Comparative Life Cycle Assessment of Stationary Battery Storage Technologies for Balancing Fluctuations of Renewable Energy Sources

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Abstract: There is a renewed interest among industries, R&D institutions and academia alike to develop and deploy better batteries in the electricity market. Therefore, more information on the environmental performance of the available battery technologies is needed at this hour, so as to make sure that the battery technologies that are going to be deployed in the near future are really the sustainable ones. This paper presents a comparative life cycle assessment of cumulative energy demand (CED) and global warming potential (GWP) of four promising stationary battery technologies: lithium-ion, lead-acid, sodium-sulfur and vanadium-redox-flow. The analyses were carried out for a complete utilization of their cycle life and for six different stationary applications. It was found that in general the use stage of batteries dominates their life cycle impacts significantly. It is therefore misleading to compare the environmental performance of batteries only on a mass or capacity basis at the manufacturing outlet (cradle-to-gate analyses) while neglecting their use stage impacts, especially when they have different characteristic parameters. Furthermore, the relative ranking of batteries does not show a significant dependency on the investigated stationary application scenarios in most cases. Based on the results obtained, the authors go on to recommend the deployment of batteries with higher round trip efficiency, such as lithium-ion, for stationary grid operation in the first instance.

1 Introduction

The combustion reaction based energy technologies that drove the industrial and technological revolutions in the last couple of centuries have done it at the cost of increasing the amounts of carbon dioxide in the atmosphere. This is causing global warming of Earth ecosystem which can be considered as one of the serious threats for the future survival of human civilization (Armand and Tarascon, 2008; IPCC, 2007). On the other hand, our dependency on technological dimension which in turn depends heavily on the combustion reaction based technologies for energy requirements (especially for heat, electricity and transport) has grown drastically in the recent decades, and is still growing in an exponential way. This has led to ever-increasing demand for electricity, and it is crudely projected that the global demand for electricity is going to be doubled by 2050 (Dunn et al., 2011). Hence, considering this twin problem of increasing electricity demand and global warming due to conventional electricity generation sources, it becomes utmost necessary to develop and deploy the alternative environmental friendly energy technologies in mass scale in the very near future; so as to avoid future negative consequences of global warming and other environmental issues.

In this direction, many governments have already started trying to reduce their carbon dioxide emissions from electricity generation by inducing ambitious targets for the development and deployment of renewable energy sources, especially, wind and solar (REN21, 2012).The key challenge in highly renewable electricity scenarios is going to be the matching of demand and supply due to intermittent and non-deterministic nature of renewable sources, especially wind and solar, which are expected to dominate the renewable electricity-mix in the future. This in-turn, leads to a series of technical challenges at various levels in the electricity grid network. For instance, the network operators in Germany are already facing problems of reverse power flows, high local voltage magnitudes and voltage violations during peak hours of solar PV generation. These issues not only induce instabilities in the grid, but also limit further penetration of renewables into it.

Because of their ability to decouple demand and supply, energy storage systems are considered to be promising candidates to address some of the major issues caused by the integration of large proportions of renewables into the future grid. Within the portfolio of available energy storage technologies, it is projected that batteries will play promising role in future highly renewable electricity scenarios, especially for storages at distribution grid level. In addition, there exists a potential synergy between battery applications for automotive and for stationary purposes. It is for these reasons that there is renewed interest within the industry, R&D institutions and academia alike to develop and deploy advanced environmentally friendly batteries for stationary applications.

This study compares four promising batteries– lead-acid (PbA), lithium-ion (Li-Ion), sodium-sulfur (NaS) and vanadium-redox-flow (V-Redox) – for near future stationary applications from an environmental life cycle assessment (LCA) perspective, keeping its focus on distribution grids. The results of our study can guide the battery industry by pointing out the key battery parameters that boost their environmental sustainability as well as aid decision makers in developing sustainable energy storage policies based on a comprehensive environmental understanding of battery systems.

Present State of Research: Various LCA studies on different kinds of batteries can be found in the literature and most of the recent LCA studies on batteries focus on their application for automotive purposes. However, there is still a significant lack of detailed LCA studies that account for all the life cycle stages of batteries, as noted by Sullivan and Gaines (2012). Furthermore, there have been very few LCA studies when it comes to stationary applications of batteries. Rydh (1999) compared V-Redox with PbA for stationary applications by accounting for five environmental impact categories. Denholm and Kulcinski (2004) compared flow batteries with other energy storage systems for utility scale applications in terms of life cycle energy requirements and GHG emissions. Rydh and Sandén (2005) evaluated life cycle energy requirements of eight batteries for their application in stand-alone PV systems. Recently, Longo et al. (2013) assessed the energy and environmental impacts of sodium/nickel chloride batteries for stationary uses, while Spanos et al. (2015) assessed the same for PbA and other batteries. However, there have been no studies that carry out a comparative life cycle assessment of battery systems for multiple stationary applications, taking into account the impacts arising from their stationary use phase.

In this paper, we address this research gap and complement the scientific literature by providing a transparent comparative LCA of the four promising batteries that covers two impact categories for seven stationary applications. Contribution and sensitivity analyses of key parameters, including the influence of power-grid mix, are also presented. Our work thus adds a considerable level of environmental specificity to the on-going discussion on stationary batteries and links earlier battery manufacturing and automotive based LCA literature to upcoming LCA studies in the context of stationary storage systems.

2 Methodology

2.1 System Description

The lifecycle stages included in this comparative LCA are the cradle-to-gate stage processes, i.e., raw materials extraction, materials processing and product manufacture, and the product use phase. The end-of-life scenario, that is, the final disposal or recycling of spent materials is excluded from the study due to the lack of availability of uniform data for all four batteries considered. As noted by earlier studies (Majeau-Bettez et al., 2011; Notter et al., 2010) the analysis can therefore be considered as a worst case scenario in which the benefits of recycling are ignored completely. However, to account for very high recycling rate of lead in today's PbA batteries, an add-on scenario (PbA-R) was modelled wherein 30% primary and 70% secondary lead mix was assumed. Because the focus of this comparative LCA study is on the evaluation of the environmental performance of batteries for stationary applications, significant emphasis was placed on the modelling of use phase scenarios. In addition to complete-battery-life utilization scenario, the following six stationary application scenarios were chosen for analysis, based on the work of Battke et al. (2013): Energy Management (Community Scale), Increase of Self Consumption, Area and Frequency Regulation, Support of Voltage Regulation, Transmission & Distribution (T&D) Investment Deferral, and Utility Energy Time-shift. Each of these application scenarios differ in terms of their power and energy capacity requirements and in the power usage frequency.

2.2 Functional Unit

The product systems are four different types of batteries that are used for stationary applications, i.e., to convert, store and provide electricity whenever required. As the service provided is electricity storage and delivery, the functional unit is set to one megawatt-hour of electricity delivery (1 MWh_d.). It is assumed that the batteries will be used for a period of 20 years in each of the application scenarios since the motivation for the study comes from increasing proportions of renewable sources in the distribution grid. In addition, the impacts arising from associated power sources is also accounted for in the batteries use phase impacts because this helps in comparing the environmental loads of battery applications with differing power-charging options (Longo et al., 2013) and also enables battery systems to be compared with other competing distributed generators.

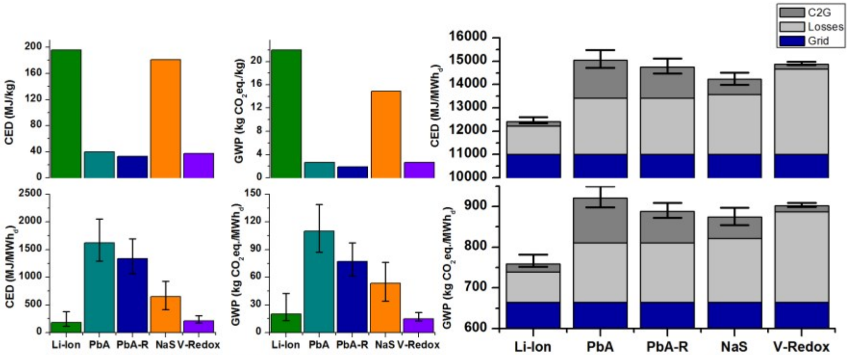
2.3 Life Cycle Inventory Analysis (LCI)

The cradle-to-gate data for Li-Ion, PbA, NaS and V-Redox primarily comes from Majeau-Bettez et al. (2011), Spanos et al. (2015), Sullivan and Gaines (2012), and Denholm and Kulcinski (2004), respectively.

The LCI data for the use phase is basically a function of the quantity and type of energy consumed to operate the batteries for a specific application. To quantify the data in terms of the amount of energy consumed, it is necessary to know the battery characteristic data and the application-specific input data. The authors primarily relied on Battke et al. (2013) for the battery characteristic data and for modelling the stationary application scenarios. The electricity mix used to charge the batteries was assumed to come from German national electricity mix at distribution grid level, and Ecoinvent 3.01 database was used as a background inventory.

3 Results

3.1 Comparative LCA for Complete Utilization



a. Cradle-to-gate Impacts

b. Life Cycle Impacts

Figure 1: (a) Average cradle-to-gate values per kilogram of battery material from the literature (top) and cradle-to-gate values per MWh_d of electricity output calculated in this study (bottom). (b) Life cycle battery impacts showing the contributions from the cradle-to-gate and use stages of the batteries. C2G – Cradle-to-gate battery impacts, Losses – Impacts due to electricity losses from battery use, Grid – Impacts from power-grid mix used to charge the batteries

The comparative results for the four batteries for complete utilization of their cycle life will be presented first. Figure 1(a) top shows CED and GWP cradle-to-gate impact values per kilogram of battery mass, while the bottom figure shows the same for the delivery of 1 MWh_d electricity output normalized across their lifetimes for Li-Ion, PbA, PbA-R, NaS and V-Redox. Li-Ion and NaS have higher impacts per kilogram of battery mass in both the impact categories when compared to PbA, but have lower impacts when compared on MWh_d basis. Also, note that PbA has the highest impacts in both the impact categories when compared on MWh_d basis, although it looked very promising in comparisons on kilogram basis. This is because the electricity stored and delivered during a battery's lifetime depends primarily on the number of cycles it can yield, i.e., its cycle life; Li-Ion and NaS have cycle lives that are, respectively, nearly 8.2 times and 2.6 times longer than the cycle life of PbA(R). In addition, the mass of battery that would be required for a specific application size depends on its energy density (i.e., Wh/kilogram rating); Li-Ion and NaS have energy densities that are, respectively, 5.2 times and 4.3 times higher than the energy density of PbA(R). This means that Li-Ion and NaS can deliver a lot more electricity per kilogram of battery mass than PbA(R) across their lifetimes. This significant increase in lifetime electricity delivered for same mass of batteries ultimately results in the decreased cradle-to-gate impacts of Li-Ion and NaS on MWh_d basis, even though they have greater impacts on mass basis. However, in contrast to these three battery types, the relative indifference in the ranking of V-Redox in both the cases is due to its high cycle life and low per kilogram impacts, which compensate for its low energy density and low round-trip efficiency.

The comparison of the four battery technologies for their life cycle impacts in the context of German distribution grid is shown in Figure 1(b). It can be seen that Li-Ion has the least impact in both the impact categories (12,402 MJ/MWh_d for CED and 759 kg-CO2eq./MWh_d for GWP), and there is a close competition between the other three batteries; though average impacts of NaS are relatively lower than PbA and V-Redox. The contribution of the cradle-to-gate stage to the life cycle impacts is very small compared to the contribution of the use stage, with the impacts coming primarily from the battery losses and the power-grid mix used to charge the batteries. The proportions of cradle-to-gate impacts in the life cycle CED impacts for Li-Ion, PbA, PbA-R, NaS and V-Redox are 1.4%, 10.8%, 9.1%, 4.6% and 1.4% respectively; the corresponding proportions for the GWP impacts are 2.7%, 11.9%, 8.7%, 6.1% and 1.6% respectively. PbA and NaS have higher proportions of cradle-to-gate values in their life cycle impacts compared to the other two because of their relatively low cycle life.

Furthermore, the use stage impacts also vary across the four battery systems, as can be seen from Figure 1(b) (shown in grey). These variations basically result from the differences in the round-trip efficiencies of the battery technologies, i.e., electricity wasted by batteries in each complete charge-discharge cycle. Li-Ion with a round-trip efficiency of 90%, has the lowest use stage impacts (12,222 MJ/MWh_d for CED & 739 kg-CO2eq./MWh_d for GWP), while V-Redox with a round-trip efficiency of 75%, has the highest use stage impacts (14,667 MJ/MWh_d & 887 kg-CO2eq./MWh_d). That is, the more efficient the battery system, the lower the losses and hence the lower the use stage impacts resulting from electricity consumption. Li-Ion therefore becomes more competitive from a life cycle perspective. This can be seen from Figure 1(a & b) that the differences between the impact values of Li-Ion and its closest competitor increase significantly in the life cycle comparisons (1,827 MJ/MWh_d for CED & 115 kg-CO2eq./MWh_d for GWP in comparison to NaS) compared to cradle-to-gate stage comparisons (28 MJ/MWh_d & -5 kg-CO2eq./MWh_d in comparison to V-Redox). Also, note the inverse case of V-Redox which was very competitive during cradle-to-gate comparisons (better than Li-Ion), but falls to last but one position in the life cycle comparisons (only next to PbA without recycling content scenario). Thus it is the use stage impacts, in particular impacts due to electricity losses, that largely determine the life cycle impacts of the battery technologies and hence their relative rankings.

3.2 Comparative LCA for Different Stationary Applications

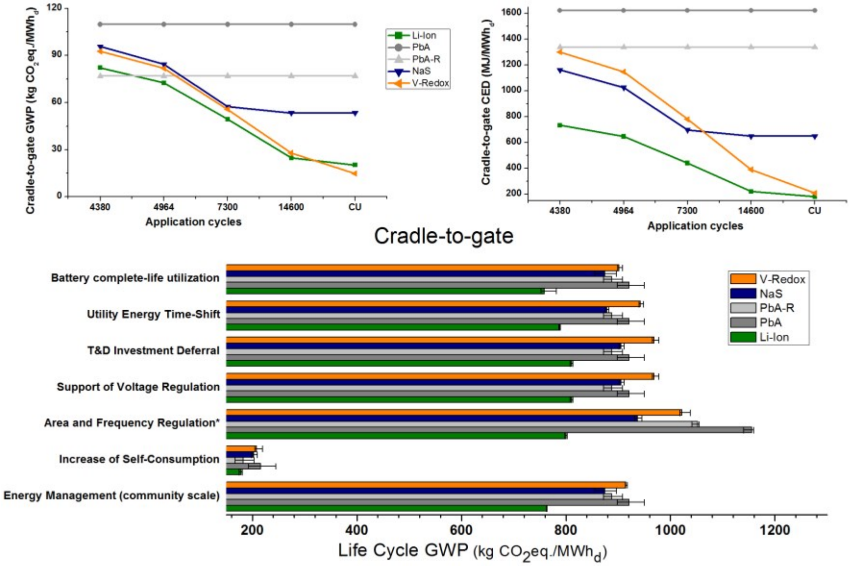


Figure 2: Comparative impact assessment of the battery systems for different stationary applications. The top figure shows the results only for cradle-to-gate impacts, while the bottom figure shows the life cycle impacts. CU - Complete Utilization of batteries cycle life; the lengths of the bars indicate the worst and best case estimations for cradle-to-gate impacts

The comparative results for the batteries for seven different stationary application scenarios are reported in Figure 2. The top figures show the GWP and CED impacts of the batteries for the cradle-to-gate stage alone, with respect to number of cycles demanded by different stationary applications in 20 years time-scale. The variations in the mean relative ranking of the batteries across different stationary applications in the cradle-to-gate results arise primarily from the under-utilization of the cycle life of the batteries. That is, if all the battery types are utilized completely in all the application scenarios, then no variation in the relative ranking of batteries would be observed across different applications and the ranking will be same as that of complete-life utilization scenario; this can be seen from the constant cradle-to-gate impacts observed for PbA and PbA-R across different application cycles as their utilization is complete in all the considered application scenarios.

However, the relative ranking and behaviour of the battery impacts across different applications changes when seen from life cycle perspective (bottom part of Figure 2). Li-Ion still has the lowest average impacts in all six scenarios and proves to be very promising compared to its competitors in most cases. There is a very close competition between PbA-R versus NaS (for second position) and PbA versus V-Redox (for last position) in most of the scenarios, except in two; note the significant changes in relative rankings between batteries for 'area and frequency regulation' (in ascending order - Li-Ion, NaS, V-Redox, PbA-R and PbA) and 'increase of self-consumption' wherein relative differences in batteries ranking is negligible (considering the overlaps in the bars). Nevertheless, the competition between NaS, PbA(R) and V-Redox across most of the applications is very close. The same arguments hold true for CED impacts as well, except that Li-Ion performs better even in self-consumption scenario because the reduction in CED impacts of solar electricity compared to grid is not as dramatic as that of GWP impacts.

3.3 Sensitivity Analyses - Round-trip Efficiency

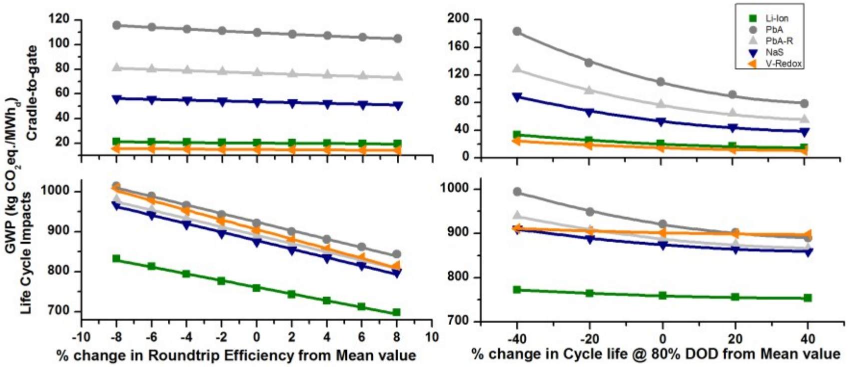


Figure 3: Impact of changing the round-trip efficiency (left) and the cycle life (right) from the mean values used in the LCA model on GWP impacts

The mean round-trip efficiency values used in the LCA model are 90%, 82%, 81% and 75% for Li-Ion, PbA(R), NaS and V-Redox respectively. Figure 3 (left) shows the effect on the GWP impacts from changing the round-trip efficiency values from the aforementioned mean values. An increase of a percentage of round-trip efficiency from the mean values will lead to a corresponding decrease in GWP impacts of 0.5%, 0.6%, 0.6%, 0.6% at cradle-to-gate stage and 1.1%, 1.1%, 1.2% and 1.3% in life cycle scenario for Li-Ion, PbA(R), NaS and V-Redox respectively. Thus the life cycle impact values are strongly dependent on the round-trip efficiency input data used in the LCA model. However, to effect any significant change in the results of this study, i.e., to have other battery types overtake the ranking of Li-Ion, the following deviations from the mean values would be required: deviations of 13%, 14%, 18% and 14% from the mean efficiency values are required for NaS, PbA-R, PbA and V-Redox respectively in order to obtain lower life cycle GWP impacts than Li-Ion; the corresponding values for CED are 12%, 16%, 18% and 15% respectively (note all values are merely indicative).

3.4 Sensitivity Analyses - Cycle Life

The mean cycle life values used in the LCA model are 10,250, 1,250, 3,333 and 13,000 for Li-Ion, PbA(R), NaS and V-Redox respectively. Figure 3 (right) shows the effect of changing the cycle life values from the aforementioned mean values on GWP impacts. A decrease of as much as 20% of the cycle life from the mean values will lead to a corresponding increase of 25% of cradle-to-gate GWP impacts for all batteries, but only 0.6%, 2.9%, 2.2%, 1.5% and 0.4% increase of life cycle GWP impacts for Li-Ion, PbA, PbA-R, NaS and V-Redox respectively (note the values are purely indicative and the relation is not linear). A similar trend is observed for CED impacts as well.

As can be seen, cycle life plays a considerable role when only cradle-to-gate impacts are considered (see Figure 3 top-right) because the lower the cycle life, the lower the lifetime electricity delivered for the same battery material and hence the higher the cradle-to-gate impacts when normalized for 1 MWh_d electricity output across its lifetime. But, the cradle-to-gate impacts make a relatively low contribution to the life cycle impacts of the battery systems, as noted earlier. Hence the life cycle impact values are only very weakly dependent on the cycle life input data used in the LCA model for Li-Ion and V-Redox, but are bit more sensitive for PbA(R) and NaS as they have relatively higher shares of cradle-to-gate impacts in their life cycle values.

3.5 Sensitivity Analyses - Power-Grid Mix

Figure 4 (left) compares life cycle GWP impacts for three different power-grid mix scenarios. It becomes quite evident that a transition towards solar only and solar-wind only energy scenarios drastically reduces the life cycle GWP impacts to as little as less than 23% of the impacts of German distribution grid scenario; this also corresponds to an increase in the contributions of the cradle-to-gate impacts to the life cycle GWP impacts from 2.7%, 11.9%, 8.7%, 6.1% and 1.6 % in German distribution grid scenario to 27%, 65%, 56%, 47% and 18 % in the “50% solar – 50% wind” scenario for Li-Ion, PbA, PbA-R, NaS and V-Redox respectively. Moreover, the differences in the relative ranking of the four batteries decrease considerably and V-Redox becomes more competitive.

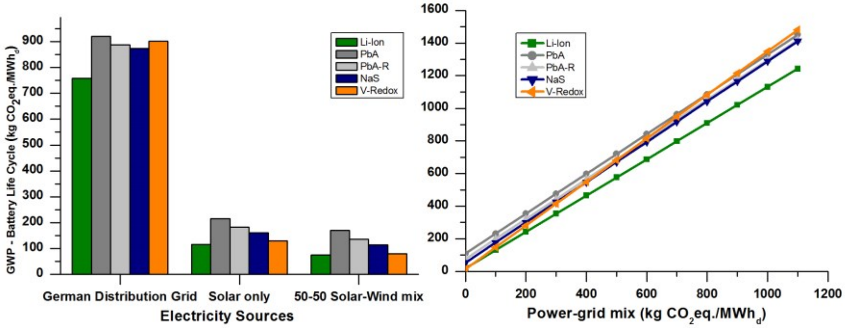


Figure 4: Dependency of the life cycle GWP impacts of batteries on the impacts of power sources. Power-grid mix scenarios assumed to charge the batteries: 'German Distribution Grid' – default mix used in the modeling; 'Solar only' – electricity production mix only from solar PV plants located in Germany; '50 – 50 Solar-Wind mix' – electricity production mix from 50% 'Solar only' and 50% wind (from EU geographical mix)

Figure 4 (right) shows the variation of the life cycle GWP impacts of the batteries with the variation of the GHG emissions of the power-grid mix. The slopes of the lines denote the inverse of the round-trip efficiency values of the batteries, i.e., higher the efficiency, the lower the slope and hence the lower the change in the life cycle GWP impacts (Y-axis) with increasing emissions by the power-grid mix. The relative ranking of V-Redox changes significantly as the GHG emissions from the electricity sources increase; it starts better than Li-Ion at X=0 (i.e., just cradle-to-gate GWP impacts), then crosses Li-Ion (24), NaS (392), PbA-R (545) and finally PbA at 835 kg-CO2eq./MWh$_d$ to become the highest GWP impact battery out of the four batteries. In contrast to this, Li-Ion becomes more promising with increasing emissions by the power-grid mix.

4 Inferences and Implications

At the cradle-to-gate stage, a more realistic comparison requires that the environmental impacts of the batteries be normalized to their lifetime electricity output, i.e., service provided, rather than to their masses or storage capacities at the manufacturing outlet as done in earlier studies (Sullivan and Gaines, 2012; Rydh, 1999); this point is recently noted by Longo et al. (2013) as well. This is mainly because of the differences in batteries energy densities, cycle lives and round-trip efficiencies, which strongly influence the amount of electricity stored and delivered during their lifetimes. Hence a battery that is environmentally friendly based on mass or storage capacity comparisons may not be necessarily attractive when compared on lifetime electricity output basis (the case of PbA in Figure 1a).

The life cycle impacts of battery systems are largely dictated by the impacts arising during their use stage for stationary applications; this is in accordance with earlier automotive battery LCA studies. The proportion of cradle-to-gate impacts in the life cycle impacts of the batteries varies from around 2% (for Li-Ion & V-Redox) to 12% (for PbA). This shows that the manufacturing phase has only a minor impact on the life cycle impacts of the batteries compared to their use phase. Hence the impacts from the use stage of the batteries largely determine their relative life cycle ranking positions. This can be seen very clearly in the case of Li-Ion and V-Redox batteries; although both of them are very competent at the cradle-to-gate stage, one performs best and the other worst when use stage impacts are taken into account. Thus, a battery that is environmentally friendly at the cradle-to-gate stage may not be necessarily attractive when compared on a life cycle basis (the case of V-Redox in Figure 1). This clearly points out the necessity of choosing a right functional unit in LCA as noted by Matheys et al. (2007) earlier.

As shown in Figure 3, round-trip efficiency turns out to be the major battery characteristic parameter that influences the life cycle results and hence the battery ranking. This is mainly because of the strong dependency of life cycle impacts on battery’s use stage impacts which in-turn depend heavily on round-trip efficiency. Although the cycle life of batteries plays a significant role in determining the cradle-to-gate impacts of batteries, its influence on the use stage and, in our case, on the life cycle impacts is insignificant. Furthermore, the change in relative ranking of V-Redox and the increasing competitiveness of Li-Ion with increasing GHG emissions by the power-grid mix as observed in Figure 4 is mainly due to the effect of their round-trip efficiencies. That is, the higher the round-trip efficiency, the better the relative performance of that battery technology at higher environmental loads and vice versa. As a direct consequence of this, given the high life cycle environmental impacts of currently existing power-grids, the authors recommend starting the deployment of battery technologies that have higher round-trip efficiency first. This will keep down the added environmental burden of battery technologies on top of the already high greenhouse gas emissions of today`s power-grid mixes. In contrast to this, from a CED and GWP perspective, the mass deployment of batteries that have lower round-trip efficiency for stationary purposes might make more environmental sense when installed in direct-conjunction with renewable energy sources or in future when the grid has higher proportions of renewable energies (hence low carbon and energy intensities) and when their technologies are more advanced. Furthermore, the breakeven points for GHG emissions from the grid, such that the life cycle impacts of the battery systems do not exceed the GHG emissions of the currently existing German distribution grid, are 580, 455, 482, 495 and 487 kg CO2eq./MWh$_d$ for Li-Ion, PbA, PbA-R, NaS and V-Redox respectively; this result hypothetically conveys that, if in case any government puts a carbon cap on mass deployment of batteries, then Li-Ion becomes capable of grid-penetration lot before the other batteries do.

Further, in the comparative analysis of battery systems for different stationary applications, significant variations in their relative rankings are observed during the cradle-to-gate stage due to under-utilization of the cycle life of some of the batteries (especially Li-Ion & V-Redox). However, these variations played relatively insignificant role in the life cycle comparisons (see Figure 2) which is mainly due to the fact that round-trip efficiency, on which the life cycle impacts depend heavily, remains constant in all the application scenarios as it is mainly a function of battery technology, not the application scenario in which the batteries are used. It should therefore be noted that the minor variations across different application scenarios observed in Figure 2 (bottom part) are due only to the variations in cradle-to-gate impacts, and the use stage plays no role in this unless there is a change in power-grid mix used to charge the batteries. For instance, the decrease in the relative differences between battery rankings in case of the self-consumption scenario is mainly because of feeding electricity from solar PVs to charge the batteries which has very low GWP impacts compared to the grid electricity. Lastly, the odd pattern observed in case of frequency regulation scenario is due to the change in batteries behaviour at 5% DoD cycles and the very high application cycles demanded by that scenario at lower discharge rates; note the competitiveness of Li-Ion and NaS compared to others in this scenario. Hence it can be said that the observed relative ranking of the batteries is not application-specific so long as the use stage impacts significantly dominate the life cycle comparisons and the round-trip efficiency values don't change considerably with the applications operating-environment.

Furthermore, when the proportion of cradle-to-gate impacts in the life cycle impacts increases significantly, for example, when the future grid has very high proportions of renewable energies (see Figure 4) or when batteries are installed directly in conjunction with renewable energy sources as noted above, it might become necessary to completely utilize the cycle life of batteries upon which the cradle-to-gate impacts are very much dependent. Given that future power-grids will have lower environmental impacts (especially GHG emissions) and the strong coupling between batteries and off-grid solar and wind power plants (which have huge application potential in global-south), it might therefore be necessary to develop innovative strategies to effectively utilize the complete cycle life of batteries. It should also be noted that higher utilization of cycle life is very essential to bring down the life cycle costs of battery technologies as noted in Battke et al. (2013). This aspect of improving the utilization of cycle life to reduce the environmental burdens will go in synergy with efforts to bring down the life cycle costs of battery technologies.

Also, note that the lower the cycle life of a battery, the more batteries are needed to meet the life time power storage requirements of a facility.

To summarize, in all the application scenarios considered in this study, it is found that Li-Ion, due to its very high cycle life and round-trip efficiency, is very competitive in both cradle-to-gate and use stage comparisons. Moreover, the competitiveness of Li-Ion increases dramatically when compared by life cycle impacts rather than at cradle-to-gate stage, and also at higher environmental loads. However, there is still a very close competition between PbA(R), NaS and V-Redox. Additionally, it should be noted that the choice of batteries becomes more stringent at higher environmental loads (e.g., grid electricity) compared to the choice at lower environmental loads as the relative differences in batteries ranking are more elevated in the former than latter.

5 Key Recommendations

(1) Considering the high environmental load of today’s power-grids, the authors recommend starting the deployment of the battery technologies that have higher round-trip efficiency first.

(2) The choice and deployment of batteries for stationary applications should be made only after considering their cradle-to-gate and use stage impacts together, including impacts arising from associated power sources, as environmental burdens are function of overall impacts arising from batteries as well as their associated power sources (battery systems), but not just the batteries.

(3) Lastly, it is suggested that the decision makers account for other associated major environmental impact categories as well, not just CED & GWP, while framing the future energy storage policies; though the present trigger is coming mainly from climate change.

6 Supporting Information

This work is already published by American Chemical Society in their journal, Environmental Science & Technology. For more information on assumptions, calculation details and elaborate discussions, the readers are requested to go through that publication and its supporting information.

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