainability of the systems from an endpoint perspective, i.e. damage to human health, ecosystem diversity and resource availability as well as the GWP midpoint indicator. The economic sustainability indicators used in this research are the net present value (NPV) and the present worth ratio (PWR) [10]. In addition to regular sustainability assessments that consider the environmental and economic components of sustainability, the exergetic sustainability of the systems is determined because of the relationship between exergy and sustainability mentioned in literature, e.g. Refs. [11,12]. Exergy, also known as the quality or work potential of energy, is needed for each and every process to take place. The indicator used for determining the exergetic sustainability of the systems is the Total Cumulative Exergy Loss (TCExL) indicator which takes into account all exergy losses caused by a technological system during its life cycle. The TCExL indicator has previously been applied to power generation systems based on fossil and renewable energy sources [13–15]. This paper presents improved models of the systems discussed by Stougie et al. [16].

2. Sustainability assessment

2.1. Comparability of the systems

An important aspect when assessing technological systems is their comparability. The life cycle phases included in the assessment are the phases of construction, operation and decommissioning. The functional unit used in the life cycle assessment is a storage capacity of 10 kWh of each of the systems and a lifetime of 20 years. If the lifetime of a technological system is shorter than 20 years, replacement of this system is included by applying a multiplication factor of 20 years over the lifetime of the system. E.g., in case the lifetime of a certain battery equals 10 years then two batteries (= 20/10) are taken into account in the assessment. The energy storage systems are modelled with the help of the life cycle assessment software tool named SimaPro [17], i.e. version 8.4.0.0, and the accompanying ecoinvent database [18]. The transportation of the energy storage systems, or their components in case of the BBS, to Delft, Netherlands, is considered in the assessment, except for the pumped hydro energy storage, where the transport of electricity via the NorNed cable is included instead. It is assumed that the electricity needed for charging the energy storage systems during the operational phase originates from the same renewable energy sources for all assessed systems. Therefore, the generation of electricity and its supply chain is not taken into account in the SimaPro models of the systems (Fig. 1).

During the end-of-life phase of the energy storage systems, recycling, reuse, incineration and possibly landfilling of the materials are considered. This is done by applying the selection and reprocessing efficiencies reported by Rigamonti et al. [19]. The amount of materials that is recycled and/or reused is considered as an avoided product in the assessment. I.e., these amounts need not be produced in the conventional way of producing these materials and result in a benefit for the assessed technological system. The materials that remain after selecting and reprocessing are assumed to be disposed of in accordance with the ecoinvent process named ‘Disposal, residues, shredder fraction from manual dismantling, in MSWI/CH U’.

2.2. Environmental sustainability indicators

The environmental sustainability of the energy storage systems is determined by applying the ReCiPe 2016 method V1.00 [9] included in the SimaPro software. The reasons for choosing the ReCiPe method is that it is developed by experts in the field of LCA and enables the calculation of (three) endpoint as well as (seventeen) midpoint indicators of the environmental impact of technological systems. The ReCiPe 2016 method is an updated version of the ReCiPe 2008 method developed by LCA experts from RIVM, Radboud University, CML and Pré consultants (Netherlands). The endpoint indicators indicate damage to human health, ecosystem diversity and resource availability. The ReCiPe method offers different perspectives to calculate the indicators, i.e. the individualistic, the hierarchist and the egalitarian perspectives. The hierarchist perspective is used in this research because it is the default perspective of the ReCiPe method and because it is ‘based on scientific consensus with regard to the time frame and plausibility of impact mechanisms’ [9, p.17]. In addition to the endpoint indicators, the midpoint indicator named global warming is used in this research because of the importance of the threat of climate change. The lower the ReCiPe indicator score of a technological system, the higher its environmental sustainability is.

2.3. Economic sustainability indicators

A well-known economic indicator is the net present value (NPV), which discounts all revenues and costs during the lifetime of a technological system. However, when choosing between technological systems, it would be better to relate this NPV to the NPV of the investment costs as shown in (1). The ratio is known as the present worth ratio (PWR) [10]. The higher the PWR, the more likely it is that the investment is made. In literature, no journal papers about the use of the PWR in the economic assessment of energy storage systems have been found. Assuming that all investment costs are made in the first year, which is not the case in this research, the PWR would equal the economic indicator known as the profitability index [20].

$$PWR = \frac{NPV}{\sum_{t=0}^{t=i} \frac{I_t}{(1+r)^t}} \quad (1)$$

with:
I_t = investment costs in year t.
i = number of years of construction.
r = discount rate.

The discount rate applied in this research equals 8%, which is the

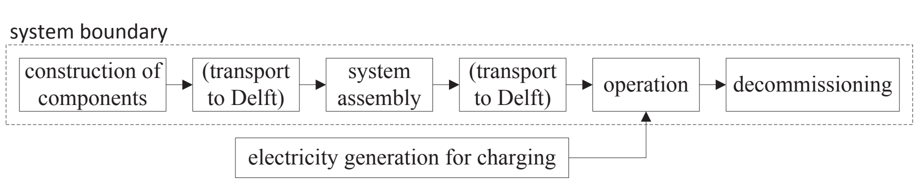

Fig. 1. System boundaries of the assessed energy storage systems.

number used for private effects in social cost-benefit analyses in the Netherlands [21]. The decommissioning costs are assumed to amount to 25% of the investment costs [12]. If a component of an energy system needs replacement, e.g. a pump needs to be replaced after 10 years, the current replacement costs of this component are added to the initial investment costs as it is assumed that the inflation and discount rates are about the same. The revenues are calculated from an electricity price of 0.20 €/kWh [22] and the assumption that during the lifetime of 20 years and during 300 operating days per year, the total amount of energy stored, i.e. 10 kWh, is discharged with the discharge efficiency of the particular energy storage system.

2.4. Exergetic sustainability indicators

The exergetic sustainability is determined by applying the Total Cumulative Exergy Loss (TCExL) method [12,15]. The TCExL indicator consists of the following three components: the internal exergy loss caused by a technological system including its supply chains during the phases of construction, operation and decommissioning, the exergy loss caused by the abatement of its emissions and waste flows to an acceptable level, and the exergy loss related to land use by the system. The higher the TCExL, the lower the exergetic sustainability of a system is.

The internal exergy loss caused by the system is equal to the exergy input minus the amount of exergy represented by the products, emissions and waste flows of the system. The electricity used for charging the energy storage system is not included in the SimaPro model but needs to be added to the Cumulative Exergy Demand (CExD, v1.05) calculated by SimaPro for the calculation of the total exergy input. Analogous to the economic sustainability assessment, the electricity needed for storage is calculated from the charging efficiency of the system and the assumption that 300 days per year an amount of 10 kWh of energy is stored during the lifetime of 20 years. The amount of electricity produced is calculated in the same way by applying the discharge efficiency. The exergy represented by emissions and waste flows is calculated from the amounts reported by SimaPro and their exergy values. These exergy values are calculated from the standard exergy values of components and other thermodynamic data, e.g. Ref. [23]. This is limited to the exergy values of the largest emissions, i.e. 95% by mass of all emissions, as it is undoable to calculate the exergy values of the more than 1000 emissions listed by SimaPro. As the CExD calculation by SimaPro/ecoinvent considers the water used by turbines as water consumption, i.e. as a positive contribution to the CExD, and the water output resulting from the water used by turbines as a negative contribution to the CExD, the subtraction of the amount of exergy represented by this water output from the CExD would result in a negative internal exergy loss, which is by definition impossible. This problem is solved by not taking into account the amount of exergy represented by this type of water output in the calculation of the internal exergy loss. Similarly, the positive contribution of water used by turbines and the negative contribution of the water output is left out of the calculation of the CExD number, although these amounts of water appear to be nearly the same (about 99%) in the background processes of the ecoinvent database used in the assessed systems. The abatement exergy loss is based on the exergy loss caused by the abatement of carbon dioxide (5.9 MJ/kg [24,25]), sulphur dioxide (57 MJ/kg [26]), nitrogen oxides (16 MJ/kg [26]) and phosphate (18 MJ/kg [26]) emissions as data about other substances have not been found in literature. The processes for the abatement of these emissions are explained in more detail in [12,24–27].

The exergy loss related to land use is equal to the amount of exergy that would have been captured from solar energy by the ecosystem if this area had not been occupied by the technological system under consideration. A worldwide average exergy loss of 215 GJ per hectare per year is calculated from the Net Primary Production [27], which is the net amount of biomass produced when land is not occupied, and an average biomass exergy conversion factor of 42.9 MJ exergy per kg of carbon [28]. To prevent double-counting, the types of land use that are related to the growing of trees or another type of biomass are not taken into account when determining the exergy loss caused by land use. The types of land use related to marine ecosystems are not considered because of the very small amount of solar energy that is captured [29].

3. Energy storage systems

This chapter presents brief descriptions of the assessed energy storage systems in an alphabetic order. Unless stated otherwise, it is assumed that the construction of the energy storage system lasts less than one year. The ecoinvent processes used for modelling sea and road transport are named ‘Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U’ and ‘Transport, lorry >16t, fleet average/RER U’, respectively.

3.1. Blue battery system

The Blue Battery system (BBS) is a concentration gradient flow battery that makes use of salinity differences in water [30,31]. It makes use of the fact that electricity can be generated when solutions with different salinities are mixed in a controlled way by applying ion-exchange membranes that are selective for cations and anions, i.e. reverse electrodialysis (RED). This mixing of high and low salinity water results in brackish water and can be reversed by applying electrodialysis, and can thus be used to store energy. A battery management system is integrated in the BBS. The BBS is a novel technology of which the development to an actual product has taken place in The Green Village in Delft since 2017 [32,33]. The BBS comprises 10 stacks, piping, three water bags containing a total amount of 16 m^3 of demineralised water and 750 kg of sodium chloride, and a control system (Fig. 2).

Since the BBS is still under development, actual data needed to be completed with estimates about the composition of the final product. The total mass of the BBS is calculated at 17 ton including nearly 16 ton of demineralised water. This is lighter than the previously modelled system [16] as it appeared that some components, like stack boxes, will not be needed anymore. It is assumed that 70 km of road transport is needed for all equipment manufactured in the Netherlands and 500 km of road transport for all equipment manufactured in Europe or at an unknown location. Including transport of equipment manufactured outside of Europe, the transport distances are calculated at 1.3 thousand tkm by road and 3.1 tkm by transoceanic freight ship. The charge and discharge efficiencies are set at the expected 65 and 75%, respectively. Its lifetime is assumed to be 20 years. The investment costs are estimated at € 1000 and the replacement costs at € 260.

3.2. Compressed air energy storage

Compressed air energy storage (CAES) uses turbomachinery to

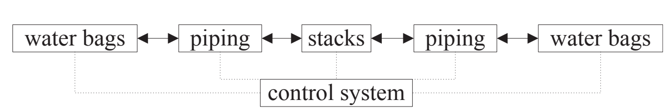

Fig. 2. Composition of the blue battery system.

compress air after which it is stored, e.g. in an underground cavern. When electricity is needed, the pressurized air is heated and subsequently led through an expansion turbine that drives a generator for electricity production. This research studies the adiabatic version of CAES, which means that the heat needed for heating the pressurized air originates from the intercoolers applied during the compression of the air. The heat is stored in a Thermal Energy Storage (TES) system, which consists of two tanks, i.e. one for the storage of hot oil and one for the storage of cold oil [34]. In addition, the system comprises two compressors, two turbines, four heat exchangers (two intercoolers, two interheaters) and piping for the transport of oil and air (Fig. 3).

The air is compressed to 50 bar and 276 °C. During charging, the oil flows from the cold tank to the hot tank and in the opposite direction during discharging. The following adjustments have been made to the model of the system presented by Innocenti [16,35]: 0.75 pieces in total of the 4 kW air compressor, i.e. two compressors of 1.5 kW each, 0.070 pieces in total of the 100 kW micro gas turbine, i.e. two expanders of 3.5 kW each, both assumptions based on the nominal flow rates mentioned by Manfrida et al. [36], 2 pieces of each type of heat exchanger, another model of the air receiver assuming that it is made of 200 kg of 18/8 chromium steel and manufactured by 'metal working, average for chromium steel product manufacturing', a total of 0.083 pieces of the oil tank which composition includes 9 kg of polyurethane [37], 10.5 kg of oil (paraffin was assumed to be best type of oil available in the ecoinvent database) and 4 and 5 m of oil and air pipes, respectively [38]. In addition, the oil and air pipes are assumed to consist of 1.05 and 1.68 kg of 18/8 chromium steel with an insulation of 2.4 and 3.2 kg of rock wool per meter (assumed insulation thickness of 80 mm), respectively. The model includes 207 tkm of road transport per 1.22 kWh of energy storage. The efficiencies of charging and discharging equal 82% [39]. The lifetime of CAES is 20 to 40 years [40] and is assumed to be 30 years for this system. The investment costs related to a 10 kWh facility are calculated at € 2782 and its O&M costs at 4.4 €/year [35], based on data provided by Zakeri and Syri [41].

3.3. Lead acid battery

Lead acid batteries have been used for energy storage since 1860 [42,43]. The type of lead acid battery assessed in this research is the Adsorbent Glass Mat (AGM) type. In this newer type, the electrolyte is suspended in a mat made of boron silicate fibre glass which absorbs the free electrolyte like a sponge (Fig. 4). The AGM type is said to be the most efficient and flexible of the lead acid types of batteries while it has a very robust construction that can withstand sever shock and vibration [44]. The data for modelling the AGM lead acid battery originate from Liu et al. [45], who assessed an AGM lead acid battery for e-bikes in China with a capacity of 1 kWh. The charging and discharging efficiencies equal 95 and 80% [45,46].

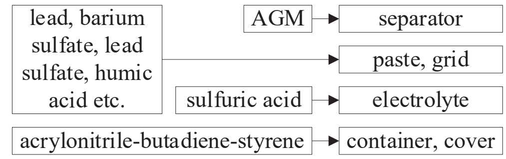

Fig. 4. Composition of the AGM lead acid battery.

A detailed description of the modelling of the system in SimaPro is provided by Del Santo [47]. The following adjustments have been made to this model: the ecoinvent process named 'lead {GLO}| market for | Alloc Def, U' is used for all lead needed for the construction of the battery, the use of 0.0575 kg/kWh of 'Calcium carbonate >63 µm, production, at plant EU-27 S' is added because of the use of calcium and the amount of glass fibre has been increased with 0.65 kg/kWh to account for the AGM material used. The amount of electricity needed for materials extraction, processing and manufacturing of an AGM lead acid battery with a capacity of 10 kWh is calculated at 1.9 MWh based on data provided by Liu et al. [45] and Rydh [48]. It is assumed that the AGM battery is constructed in China and therefore its transport to Delft via ship and road is considered as well, i.e. 682 tkm of transport by transoceanic freight ship and 1.4 tkm by road per kWh. The capacity of an AGM lead acid battery becomes lower than 80% after 1300 cycles [49], i.e. its lifetime amounts to 4.3 years with 300 cycles per year at a discharge efficiency of 80%. The investment costs of a 10 kWh system and the yearly O&M costs amount to € 4370 and € 17 per year, respectively [47]. The replacement costs of the system are calculated at € 344, based on data provided by Zakeri and Syri [41].

3.4. Lithium ion battery

The lithium-ion (Li-ion) battery is named after its electrolyte, i.e. a lithium salt dissolved in an organic solvent solution (ethylene carbonate and lithium hexafluorophosphate). The system assessed in this research is a model of the Powerwall manufactured by Tesla [50] The cathode consists of a combination of nickel, manganese and cobalt (NMC), usually one third by mass of each metal, i.e. the 1-1-1 type. The anode consists of a copper current collector with a coat of negative electrode paste made of mainly synthetic graphite. The third solid component of a Li-ion battery is a porous polymer (usually polyethylene or polypropylene) which separates the cathode and the anode. Cathode, anode and the separator are immersed in the liquid electrolyte solution [51] (Fig. 5).

The capacity of a Powerwall is 13.5 kWh, its charging and discharging efficiencies are estimated at 95% [52,53] and its lifetime amounts to 10 years [50]. The mass of a Powerwall equals 125 kg [50]. The data used for modelling this energy storage system originate from Li et al. [54] who describe a battery of this type with a mass of 1 kg. Innocenti [35] presents a detailed description of the

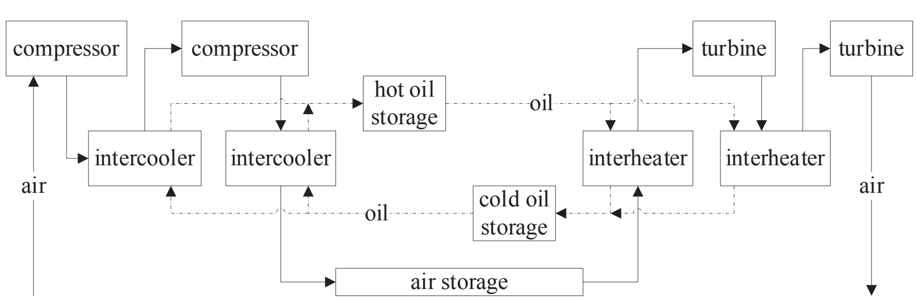

Fig. 3. Composition of the adiabatic CAES system (adapted from [34]).

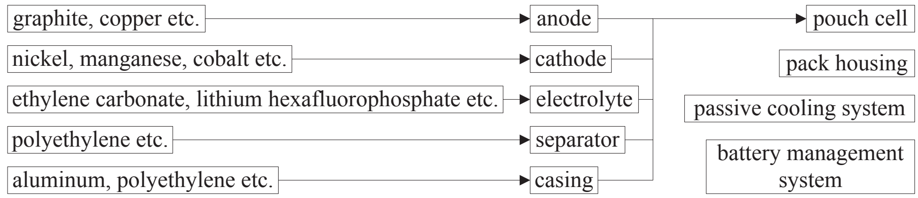

Fig. 5. Composition of the Li-ion battery.

modelling of the system in SimaPro. The following adaptations have been made to the model by Innocenti. The stainless steel needed for the pouch cell is modelled as 'Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc DEF U' and the aluminium foil used for the casing as 'Aluminium foil B250' originating from the BUWAL 250 (1996) database included in SimaPro. The copper needed for the anode is modelled as 0.524 kg of 'Copper sheet, technology mix, market mix, at plant, EU-25 S', the use of sulfuric acid is changed into the emission of sulfamic acid [54] and it is assumed that 1.5331 MJ of electricity is meant where it says 1.5331 kg of electricity [54]. The aluminium foil needed for the cathode is the same material as used for the anode and latex is modelled as 'Latex, at plant/RER S'. It is assumed that the pouch cell is manufactured in China and transported to San Francisco where the battery is assembled [50]. Therefore, the electricity used for construction of the pouch cell and its components is set at 'Electricity, low voltage {CN}| market group for | Alloc Def, U' and at 'Electricity, low voltage {US}| market group for | Alloc Def, U' for the electricity used in the US. The transport of the pouch cell to San Francisco is calculated at 8.0 tkm by transoceanic freight ship per kg of battery. The shipping of the battery to Delft amounts to 2.8 thousand tkm by ship and 7.4 tkm by road. The investment and replacement costs of a 10 kWh system are calculated at € 10265 and € 1107, respectively and its O&M costs amount to € 34.5 per year [35,41].

3.5. Pumped hydro energy storage

The pumped hydro energy storage system (PHES) is not really a decentralised type of energy storage, but it is considered in this research because of the potential of 'Norway as the battery of Europe'. Its technical potential is said to be at least 20 GW by 2030 [55,56]. PHES is an established technology. It makes use of the potential energy of water that is pumped from a lower to a higher level reservoir. The water is pumped up when electricity is cheap and runs the other way to drive hydro turbines in times of a (high) demand for electricity. The assessment of this system includes transport of electricity via the NorNed cable between Norway and the Netherlands. The data used for modelling this system originate from Flury et al. [57], who consider an average storage hydropower system with a capacity of 95 MW, an expected net production of 190 GWh/a and a lifetime of 150 years. A detailed description of the modelling of the system in SimaPro is provided by Del Santo [47]. The model used in this research is different in the sense that the SimaPro process 'Electricity, hydropower, at pumped storage power plant/NO U' is used to model the PHES, but without considering the electricity use, since charging of the energy storage systems is not included in the SimaPro models of the systems. The ecoinvent process 'Transmission network, long-distance {UCTE}| construction | Alloc Def, U' is used to model the transport of electricity from the PHES to Delft. The total transport distance is calculated at 580 km of the NorNed cable [58] plus about 200 km in Norway and 250 km in the Netherlands (Fig. 6).

It is assumed that 1 kW of the 1 GW capacity of the cable is used and that the lifetime of the NorNed cable equals 30 years. The charging and discharging efficiencies of the PHES equal 80 and 98%, respectively [59]. It is assumed that it takes five years to construct this energy storage system as it takes three years to upgrade a hydropower plant to a PHES system [55]. The investment costs and O&M costs for a PHES with a capacity of 95 MW and a yearly electricity production of 190 GWh are calculated at € 9.79×10^7 and € 4.4×10^5 per year, respectively [47], based on data provided by Zakeri and Syri [41]. Linear downscaling of these numbers to the yearly electricity generation by a 10 kWh PHES results in € 1514 investment costs and € 6.76 per year of O&M costs. The total investment costs of the NorNed cable equal € 6×10^8 [60], which is calculated at € 400 for the functional unit.

4. Results and discussion

Table 1 presents the results of the environmental sustainability assessment of the five energy storage systems. The PHES system is preferred from an environmental sustainability point of view, as it results in the lowest scores for all three damage categories and has the lowest global warming potential of all systems. The BBS performs second-best. The lead acid battery is the least-preferred system with regard to human health and ecosystem diversity. The relatively high scores are for about 46% caused by the use of antimony and primary aluminium, respectively. The relatively high impact of the CAES system in the field of ecosystem diversity is for more than 40% the result of the use of chromium steel for the construction of the air receiver.

In literature, neither ReCiPe endpoint indicators nor GWP scores of similar energy storage systems have been found to compare the results of Table 1 with. The following GWP scores have been found of less similar systems that include one of the energy storage options of this research, but have different system boundaries and sometimes present their results in kg CO_2-eq per kWh electricity delivered to the grid, i.e. Refs. [2,7,8], instead of per kWh energy stored: adiabatic CAES: 0.0038 (estimated from graph) [7], 0.007 (estimated from graph) [8] and 0.2312 [2], lead acid battery: 0.1025 (estimated from graph) [8] and 0.10276 [3], lithium manganese battery: 0.0278 [3], lithium battery: 0.0625 (estimated from graph) [8] and 0.1833 (estimated from 110 g per Wh) [5] and finally PHES: 0.2111 [2]. It is learnt from the comparison that the GWP scores of Table 1 are quite similar to the results found in literature given the differences between the systems.

SimaPro/ecoinvent offers the possibility to exclude infrastructure processes, e.g. the construction and dismantling of battery components, reservoirs, the electricity transmission network etc., from the life cycle assessment. Table 2 presents the results of the environmental assessment of the systems without these infrastructure processes. It is learnt from a comparison of Tables 1 and 2 that 96–100% of the human health and ecosystem indicator scores is caused by infrastructure processes, 85–99% of the resource indicator score and 91–99% of the GWP. The generation of electricity needed for charging the systems is not included in the systems, but assuming that renewable energy sources are used for electricity

Fig. 6. Composition of the PHES system.

Table 1
Results of the environmental assessment.

	BBS	CAES	Lead acid	Li-ion	PHES
Human health [DALY]	8.3e-3	9.8e-2	1.6e-1	3.2e-2	2.0e-3
Ecosystems [species.yr]	2.9e-5	1.2e-4	3.2e-4	1.4e-4	3.4e-6
Resources [USD2013]	1.5e2	1.1e3	7.5e2	1.8e2	3.5e1
Global warming [kg CO_2- eq.]	1.9e3	1.9e4	3.1e4	1.9e3	7.4e2
idem, per kWh[a]	0.031	0.32	0.52	0.032	0.012

[a] Calculated from 10 kWh of storage capacity which is discharged 300 days per year during the lifetime of 20 years.

Table 2
Results of the environmental assessment excluding infrastructure processes.

	BBS	CAES	Lead acid	Li-ion	PHES
Human health [DALY]	3.3e-4	2.6e-4	1.1e-3	1.0e-4	3.9e-5
Ecosystems [species.yr]	1.2e-6	9.8e-7	2.7e-6	2.7e-7	1.5e-7
Resources [USD2013]	2.3e1	4.6e1	4.4e1	3.6e0	3.3e-1
Global warming [kg CO_2- eq.]	1.7e2	1.6e2	2.9e2	2.5e1	2.9e1

generation, the percentages will remain high. E.g., 97–99% of the ReCiPe endpoint indicator scores is the result of infrastructure processes when assessing the ecoinvent processes 'Electricity, at wind power plant/RER U' or 'Electricity, production mix photovoltaic, at plant/NL U'. In contrast, infrastructure processes account for only 23, 25, 2 and 2% of the human health, ecosystem diversity, resource availability indicator and GWP scores of the ecoinvent process 'Electricity, low voltage, production NL, at grid/NL U', respectively.

In contrast with the ReCiPe 2008 method, the ReCiPe 2016 method does not provide normalisation and weighting factors to calculate one overall endpoint indicator. However, if the results of each endpoint indicator are normalised by dividing them by the lowest score and the default weighting set of ReCiPe2008 is applied, i.e. human health 40%, ecosystems 40% and resources 20%, the overall results presented in Table 3 are obtained. As expected from the results of Table 1, the PHES is preferred and the BBS performs second-best. These systems are followed by the Li-ion battery and CAES, while the lead acid battery appears to be the least-preferred system.

The results of the economic sustainability assessment are presented in Table 4. All numbers are related to the storage capacity of the functional unit, i.e. 10 kWh. The NPV of the original 95 MW PHES including the NorNed cable would equal € 1.4×10^8. The capacity of the PHES does not influence the PWR as it is assumed that the investment costs and all other costs and revenues are proportional to the original costs of the 95 MW PHES. The BBS is preferred from an economic sustainability point of view, but the difference with the assessment results of the PHES is not large. The

Table 3
Normalised environmental assessment results.

	BBS	CAES	Lead acid	Li-ion	PHES
Human health	411	4895	7852	1580	100
Ecosystems	839	3435	9366	4034	100
Resources	429	3192	2113	501	100
Total[a]	586	3970	7310	2346	100

[a] 40% human health, 40% ecosystems and 20% resources.

Table 4
Results of the economic assessment.

	BBS	CAES	Lead acid	Li-ion	PHES
NPV [€]	2.9e3	1.3e3	−2.6e3	−1.3e4	2.2e3
PWR [−]	1.9e0	3.8e-1	−3.7e-1	−7.1e-1	1.1e0

PHES is followed by CAES. The lead acid and Li-ion batteries appear to be not profitable at all as they result in negative economic scores.

Table 5 shows the results of the exergetic sustainability assessment. The different amounts of electricity input are in accordance with the different charging efficiencies of the systems. According to the results, the Li-ion battery is the preferred energy storage system from an exergetic sustainability point of view, but the difference with the second-best system, PHES, is small. Third-best are CAES and BBS with quite similar scores. The TCExL caused by the lead acid battery is about five times as much as the TCExL caused by the Li-ion battery and PHES.

Analogous to the normalisation of the endpoint indicators of the environmental sustainability assessment, the resulting scores of the three dimensions of the sustainability assessment, i.e. the total normalised environmental scores of Table 3, the PWR scores of Table 4 and the TCExL scores of Table 5, could be normalised. However, the economic sustainability score differs from the other sustainability scores in the sense that the higher the economic indicator, the better it is. This is dealt with by setting the lowest, and negative, score at 100%, with the result that the higher the normalised economic indicator is, the worse the system performs, exactly like the two other normalised sustainability indicators do. It is not likely that all three assessment methods are of the same importance, but assuming they are, this would lead to an overall score of 63 for the PHES system, which would be the preferred system. This is followed by 684 for the BBS, 2546 for the Li-ion battery, 4240 for CAES and 7885 for the lead acid battery.

It is important to realize that it is impossible to model these energy storage systems, like any other technological system, without making many assumptions with regard to e.g. the materials and equipment needed. Besides, the BBS is still under development. Another assumption made in this research is that the end-of-life phase of the systems can be modelled similarly.

As it is undoable to investigate the influence of all assumptions on the results, this is limited to the assumptions related to the

Table 5
Results of the exergetic assessment.

[MJ]	BBS	CAES	Lead acid	Li-ion	PHES
Electricity input	3.3e5	2.6e5	2.3e5	2.3e5	2.7e5
CExD	3.3e4	3.1e5	3.1e5	4.0e4	9.0e3
Total exergy input	3.6e5	5.7e5	5.3e5	2.7e5	2.8e5
Electricity output	1.6e5	1.8e5	1.7e5	2.1e5	2.1e5
Exergy of emissions and waste flows	2.9e4	3.4e5	2.7e5	2.4e4	1.1e4
Total exergy output	1.9e5	5.2e5	4.4e5	2.3e5	2.2e5
Internal exergy loss	1.7e5	4.9e4	8.8e4	3.8e4	5.6e4
Abatement exergy loss	1.0e4	1.1e5	1.7e5	1.1e4	3.9e3
Exergy loss land use	3.1e2	4.6e3	5.4e3	7.1e2	1.7e2
TCExL	1.8e5	1.6e5	2.6e5	5.0e4	6.0e4

Table 6
Main results of the contribution analysis, percentages.

	Subsystem	Human health	Ecosystems	Resources
BBS	Control system	54	55	31
	Water bags	19	13	32
CAES	Air receiver	33	38	42
	Micro gasturbine	33	29	29
Lead acid	Antimony	46	14	12
	Aluminium	16	46	3.7
Li-ion	Battery management system	56	55	38
	Three-conductor cable	27	22	23
PHES	Transmission network	51	47	41
	Electricity from hydropower	49	53	59

components of the systems with the highest influence on the environmental assessment scores (Table 6).

Looking in more detail at the subsystems that contribute most to the assessment results and the assumptions made during the modelling of these parts of the systems, it was decided to investigate the following processes and assumptions during the sensitivity analysis: the influence of the touchscreen of the BBS, which is responsible for 33, 46 and 9.6% of the human health, ecosystems and resources endpoint indicator scores, respectively, the reuse of demineralised water and sodium chloride in the water bags subsystem of the BBS, the composition of the equipment of the control system of the BBS, the influence of the size of the air receiver of the CAES, the assumed lifetime of the lead acid battery as the results of the lead acid battery are caused by many processes, the size of the printed wiring board of the Li-ion battery, which causes 51, 49 and 36% of the endpoint indicator scores, respectively, and the length of the transmission network that is part of the PHES.

Assuming that the BBS does not need a touchscreen, as it is not really sure that a battery management system is included in all assessed systems, its normalised environmental score would decrease from 586 to 370. Assuming that all demineralised water and sodium chloride of the BBS can be reused, its environmental score would equal 542. A combination of both assumptions would lead to an environmental score of 326, thus still higher than the environmental score of the PHES. An important assumption of the PHES is the length of the electricity transmission network. Increasing the length of the cable with 25% would lead to a normalised environmental score of 112, which is lower than the lowest environmental score of the BBS mentioned above. One of the assumptions in the model of the BBS is the composition of equipment like pumps, which are mainly composed of plastics like polypropylene. Assuming that 25 mass% of the polypropylene of the control system is replaced with copper, which has a higher environmental impact that polypropylene or 18/8 chromium steel, the normalised environmental score of the BBS would increase to 808, which is lower than the scores of the three remaining systems, i.e. CAES and the lead acid and Li-ion battery systems. The influence of the size of the wiring board of the Li-ion battery on the results has been investigated by decreasing and increasing its mass with 25%, resulting in a normalised environmental score that decreases and increases to 2059 and 2633, respectively. The same has been done with the size of the air receiver of CAES, resulting in normalised environmental scores of 3608 and 4332 respectively. Lastly, the influence of the assumption related to the lifetime of the lead acid battery has been investigated by increasing and decreasing the lifetime with 25%, resulting in normalised environmental scores of 5848 and 9747, respectively.

On the basis of the aforementioned sensitivity analysis, it seems that the order of preference of the modelled systems from an environmental sustainability point of view is the following: PHES, BBS, Li-ion battery, CAES and lead acid battery, as shown in Fig. 7. However, the results presented here are not meant to draw firm conclusions with regard to which system is preferred or not.

It would be interesting to investigate the energy storage systems including the generation of electricity needed for charging the energy storage systems. The rationale behind this is that the system for capturing renewable energy is already included in the PHES system, while e.g. photovoltaic systems are needed for the generation of electricity to be stored, and released later, by the decentralised energy storage systems applied in households. Nevertheless, the BBS could be located near a river that flows into an ocean and use the salinity difference to generate electricity, while the other systems cannot generate their own electricity.

5. Conclusions and recommendations

The three dimensions of the sustainability assessment lead to different preferences. From an environmental sustainability point of view, the PHES is the preferred system and the BBS performs second-best. The order of preference of the other systems is unclear as the ReCiPe 2016 method does not result in one overall indicator of the environmental sustainability. According to the results, the lead acid battery causes the highest damage to human health and ecosystem diversity, the CAES causes the highest damage to resource availability and the lead acid battery is the least-preferred system when looking at the ReCiPe midpoint indicator named global warming potential.

Normalisation of each of the three environmental endpoint indicator scores by dividing them by the lowest score for that

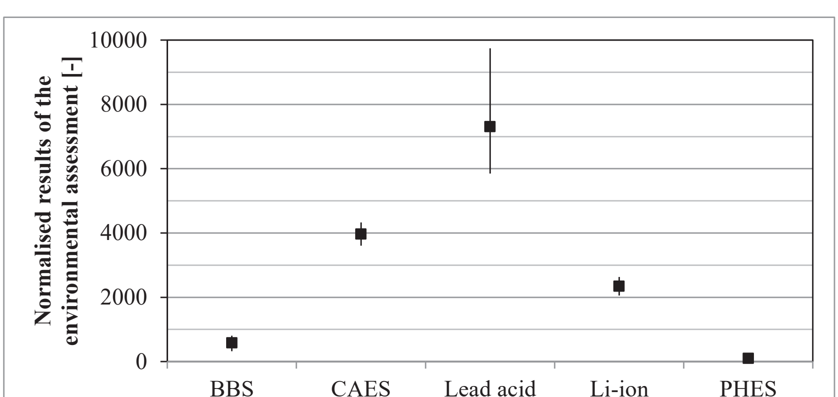

Fig. 7. Sensitivity analysis of the normalised environmental assessment results.

indicator and subsequently weighting the normalised results in accordance with the default weighting set of the ReCiPe 2008 method would lead to a preference for the PHES, the BBS as the second-best system, then the Li-ion battery, CAES and the lead acid battery as the least-preferred system.

The BBS is preferred from an economic sustainability point of view with a PWR of 1.9. The PHES performs second-best with a PWR of 1.1. The assessment of CAES results in a PWR of 0.38 and the PWR scores of the Li-ion and lead acid batteries are negative, meaning that it would not be profitable to invest in these systems.

From an exergetic sustainability point of view, the Li-ion battery is preferred, followed by PHES. CAES and BBS cause about three times as much total cumulative exergy loss. The least-preferred system from an exergetic point of view is the lead acid battery, which causes about five times as much total cumulative exergy loss as the Li-ion battery does.

An advantage of the exergetic sustainability indicator over the environmental and economic sustainability indicators is its independence of changing environmental models and weighting factors, market prices and subsidies. It is therefore advised that attention be paid to the exergetic sustainability of technological systems such as energy storage.

It is recommended to investigate the energy storage systems in more detail, including the assumptions that have been made during the modelling of the systems in SimaPro, in order to be able to draw firm conclusions with regard to which system is preferred or not.

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