

Material Selection for Battery Cell Casings Based on LCA and Steady-State Thermal Performance (Comparative Analysis)

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Abstract. This study compares eight materials for cylindrical 18650 battery casings by combining a cradle-to-gate Life Cycle Assessment (LCA, A1–A3) with a steady-state radial heat-transfer calculation that includes wall conduction and external convection. The candidates are nickel-plated low-carbon steel, stainless steel 304, aluminum 6061, 70% recycled aluminum, polypropylene, polycarbonate, GFRP, and CFRP. The minimum wall thickness is governed by a 0.5 MPa design pressure with a safety factor of 2, together with practical lower limits of 0.15 mm for metals and 0.7 mm for polymers and composites. At a 5 W heat load, the model gives ΔT values of about 26.7–29.9 K under $h = 50 \text{ W/m}^2\text{K}$ and much larger temperature rises when $h = 10 \text{ W/m}^2\text{K}$. The thermal calculations show that external convection contributes most of the total resistance. The LCA estimates casing-level GWP from about 6.4 g CO_2e for nickel-plated steel to about 74 g CO_2e for CFRP. The MCDA results vary with the weighting scheme, while the Pareto analysis places nickel-plated steel and 70% recycled aluminum on the main trade-off boundary. Overall, the calculations indicate that improving the convective boundary can reduce temperature more effectively than changing casing conductivity, whereas recycled content can produce a substantial reduction in embodied GWP.

1. INTRODUCTION

Lithium ion batteries are being employed in electric cars, portable devices, and stationary energy storage systems, and the materials being used for each component of the cells are important from both performance and sustainability perspectives. The material for the cell casing becomes pertinent due to the mechanical strength, protection against external environment, and heat transfer properties provided by it. 18650 cylindrical cells are typically enclosed in low carbon steel plated with nickel since it has sufficient strength, formability, and corrosion resistance properties. On the other hand, reduction in carbon emissions and material recycling has prompted

exploration of materials for the casing other than the typical one. Most studies regarding battery thermal management have focused on active cooling using air, liquids, and phase change mediums and the heat transfer mechanisms in the modules as opposed to the casing material. Studies [1], [2], and [3] suggest that convection and conductance changes are far more effective than casing material change for reducing temperature gradients. LCA studies have similarly been done on battery electrodes, electrolyte solutions, and the manufacturing process; however, the contribution of the casing has not been widely studied even though the casing constitutes 10–15% of the cell weight and the energy content

of the materials used in it. All the above-mentioned studies indicate an inverse relationship between thermal conductivity and environmental impact.

In the case of metallic casing options such as aluminum and steel, heat conduction is easy, but the GWP of these options varies depending on the type of alloy and recycling rate of the material. Polymers and composite materials have low weight and are corrosion-resistant, but the problem is their poor thermal conductivity, and high energy consumption for resin and fiber production. What is missing from the literature is a study where the results from both steady-state thermal behavior and LCA are done on the same conditions. Therefore, this study will compare eight material options, including metals, polymer and composites, using a steady-state thermal analysis together with LCA cradle-to-gate analysis. The study will address the following three objectives:

1. To assess the impact of material thermal conductivity on casing temperature rise (ΔT) along with the convective heat transfer characteristics for heat loads.
2. To evaluate the GWP and energy requirements related to manufacturing one casing from the chosen LCA datasets.
3. To analyze the candidate alternatives and derive the Pareto-optimal solution via multi-criteria decision making (MCDM).

A combination of engineering and environmental performance indicators is expected to provide a practical benchmark for comparing casing materials.. Rather than evaluating conductivity, weight, or environmental burden separately, the study considers how these properties interact when a common 18650 geometry and a common set of operating assumptions are used [4], [5].

2. MATERIALS AND METHODS

2.1. Scope and functional unit

The functional unit is one cylindrical 18650 battery-cell casing with a nominal outer diameter of 18 mm and a height of 65 mm. Two groups of performance indicators are considered in the assessment:

1. Engineering performance, represented by steady-state temperature rise (ΔT) and the minimum wall thickness required for mechanical integrity.
2. Environmental performance, represented by cradle-to-gate Global Warming Potential (GWP, kg CO₂e) and Primary Energy Demand (MJ) per casing.

The LCA system boundary includes stages A1–A3: extraction and processing of the raw material, followed by manufacture of the semi-finished product. Cell assembly, the use phase, logistics, and end-of-life recycling are outside the boundary. This definition follows the cradle-to-gate scope described in ISO 14040/14044 [1], [4], [6], [7].

2.2. Candidate materials and property data

Eight materials that are used or proposed for battery enclosures were included in the comparison (Table 1). Density, conductivity, strength, GWP, and primary-energy data were taken from ICE v2.0 (University of Bath) together with supplementary industrial LCI sources. For the composites, the reported properties were formed from a mass-weighted mixture containing 60% fiber and 40% epoxy resin. The recycled-aluminum case was treated as a mixture of 70% recycled and 30% virgin aluminum, consistent with the assumed rolled-sheet feedstock [8], [9], [10].

Table 1. Materials for battery enclosures

Category	Material	Density (kg/m ³)	Thermal conductivity (W/m·K)	Yield strength (MPa)	GWP (kg CO ₂ e/kg)	Primary energy (MJ/kg)
Metals	Low-carbon steel (Ni-plated)	7850	50	250	1.46	20.1
	Stainless steel 304	8000	16	215	6.15	56.7
	Aluminum 6061 (general)	2700	167	240	9.16	155.0
	Aluminum (70% recycled)	2700	167	240	4.9 (weighted)	78.9 (weighted)
Polymers	Polypropylene (PP, injection-molded)	900	0.22	30	4.49	115.1
	Polycarbonate (PC)	1200	0.20	65	7.62	112.9
Composites	GFRP (60/40 glass/epoxy)	1850	0.30	150	3.9 (weighted)	78.8 (weighted)
	CFRP (60/40 carbon/epoxy)	1600	0.60	500	20.4 (weighted)	244 (weighted)

2.3. Mechanical sizing and geometric modeling

The casing geometry was treated as a thin cylindrical wall; the top and bottom end-caps were not included in the main radial conduction path. The required wall thickness was first obtained from the hoop-stress relation for an internally pressurized cylinder:

$$t_{\text{req}} = \frac{p r_i}{\sigma_{\text{allow}}}, \sigma_{\text{allow}} = \frac{\sigma_y}{\text{FS}} \quad (1)$$

Here, the assumed internal design pressure is $p = 0.5$ MPa and the inner radius is $r_i = 9$ mm, while the factor of safety is $\text{FS} = 2$. The calculated metal thickness is about 0.04 mm. Because this value is below a practical deep-drawing limit, a minimum thickness of 0.15 mm was imposed for metallic casings. For polymers and composites, the lower bound was set to 0.7 mm to account for molding requirements and mechanical stability [11], [12], [13]. The casing mass was then obtained from the cylindrical shell volume using Eq. (2):

$$m = \rho \pi L (r_o^2 - r_i^2) \quad (2)$$

where L denotes the casing height; the outer radius is $r_o = r_i + t$.

2.4. Thermal modeling

Thermal properties were investigated for steady-state conditions with a constant internal heat generation of $Q = 5$ W. Heat is lost from the cell through the shell via conduction, followed by convection from the outer surface. The thermal resistance can be expressed as:

$$R_{\text{th}} = \underbrace{\frac{\ln(r_o/r_i)}{2\pi k L}}_{\text{conduction}} + \underbrace{\frac{1}{2\pi h r_o L}}_{\text{convection}} \quad (3)$$

$$\Delta T = Q \times R_{\text{th}} \quad (4)$$

Two convection regimes were analyzed:

1. For forced convection, the heat-transfer coefficient was set to

$$h = 50 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$$

This value represents a moderate external cooling condition that can be associated with air- or liquid-cooled battery enclosures.

2. For natural convection,

For natural convection, $h = 10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ was used, corresponding to free convection to ambient air.

The thermal resistance relation distinguishes the effect of wall conductance from the convective boundary layer outside the wall. The sensitivity analysis was performed for different values of h ranging between 10 and $100 \text{ W/m}^2\text{K}$ to study the impact of increased convection versus variation in case conductivity [14], [15].

2.5. Life Cycle Assessment (LCA) approach

The environmental assessment was performed according to the standards ISO 14040/14044 and the indicators applied included Global Warming Potential (GWP, $\text{kg CO}_2\text{e/kg}$) and Primary Energy Demand (MJ/kg). The data for metals and polymers came from ICE v2.0 whereas the data on other LCIs was gathered from different sources [16], [17]. Casing GWP and primary energy consumption were determined by means of multiplying the casing mass by the corresponding material factors:

$$\begin{aligned} \text{GWP}_{\text{casing}} &= m \times \text{GWP}_{\text{material}} \\ E_{\text{casing}} &= m \times E_{\text{material}} \end{aligned} \quad (5)$$

This calculation gives a first-order cradle-to-gate estimate for an individual casing and keeps the comparison independent of a particular factory electricity mix.

2.6. Multi-criteria evaluation

Thermal and environmental results were combined through a Multi-Criteria Decision Analysis (MCDA). Four criteria were normalized as lower-is-better indicators:

1. Global Warming Potential (GWP)
2. Primary Energy Demand (PE)
3. Steady-state temperature rise (ΔT)
4. Casing mass

The overall MCDA score was calculated as:

$$S = w_1 B_{\text{GWP}} + w_2 B_{\text{PE}} + w_3 B_{\Delta T} + w_4 B_{\text{mass}} \quad (6)$$

where

$$B_i = 1 - \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}$$

is the normalized benefit value, with lower values of the original criterion receiving a higher normalized score.

Three sets of weights were applied to represent different design priorities:

1. Balanced: (0.35, 0.15, 0.30, 0.20)
2. Thermal-priority: (0.20, 0.10, 0.50, 0.20)
3. LCA-priority: (0.55, 0.25, 0.10, 0.10)

The MCDA outputs were plotted as horizontal bar charts in Figures 5–7. The three weighting sets were not intended to imply one universal preference; instead, they represent different ways the same data might be interpreted in practice [18], [19]. The balanced case gives simultaneous importance to thermal behavior, environmental impact, and mass. The thermal-priority case places more emphasis on temperature control, as would be relevant to many electric-vehicle battery systems. The LCA-priority case gives greater weight to embodied emissions and primary energy, which is appropriate when environmental performance is the main design concern. In this way, the MCDA shows how the relative position of a material changes when the decision context changes.

3. RESULTS AND DISCUSSION

Under forced convection ($h = 50 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$), the calculated temperature rise ΔT of the casing falls between 26.7 K and 29.9 K for the eight materials. The metallic cases differ by only about $\pm 0.2 \text{ K}$, showing that the external convective resistance is much larger than the conduction resistance of the thin metal wall. Polymeric and composite casings have lower thermal conductivity, between 0.2 and $0.6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, and consequently show temperature rises about 2–3 K above the metallic cases. When h is reduced to $10 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, the total resistance increases substantially and the temperature rise reaches roughly 56–62 K. These results indicate that changing the external convective condition has a much larger effect than replacing one conductive casing material with another. For

instance, raising h from 50 to 100 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ decreases ΔT by around 10-12 K in the metallic cases, while substitution of steel with aluminum influences ΔT by less than 0.3 K in the same forced convection environment.

The LCA analysis yields considerably different results. Cradle-to-gate GWP is estimated to range between 6.4 g CO_{2e} per casing in the case of nickel-plated low-carbon steel and about 74 g CO_{2e} in the CFRP case. In the case of 70% recycled aluminum, GWP amounts to 7.6 g CO_{2e}; the casing mass is 3.8 g, and temperature difference is 26.7 K. CFRP is much lighter material with density of about 1.6 g/cm³ and through-thickness thermal conductivity equal to approximately 0.6 W/m·K; however, its manufacturing process has a significantly higher embodied carbon cost. Its casing-level GWP is over nine times higher compared to aluminum while reducing the ΔT insignificantly.

Taking into account all three parameters simultaneously, Pareto front analysis puts both nickel-plated low-carbon steel and 70% recycled aluminum on the lower-bound trade-off frontier. Steel offers low casing-level GWP and established manufacturing process. Recycled aluminum removes roughly 60% of the mass relative to steel and gives a slightly lower ΔT , although its GWP is modestly higher. The two materials therefore represent different points on the same thermal–mass–environmental trade-off rather than identical solutions.

PP, PC, and GFRP fall between the metallic and CFRP cases in the trade-off plots. Their lower density is accompanied by lower conductivity and, for some cases, higher embodied impacts. CFRP shows a particularly large environmental burden because the energy demand of carbon-fiber manufacture is high relative to the mass savings obtained here [4], [18], [20]. The MCDA results change with the assigned weights. With the balanced weights, recycled aluminum receives the highest score, followed by aluminum 6061 and nickel-plated steel. When thermal performance receives the strongest weight, aluminum-based materials move to the front because of their higher conductivity and low density. With the LCA-focused weights, nickel-plated steel moves upward because its GWP and primary-energy

values are low relative to the other candidates [6], [7], [16].

Taken together, the calculations point to three observations:

1. The external convection condition has a stronger effect on temperature than a moderate increase in wall conductivity. Increasing h through airflow or improved thermal interfaces produces a larger temperature reduction.
2. The material route is important. The use of recycled aluminum lowers GWP substantially while retaining the same conductivity as the corresponding virgin alloy.
3. For the present thin-wall geometry, the higher embodied burden of carbon-intensive composites is not compensated by a meaningful thermal benefit.

The combined results show that casing selection cannot be separated from the design of the heat-transfer boundary. Figure 1 compares the cradle-to-gate GWP of one casing for each material and shows a spread of more than one order of magnitude. The difference is driven by the energy and processing requirements of the material routes, as well as the contribution of recycled feedstock. Nickel-plated low-carbon steel gives about 6.4 g CO_{2e} per casing. Although steel has the highest density among the metals considered, the assumed thin wall keeps the mass small enough that the low material-specific GWP results in a low casing-level impact.

The 70% recycled-aluminum case gives about 7.6 g CO_{2e} per casing, which is close to the steel result on a functional basis. Its lower impact compared with virgin aluminum is associated with the much smaller energy requirement of secondary aluminum production; the study uses an approximately 95% lower energy demand for secondary smelting than for the virgin route. In comparison, aluminum 6061 gives about 14 g CO_{2e} per casing. Stainless steel 304 reaches roughly 27 g CO_{2e} because nickel and chromium additions increase the material-processing burden. PP and PC show intermediate casing-level values of around 17–20 g CO_{2e}. Their low density reduces the amount of material required, but their GWP per

kilogram remains higher than that of the recycled metallic options.

The largest impacts are associated with GFRP and CFRP. The estimated values are about 30 g CO₂e per casing for GFRP and more than 70 g CO₂e for CFRP. In the latter case, the carbon-fiber precursor and the energy used during stabilization and graphitization account for a substantial part of the burden. The results therefore illustrate a common lightweighting trade-off: reducing mass does not necessarily reduce cradle-to-gate emissions when the replacement material has a high production footprint [13], [15]. Within the assumptions of this study, processing route and recycled content have a greater influence on casing GWP than density alone or a moderate change in thermal conductivity.

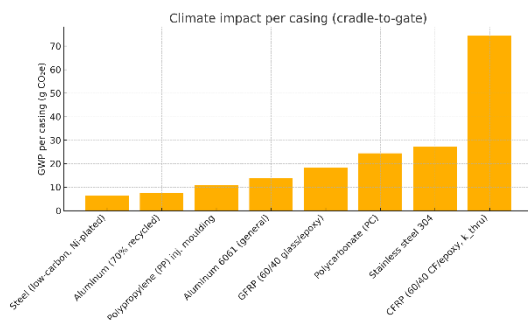


Figure 1. Climate impact per casing (GWP, cradle-to-gate).

Figures 2 and 3 compare the steady-state temperature rise ΔT for forced convection ($h = 50 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$) and natural convection ($h = 10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$). The comparison separates the effect of material conductivity from the effect of the external boundary condition. At $h = 50 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, the calculated ΔT values are approximately 26.7–29.9 K. The aluminum alloys and low-carbon steel are grouped within about $\pm 0.2 \text{ K}$, so the conduction resistance of their thin walls contributes very little to the total resistance. Aluminum has a conductivity of $167 \text{ W/m}\cdot\text{K}$, more than three times the $50 \text{ W/m}\cdot\text{K}$ used for steel, but the resulting temperature difference is less than 0.3 K at a 5 W heat load. The small change is consistent with the dominance of the external convective layer. The non-metallic cases behave differently because their conductivity is much lower. With values of $0.2\text{--}0.6 \text{ W/m}\cdot\text{K}$, the conductive resistance is no longer negligible and ΔT

increases by about $2\text{--}3 \text{ K}$ relative to the metallic cases. Even so, more than 90% of the total resistance remains associated with external convection in these calculations. Improving the casing conductivity without changing the surrounding cooling condition therefore has a limited effect [10], [12], [14].

Under natural convection, h is reduced to $10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ and the temperature rise ΔT increases to roughly $56\text{--}62 \text{ K}$. The ordering among materials is broadly unchanged: metallic casings remain at the lower end, while composites and polymers show higher ΔT . The absolute increase is much larger than the differences caused by changing between metallic materials.

The same behavior can be seen directly from the thermal-resistance expression:

$$R_{th} = R_{cond} + R_{conv}$$

were

$$R_{conv} = \frac{1}{2\pi h r_o L}$$

Because the convective resistance R_{conv} varies inversely with h , reducing h by a factor of five produces a comparable increase in the convective part of the resistance. This effect is large enough to mask most of the improvement that can be obtained by selecting a higher-conductivity casing material.

In the sensitivity calculation, increasing h from 50 to $100 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ reduces the steady-state temperature rise by about $10\text{--}12 \text{ K}$ for the metallic cases. By comparison, substituting aluminum for steel changes ΔT by less than 1% . The implication of this is that the airflow configuration, surface modification, thermal interface and other systems-based strategies have more influence on the cell temperature than the simple replacement of the casing material.

This Figures 2 and 3 lead to the same conclusion. Conductivity does matter especially when we deal with a poor conductivity of the composite or polymer, but the convective boundary condition on the exterior surface is the key limiting resistance for the 18650 thin-walled geometry under discussion. With the required conductivity attained, mechanical strength, ecology, and fabrication issues

become more meaningful material selection criteria.

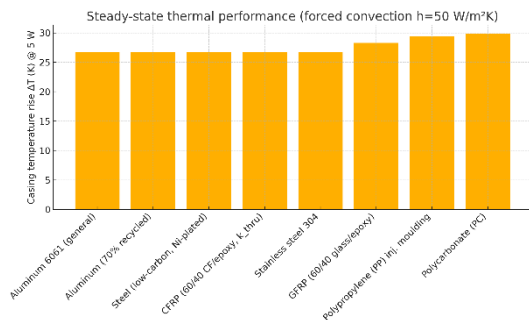


Figure 2. ΔT at 5 W under forced convection ($h = 50 \text{ W/m}^2\text{K}$)

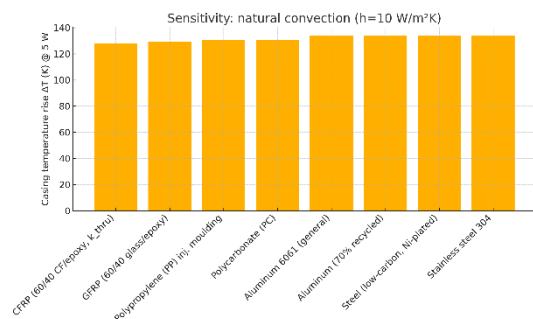


Figure 3. ΔT at 5 W under natural convection ($h = 10 \text{ W/m}^2\text{K}$)

In Fig. 4, the casing-level GWP is shown versus steady-state temperature rise for forced convection ($h = 50 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) scenario. The marker size is indicative of casing weight. Hence, the relationship between the thermal performance, environmental impacts, and weight saving can be seen from this plot. The data points define the trade-off curve where the data points on the left-hand side denote smaller GWP as well as lower ΔT . Nickel-coated low-carbon steel and recycled aluminum make up part of the trade-off curve. Steel casing gives GWP of about $6.4 \text{ g CO}_2\text{e}$ at ΔT around 27 K . In contrast, the GWP of the recycled aluminum is about $7.6 \text{ g CO}_2\text{e}$ at ΔT of 26.7 K and is about 60% lighter. Thus, the two casings have similar thermal performance but different weights.

Aluminum 6061 and stainless steel 304 sit above this boundary. Aluminum 6061 has high conductivity ($167 \text{ W/m} \cdot \text{K}$), but its larger virgin fraction raises its GWP to roughly twice that of recycled aluminum. Stainless steel 304 has moderate thermal performance and a much

higher casing-level GWP, about $27 \text{ g CO}_2\text{e}$, which is associated in the dataset with the processing of nickel- and chromium-containing alloying additions.

The polymeric and composite candidates occupy the higher-GWP and higher- ΔT part of the plot. PP and PC reduce mass compared with steel, but their ΔT is roughly $2\text{--}3 \text{ K}$ higher and their GWP is substantially larger. GFRP moves further in the same direction. CFRP is an outlier, with a casing-level GWP above $70 \text{ g CO}_2\text{e}$ and no corresponding gain in steady-state thermal performance. For this thin-wall geometry, the environmental burden of carbon-fiber production is therefore not offset by the mass reduction [1], [8], [9].

Across the eight candidates, the relationship between ΔT and GWP is weak ($R^2 < 0.2$). Thermal behavior and climate impact are not controlled by the same material property, so an improvement in one does not necessarily produce an improvement in the other. The design decision consequently needs to consider both measures at the same time [2], [3], [5]. From a design perspective, the metallic cases illustrate two different trade-off positions. Recycled aluminum provides a lower casing mass with slightly better heat transfer, whereas nickel-plated steel provides the lower absolute casing-level GWP in the dataset and relies on an established manufacturing route. These characteristics place both materials within the Pareto region shown in Figure 4, although for different reasons.

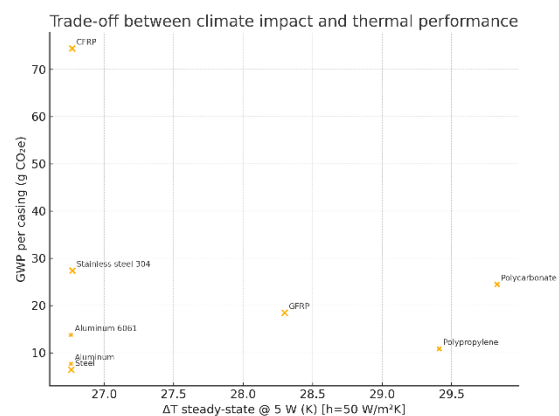


Figure 4. Trade-off between GWP and ΔT ; marker size $\propto$ mass.

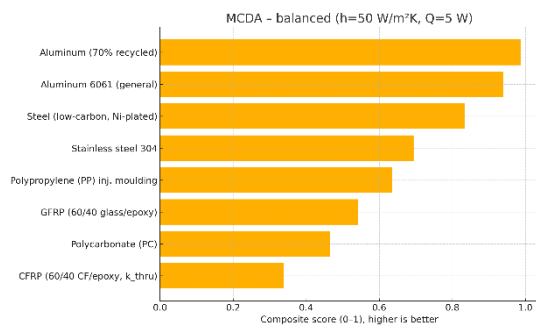


Figure 5. MCDA ranking with balanced weights.

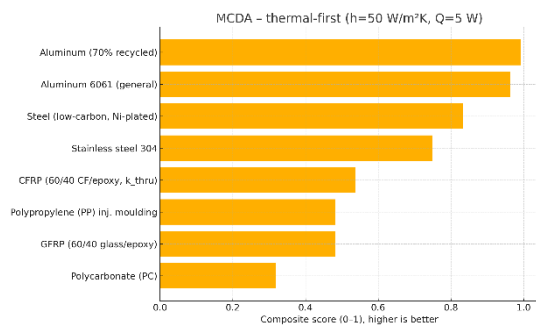


Figure 6. MCDA ranking with thermal-first weights.

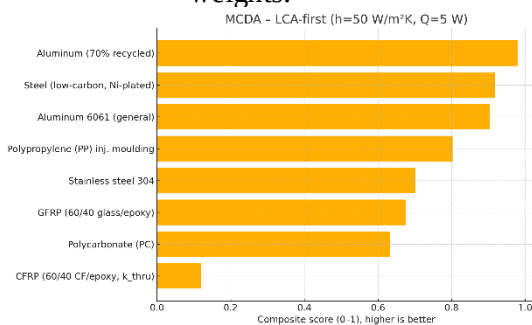


Figure 7. MCDA ranking with LCA-first weights.

Figures 5–7 summarize the MCDA results obtained after normalizing four indicators: steady-state temperature rise (ΔT), casing mass, GWP, and Primary Energy Demand (PE). Three weight sets were examined to represent different design priorities: a balanced case, a thermal-priority case, and an LCA-priority case [4], [7], [18], [20]. The purpose of using several weight sets is to show how the relative standing of a material changes when the emphasis of the decision is changed. For the balanced weights (GWP 0.35, PE 0.15, ΔT 0.30, mass 0.20), the 70% recycled-aluminum case receives the

highest composite score. Its result is driven by the combination of low mass, low ΔT , and a lower GWP than virgin aluminum. The score is therefore not associated with a single property; it comes from the simultaneous contribution of several criteria.

Nickel-plated low-carbon steel is next in this scenario. Its casing is heavier than the aluminum cases, but the GWP is only 6.4 g CO₂e and the primary-energy value is relatively low in the dataset. Aluminum 6061 follows, with thermal behavior close to recycled aluminum but a larger penalty from the energy intensity of virgin aluminum production. PP, PC, GFRP, and CFRP lie in the bottom of the well-balanced ranking due to low conductivity and high production burdens, which result in increased ΔT and decreased the environmental factor of the composite index. CFRP is especially sensitive to this factor due to its application.

Under the thermal priority, when ΔT is weighted 50%, followed by 20% mass, 20% GWP, and 10% PE, aluminum cases become the top of the MCDA ranking. Recycled aluminum and aluminum 6061 both have a high conductivity of 167 W/m·K and thus provide almost equal ΔT values. Thermal gap from steel is 0.3 K, but due to increased thermal weight, this difference becomes crucial for the composite ranking index. Low density also helps, as the mass is contributing another 20% to the index.

Nickel-plated steel drops to third place with the thermal priority weights since it has a higher density than other materials. Stainless steel 304 maintains its middle place, while the non-metallic materials rank even lower due to the greater importance of their poor thermal conductivity within the thermal criterion. The current case clearly demonstrates the effect of sensitivity of the multi-criteria ranking to the priorities of the decision maker.

Using the LCA-priority weights (GWP – 0.55, PE – 0.25, ΔT – 0.10, mass – 0.10), the rankings change so that preference is given to materials with lower cradle-to-gate impacts. Nickel-plated low-carbon steel becomes the top-ranking material since it has not only the lowest casing-level GWP but also a rather low primary energy value. Recycled aluminum still ranks close to the top since the use of the recycled feedstock minimizes its environmental

impacts. The high embodied energy makes CFRP again be heavily penalized. The lower weighting on ΔT means that the small thermal differences have much less influence on the final composite score.

The three weighting cases lead to the same general conclusion about the role of the decision criteria: the material that performs well on one measure is not automatically the same material that performs well when the full set of indicators is considered. Recycled content changes the environmental result substantially, while conductivity differences among metallic cases have only a small effect on ΔT in this geometry.

1. The 70% recycled-aluminum case and nickel-plated low-carbon steel remain near the upper end of the MCDA results across the three weighting scenarios.
2. Aluminum 6061 benefits most when thermal conductivity carries a large weight, but its higher embodied burden reduces its position when the environmental criteria become more important.
3. The polymer and composite cases are affected by the combination of low conductivity and relatively high embodied energy, which limits their suitability for the present structural-casing comparison.

Figures 5–7 also show that the MCDA does not identify one material as optimal for every possible design priority. Instead, the relative position changes with the weights. Materials with recycled feedstock perform well when environmental indicators matter, while high-conductivity aluminum gains more when the decision gives greater importance to temperature rise. The MCDA is therefore useful here as a transparent way to examine these trade-offs rather than as a substitute for application-specific design judgment.

Figure 8 examines the sensitivity of steady-state ΔT to the external heat-transfer coefficient h for low-carbon steel, aluminum 6061, and polycarbonate. The sweep covers $h = 10$ to $100 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, from natural convection to enhanced forced convection. At $h = 10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, all three materials show large temperature rises, about 56–62 K, because the convective resistance is dominant. Raising h reduces ΔT for every material, showing that the

external cooling condition is an important control variable regardless of the casing material.

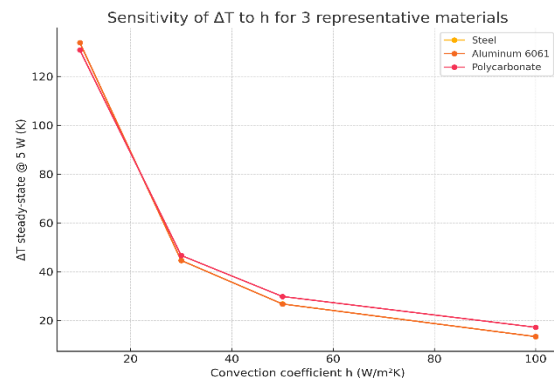


Figure 8. Sensitivity of ΔT to convection coefficient h .

The decrease in temperature rise follows the inverse dependence of the convective resistance on h , as expressed by the analytical relation:

$$R_{th} = R_{cond} + R_{conv}, \text{ where } R_{conv} \propto \frac{1}{h}$$

At $h = 50 \text{ W}/\text{m}^2\cdot\text{K}$, indicating a medium case of forced convection, the ΔT is predicted to be around 27 K for aluminum, 27.3 K for steel, and 29.5 K for PC.

Beyond this value, the benefits become increasingly marginal. As can be seen from the slopes, at this point the impact of reducing the convective resistance becomes the primary factor in overall heat transfer, while the impact of changing the casing conductivity becomes a secondary one. For $h = 100 \text{ W}/\text{m}^2\cdot\text{K}$, the predicted ΔT is about 22–23 K. While aluminum has a conductivity three times greater than steel (167 versus $50 \text{ W}/\text{m}\cdot\text{K}$), the difference in ΔT between the two metals is less than 1 K within the entire studied range. PC, which is much worse in terms of conductivity ($0.2 \text{ W}/\text{m}\cdot\text{K}$), remains warmer than both the metals, though still following the decreasing trend with increasing h .

Possible system-level measures include increasing air velocity, adding surface fins, improving cell spacing for flow distribution, or replacing air cooling with liquid or vapor-based cooling. These changes directly act on the dominant convective resistance and therefore have greater potential to reduce temperature

than a material substitution with only a modest conductivity difference.

Once h exceeds roughly $30 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, the temperature curves become less sensitive to the choice among the three representative materials. At that point, recyclability, manufacturability, corrosion resistance, and other non-thermal properties become more relevant for material selection than a small increase in conductivity.

The sensitivity results reinforce the central interpretation of the thermal model: for the cylindrical 18650 geometry used here, temperature control is mainly a system-level heat-transfer problem. Changing the casing material can help, especially for poorly conducting polymers and composites, but the benefit is limited unless the external convective condition is improved at the same time.

Table 2. Summary under forced convection ($h=50 \text{ W/m}^2\text{K}$)

Material	ΔT (K) @5W	Mass (g)	R_{cond} (K/W)	R_{conv} (K/W)	GWP (g CO _{2e})
Aluminum 6061 (general)	26.761	1.501	0.000	5.352	13.750
Aluminum (70% recycled)	26.761	1.501	0.000	5.352	7.622
Steel (low-carbon, Ni-plated)	26.764	4.364	0.001	5.352	6.372
CFRP (60/40 CF/epoxy, k_{thru})	26.771	4.277	0.306	5.049	74.417
Stainless steel 304	26.773	4.448	0.003	5.352	27.352
GFRP (60/40 glass/epoxy)	28.299	4.945	0.611	5.049	18.425
Polypropylene (PP) inj. moulding	29.411	2.406	0.834	5.049	10.802
Polycarbonate (PC)	29.828	3.208	0.917	5.049	24.442

Table 3. Summary under natural convection ($h=10 \text{ W/m}^2\text{K}$)

Material	ΔT (K) @5W	Mass (g)	R_{cond} (K/W)	R_{conv} (K/W)	GWP (g CO _{2e})
CFRP (60/40 CF/epoxy, k_{thru})	127.742	4.277	0.306	25.243	74.417
GFRP (60/40 glass/epoxy)	129.270	4.945	0.611	25.243	18.425
Polypropylene (PP) inj. moulding	130.381	2.406	0.834	25.243	10.802
Polycarbonate (PC)	130.798	3.208	0.917	25.243	24.442
Aluminum 6061 (general)	133.801	1.501	0.000	26.760	13.750
Aluminum (70% recycled)	133.801	1.501	0.000	26.760	7.622
Steel (low-carbon, Ni-plated)	133.804	4.364	0.001	26.760	6.372
Stainless steel 304	133.813	4.448	0.003	26.760	27.352

Limitations and Recommendations. The thermal model is deliberately simplified and is intended for first-order comparison rather than full battery thermal prediction. Even with this simplification, the calculated results consistently show that the convective part of the thermal resistance is much larger than the conduction resistance of metallic walls. This explains the small ΔT difference among metals under the same cooling condition and the much larger change obtained when h is increased. The qualitative trend is also consistent with previous battery thermal studies in which external cooling and contact conductance have a stronger effect than small changes in casing conductivity.

Several assumptions should be kept in mind when using the results [22], [23]. First, the thermal calculation is steady state and therefore

does not describe transient temperature changes during charging or discharging, nor thermal-runaway propagation. Second, a uniform 5 W heat load is applied to all candidates so that the materials are compared on the same basis, although an actual cell may generate heat that varies with time and position. Third, radiation and heat transfer through the end-caps are omitted. For the geometry and temperature range considered, this has a limited effect on the comparative result because convection remains dominant, but it can influence the absolute ΔT . Fourth, composite materials are described with effective conductivity values, so directional anisotropy is not resolved.

For these reasons, the reported ΔT values should be read as comparative estimates, not as exact cell operating temperatures. The LCA is likewise limited to cradle-to-gate stages and

excludes logistics, assembly, use, and end-of-life. Within those boundaries, the results are sufficient to show the main influence of the convective boundary condition. A practical next step is therefore to improve h through airflow, liquid cooling, ducting, or better thermal interfaces and then use recycled-content information as an important input when selecting the casing material.

4. CONCLUSION

Thermal behavior of eight different casing materials was evaluated by integrating steady state thermal analysis and cradle-to-gate Life Cycle Assessment of a cylindrical 18650 battery casing. Calculations have shown that material thermal conductivity influences the temperature increase, while external convection resistance is the dominating component of the heat transfer path for a thin wall design. Main results of this study are summarized below. At $h = 50 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, temperature increase is approximately equal to 26.7–29.9 K, and the differences between metallic casings are less than 1%. An increase of h from 50 to $100 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ decreases ΔT by approximately 10–12 K, while replacement of steel by aluminum causes ΔT change less than 0.3 K under the same conditions. The calculated cradle-to-gate GWP values range from 6.4 g CO₂e per casing of nickel-plated low-carbon steel to about 74 g CO₂e per casing of CFRP.

Recycled aluminum casing with 70% recycled aluminum has ΔT similar to virgin aluminum casing but has about 45% lower GWP. MCDA result depends on the choice of weighting scheme. In the balanced weighting scheme, recycled aluminum ranks the first, whereas aluminum alloys have greater importance in the scenario where thermal parameters are given maximum weightage. Nickel-plated steel ranks higher in case of maximum weightage given to the LCA indicators. These rank variations depend on contributions of ΔT , mass, GWP, and primary energy rather than any single material parameter. These results lead to two steps in the design process. Firstly, make sure there is enough heat transfer from outside and suitable thermal interfaces so that convection does not dominate cell temperatures. Secondly, choose among those materials which can fulfill the thermal and mechanical criteria based on mass,

GWP, percentage of recycling, corrosion resistance and manufacturability. As per current dataset, low carbon steel with nickel coating has lowest GWP at the casing level, whereas recycled aluminum has maximum contribution in reducing the mass along with slightly lower ΔT .

REFERENCES

- [1] L. A. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman, "Life cycle assessment of a lithium-ion battery vehicle pack," *J. Ind. Ecol.*, vol. 18, no. 1, pp. 113–124, 2014.
- [2] S. Troy *et al.*, "Life Cycle Assessment and resource analysis of all-solid-state batteries," *Appl. Energy*, vol. 169, pp. 757–767, 2016.
- [3] F. Degen, M. Mitterfellner, and A. Kampker, "Comparative life cycle assessment of lithium-ion, sodium-ion, and solid-state battery cells for electric vehicles," *J. Ind. Ecol.*, vol. 29, no. 1, pp. 113–128, 2025.
- [4] J. Zhang *et al.*, "Cradle-to-gate life cycle assessment of all-solid-state lithium-ion batteries for sustainable design and manufacturing," *Int. J. Life Cycle Assess.*, vol. 27, no. 2, pp. 227–237, 2022.
- [5] C. Rietdorf, C. De la Rúa, S. Kiemel, and R. Mieke, "Cradle-to-gate life cycle assessment of cylindrical sulfide-based solid-state batteries," *Int. J. Life Cycle Assess.*, vol. 29, no. 11, pp. 1992–2003, 2024.
- [6] P. Mandade, M. Weil, M. Baumann, and Z. Wei, "Environmental life cycle assessment of emerging solid-state batteries: A review," *Chem. Eng. J. Adv.*, vol. 13, p. 100439, 2023.
- [7] H. Pourrahmani, C. Xu, and J. Van Herle, "The thermodynamic and life-cycle assessments of a novel charging station for electric vehicles in dynamic and steady-state conditions," *Sci. Rep.*, vol. 13, no. 1, p. 11159, 2023.
- [8] M. Lybbert, Z. Ghaemi, A. K. Balaji, and R. Warren, "Integrating life cycle assessment and electrochemical modeling to study the effects of cell design and operating conditions on the environmental impacts of lithium-ion batteries," *Renew. Sustain. Energy Rev.*, vol. 144, p. 111004, 2021.
- [9] F. Hermansson, F. Edgren, J. Xu, L. E. Asp, M. Janssen, and M. Svanström, "Climate impact and energy use of structural battery composites in electrical vehicles—a comparative prospective life cycle assessment," *Int. J. Life Cycle Assess.*, vol. 28, no. 10, pp. 1366–1381, 2023.
- [10] M. A. Salgado Delgado, L. Usai, L. A.-W.

- Ellingsen, Q. Pan, and A. Hammer Strømman, "Comparative life cycle assessment of a novel Al-ion and a Li-ion battery for stationary applications," *Materials (Basel)*, vol. 12, no. 19, p. 3270, 2019.
- [11] S. Zhao and F. You, "Comparative life-cycle assessment of Li-ion batteries through process-based and integrated hybrid approaches," *ACS Sustain. Chem. Eng.*, vol. 7, no. 5, pp. 5082–5094, 2019.
- [12] X. Han *et al.*, "Comparative life cycle greenhouse gas emissions assessment of battery energy storage technologies for grid applications," *J. Clean. Prod.*, vol. 392, p. 136251, 2023.
- [13] M. Weeber, J. Wanner, P. Schlegel, K. P. Birke, and A. Sauer, "Methodology for the simulation based energy efficiency assessment of battery cell manufacturing systems," *Procedia Manuf.*, vol. 43, pp. 32–39, 2020.
- [14] A. Jinasena, O. S. Burheim, and A. H. Strømman, "A flexible model for benchmarking the energy usage of automotive lithium-ion battery cell manufacturing," *Batteries*, vol. 7, no. 1, p. 14, 2021.
- [15] Y. Deng, L. Ma, T. Li, J. Li, and C. Yuan, "Life cycle assessment of silicon-nanotube-based lithium ion battery for electric vehicles," *ACS Sustain. Chem. Eng.*, vol. 7, no. 1, pp. 599–610, 2018.
- [16] M. Falcone, N. F. Quattromini, C. Rossi, and B. Pulvirenti, "Life cycle assessment of a lithium-ion battery pack unit made of cylindrical cells," *Batteries*, vol. 8, no. 8, p. 76, 2022.
- [17] M. Philippot, J. Smekens, J. Van Mierlo, and M. Messagie, "Life cycle assessment of silicon alloy-based lithium-ion battery for electric vehicles," *WIT Trans. Built Env.*, vol. 182, pp. 129–139, 2019.
- [18] M. Thomitzek, N. Von Drachenfels, F. Cerdas, C. Herrmann, and S. Thiede, "Simulation-based assessment of the energy demand in battery cell manufacturing," *Procedia Cirp*, vol. 80, pp. 126–131, 2019.
- [19] A. Maulana, N. U. Putri, A. W. Murti, A. Apriyanto, F. Ibrahim, and B. Wibowo, "Analisis Perbandingan Tegangan Pada Baterai Berbahan Baku Limbah Batubara dengan Kulit Pisang sebagai Energi Alternatif".
- [20] F. Degen and M. Schütte, "Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production," *J. Clean. Prod.*, vol. 330, p. 129798, 2022.
- [21] J. Song, G. Cui, Y. Han, X. Yao, X. Shen, and Y. Wang, "Review on environmental impacts of various types of power batteries using LCA," *Environ. Dev. Sustain.*, pp. 1–25, 2025.
- [22] F. Ibrahim *et al.*, "Optimization of Environmentally Friendly Material Selection for Automotive Mechatronics Components Using LCA Data and Multi-Criteria Decision Making (MCDM)," *JEECS (Journal Electr. Eng. Comput. Sci.)*, vol. 10, no. 2, pp. 168–178, 2025.
- [23] F. Ibrahim, "Life Cycle Assessment (LCA) of Natural Fiber Reinforced Polymer Composites for Automotive Interior Panels: A Comparative Study vs. Glass Fiber Composites," *J. Rekayasa, Teknol. dan Sains*, vol. 10, no. 1, pp. 859–865, 2026.