

Requirement for metals of electric vehicle batteries

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Abstract

The purpose of this paper is to review the requirement for potentially scarce or hazardous metals used in a wide range of electric vehicle batteries, in order to provide datasets that could be used as a basis for a variety of assessments of electric vehicles and batteries, such as life-cycle assessments (LCA) and material availability assessments. It is an explicit objective to make the calculations and assumptions transparent so that the datasets can easily be recalculated with different assumptions. We investigate the requirement for metals of nine types of batteries: Li-metal(V), Li-ion(Mn, Ni and Co), NaNiCl, NiMH(AB₂ and AB₅), NiCd and PbA, which contain seven potentially scarce or hazardous metals/group of metals: lithium, nickel, cobalt, vanadium, cadmium, lead and mischmetal (rare-earth elements). We provide datasets for both near-term and improved technology of the requirement for metals per kWh battery as well as per battery electric vehicle. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Electric vehicles; Metal requirement; Lithium batteries; Sodium/nickel chloride batteries; Nickel metal hydride batteries; Cadmium batteries; Lead-acid batteries

1. Introduction

1.1. Background

Battery electric vehicles (BEVs) have been considered as a means to meet some of the environmental and resource challenges of today's road vehicle system. BEVs are locally non-polluting, they are more energy efficient than internal combustion engine vehicles, and they are flexible concerning primary energy source. However, several electric vehicle (EV) batteries contain metals that are toxic, have detrimental environmental effects or are potentially scarce. A large-scale introduction of BEVs could introduce new environmental and resource issues, where one cause could be the use of metals. A number of such issues have been addressed in the literature.

Positive and negative environmental effects of a large-scale introduction of lead-acid battery EVs have been the subject of a recent debate [1–6]. During the 1990s, a number of assessments have been published that cover a range of battery types and focus on environmental effects, health effects and the feasibility of battery recycling [7–13]. Lithium availability in relation to the growth of an EV

industry, was assessed already in the 1970s [14,15] and more recently by Will [16].

It is possible that the use of metals in batteries could become (or should be) a restraining factor for the expansion of BEV fleets, due to limited raw materials availability or negative environmental effects. The extent of these restraints will be determined by factors such as battery life-time, recycling feasibility, emissions from primary and secondary production, metals scarcity, mining technology, and environmental and toxic effects of the metals. In addition, a fundamental and decisive factor is the metal requirement per vehicle.

The purpose of this paper is to review the requirement for potentially scarce and hazardous metals used in a wide range of electric vehicle batteries, in order to provide datasets that could be used as a basis for a variety of assessments of EVs and batteries, such as life-cycle assessments (LCA) and material availability assessments. We provide datasets of the requirement for metals per kWh battery as well as per BEV. Near-term and future datasets are provided to reflect both 'state-of-the-art' technology and prospects for improved technology. Our intention is that the analysis could serve as a bridge between the highly specialised literature on battery development and the more electric vehicle oriented literature. It is an explicit objective to make the calculations and assumptions transparent so that the datasets can easily be recalculated with different assumptions.

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Table 1
Investigated batteries and metals in the active electrode materials

Battery group	Abbreviation	Battery type	Ni	Li	Co	V	Mm	Cd	Pb
Lithium-metal ^a	Li-metal	Li-metal(V)		×		×			
Lithium-ion	Li-ion	Li-ion(Mn)		×					
		Li-ion(Ni)	×	×					
		Li-ion(Co)		×	×				
Sodium-beta	Na-beta	NaNiCl	×						
Nickel-hydroxide	NiOOH	NiMH(AB ₂)	×		×	×			
		NiMH(AB ₅)	×		×		×		
		NiCd	×						×
Lead-acid	PbA	PbA							×

^a Lithium-metal batteries are more commonly called lithium-polymer batteries, with polymer referring to the electrolyte. However, in this context a more important feature is that the anode consists of lithium in *metal* form in contrast to the other lithium battery group we investigate, lithium-ion batteries, where lithium ions are intercalated at the anode. This difference is of importance for the lithium requirement.

This paper is part of the project ‘Material Constraints for Large-Scale Electric and Hybrid Electric Vehicle Systems’, and the derived datasets are used to analyse long-term metal resource constraints for large-scale BEV fleets [17].

1.2. Scope

The paper is restricted to secondary batteries and we only include the active electrode materials, i.e. electrode materials that take part in the electrochemical reactions. However, current collectors are included when they have metals in common with the active materials.

We investigate nine different batteries considered for BEVs today, and six metals and one group of metals, that are potentially hazardous or scarce: cobalt (Co), nickel (Ni), lithium (Li), vanadium (V), cadmium (Cd), lead (Pb) and mischmetal (Mm) (a mixture of rare-earth elements). They are used in the investigated batteries according to Table 1.

The paper is limited to passenger vehicles, i.e. the batteries are dimensioned for full-size passenger cars. However, the data on the requirement for metals per kWh battery can be used to assess the requirement for metals of other types of vehicles with another battery dimensioning.

The requirements for metals per kWh and per BEV are discussed in Sections 2 and 3, respectively.

2. The requirement for metals per kWh battery

In this section, first two datasets of the requirement for metals per kWh battery are provided and related to assumed theoretical limits.¹ These datasets are then discussed in the context of a review of battery performance parameters.

2.1. Datasets of metal intensities

To estimate the *metal intensity* (requirement for metal per kWh battery), I (kg/kWh), we start from a *theoretical metal*

intensity (Table 2). The major reason for doing this is to give a notion of the *theoretical* potential for lower metal intensity, compared to the presented datasets. We calculate the theoretical metal intensity, I_{th} (kg/kWh), from a *theoretical specific capacity* of the metal, C (mAh/g), and a *theoretical voltage* (open-circuit-voltage (OCV) at full charge) of the battery, U (V). The theoretical specific capacity of a metal is calculated by dividing a theoretical electron transfer capability of the metal atom by its mass. We then include the *material utilisation*, η_m , that is the share of the metal in the practical battery that is actually used in the electrochemical reaction, and the *voltage utilisation*, η_u , that is the average discharge voltage divided by the theoretical voltage. Thus, we have

$$I = \frac{I_{th}}{\eta_m \eta_u} = \frac{1000}{\eta_m \eta_u C U}. \quad (1)$$

There are several reasons why 100% material utilisation is not reached in practical batteries: the *active material utilisation* (AMU) is below 100%; one of the electrodes is often overdimensioned compared to the other (*excess*); and grids and current collectors contain the metal. The electrochemical reactions, on which the metal intensity calculations are based, are listed in Appendix A.

Two datasets of metal intensities are provided: one *near-term* and one *future*. Both are based on the same theoretical specific capacity, C , theoretical voltage, U , and voltage utilisation, η_u . The only difference between the two cases is the material utilisation, η_m . An exception is the NiMH(AB₂) battery, where different metal hydride alloy compositions are assumed for the two datasets. The set of near-term metal intensities is intended to reflect state-of-the-art for commercial EV batteries.² In the set of future metal intensities, improved technology is assumed, and thus reflects what can be expected to become commercial in the future.

¹ The word ‘theoretical’ should be interpreted with some caution. For example, for some of the metals, higher electron transfer capability, than the one assumed here, can be achieved under certain circumstances.

² However, it should be noted that some of the investigated batteries are not at present commercially available for BEVs.

Table 2
Datasets of near-term and future metal intensities for the investigated batteries^a

Battery type	Metal	Battery part ^b	Theoretical			Practical								
			Specific capacity, C (mAh/g)	Voltage, U (V)	Metal intensity, I_{th} (kg/kWh)	Material utilisation, η_m		Specific capacity		Voltage utilisation, η_u (%)	Voltage (V)	Metal intensity, I		
						Near-term (%)	Future (%)	Near-term (mAh/g)	Future (mAh/g)			Near-term ^c (kg/kWh)	Future ^c (kg/kWh)	Near-term/future
Li-metal(V)	Li	a + g	3861	3.2	0.081	20	40	772	1545	78	2.5	0.52	0.26	2.0
	V	c	701		0.45	31	75	219	526			1.8	0.76	2.4
Li-ion(Mn)	Li	c	3861	4.0	0.065	50	80	1931	3089	95	3.8	0.14	0.085	1.6
Li-ion(Ni)	Li	c	3861	4.0	0.065	50	70	1931	2703	90	3.6	0.14	0.10	1.4
	Ni	c	457		0.55	50	70	228	320			1.2	0.87	1.4
Li-ion(Co)	Li	c	3861	4.1	0.063	50	60	1931	2317	93	3.8	0.14	0.11	1.2
	Co	c	455		0.54	50	60	227	273			1.2	0.96	1.2
NaNiCl	Ni	c + g	913	2.6	0.42	20	50	183	457	88	2.3	2.4	0.95	2.5
NiMH(AB ₂) ^d	V	a	–	1.3	–	–	–	1686	7892	92	1.2	0.49	0.11	4.5
	Co	a	–	–	–	–	–	–	9095			0	0.088	–
	Ni	a	–	–	–	–	–	732	1713			1.1	0.50	2.3
		c	457		1.7	80	100	365	457			2.3	1.8	1.3
		g	–	–	–	–	–	–	–			1.1	0.55	2.0
		Total (a + c + g)	–	–	–	–	–	184	290			4.5	2.9	1.6
		Mm	a	1131	1.3	0.68	62	86	696	977	92	1.2	1.2	0.85
NiMH(AB ₃) ^e	Co	a	3578		0.22	62	86	2202	3090			0.38	0.27	1.4
	Ni	a	759		1.0	62	86	467	655			1.8	1.3	1.4
	Total (a + c + g)	285		2.7	57	80	161	229			5.2	3.6	1.4	
NiCd ^e	Cd	a	477	1.3	1.6	48	71	229	341	92	1.2	3.6	2.4	1.5
	Ni	Total (c + g)	457		1.7	54	77	246	351			3.4	2.4	1.4
PbA	Pb	a	259	2.1	1.8	35	52	90	136	95	2.0	5.6	3.7	1.5
		c	259		1.8	40	55	103	142			4.8	3.5	1.4
		g	–	–	–	–	–	–	–			8.5	1.8	4.7
		Total (a + c + g)	129		3.7	20	43	26	56			19	9.0	2.1

^a Some data are different as if calculated from provided data due to the use of a larger number of significant digits when calculated. All values are given with two significant digits, except the specific capacities which are rounded to closest integer.

^b a, anode; c, cathode; g, grid, current collector etc.

^c Bold values refer to the *total* metal intensity for each metal and battery.

^d No theoretical specific capacities and material utilisations are given for the NiMH(AB₂) battery, since we have no data on the theoretical hydrogen storage capacity for the assumed alloys.

^e For cathodic nickel in the active material (c) and the grid (g), see the NiMH(AB₂) battery.

2.2. Discussion on battery performance parameters

In this section we discuss the assumptions behind the two sets of metal intensities in Table 2. Of the four factors used to calculate the metal intensities (Eq. (1)), we put most emphasis on the material utilisation.

2.2.1. Lithium batteries

The theoretical specific capacity for lithium is the same for all investigated lithium batteries (Table 2). However, the lithium intensity for the investigated batteries varies due to different voltage and lithium utilisation. The lithium requirement for Li-metal batteries is higher than for Li-ion batteries, since '3 V cathodes' are used, while '4 V cathodes' are used in Li-ion batteries. The Li-metal battery has a polymer electrolyte and operates at temperatures above 60°C to obtain sufficient power. At such operating temperatures, 4 V cathodes would enhance electrolyte degradation and cause irreversible changes of the cathode [18]. Li-ion batteries, on the other hand, use electrolytes which do not need to be operated at elevated temperatures, such as organic liquid electrolytes and polymer gels. However, these electrolytes are not stable in contact with Li-metal. We assume an average practical voltage of 2.5 V for Li-metal(V) [18,19], 3.8 V for Li-ion(Co) [20] and Li-ion(Mn) [21–23], and 3.6 V for Li-ion(Ni) batteries [24,25].

2.2.2. The Li-metal(V) battery

Li-metal batteries have lower lithium utilisation than Li-ion batteries. Firstly, the anode reaction is not completely reversible, why with each cycle some lithium loses its electrochemical activity [26]. Secondly, the lithium anode also functions as current collector (at least in the cell developed by Hydro-Quebec/3M [27]). Thus, all of the lithium in the anode cannot be cycled to the cathode, and as a consequence, much less than 100% material utilization can be achieved.

We assume a lithium utilisation of 20% for the near-term case. This is based on the lithium utilisation of 20–33% generally stated in the literature [20,21,28,29]. In the future case we assume an improvement of lithium utilisation by a factor of two to 40%. Values in this range have been indicated by Cairns [30]. To achieve 1000 cycles (USABC's commercialisation criterion) of 80% depth of discharge (DOD) and still have the rated capacity left, would necessitate a cycling efficiency of about 99.50 and 99.81% in the near-term and future case, respectively.³ This is substantially more than the 99% that was reported as the highest cycling efficiency in 1998 [26]. 300 cycles at 80% (DOD) was reported in 1998 at the module level by Hydro-Quebec/3M [19].

³ The cycling efficiency of a lithium anode can be described as 100% minus the amount of lithium lost during one charge/discharge cycle. For an exact definition see [26].

Several cathodes are considered for lithium-metal batteries. One of the more promising cathodes is vanadium oxide, which is used both by Hydro-Quebec/3M [27] and within the French program for lithium polymer EV batteries [18,31]. Among the various vanadium oxides, V_6O_{13} seems to have received the most attention [32]. Theoretically, eight lithium ions can be chemically inserted into stoichiometric V_6O_{13} , while six lithium ions can be reversibly electrochemically inserted, which is what we assume in the future case (75% AMU). Within the French program [18], initial capacities of about 250 mAh/g have been reached, stabilising at 150 mAh/g for 300–400 cycles at the C/4-rate⁴ for VO_x . In a later paper, a higher stabilised specific capacity of 200 mAh/g is reported for VO_x [31]. If VO_x is equivalent to V_6O_{13} , 150, 200 and 250 mAh/g correspond to an AMU of 36, 48 and 60%, respectively. 36–48% AMU is within the range of what is often stated as the practical range of 2.5–4 lithium ions per V_6O_{13} (31–50% AMU) [21,28,29,32,33]. We assume the lower end of this range for the near-term case (31% AMU).

2.2.3. Li-ion batteries

Also for Li-ion batteries, a variety of cathodes are considered. At present, the most used and studied families of cathodes are $LiCoO_2$, $LiNiO_2$ and $LiMn_2O_4$ [34]. Less than 100% AMU in the Li-ion batteries is mostly due to the fact that all lithium cannot be cycled from the cathode, in contrast to the Li-metal batteries where all lithium cannot be cycled from the anode (Appendix A). In practice, some lithium is lost at the anode during the first cycles due to the forming of a solid electrolyte interface (SEI). For graphite materials, this irreversible capacity is as low as 8–15% [35].

2.2.4. The Li-ion(Mn) battery

Theoretically, two lithium ions can be cycled per Mn_2O_4 , the first in the 4-V region and the second in the 3-V region. In this paper we assume that only the intercalation in the 4-V region will be used, since most research and development is focused on this region. Consequently, the cycling of one lithium atom per Mn_2O_4 is considered as 100% AMU (Appendix A). The three-dimensional $Li_xMn_2O_4$ spinel is thermodynamically stable over the interval $0 < x \leq 1$, and no irreversible structural changes take place in this region.

Reversible practical capacities as high as 130–135 mAh/g (88–91% AMU) are reported [28,36]. In the future case we have settled for a slightly lower AMU of 80%, due to the fact that commonly the practical reversible capacity is given as about 100–120 mAh/g (75–81% AMU) [28,29,34,36], and Japan Heavy Chemical Industry delivers manganese cathodes materials with discharge capacities within this range [37]. However, there are still severe fading problems with

⁴ The C/4 rate means that the battery is discharged during 4 h. For example, if a battery has a capacity of 10 Ah, then the discharge current is 2.5 A.

batteries using this cathode and for the near-term case, we therefore assume an AMU as low as 50%. This AMU, which corresponds to 75 mAh/g, has been reported after more than 1000 deep cycles [36].

2.2.5. The Li-ion(Ni and Co) batteries

Both LiNiO₂ and LiCoO₂ have a two-dimensional layer structure, and in opposite to the LiMn₂O₄ spinel, they are thermodynamically stable only in the fully intercalated state. An AMU of 100% is not reached due to irreversible structure changes in the cathode and/or decomposition of the electrolyte and current collectors.

For both Li-ion(Ni) and (Co) we assume 50% AMU in the near-term case. The reversible specific capacity for the LiNiO₂ and the LiCoO₂ cathodes are often stated as 120–150 mAh/g (44–55% AMU) [20,21,28,29,34–38].

For the future case we assume different AMUs for the Li-ion(Ni) and Li-ion(Co) cathodes. For Li-ion(Co), we assume 60% AMU (164 mAh/g) [39]. Even higher values can be found, such as a maximum capacity of 180 mAh/g (66% AMU) [29] and a reversible cycling of 0.7 lithium per mol (70% AMU) has been reported with inorganic electrolytes [38].

For Li-ion(Ni), higher AMUs than 55% can be found, for example, 160–180 mAh/g (58–66% AMU) are given by Nomura Research Institute [37] and 60% AMU is stated as the reversible range in [35]. We assume 70% AMU (192 mAh/g) for the futures case [21]. Even higher values can be found, for example, capacities in the range 185–210 mAh/g (67–76% AMU) [34] and a maximum capacity of 220 mAh/g (80% AMU) [29]. However, according to [36], high cycle numbers are achieved only for specific capacities as low as 100–120 mAh/g (36–44% AMU).

2.2.6. The NaNiCl battery

We assume a nickel utilisation of 20 and 50% for the near-term and future cases, respectively. These nickel utilisations are among the lowest material utilisation factors assumed in this paper, due to the fact that cathodic nickel is also used as current collector. Experiments have indicated that 50% nickel utilisation is possible, but at the cost of low cycle life [40]. 30% nickel utilisation is often stated [40–42], but even lower nickel utilisation of about 20% can be found in the literature [43].⁵ However, to increase the nickel utilisation does not seem to be a central issue for battery developers; at least in 1998, no efforts were being made to reduce the nickel use in the NaNiCl battery at AEG ZEBRA [44]. The OCV is 2.6 V and we assume an average discharge voltage of 2.3 V [41].⁶

2.2.7. NiOOH batteries

Typical OCVs are 1.4 and 1.3 V for NiCd and NiMH batteries, respectively [45]. For the sake of simplicity, we

assume 1.3 V as theoretical voltage for all three NiOOH batteries. The same average voltage, 1.2 V, is also assumed for all three NiOOH batteries [45]. The low voltage contributes to higher theoretical cathodic nickel intensity of the NiOOH batteries than of the NaNiCl and Li-ion(Ni) batteries.

2.2.8. The NiOOH cathode

Another reason for differing theoretical cathodic nickel intensities, is varying theoretical specific nickel capacities, due to varying electron transfer capabilities per nickel atom (Appendix A). In the NaNiCl battery, two electrons can be transferred per nickel atom, and in the Li-ion(Ni) battery one electron. Normally, one electron can be transferred per nickel atom in the NiOOH cathode. However, in theory, transfers of up to as much as two electrons is possible under certain circumstances [46]. We base the theoretical nickel intensity on one electron transfer, and assume the same cathodic nickel intensity for all three NiOOH batteries.

In the near-term case we assume an AMU of 80%. Around 80% AMU is assumed in a cost analysis of a bipolar NiMH(AB₅) battery [47],⁷ and is also achieved in a NiMH(AB₅) battery for Toyota RAV4 [48].⁸ In a cost study of EV-batteries [49], the assumptions on cathodic active nickel for NiMH(AB₂) batteries are 2.3 kg Ni/kWh (73% AMU) and 1.8 kg Ni/kWh (93% AMU) for generation 1 and 4 batteries, respectively.⁹ In the future case, we even go one step further and assume an AMU of 100%, thus implicitly assuming a higher electron transfer than one per nickel atom.

In the near-term case we assume 1.1 kg Ni/kWh in the grid [48]. In the previously mentioned cost study [49], nickel in the cathode foam substrate (the grid) is assumed to be 1.1 and 0.57 kg Ni/kWh in generation 1 and 4 batteries, respectively. In the future case we assume a similar value as for the generation 4 battery, 0.55 kg/kWh.

This leads to a total utilisation of cathodic nickel of 54 and 77% for the near-term and future case, respectively, leading to 4.1 and 3.4 kg Ni/kWh. Higher nickel intensities are assumed in two LCAs of NiCd batteries for BEVs. Koontz et al. [10] assume 4.7 and 6.0 kg Ni/kWh for batteries of 55 and 52 Wh/kg, respectively. Almemark and Granath [50] assume 4.6 kg Ni/kWh, based on the SAFT NiCd battery in Renault Clio. These LCAs probably include nickel in grid tabs and anode grids, which we do not include. Lipman [49] estimates nickel in grid tabs at about 0.2 kg/kWh. No estimates of nickel in anode grids are found.

⁷ 85 g Ni(OH)₂ for a 20 Ah cell leads to 82% AMU.

⁸ 2.1 kg nickel per kWh.

⁹ Generation 1 appears to be current battery technology and the specific energy is 70 Wh/kg. Generation 4 is termed 'future technology' and is based on 363 mAh/g theoretical capacity for the Ni(OH)₂ cathode (1.25 electron transfer per nickel atom) and a magnesium based anode of 600 mAh/g and a specific energy of 120 Wh/kg.

⁵ 70 kg nickel for a 30 kWh battery.

⁶ The average discharge voltage is estimated from Fig. 40.17 of [41].

Table 3
Some MH (AB₂) alloy compositions from the literature, ranked according to molar mass^a

Reference	Zr	Ti	Total A	V	Ni	Cr	Fe	Al	Co	Mn	Total B	Total	Molar mass (g)
Ovshinsky et al. B [55]	0.58	0.42	1	0.42	0.86	0.17	0.17		0.17		1.78	2.78	173
Ovshinsky et al. D [55]	0.57	0.43	1	0.43	0.80	0.14	0.17		0.14	0.17	1.86	2.86	176
Young et al. Ov372 [57]	0.45	0.55	1	0.36	1.03	0.30				0.30	1.99	2.99	178
Shaju et al. [53]	0.50	0.50	1	0.60	1.20	0.20					2.00	3.00	181
Verbetsky et al. [64]	0.50	0.50	1	0.50	1.30	0.20					2.00	3.00	182
Young et al. Ov313 [57]	0.57	0.43	1	0.36	1.03	0.30				0.30	1.99	2.99	183
Fetcenko et al. [65]	0.48	0.52	1	0.67	1.18	0.21					2.06	3.06	183
Ovshinsky et al. C [55]	0.55	0.45	1	0.55	0.94	0.18	0.18		0.18		2.03	3.03	185
Anani et al. [63]	0.49	0.51	1	0.76	1.18	0.21					2.15	3.15	188
Kim et al. 1 [61]	0.70	0.30	1	0.40	1.00	0.30				0.30	2.00	3.00	189
Venkatesan et al. [56]^b	0.80	0.20	1	0.20	0.80			0.05	0.15	0.80	2.00	3.00	194
Ovshinsky et al. A [55]	0.50	0.50	1	0.70	1.03	0.20	0.20		0.20		2.33	3.33	199
Moriwaki et al. [62]	1.00		1	0.30	1.20	0.20				0.30	2.00	3.00	204
Knosp et al. [60]	1.00		1	0.20	1.20	0.05			0.05	0.60	2.10	3.10	210
Kim et al. 2 [61]	0.90	0.10	1	0.46	1.10					0.64	2.21	3.21	210

^a All compositions are normalised to one A atom per AB₂. Bold values refer to the ones used in this study.

^b From [49].

2.2.9. Nickel metal hydride batteries

For the metal hydride anode (MH) in the NiMH batteries, it is in several respects more complicated to estimate the metal intensities than for the other electrodes, since a variety of hydrogen storing alloys with quite different compositions have been suggested. None of our assumed compositions are believed to be the state-of-the-art, but compositions used by battery developers are proprietary information, and are therefore not released.

In sealed NiMH batteries, the anode is overdimensioned for over-charge/discharge protection [51]. The initial anodic excess can be as much as 30% [52], which is what we assume for the near-term case. In some references even an excess as high as 50% is given [47,53].¹⁰ Lower excess is assumed in [54], where one cell consists of 9 cathodes and 10 anodes, leading to 11% excess, which is close to the 10% we assume for the future case.

2.2.10. The AB₂ anode

As mentioned in Section 2.1, a slightly different approach is used for the NiMH(AB₂) battery compared to the other batteries. A great variety of AB₂ compositions can be found in the literature, where some are listed in Table 3, and it is still an open question which composition(s) might come into commercial use. Therefore, we have chosen two quite different compositions for the near-term and future cases.

Of the compositions in Table 3, basically all contain zirconium, titanium, vanadium, nickel and chromium. However, the amount of these metals vary substantially. The amount of vanadium varies by almost a factor of four, from 0.20 to 0.76 atoms per AB₂. The amount of nickel varies less, around a factor of 1.5. Quite a few of the compositions

contain cobalt and manganese, while only four contain iron [55] and only one aluminium [56]. The molar mass of the compositions in Table 3 varies from 173 to 210 g. The difference principally reflects the amount of zirconium and the ratio between the number of A and B atoms.

Another property that influences the metal requirement for a certain AB₂ composition is the hydrogen storage capability. For the AB₂ paradigm compound, ZrV₂, the theoretical storage capability is 5.3 hydrogen atoms [32,57]. This is probably much higher than what can be achieved for alloys suitable for commercial use.

For the near-term case, we assume a specific alloy capacity of 370 mAh/g. This is slightly higher than what we assume for the NiMH(AB₅) future case but less than the 400 mAh/g claimed by Ovonic to be the present practical capacity [55,58,59]. Ovonic also claims prospects for even higher specific AB₂ alloy capacities and achievements of 550 mAh/g at the laboratory scale are reported [59]. However, it should be noted that some of their compositions contain palladium [57]¹¹ which quite likely make them practically unfeasible for EV applications. For the future case we have settled for 450 mAh/g, which is higher than anything we have found reported for a specific composition in the literature, but much lower than Ovonic's claims.

In the following, the discharge capacities obtained for the compositions in Table 3 are accounted for. Discharge capacities of about 400 mAh/g are reported for the Ovonic compositions Ov313 and Ov372 at the C/4-rate. Similar discharge capacities of 375–400 mAh/g are reported at the C/5-rate by SAFT [60]. Also at the Korean Institute of Science and Technology specific capacities in this range

¹⁰ In [47], a capacity ratio of 1.5 (20 Ah cathode, 32 Ah anode) is assumed. In [53], each cell consists of three anodes and two cathodes.

¹¹ If we assume a capacity of 450 mAh/g for the Ov212 composition (Zr_{2.5}Ti_{8.5}V₈Cr₂₀Mn₁₃Ni_{24.5}Pd₁) the palladium intensity is about 30 g/kWh.

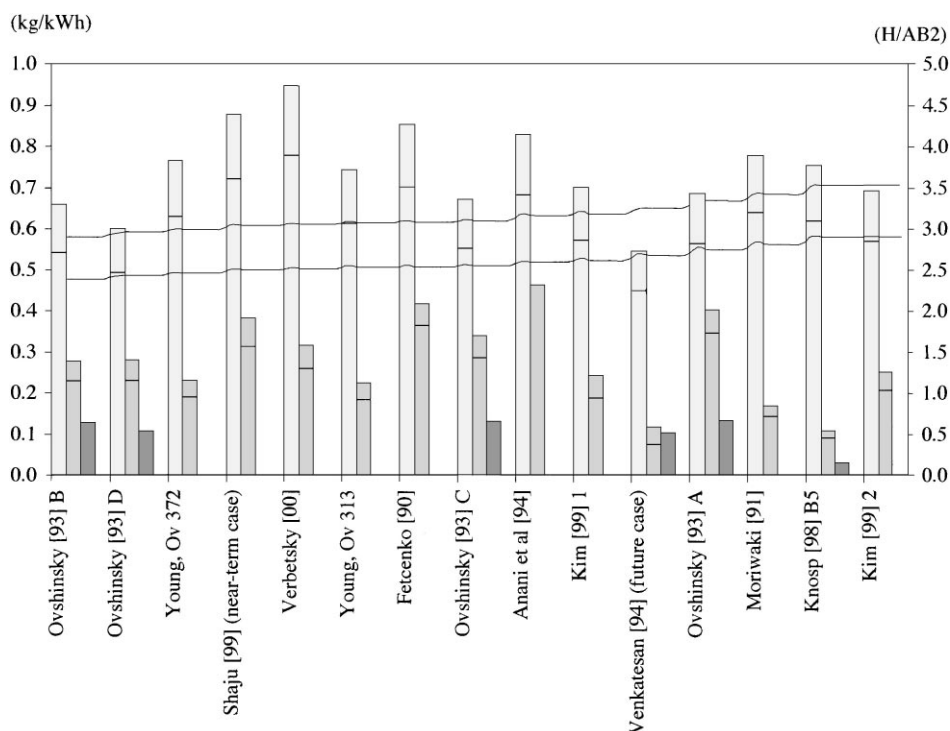


Fig. 1. Metal intensities and hydrogen storage capability for the compositions in Table 3, assuming a specific alloy capacity of 370 and 450 mAh/g, respectively. The bars denote metal intensities: light grey for nickel, medium grey for vanadium and dark grey for cobalt. The span depicts the metal intensity assuming 450 mAh/g (lower) and 370 mAh/g (higher). The upper and the lower line depict the hydrogen storage capability necessary to achieve 450 and 370 mAh/g, respectively. The compositions are ordered according to increasing molar mass, with the lowest to the left.

have been achieved [61]. For the Kim et al. 2 composition, 394 mAh/g has been achieved at the $C/4$ -rate, while for the Kim et al. 1 composition about 360 mAh/g is achieved at a current density of 100 mA/g. For the Moriwaki et al. composition [62], 360 mAh/g is reported, and a slightly lower capacity, 350 mAh/g, is reported by Anani et al. [63]. The Shaju et al. [53] and the Verbetsky et al. [64] compositions are very similar, and for the Shaju composition only 300 mAh/g is reported [54]. No data on discharge capacity are found for the Fetcenko et al. composition [65], but it is included since it is presented as the base composition of the V–Ti–Zr–Ni–Cr alloys developed by Ovonic.

In Fig. 1 we show the vanadium, nickel and cobalt intensities for the compositions in Table 3, assuming specific alloy capacities of 370 and 450 mAh/g. For the near-term case we have chosen a composition with high nickel and vanadium intensities, the Shaju et al. composition [53], and for the future case one with low nickel and vanadium intensities, the Venkatesan et al. composition [56]. 370 and 450 mAh/g do not reflect specific capacities actually obtained with these compositions. For the near-term composition, only 300 mAh/g is reported while we have no reports on specific capacity for the future case composition. The rationale behind this choice is an ambition to try to, at least, picture some kind of reasonable span of these metal intensities for AB_2 anodes.

Furthermore, the cobalt content is higher in the future case than in the near-term case. As can be observed in Table 3 and Fig. 1, there is a pattern of decreasing cobalt intensities with

increasing nickel intensities. Therefore, none of the compositions in Table 3 lie in the higher metal intensity range for all three considered metals: vanadium, nickel and cobalt.

2.2.11. The AB_5 anode

In contrast to AB_2 compositions, we have not found a great variety of AB_5 compositions in the literature; almost all manufacturers use about the same composition [66]. Our assumed composition, $MmNi_{3.55}Mn_{0.4}Al_{0.3}Co_{0.75}$, is stated as typical [32,67]. The nickel (49 wt.%) and mischmetal (33 wt.%) content is about the same for all compositions found in the literature. Cobalt is added to achieve longer cycle life, and the cobalt content in our assumed alloy is 10 wt.%. However, there are work in progress on reducing the cobalt content, where promising cycle lives with a cobalt content of 4.2 wt.% have been observed [68].

The maximal hydrogen storage capability of the AB_5 paradigm compound, $LaNi_5$, is 6–7 hydrogen atoms (7 atoms [32], 6.48 atoms [69]). The hydrogen storage capability of $MmNi_5$ is slightly lower, 6.36, and for $MmNi_{4.2}Mn_{0.3}Al_{0.3}Co_{0.2}$, an alloy similar to ours, it is even lower, 5.88 [69]. Based on this, we assume a theoretical limit of 5.9 hydrogen atoms for our alloy, resulting in a theoretical capacity of 374 mAh/g.¹²

¹² We assume a composition of Mm corresponding to an atomic mass of 139.84 u. This is approximately the same composition as the ‘normal’ composition given by Reilly [70].

Several references state typical practical specific capacities for AB₅ alloys at 250–300 mAh/g [51–56,71,72]. For the near-term case we have settled for the higher end of this range, 299 mAh/g (80% AMU). In a battery forecast [37], the specific alloy capacity for small batteries is set to 300 mAh/g in 1995 and to 365 mAh/g in 2005–2007, which is ‘... as close as possible to 367 mAh/g, which is the theoretical limit’. We have settled for a slightly lower value, 356 mAh/g (95% AMU), for the future case.

2.2.12. The cadmium anode

For the cadmium anode in the NiCd battery, we assume an AMU of 60 and 75% for the near-term and future case, respectively. In sealed NiCd-batteries, there is an anodic excess for the same reasons as for the NiMH batteries (see above). For the near-term case we assume an anode excess of 25%, the same value as used in SAFT EV batteries [73]. In the future case we assume only 5% [74]. This leads to a total cadmium utilisation of 48 and 71% for the near-term and future cases, respectively. Our near-term case is about the same as the SAFT NiCd battery in Renault Clio [50], with a total cadmium utilisation of 51%. In a LCA of NiCd batteries for EVs [9], a cadmium utilisation of 42 and 54% is assumed for batteries with 52 and 55 Wh/kg specific energy, respectively. References that might imply a higher cadmium utilisation can also be found. An average cadmium content of 15% of total battery weight is mentioned in [8], leading to a total cadmium utilisation of 70% for a battery with a specific energy of 60 Wh/kg, which about corresponds to our future case.

2.2.13. The lead-acid battery

The main factors that affect the AMU for lead-acid batteries are: current density, plate thickness, active material structure and conductivity of active material, grid and electrolyte [75]. Most references regarding AMU deal with the positive active material (PAM), i.e. the cathode. However, we assume the same lead utilisation for both the anode and the cathode. The state of the art seems to be 30–40% PAM utilisation at discharge rates relevant for EVs [75–78]. Based on this we assume 40% AMU in the near-term case. Higher PAM utilisation can be reached. A PAM utilisation of over 50% at the C/3-rate is mentioned for a tubular design at Yuasa with a projected specific energy of 42 Wh/kg [79]. It should be possible to increase the AMU to 60% for high power uses [80], but McGregor [81] claims that it is accepted that the PAM utilisation limits are in the order of 55% at the C/3-rate. We have settled for 55% AMU in the future case. Metzendorf [82] reaches a maximum of 70% AMU at low discharge rates and with an excess of electrolyte at the cathode. He concludes that electronic conductivity breakdown appears at a certain AMU.

The near-term and the future cases are based on an anode excess of 15 and 5%, respectively. There are different opinions whether to have an anodic or a cathodic excess. According to Hammel et al. [83], sealed lead-acid batteries

have an anodic excess to facilitate the recombination of oxygen or to prevent gassing, e.g. over-charge/discharge protection. A Panasonic representative at EVS-15 in 1998, stated that their anode has an excess of 17%. However, according to Rand et al. [76], it is recommended to have a cathodic excess in order to protect the cathode, which is more susceptible to degradation. This issue is further discussed in reference [84].¹³

The share of grid and top lead of total lead has decreased from 50% in 1986 to 45% in 1996, and is expected to decrease further to 42% by 2006 [85]. Koontz et al. [9] assume 45% of total lead in grid and top lead for one of their investigated batteries. Based on this we assume 45% for the near-term case. Various approaches are taken to reduce the amount of grid and top lead. One is to use a composite material with a core covered by lead. These composites have included lead-coated aluminium, copper, steel, nickel, titanium, metal-coated graphite, fibreglass, plastics and ceramics. None of these alternatives, with the possible exception of metal/fibreglass grids has proven to work satisfactory [86]. We, however, assume the viability of such grids in our future case based on 20% of total lead in grid and top lead.

Consequently, the near-term and the future cases are based on 20 and 43% total lead utilisation, respectively. Table 4 summarises total lead utilisation and some other battery parameters from various battery assessments, including our assumptions as well as data from a Panasonic representative at EVS-15 in 1998. The total lead utilisation in Table 4, excluding our future case, varies from 10 to 32%.

The OCV is typically 2.1 V and an average discharge voltage of 2.0 V is assumed [45].

2.2.14. Summary

In Fig. 2, the spans of material utilisation given in this section’s review are depicted, as well as the material utilisations we use in our two datasets. The metals that are used in current collectors and grids as lithium in Li-metal(V), nickel in NaNiCl and lead in lead-acid batteries have the lowest utilisation factors, 20–50%. An exception is cathodic nickel for NiOOH batteries where we assume utilisation factors above 50%. This is due to the fact that the NiOOH cathode, together with the NiMH(AB₅) anode, have by far the highest assumed active material utilisation, 80–100%. The AB₂ alloy is not included since we have no data on the theoretical hydrogen storage capacities for the assumed alloys.

In the future case, the most optimistic assumptions are probably made for vanadium in the Li-metal(V) battery, lead in the lead-acid battery and nickel in the NiOOH cathode. The most pessimistic assumption in the near-term case is probably lithium in the Li-ion(Mn) battery.

¹³ Our results would not change assuming a cathodic excess of the same magnitude, since we assume the same active material utilisation for both the anode and the cathode.

Table 4
Lead-acid battery parameters

Reference	Specific energy (Wh/kg)	Lead intensity (kg/kWh)	Total lead utilisation (%)	Lead share of total mass (%)	Comment
Lave et al. [1]	18	39	10	70	'Available technology' scenario
Vimmerstedt et al. [13]	30	24	16	73	The year 1995
Koontz et al. [9]	30	21	18	63	Tubular, flooded
Koontz et al. [9]	30	20	19	60	Gelled electrolyte, valve-regulated
Our near-term case	40	19	20	76	
Panasonic	35	18	21	63	6 kg cathodic and 7 kg anodic Pb in a 60 Ah and 12 V module (model EC-EV1260)
Koontz et al. [9]	40	16	24	64	Starved electrolyte, valve-regulated
Vimmerstedt et al. [13]	50	15	27	73	The year 2005
Koontz et al. [9]	50	14	28	69	Starved electrolyte, valve-regulated, glass-fibre grids covered with lead, at R&D stage
Lave et al. [1]	56	12	32	70	'Goal technology' scenario
Our future case	50	9	43	45	

3. The requirement for metals per vehicle

In this section, first four datasets of the requirement for metals per BEV are provided. These datasets are then discussed in the context of battery specific energies as well as BEV design and performance parameters.

3.1. Datasets of metal requirements

To estimate the *metal requirement* per BEV, A (kg), we use two reference vehicles and assumptions on battery specific energy to determine the *energy capacity* per vehicle battery, E (kWh) (Table 5). These energy capacities are then

used together with the metal intensities, I , from Table 2 to calculate the metal requirement

$$A = EI. \tag{2}$$

The two reference vehicles, vehicle M and vehicle R (Table 6), are chosen in order to show the metal requirements for two quite different full-size passenger vehicles, and to illustrate how different criteria for battery dimensioning affect the required energy capacity of different batteries. The vehicles differ regarding *vehicle technology* (curb mass and specific energy use) as well as *battery dimensioning criterion* (battery mass or range).

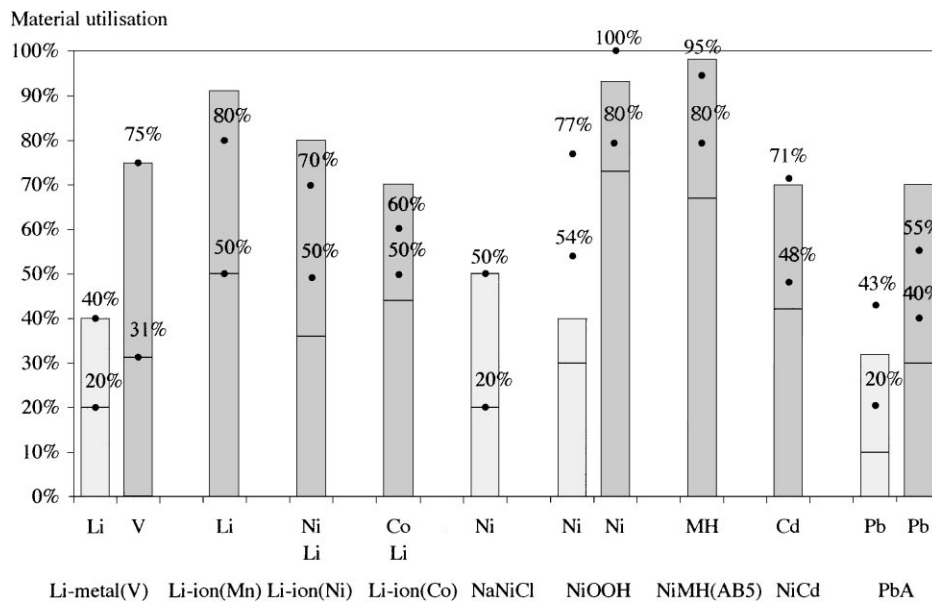


Fig. 2. Material utilisations. The span between the lowest and highest material utilisations reviewed in the previous sections (bars), as well as the material utilisations we use in the provided datasets (black dots). The dark grey columns show active material utilisation (the excess is included for Cd but not for MH and Pb). The light grey columns show total materials utilisation for the metals where the current collector is of the same material as the active material (active materials + current collectors). No material utilisation is given for the anode of the NiMH(AB₂) battery (see the text).

Table 5
Four datasets of metal requirements per BEV^{a,b}

Battery type	Battery		Vehicle M		Vehicle R		Metal requirement					Vehicle M		Vehicle R				
	Specific energy, e_b (Wh/kg)		Energy capacity, E_M (kWh)		Energy capacity, E_R (kWh)		Metal	Vehicle M, A_M (kg)		Vehicle R, A_R (kg)		Highest/lowest	Range (km)		Battery mass share (wt.%)		Battery mass (kg)	
	Near-term	Future	Near-term	Future	Near-term	Future		Near-term	Future	Near-term	Future		Near-term	Future	Near-term	Future	Near-term	Future
Li-metal(V)	128	160	34	43	17	16	Li	18	11	8.6	4.1	4.3	205	256	16	13	130	100
							V	62	32	30	12	5.1						
Li-ion(Mn)	104	130	28	35	17	17	Li	3.8	3.0	2.4	1.4	2.7	167	208	19	15	167	127
Li-ion(Ni)	104	130	28	35	17	17	Li	4.0	3.6	2.5	1.7	2.3	167	208	19	15	167	127
							Ni	34	30	21	14	2.3						
Li-ion(Co)	104	130	28	35	17	17	Li	3.8	3.9	2.4	1.9	2.0	167	208	19	15	167	127
							Co	32	33	20	16	2.0						
NaNiCl	80	100	21	27	19	18	Ni	51	25	44	17	2.7	128	160	25	20	233	175
NiMH(AB ₂)	72	90	19	24	19	18	V	9.5	2.6	9.6	2.0	4.8	115	144	28	22	269	200
							Co	0	2.1	0	1.6	–						
							Ni	87	69	88	52	1.7						
NiMH(AB ₃)	64	80	17	21	20	19	Mm	20	18	24	16	1.5	102	128	31	25	318	233
							Co	6.5	5.8	7.7	5.0	1.5						
							Ni	88	78	110	68	1.5						
NiCd	48	60	13	16	24	21	Cd	47	39	87	51	2.2	77	96	42	33	500	350
							Ni	43	38	81	50	2.1						
PbA	40	50	11	13	28	23	Pb	200	120	530	210	4.4	64	80	50	40	700	467

^a Additional parameters are given for vehicle M (range) and vehicle R (battery mass share and battery mass). For vehicle M, the battery mass share is 20% and the battery mass is 267 kg. The range for vehicle R is 240 km. Bold values refer to the highest and lowest metal requirement for each metal and battery.

^b Some data are different as if calculated from provided data due to the use of a larger number of significant digits when calculated. All values are given with two significant digits, except the specific energy, range and battery mass which are rounded to closest integer.

Table 6
Parameters for BEVs^a

Model	Vehicle					Battery			
	Total curb mass, M_t (t)	Net curb mass, M_n (t)	Energy use, e_v (kWh/tonkm)	Seats	Range, r (km)	Type	Mass (kg)	Battery share, s (%)	Energy capacity, E (kWh)
Vehicle M	1.334	1.067	0.10	–	64–256	–	267	20	11–43
Vehicle R	0.8–1.4	0.700	0.067	–	240	–	100–700	13–50	16–28
USABC commercialisation criteria	1.334	1.067	0.10	–	240	–	267	20	40
VW Future EV (1998)	1.390	1.060	0.12	–	160	–	330	24	33
VW Future EV (2003+)	1.125	0.915	0.11	–	280	–	210	19	42
Nissan Altra EV	1.702	1.342	0.079	4	192	Li-ion	360	21	32
Chrysler EPIC	2.681	2.096	0.098	5	110	NiMH	585	22	36
Honda EV PLUS	1.630	1.219	0.14 0.084	4	96 160	NiMH	411	25	27
Toyota RAV4 EV	1.560	1.110	0.070	5	200	NiMH	450	29	27
Renault Clio	1.150	0.852	0.16 0.083	4	50 95	NiCd	298	26	11
Peugeot 106	1.087	0.832	0.11	4	80	NiCd	255	23	12
GM EV1	1.350	0.817	0.089 0.065	2	110 150	PbA	533	39	17
Fiat Seicento Elettra	1.200	0.800	0.096	4	90	PbA	400	33	13

^a For data on vehicle M and R see text and Table 5. Data for other vehicles are from [87,100] and various company leaflets. For vehicles other than vehicle M and R, the energy capacity is calculated from stated capacity and voltage, and the energy use is calculated from stated mass, range and the calculated energy capacity (80% depth of discharge is assumed).

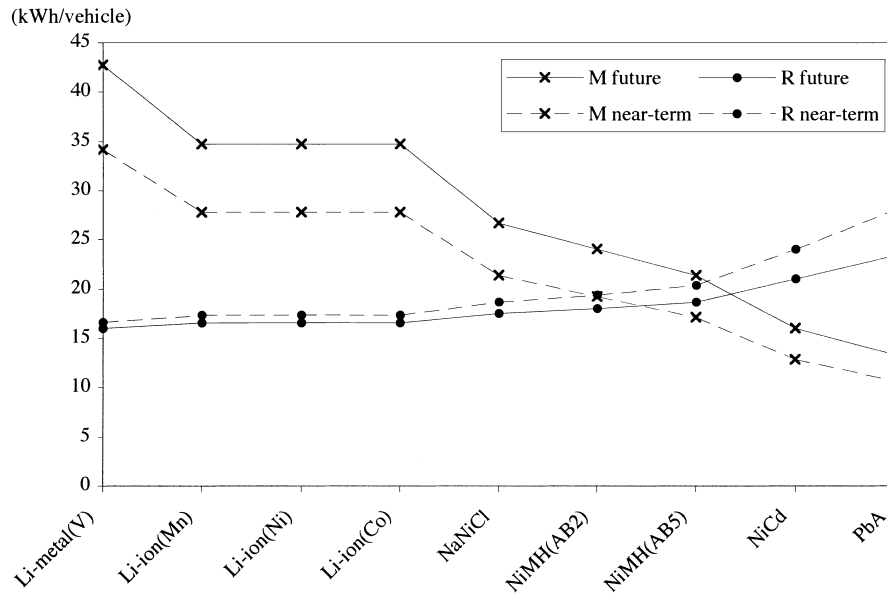


Fig. 3. Battery energy capacities per vehicle for the four datasets of metal requirements: two sets for each reference vehicle (M and R), based on the near-term and future metal intensity sets, respectively. The batteries are ordered according to assumed specific energy, with the highest to the left. Data from Table 5.

The battery of vehicle M is dimensioned to have a fixed battery share of the total curb mass, i.e. fixed battery mass. The energy capacity of vehicle M, E_M (kWh), is calculated from

$$E_M = M_t s e_b, \quad (3a)$$

where $M_t(t)$ is the total curb mass (including the battery), s is the battery share of the total curb mass and e_b (Wh/kg) is the specific energy of the battery. The battery of vehicle R is dimensioned to provide a fixed range. The energy capacity of vehicle R, E_R (kWh), is calculated from

$$E_R = \frac{M_n}{(0.8/(r e_v)) - (1/e_b)}, \quad (3b)$$

where $M_n(t)$ is the net curb mass (excluding the battery), r (km) is the range of the vehicle to 80% DOD, e_v (kWh/tonkm)¹⁴ is the specific energy use for the total curb mass as delivered from the battery.

For vehicle M, the same battery share and vehicle technology are assumed as for the reference vehicle used for US Advanced Battery Consortium's (USABC) commercialisation criteria [87]: a battery share of 20%, a total curb mass of 1.334 t (1.067 t net curb mass) and an energy use of 0.10 kWh/tonkm.^{15,16} For vehicle R, improved vehicle tech-

nology of about 33% as compared to vehicle M is assumed: 0.7 t net curb mass and an energy use of 0.067 kWh/tonkm. However, the same range, 240 km, as for USABC's commercialisation criterion is assumed [87].

Four datasets of metal requirements are calculated. There are two sets for each reference vehicle, one near-term and one future, which differ regarding specific energy and metal intensity. Regarding the metal intensity, they are based on the near-term and future metal intensity cases, respectively. The near-term and future cases of specific energies (Table 5 and Section 3.2.1) are derived from literature values and not calculated from the metal intensities derived in Section 2, even though the specific energy of course partly depends on the metal intensities. However, to calculate the specific energy from metal intensities would require additional information on the weight of other battery components. In this paper, we have put less effort into assigning values to the parameters in Eq. (3) than in the calculation of metal intensities, since the metal requirement per vehicle is more arbitrary in nature. Therefore, and due to the extent of the task, we here chose not to carry through such an assessment.

The energy capacities in the four cases are depicted in Fig. 3. For vehicle M, the energy capacity decreases with lower specific energy as opposed to vehicle R for which it increases. Another difference between the two vehicles is that for vehicle M, the energy capacity is larger in the future case than in the near-term case as opposed to for vehicle R. This is due to the fact that the specific energy of the battery is higher in the future case than in the near-term case. Therefore, in the future case, there is room for a larger battery in terms of energy capacity for vehicle M, while a smaller battery in terms of mass is needed for vehicle R to reach the stipulated 240 km. As a result of this, the ratio of near-term and future metal requirements for vehicle M is lower than

¹⁴ 'Ton' refers to metric tonne.

¹⁵ Some of the parameters for vehicle M are not explicitly stated in the reference, but are derived from it. The stated parameters we use are: a specific energy of 150 Wh/kg; 40 kWh battery pack; 20% battery share; and a range of 240 km (150 mile). Based on this we derive a battery mass of 267 kg and a net curb mass of 1067 kg (1334 μm total curb mass). Assuming the range is given for 80% depth of discharge, we derive an energy use of 0.10 kWh/tonkm.

¹⁶ The energy use is not used to calculate the energy capacity, but to calculate the range (Table 5).

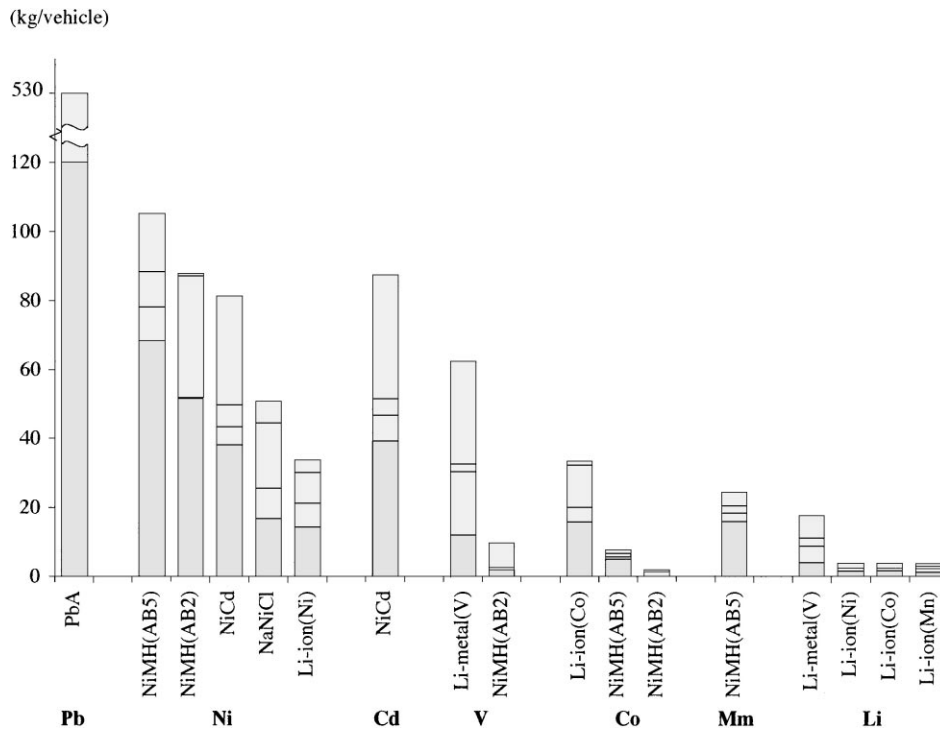


Fig. 4. Metal requirements per vehicle. The lines on the bars depict the metal requirement for the four sets: two sets for each reference vehicle (M and R), based on the near-term and future metal requirement sets, respectively. The span between the lowest and highest metal requirement for each metal and battery is marked in light grey. Data from Table 5.

the ratio of near-term and future metal intensities. The opposite is true for vehicle R (Tables 2 and 5). The metal requirements in the four cases are summarised in Fig. 4.

3.2. Discussion on battery specific energy and vehicle parameters

In this section we discuss the assumptions behind the parameters in Eq. (3), firstly battery specific energies, secondly vehicle parameters and derived energy capacities and finally the sensitivity of the metal requirement to the parameters in Eqs. (2) and (3).

3.2.1. Battery specific energy

The battery specific energies of the future case are mainly based on CARB [88], that for the year 2003 estimates 150 Wh/kg for Li-metal, 120 Wh/kg for Li-ion, 100 Wh/kg for NaNiCl and 80 Wh/kg for NiMH batteries. We have added 10 Wh/kg to the NiMH(AB₂) battery [32], as well as to the lithium batteries since they are in an earlier R&D phase than the other batteries. For NiCd and lead-acid batteries, we use estimations for the year 1998 [32], since these two batteries are not included in the 1998 CARB report. The battery specific energies for the near-term case are set at 80% of those used for the future case.

To be kept in mind in the following is that the specific energy of a battery can be reported on different system levels: cell-, module- or battery-level. For each of these

levels, additional materials, besides the active materials, are added resulting in lower specific energy. How much that is added at each level is battery dependent, but a rough thumb rule is that the battery specific energy is 80–95% of the module specific energy which in turn is 75–90% of the cell specific energy.

For the Li-metal battery, Hydro-Quebec/3 M reported 155 Wh/kg for a 2.3 kWh prototype module in 1998 [19]. Within the French program on lithium polymer batteries, performance only on the cell-level were reported in 1998, but the target for the year 2000 is 120 Wh/kg at the C/2-rate for a 2 kWh module [31]. For the Li-ion(Mn) battery, Varta presented a Li-ion(Mn) 2.4 kWh prototype module with a specific energy of 90 Wh/kg in 1998 [89]. Within the Japanese LIBES program (lithium battery energy storage technology research association), higher values of 102 Wh/kg were reported for a 3 kWh module in 1997 [90]. For the Li-ion(Ni) battery, SAFT's 1 kWh module has a specific energy of 138 Wh/kg at present and the next generation module is expected to reach 147 Wh/kg [91]. On the battery-level, SAFT has demonstrated 100 Wh/kg for batteries currently being tested on the road and 120 Wh/kg is targeted for the summer of 2000. The ultimate goal is set as high as 140 Wh/kg [25]. For the Li-ion(Co) battery, Sony announced the production and testing of a 35 kWh Li-ion(Co) EV battery of 91 Wh/kg in 1995 [29,32], and within the LIBES project, 132 Wh/kg were reached for a 3.2 kWh module in 1997 [90].

For the NaNiCl battery, Beta Research & Development reported 86 Wh/kg for a 30 kWh battery in 1999. Cells with a specific energy in excess of 140 Wh/kg is claimed, which according to the authors, translates to battery energies over 100 Wh/kg [42].

For the NiMH(AB₂) battery, GM Ovonic introduced a product development strategy in 1997 based on the GMO1-GMO3 battery modules. The 1.2 kWh GMO1 module of 70 Wh/kg is currently in production, and 80 Wh/kg and over 90 Wh/kg are projected for the GMO2 and GMO3 modules, respectively [92]. Several major companies, such as SAFT, JSB, Yuasa and Panasonic, have developed NiMH(AB₅) batteries for EVs with specific energies on the module-level of 62–65 Wh/kg [93–97]. For example, Panasonic has a pilot plant production of the 1.1 kWh EV-95 module, with a specific energy of 65 Wh/kg. For a 28 kWh battery pack based on this module a specific energy of 62 Wh/kg is reported [93,94]. The leading developer of NiCd batteries is SAFT, which has pilot line with a production capacity of 200 000 modules per year. The previously mentioned SAFT NiCd battery with a specific energy of 39 Wh/kg, is based on the 0.6 kWh STM5-100MRE module of 47 Wh/kg [50].

For the lead-acid battery, specific energies ranging from 18 to 56 Wh/kg are reported in Table 4. The specific energy target of the Advanced Lead-Acid Battery Consortium (ALABC) is 50 Wh/kg, and 48 Wh/kg is claimed [87]. However, it is not explicitly stated on which system level. Electrosource claims a specific energy of 40 Wh/kg for the 1 kWh 12H85 Horizon module [98].

Our most optimistic assumptions on specific energy appears to be for Li-ion(Mn), NiMH(AB₂), NiCd and lead-acid batteries. Specific energies on the module-level similar to our near-term case are reported for the Li-ion(Mn), NiMH(AB₂) and lead-acid batteries, while a specific energy on the battery level of about 80% of our near-term case is reported for the NiCd battery. For the Li-metal(V) and Li-ion(Co) batteries, specific energies close to our future case are reported on the module-level. For the Li-ion(Ni), NaNiCl and NiMH(AB₅) batteries, specific energies close to our near-term case are reported on the battery-level.

3.2.2. Vehicle parameters

In Table 6, the design and performance of vehicle R and M are compared to three other hypothetical vehicles, as well as to eight commercial vehicles. Among the vehicles in Table 6, some groups can be discerned regarding net curb mass. One group, around 0.8 t, contains the European vehicles and GM EV1. The hypothetical VW Future EV (2003+) has a slightly higher net curb mass, slightly above 0.9 t. The next group, about 1.0–1.3 t, contains the three Japanese cars, the USABC reference car for the commercialisation criteria (and thus vehicle M) as well as the hypothetical Future EV (1998). The Chrysler EPIC then is in a class of its own with over 2 t. All vehicles in Table 6 thus have higher net curb mass, than vehicle R. However, even lighter vehicles

than vehicle R have been suggested, for example a four to five passenger concept car, the Hypercar by Rocky Mountain Institute, of 0.521 t total curb mass [99]. This is a hybrid vehicle with a NiMH battery and a Stirling motor.

The energy use varies from 0.065 to 0.16 kWh/tonkm for the commercial vehicles (Table 6). Some of these figures are probably very optimistic for actual driving cycles. In addition, the energy use might be measured as delivered from the electrical motor, and not as from the battery which we assume in our calculations. USABC assumes 0.10 kWh/tonkm (also assumed for vehicle M), and for the VW Future EV (2003+) 0.11 kWh/tonkm is assumed. The energy use for vehicle R, 0.067 kWh/tonkm, is similar to one of the values for GM EV 1 and the Toyota RAV4 EV value.

For vehicle M, the range extends from 64 km with a lead-acid battery (near-term case) to 256 km with a Li-metal(V) battery (future case) (Tables 5 and 6). The range is below the USABC criterion of 240 km for all vehicles, except the one equipped with Li-metal(V) batteries (future case). This is not surprising, since the criterion leads to a battery specific energy of at least 150 kWh/kg. Of our batteries, only the Li-metal(V) battery in the future case exceeds this specific energy.

For vehicle R, the battery mass share varies between 13 and 50% (Tables 5 and 6). Compared to the USABC's commercialisation criterion of 20%, the lithium batteries for vehicle R are under-dimensioned in this respect (13–19%). According to this criterion, there is room to enlarge these batteries to give a longer range. The other batteries (except NaNiCl, future case) are over-dimensioned in this respect, especially the lead-acid and one of the NiCd batteries with over 40% battery share. For all manufactured vehicles in Table 6, the battery share is higher than 20%, ranging from 21% for Nissan Altra EV with a Li-ion battery to 39% for GM EV1 with a lead-acid battery.

The energy capacities of our reference vehicles are in the range 11–43 kWh (Tables 5 and 6), that is, in about the same range as the other vehicle batteries in Table 6. For the listed commercial vehicles, the energy capacity varies from 11 to 36 kWh, while it ranges from 33 to 42 kWh for the other three hypothetical vehicles.

3.2.3. Parameter sensitivity

As mentioned above, we have put less effort into assigning values to the parameters in Eq. (3), than in the calculation of metal intensities. One question is then how the parameters in Eq. (3) affect the resulting metal requirements per vehicle, which according to Eq. (2), depend linearly on the energy capacity. For vehicle M it is quite simple since the energy capacity depends linearly on all parameters in Eq. (3a). For example, the energy capacity of the near-term-case is 80% of the future case for all batteries.

However, for vehicle R, the energy capacity only depends linearly on net curb mass M_n , while it depends as $(+/-) 1/(1 - 1/x)$ on specific energy e_b (+) and on range r and energy use e_v (-). One effect of this is that as the specific

energy approaches values as low as 20 Wh/kg ($re_v/0.8$), the energy capacity tends towards infinity. A battery of 20 Wh/kg cannot transport *itself* 240 km with an energy use of 0.067 kWh/tonkm and 80% DOD. Another effect is that, since the term $1/e_b$ represents the energy required to transport the battery mass, the energy capacity approximates to 14 kWh ($M_n re_v/0.8$), for high specific energies, that is, the energy required to transport the net curb mass. Subsequently, for high specific energies the energy capacity approximately depends linearly also on range and energy use and is independent of specific energy.

In summary, with lower specific energy, the energy capacity gets more sensitive to changes in the parameters in Eq. (3b), except for the net curb mass. For example, the increase in specific energy of 25% from the near-term to the future case, decreases the energy capacity with 17% for the lead-acid battery while only with 4% for the Li-metal(V)

battery. If the energy use of vehicle R is increased by 50% to the 0.1 kWh/tonkm of vehicle M, the required energy capacity increases with 61% for the Li-metal(V) battery and with as much as 200% for the lead-acid battery. If the range is decreased by 50% to 120 km, the energy capacity decreases with 53% for the Li-metal(V) battery and with 67% for the lead-acid battery.¹⁷

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Appendix A.

Electrochemical reactions for the investigated batteries. First the theoretical reaction is given, then the reactions used for the near-term and future cases. ((g) = grid; x in the NiMH(AB_2) battery denotes the theoretical hydrogen storage capability of the AB_2 alloy, see text.)

Li-metal(V)	$8Li + V_6O_{13}$	\leftrightarrow	$Li_8V_6O_{13}$	$(8e^-)$
	$12.5Li + V_6O_{13}$	\leftrightarrow	$10Li + Li_{2.5}V_6O_{13}$	$(2.5e^-)$
	$15Li + V_6O_{13}$	\leftrightarrow	$9Li + Li_6V_6O_{13}$	$(6e^-)$
Li-ion(Mn)	$LiC_6 + Mn_2O_4$	\leftrightarrow	$C_6 + LiMn_2O_4$	$(1e^-)$
	$0.5LiC_6 + Li_{0.5}Mn_2O_4$	\leftrightarrow	$0.5C_6 + LiMn_2O_4$	$(0.5e^-)$
	$0.8LiC_6 + Li_{0.2}Mn_2O_4$	\leftrightarrow	$0.8C_6 + LiMn_2O_4$	$(0.8e^-)$
Li-ion(Ni)	$LiC_6 + NiO_2$	\leftrightarrow	$C_6 + LiNiO_2$	$(1e^-)$
	$0.5LiC_6 + Li_{0.5}NiO_2$	\leftrightarrow	$0.5C_6 + LiNiO_2$	$(0.5e^-)$
	$0.7LiC_6 + Li_{0.3}NiO_2$	\leftrightarrow	$0.7C_6 + LiNiO_2$	$(0.7e^-)$
Li-ion(Co)	$LiC_6 + CoO_2$	\leftrightarrow	$C_6 + LiCoO_2$	$(1e^-)$
	$0.5LiC_6 + Li_{0.5}CoO_2$	\leftrightarrow	$0.5C_6 + LiCoO_2$	$(0.5e^-)$
	$0.6LiC_6 + Li_{0.4}CoO_2$	\leftrightarrow	$0.6C_6 + LiCoO_2$	$(0.6e^-)$
NiNaCl	$2Na + NiCl_2$	\leftrightarrow	$2NaCl + Ni$	$(2e^-)$
	$2Na + NiCl_2 + 4Ni$	\leftrightarrow	$2NaCl + 5Ni$	$(2e^-)$
	$2Na + NiCl_2 + Ni$	\leftrightarrow	$2NaCl + 2Ni$	$(2e^-)$
NiMH(AB_2)	$MH_x + xNiOOH$	\leftrightarrow	$M + xNi(OH)_2$	(xe^-)
	$1.3MH_{2.5} + 3.1NiOOH + 1.5Ni(g)$	\leftrightarrow	$M + 0.3MH_{2.5} + 2.5Ni(OH)_2 + 0.6NiOOH + 1.5Ni(g)$	$(2.5e^-)$
	$1.1MH_{3.3} + 3.3NiOOH + 1.0Ni(g)$	\leftrightarrow	$M + 0.1MH_{3.3} + 3.3Ni(OH)_2 + 1.0Ni(g)$	$(3.3e^-)$
NiMH(AB_5)	$MH_{5.9} + 5.9NiOOH$	\leftrightarrow	$M + 5.9Ni(OH)_2$	$(5.9e^-)$
	$1.3MH_{4.3} + 5.4NiOOH + 2.6Ni(g)$	\leftrightarrow	$M + 0.3MH_{4.3} + 4.3Ni(OH)_2 + 1.1NiOOH + 2.6Ni(g)$	$(4.3e^-)$
	$1.1MH_{5.1} + 5.1NiOOH + 1.5Ni(g)$	\leftrightarrow	$M + 0.1MH_{5.1} + 5.1Ni(OH)_2 + 1.5Ni(g)$	$(5.1e^-)$
NiCd	$Cd + 2NiOOH + 2H_2O$	\leftrightarrow	$Cd(OH)_2 + 2Ni(OH)_2$	$(2e^-)$
	$2.1Cd + 2.5NiOOH + 2H_2O + 1.2Ni(g)$	\leftrightarrow	$Cd(OH)_2 + 1.1Cd + 2Ni(OH)_2 + 0.5NiOOH + 1.2Ni(g)$	$(2e^-)$
	$1.4Cd + 2NiOOH + 2H_2O + 0.6Ni(g)$	\leftrightarrow	$Cd(OH)_2 + 0.4Cd + 2Ni(OH)_2 + 0.6Ni(g)$	$(2e^-)$
PbA	$Pb + PbO_2 + 2H_2SO_4$	\leftrightarrow	$2PbSO_4 + 2H_2O$	$(2e^-)$
	$2.9Pb + 2.5PbO_2 + 2H_2SO_4 + 4.6Pb(g)$	\leftrightarrow	$2PbSO_4 + 2H_2O + 1.9Pb + 1.5PbO_2 + 4.6Pb(g)$	$(2e^-)$
	$1.9Pb + 1.8PbO_2 + 2H_2SO_4 + 1.0Pb(g)$	\leftrightarrow	$2PbSO_4 + 2H_2O + 0.9Pb + 0.8PbO_2 + 1.0Pb(g)$	$(2e^-)$

¹⁷ In both these examples, the specific energy of the future case and the near-term is used for the Li-metal(V) and lead-acid battery, respectively.

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