The choice and architectural requirements of battery storage technologies in residential buildings

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Abstract: This study has been undertaken to gain a better understanding regarding the choice and architectural implications of battery storage technologies in a future built environment benefiting from renewable energy systems and energy storage technologies. As no models or tools have been found dealing specifically with the size of energy storage systems, this work has partially addressed this shortcoming through the consideration of a framework, within which these issues are explored. The study assessed the requirements of nine battery technologies for different residential building scales at the distribution level in the UK using quantitative methods. Three scenarios for 2030 were considered; the business as usual scenario, a scenario assuming electrification of heating and energy efficiency measures and a scenario in which one electric vehicle is assumed for each house. After deriving the nominal capacity for each technology and identifying key aspects for building integration, several spatial and other requirements, including footprint, volume, mass and cost for the scales of interest were estimated in each scenario considering daily autonomy. The investigation led to a schematic characterisation of the battery technologies according to their suitability across these requirements and their applicability in different building scales. The study showed that the architectural implications of the battery technologies' integration considering daily autonomy are of little importance to designers. Attention should be given when more than one day of autonomy is applied. The choice of the most suitable technology according to its applicability in different building scales and different daily autonomy periods should also be carefully assessed.

Keywords: battery technologies, energy storage, residential buildings, scenario modelling, architectural implications

Introduction

In the last two decades, sustainability and the irreversible depletion of natural resources has been the subject of constant debate in a global scale. The energy sector today is mainly responsible for the greenhouse gas emissions. Emissions coming from energy-related activities accounted for 68% of the global emissions in 2005 (International Energy Agency 2012) and the building sector is found to be in charge of over 40% of the total energy consumption in Europe (World Business Council for Sustainable Development 2010). Identifying opportunities to reduce this consumption has become a priority in the global effort to deal with climate change. In addition, a very ambitious target set by the EU entails a significant CO_2 reduction by 80 to 95% by 2050 compared to 1990 levels (European Council 2014). An increasing demand in the electricity sector is anticipated in the upcoming years due to the extension of the electrification of different regions worldwide, the increase in energy consumption due to economic growth, the use of electrical energy for heating and cooling and the use of electricity in the transport sector (DECC 2011). Electricity is therefore likely to become a universal and versatile source of low carbon energy for the building sector, but at the same time this is debatable due to scenarios that favour an energy mix in the domestic energy consumption (The Institution of Mechanical Engineers 2014). Expansion of the electricity generation from renewable energy sources is already at the forefront of energy planning and along with electrical energy storage, they are expected to play a key role in the future built environment (Teske et al. 2010; European Commission 2010), contributing to carbon emissions reductions.

The aim of this study is to investigate the architectural requirements of battery storage technologies in residential buildings, which account for the biggest share among commercial, industrial, agriculture, public administration and transport sectors (U.S. Energy Information Administration 2014). The investigation addressed battery integration at building or community scale in the UK, considering only high energy battery storage applications in grid-connected systems, providing the possibility of 'island' mode operation for several days. The research work indicates what considerations architects would need to give to this subject in the design of buildings in the future, where electrical energy storage systems are likely to be part of the design, as indicated in numerous studies (Droege 2008; Inage 2011). As no models or tools have been found dealing specifically with the size and location of energy storage systems (Tan et al. 2013), this research work has partially addressed this shortcoming through the consideration of a framework, within which these issues are explored. The presented work could facilitate making informed design decisions with regard to energy storage systems in the medium term from the end-users' point of view.

Methodology

In this study nine battery technologies were investigated, the data for which were derived from (Chatzivasileiadi et al. 2013). The technologies are applicable to new or existing buildings. After establishing a baseline scenario in 2015 (BS 2015), three scenarios in 2030 were explored: the business as usual scenario (BAU 2030), a scenario assuming electrification of heating and energy efficiency measures (EE 2030) and a scenario in which one electric vehicle is assumed for each house as well (Te 2030). The investigation is based on the electricity consumption data for UK households in the above scenarios derived from a previous study (Chatzivasileiadi et al. 2017). The data, which inform the effective capacity of the battery, are derived in ranges, meaning that the lowest and highest consumption values correspond to low and high consumption households respectively. The study focuses on the final level of distribution in the UK and the number of electrically heated households supplied at this level was found to be 75 (UK Power Networks 2013), which set the upper boundary of the community scale in this study. Intermediate scales were also created for additional reliability on the results.

In order to specify the electricity storage requirements for the residential sector, three steps were followed. First, the specification of the nominal capacity of the battery bank was calculated, then the technologies' applicability in the different scales was assessed and finally the specification of the technologies' spatial and cost requirements were estimated based on the nominal capacity values. As the requirements for nominal electricity storage capacity are higher in winter than summer and the battery is assumed to be used all year round, the sizing of the storage system was based on winter's values. For the values that appear in ranges, two separate sets of data and graphs were produced. Thus a low range and a high range were derived respectively, as indicated in the figures.

Electrical energy storage capacity for the nine battery technologies and their applicability at the different scales

For the calculation of the nominal battery capacity, the following dimensionless parameters were identified as critical to the sizing of the storage system and were therefore considered: round-trip efficiency (η_b), daily self-discharge factor (k_{sd}), depth of discharge (DOD), autonomy period[1], temperature factor (k_t), aging factor (k_a), design margin (DM) and the inverter's efficiency (η_{inv}). A schematic diagram of electricity flow through a storage system including the above parameters is presented in Figure 1 and the associated values for these parameters are included in Table 1.

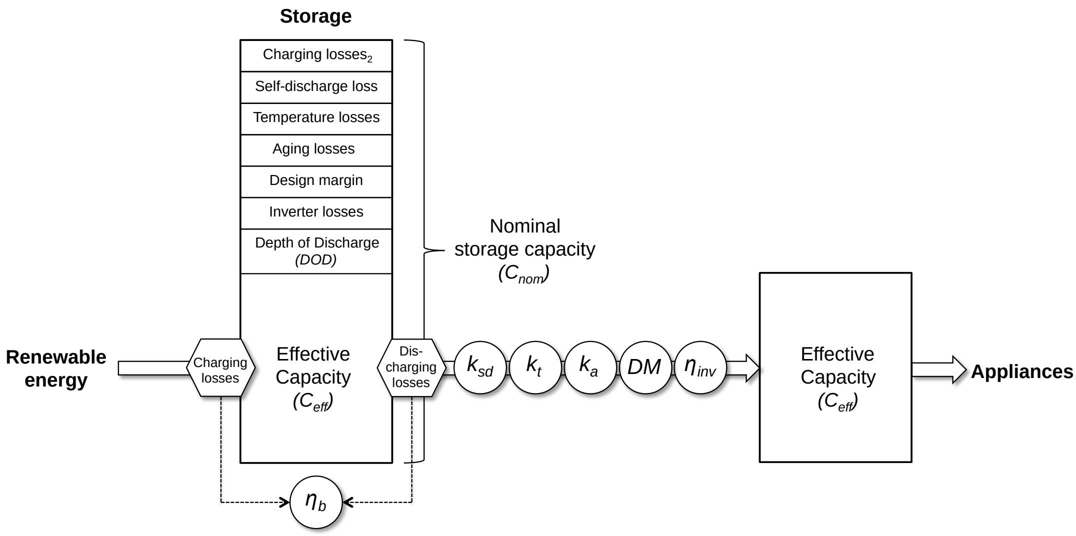


Figure 1: Illustration of electricity flow through a storage system (author's own)

Table 1. Parameters considered and associated values [information compiled from (Chatzivasileiadi et al. 2013; IEEE 2011; Trojan Battery Company 2013; Alcad 2012; Riffonneau et al. 2011)]

	Round-trip eff. η_{batt}	Lifetime (cycles)	DOD %	Self-discharge/ day k_{sd}	Temp. factor k_t	Aging factor k_a	Design margin DM	Inv. eff. η_{inv}	Spatial requirement m²/kWh	Energy density kWh/m³	Specific energy Wh/kg	Investment energy cost €/kWh
Pb-acid	0.8	1200	50	1.003	1.11	1.25	1.1	0.9	0.057-0.22	40-80	27-50	50-300
NiCd	0.7	1500	75	1.006	1	1.25	1.1	0.9	0.009-0.038	<200	45-80	200-1,000
NiMH	0.7	500	80	1.012	1	1	1.1	0.9	0.032	<350	60-120	240-1,200
Li-ion	0.9	4000	80	1.003	1	1	1.1	0.9	0.005-0.013	103-630	100-250	200-1,800
NaS	0.85	4500	80	1.2	1	1	1.1	0.9	0.004	<400	150-240	200-900
NaNiCl	0.9	2500	80	1.15	1	1	1.1	0.9	0.017-0.022	150-200	125	70-150
V-Redox	0.75	13000	100	1.1	1	1	1.1	0.9	0.024-0.042	20-35	75	100-1,000
ZnBr	0.7	2000	100	1.01	1	1	1.1	0.9	0.014-0.025	20-35	60-80	100-700
Zn-air	0.75	10000	100	1	1	1	1.1	0.9	0.006	800	400	126

Based on equations (1) and (2) below for the case of one-day and for four-day battery supply respectively, the required nominal battery capacity for each of the nine technologies and for the scales of interest in the different scenarios was estimated.

$$C_{nom1} = \frac{\frac{C_{eff}*k_t*k_a*DM*k_{sd}}{we}}{\eta_{batt}*DOD*\eta_{inv}} \quad (1) \qquad C_{nom4} = \frac{4*(\frac{C_{eff}}{we}+\frac{C_{eff}}{wd})*k_t*k_a*DM*k_{sd}}{\eta_{batt}*DOD*\eta_{inv}} \quad (2)$$

[1] The investigation on both 4 and 1 days of autonomy, which was based on current rules of thumb (Murphy 2011) and current practices (Little 2013), is useful for 2 reasons: first, the nominal capacity is not linear, so the capacity for 4 days will not be 4 times the capacity required for 1 day. This is due to the inconsistent electricity consumption values on weekdays and weekends. Secondly, depending on the nominal capacity required, some technologies are likely to be unavailable according to their energy rating, which would be useful to explore.

where C_{nom1} is the nominal capacity of the battery for one day

$C_{eff_{we}}$ is the effective capacity of the battery for a day in the weekend

C_{nom4} is the nominal capacity of the battery for four days

$C_{eff_{we}}$ is the effective capacity of the battery for a day in the weekend

$C_{eff_{wd}}$ is the effective capacity of the battery for a weekday

For the assessment of the batteries' applicability in different scales, the nominal capacity values were compared against the energy rating range for each battery technology found in (Chatzivasileiadi et al. 2013). Where the required nominal capacity value was outside the energy rating range, the technology was considered unsuitable for the respective scale[2].

Footprint, volume, mass, investment cost and levelised cost of electricity

The footprint, volume, mass, the investment cost and the levelised cost of electricity (LCOE) for the nine battery technologies at different scales were derived, based on the nominal battery capacity values calculated in the previous section and the information included in Table 1. The analysis was performed using the columns referring to the spatial requirement (m2/kWh), the energy density (kWh/m3), the specific energy (Wh/kg), the investment energy cost (€/kWh), the round-trip efficiency (η_{batt}), the lifetime in cycles and the DOD from Table 1. The LCOE of the battery, C_{LCOE} (€/kWh of electricity generated over lifetime of technology), is calculated using equation (3) below. Equation (3) is a synthesis from the equations presented in (Dennis Barley & Byron Winn 1996) and (Dufo-López et al. 2007).

$$C_{LCOE} = \frac{C_{batt}}{C_{nom} * \eta_{batt} * N_{cycles} * DOD} \qquad (3)$$

where C_{batt} (€/kWh) is the battery investment cost

C_{nom} is the nominal capacity of the battery

η_{batt} is the round-trip efficiency of the battery

N_{cycles} is the battery's cycle life at the specified DOD and

DOD is the depth of discharge

For the values that appear in ranges, two separate sets of data and graphs are produced and presented in this section. Thus through the consideration of the minimum and maximum values a low range and a high range are derived respectively, as indicated in the figures.

Results

As there is a linear correlation between the number of properties and the derived values regarding nominal battery capacity and spatial requirements, the results for up to 5 properties are displayed. Due to the limited suggested length of this paper, it was impossible to include the illustrations for all explorations, so a selection is presented; however, the discussion covers the full scope of this study.

[2] It should be noted that if the required nominal storage capacity is lower than a technology's lower bound of the energy rating range, this does not mean that the technology is not applicable; yet the battery would possibly be oversized. This would only be an energy efficiency issue, but not an applicability issue.

Electrical energy storage capacity for the nine battery technologies and their applicability at the different scales

An illustration of the battery technologies' nominal capacity values and their applicability or not to community scales up to 5 households for 4 days of autonomy is presented in Figure 4. In case of no applicability, the coloured blocks - which the columns consist of and which address minimum or maximum nominal capacity values - are void. Minimum and maximum nominal capacity correspond to low and high consumption households respectively. So, for example, looking at Figure 4, as NaS is not applicable for one or two low consumption households in BS 2015 and BAU 2030, the yellow and blue blocks in the NaS mimimum column in the graphs for BS 2015 and BAU 2030 are void.

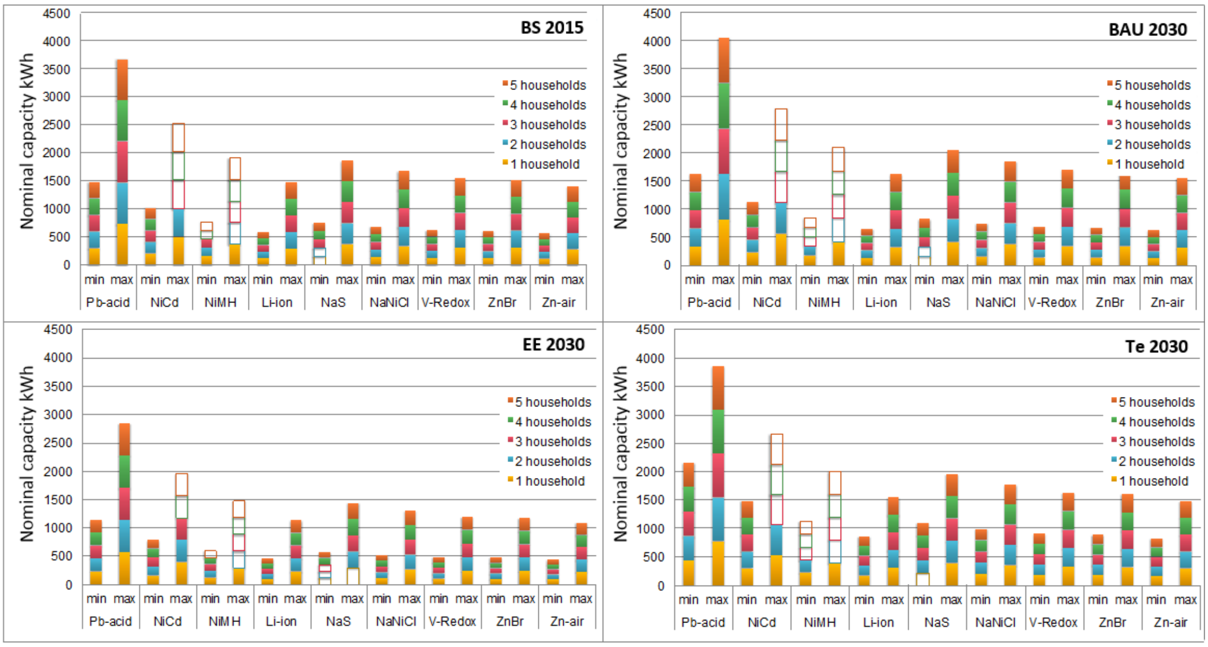


Figure 2: Nominal capacity and applicability of battery technologies for different scales up to 5 households if 4 days of autonomy are applied in winter in all scenarios

It was observed from this exploration that the Pb-acid and Li-ion technologies already have a wide enough energy rating range to be able to serve all scales at distribution level for an autonomy period of 4 days in all scenarios in 2030. NaNiCl would be capable of serving a community of up to about 25 residential buildings, as is the case for ZnBr. These technologies would not be able to be applied to a larger district scheme, due to the limitations posed by the technologies' energy rating range. Moreover, V-Redox would be able to serve up to 25 houses regardless of their electricity consumption and up to 75 houses if their consumption was towards the lower bound of the range assumed in this study. This is the case for Zn-air too. As shown in Figure 4, NiCd and NiMH technologies with their current limited energy ratings cannot meet the requirements for a group of households bigger than 5. In addition, as seen in Figure 4, NaS is able to serve all scales in all scenarios, except a single household in EE 2030 or a single household or two with generally low consumption in the rest of the scenarios. This can be explained by the fact that NaS cells are primarily suitable for large-scale, non-mobile applications such as grid energy storage (Doughty et al. 2010). This is attributed to the batteries' high operating temperature range of 300°C to 350°C and the highly corrosive nature of the sodium polysulfide discharge products.

Footprint, volume, mass, investment cost and levelised cost of energy

The Te 2030 scenario in the case of four days of autonomy has been chosen as an example for illustration in this section. The respective graphs for footprint, volume, mass, investment cost and LCOE for communities comprising up to 5 households in Te 2030 are presented in Figure 3 below. On the left hand side of the figure the low range of the various aspects is presented, while the high range is on the right hand side.

Figure 3. Comparison among footprint, volume, mass, investment cost and LCOE of battery technologies for four days of autonomy in Te 2030

Discussion

The Te 2030 scenario for the case of four days of autonomy has been chosen as an example for discussion, as the comparisons across scenarios are similar due to the linearity of the values. Figure 3 allows for comparisons among the quantitative aspects of integration assessed in this chapter. The technologies are compared vertically across the aforementioned aspects and the strenghts and the weaknesses of each battery option are then discussed. From the investigation regarding four and one days of autonomy it was observed that the different aspects present a similar picture. The only aspect that is different and could affect the ranking of the technologies is their applicability to the different scales.

Pb-acid requires the biggest nominal capacity and is by far the most unfavourable technology in terms of footprint, volume and mass. However, is applicable at all scales for both one and four days of autonomy, which is a convenient aspect. It has medium investment cost and relatively low LCOE, which makes it an economic option.

NiCd is just behind Pb-acid as regards the nominal capacity and the mass and is only able to serve up to about 5 houses in the case of four autonomy days depending on the scenario, rendering it largely unfavourable in terms of these three aspects. If one autonomy day is required, NiCd would then be problematic for communities of 25 or more households. It has a big footprint especially when the maximum spatial requirement is assumed and medium volume. It has the highest investment cost per connection and high LCOE, making it an expensive storage option.

NiMH has medium capacity requirement and has little applicability, being able to serve up to 4 houses in the case of four autonomy days depending on the scenario. If one autonomy day is required, NiMH would then be problematic for communities of 10 or more households. It also has a quite big footprint especially in the case where the minimum spatial requirement has been considered. It has medium volume and mass values. It has high investment cost and the highest LCOE, making it the most expensive option over its lifetime.

Li-ion ranks second in terms of nominal capacity requirement and being applicable at all scales for either one of four days of autonomy makes it a highly favourable technology. It is among the top three technologies regarding the footprint and ranks second in terms of volume and mass when the maximum energy density and specific energy values are assumed. Li-ion, along with NaS, are among the most expensive technologies in terms of investment cost in both the low and high range graphs, yet it has medium to low LCOE assuming a great reduction in investment cost by 2030 due to R&D.

NaS has medium nominal capacity requirement and might not be applicable for communities up to 3 households if four autonomy days are required depending on the scenario. In the case of one autonomy day, NaS might be problematic for communities of 10 or less households. It ranks either first or second as regards the footprint. NaS is among the top three technologies as regards the volume and the mass, regardless of whether the minimum or maximum energy density and specific energy values is considered. It has high investment cost, but medium to low LCOE.

NaNiCl has medium nominal capacity requirement and is not applicable in communities consisting of 25 houses or more if four days of autonomy are required. Yet in the case of one autonomy day NaNiCl is applicable in all scales. It is a medium option regarding footprint. It ranks third in terms of mass if the maximum specific energy values are assumed and fourth if the minimum specific energy values are assumed. It has medium volume range like NiCd and NiMH. It has very low investment cost and LCOE.

V-Redox has medium to low capacity requirement and might be problematic in serving communities of 50 households or more in the case of four autonomy days. Though it is applicable in all scales if one autonomy day is required. It is a relatively unfavourable technology regarding its footprint. It has medium mass values and considerably unfavourable volume requirements due to its low energy density. It has medium to low investment cost and the lowest LCOE assuming the low investment cost value expected in 2030.

ZnBr has medium to low capacity requirement and is likely not to be applicable to communities comprising 25 households or more in the case of four autonomy days. If one autonomy day is required, ZnBr might be problematic in serving a group of 3 or less households. It is a medium option regarding footprint, ranking fourth if the minimum value for spatial requirement is assumed .It has medium mass values and just like V-Redox, it is unfavourable in terms of volume. It has low or medium investment cost in the low and high cost range graphs respectively and medium to low LCOE.

Zn-air requires the least nominal capacity and in terms of applicability in the case of 4 autonomy days it performs exactly the same as V-Redox, being potentially problematic for communities of 50 households or more. If one autonomy day is required, Zn-air might not be able to serve communities comprising up to five households. It is one of the top three technologies regarding footprint and also the top technology in terms of the lowest volume and mass, exhibiting the highest energy density and specific energy among all battery technologies. It also has medium to low investment cost and one of the lowest LCOE values.

Regarding community-wide applications, e.g. 75 households, and considering the minimum footprint values from Table 1, the required space for the suitable battery technologies in Te 2030 under four days of autonomy ranges from 1,850-3,300m^2 for Pb-acid, 65-116m^2 for Li-ion and 66-118m^2 for NaS. Assuming the minimum volume values from Table 1, the required volume ranges from 810-1,450m^3 for Pb-acid, 126-225m^3 for Li-ion and 41-74m^3 for NaS. Alongside the above spatial requirements, future research could include further architectural considerations, for example chemical gases release in the room and fire safety considerations, ventilation requirements for the room as well as the identification of the structural implications arising from the mass of the batteries.

Volumetric analogy

In order to assess the implications of the batteries' volume on building design, a volumetric analogy was performed considering a standard washer device measuring 0.8m*0.8m*0.9m[3] (BUILD 2018) and assuming one household[4]. A volumetric analogy is presented for 4 and 1 days of autonomy in Figure 4.

[3] The dimensions refer to (width*depth*height) respectively.

[4] The investigation in this section addresses only the scale of a single household, as the number of washers is proportional to the number of households. The impact will therefore be proportional to the number of households.

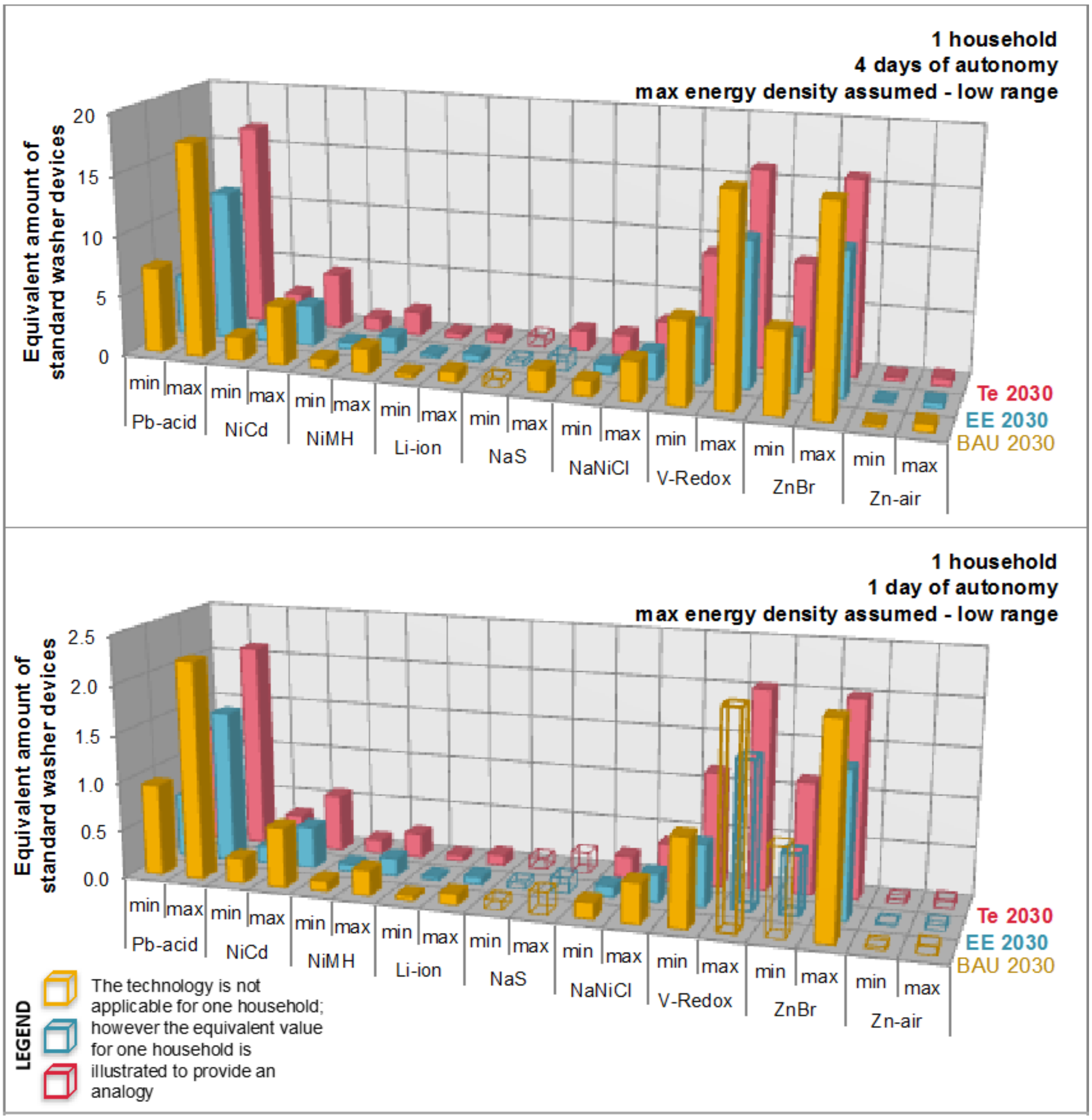


Figure 4: Volumetric analogy demonstrating the number of standard washers required in each scenario

As shown in Figure 4, considering the maximum energy density values that are more likely in 2030 due to R&D, a single household would need a maximum equivalent volume of about 15 standard washers (Pb-acid, V-Redox and ZnBr technologies) for 4 days of autonomy. The rest of the technologies could be used as an alternative in cases of limited space, as they would require an equivalent amount of less than 5 standard washers. In the case of 1 autonomy day, assuming the maximum energy density values, a single household would need a maximum equivalent volume of about 2 standard washers. This volume would apply again for Pb-acid, V-Redox and ZnBr technologies. The rest of the technologies would require an equivalent amount of less than 1 standard washer. The volumetric analogy shows that the implications of the integration of battery technologies on the spatial requirements are of little importance to designers. Greater attention should be given in the case of four days of autonomy, which indicates that consideration should be generally given for any period of over four days. For intermediate periods further analysis is suggested.

Gravimetric analogy

In order to further assess the implications of the batteries' volume on building design, a gravimetric analogy was performed considering the same standard washer device, assuming a washer with a mass of 80kg (BUILD 2018). A gravimetric analogy is presented for 4 and 1 days of autonomy in Figure 5.

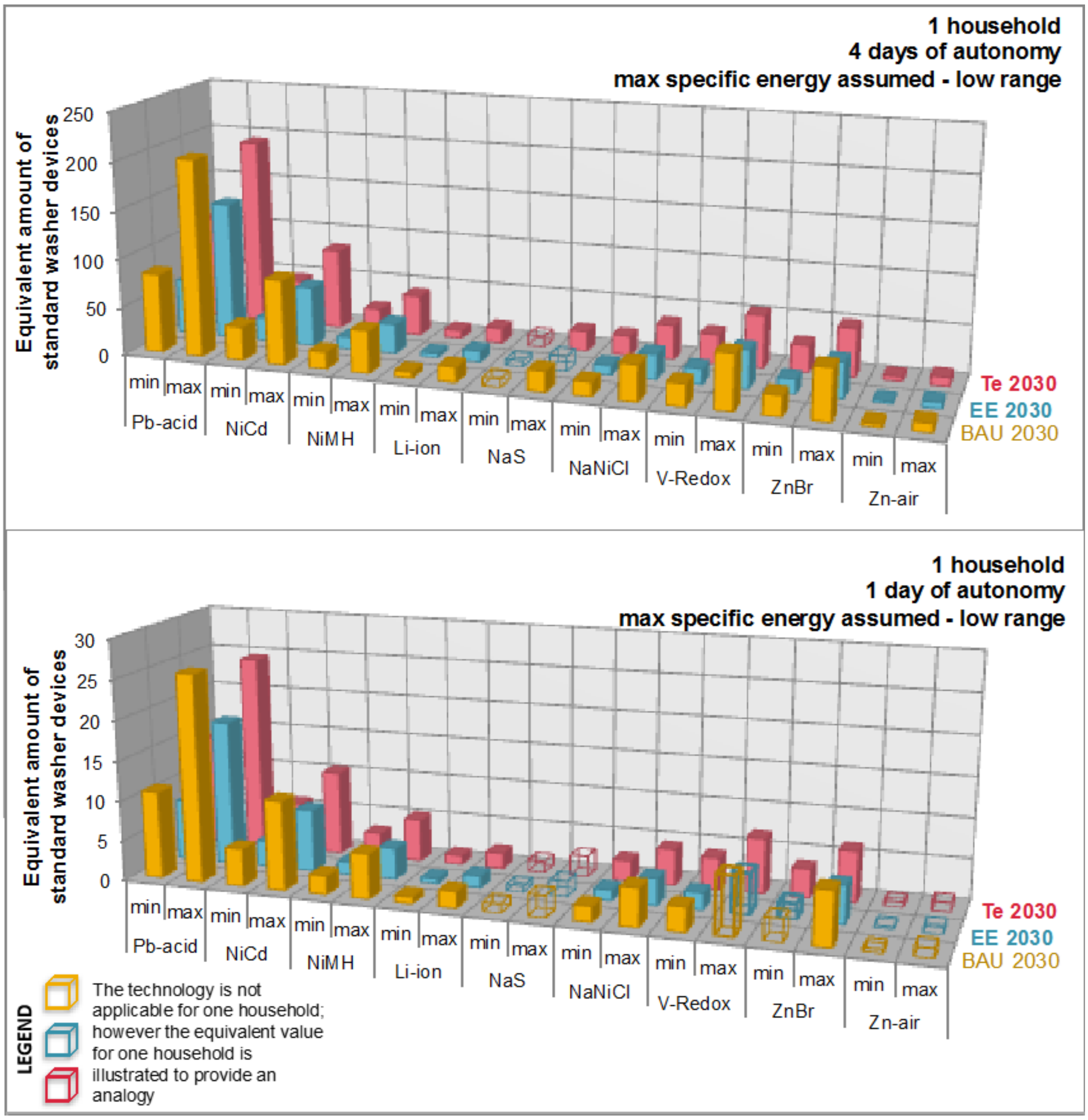
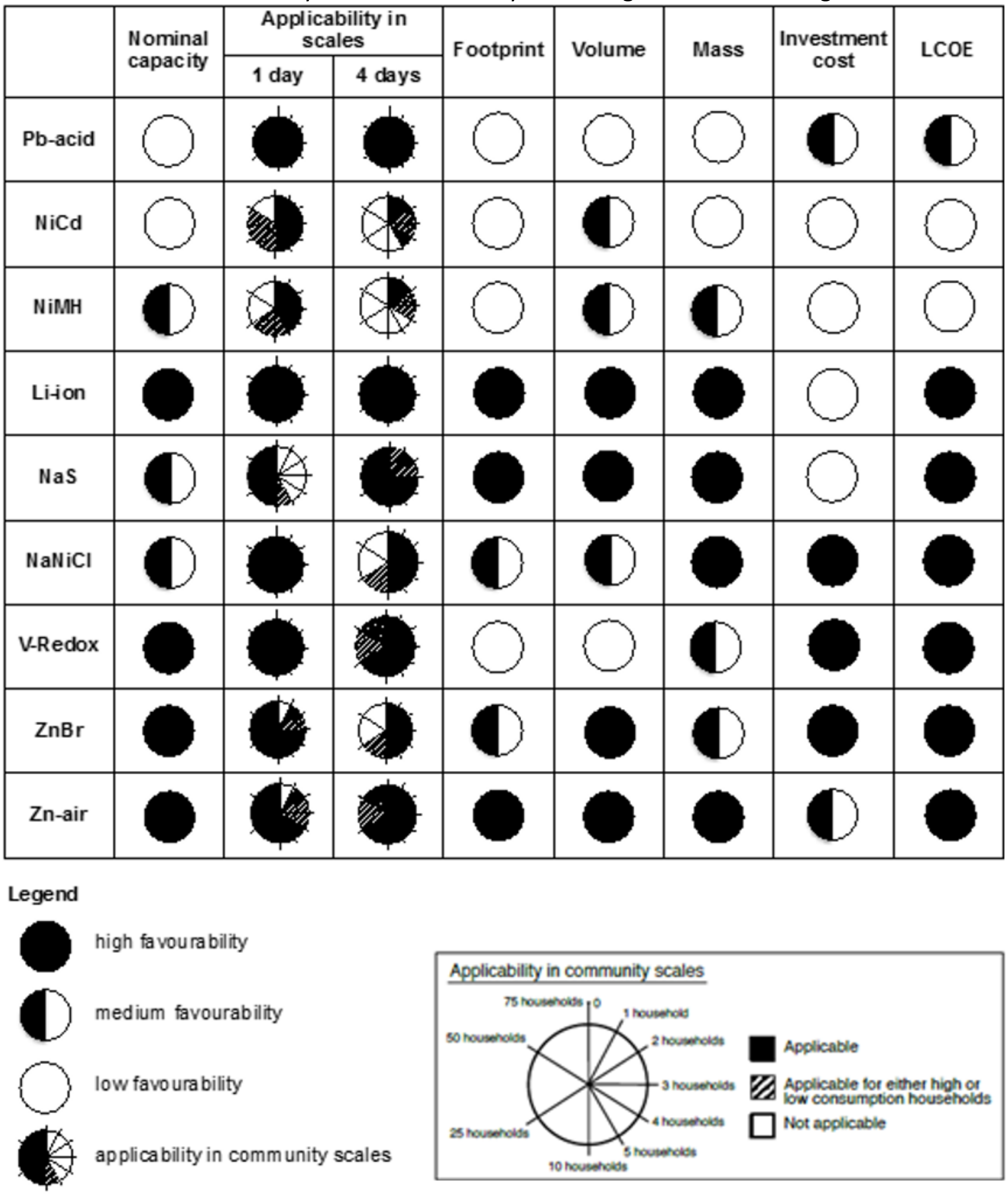


Figure 5: Gravimetric analogy demonstrating the number of standard washers required in each scenario

As shown in Figure 5, considering the maximum specific energy values that are more likely in 2030 due to R&D, a single household would have a maximum equivalent mass of about 200 standard washers for 4 days of autonomy. This mass is remarkably high, but it would apply only for Pb-acid, which have low specific energy values. In order to circumvent any structural limitations in the design of the floor, Li-ion, NaS and Zn-air could serve as good alternatives, having only 5-10% of this mass, thus an equivalent mass of 5-20 washers. In the case of 1 autonomy day, assuming the maximum specific energy values, a single household would have a maximum equivalent mass of about 25 standard washers. This mass would apply again only for Pb-acid, whilst Li-ion, NaS and Zn-air would have an equivalent mass of less than 3 standard washer. The gravimetric analogy shows that the implications of the integration of battery technologies regarding their mass and associated structural requirements of the floor are of little importance to designers. Greater attention should be given when more than one day of autonomy is applied.

Based on the findings from this study, Table 2 below presents a schematic characterisation of the battery technologies according to their suitability across the integration criteria as well as their applicability in different building scales. The picture presented there is that of the low range scenarios and is based on the minimum spatial requirement, maximum energy density, maximum specific energy and minimum investment cost from the range in Table 1, as these figures are more likely in 2030 due to R&D.

Table 2. Illustration of suitability criteria for battery technologies in the low range scenarios in 2030



Conclusions

The architectural implications of the integration of battery storage technologies considering daily storage are of little importance to designers. Attention should be given when more than one day of autonomy is applied. The choice of the most suitable technology according to its applicability in different building scales according to different daily autonomy periods should be carefully assessed. More specifically, in the case of an autonomy period of 4 days, as the number of properties increases, fewer technologies are available. In the case of an autonomy period of 1 day, for 10 households all technologies are available and then on both sides of it, i.e. for either more or less households, the number of technologies gradually decreases. Hence, only 6 technologies are available for one household and only 7 for 75 households. In addition, Pb-acid and Li-ion technologies already have a wide enough energy rating range to be able to serve all scales at distribution level for an autonomy period of 4 days in all scenarios in 2030. NaNiCl and V-Redox are also suitable at all scales if 1 day of autonomy is applied.

In terms of the suitability criteria, if a technology is the most favourable in terms of nominal capacity, footprint, volume or mass doesn't mean that it is the most favourable one in terms of investment cost too and vice versa. Li-ion, NaS and Zn-air are the top three technologies exhibiting the smallest footprint and Pb-acid the last one having the biggest footprint. Regarding volume, in the case that the maximum values are considered (which are more likely in 2030 due to R&D), the top three are Zn-air, Li-ion and NaS. Regarding mass, in the case where the maximum values are considered, the top three are Zn-air, Li-ion and NaS.. In terms of investment cost, in the case where the minimum cost per kWh is considered, NaNiCl, ZnBr and V-Redox are the top three technologies having the lowest investment cost. In terms of LCOE Zn-air, NaNiCl and V-Redox are the top three options, while NiMH, NiCd and Pb-acid rank last.

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