Effect of Energy Efficiencies on Embodied Emissions

Advanced Propulsion Centre UK (APC)

31st March 2026

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This report was funded by UKCAAR as part of the UK Government's £4 billion DRIVE35 programme, delivered by the Department for Business and Trade in partnership with the Advanced Propulsion Centre UK and Innovate UK.

All UK Government grant funding is subject to HMG approval

Contents

Introduction and objectives

Energy and resource efficiency are widely recognised as a cornerstone of climate mitigation, industrial competitiveness and national energy security. Improvements in energy and material efficiency reduce overall demand, lower operational costs, and lessen greenhouse gas emissions; benefits that are critical for the automotive sector given its high energy intensity and complex global supply chains.

According to the International Energy Agency's *Energy Efficiency 2022* report, global energy intensity improvements are forecast to reach about 2 % in 2022, following slower progress earlier in the decade, but still remain below the level required to achieve decarbonisation by 2030 [1]. Energy efficiency has been called the "first fuel" of clean energy transitions because it offers some of the most cost-effective and rapid methods for energy use and emission reduction while enhancing affordability and energy supply security [2]. Energy efficiency also plays a key role in industrial decarbonisation, as the industrial sector accounted for 37% of global energy use in 2022, highlighting the importance of targeted efficiency improvements in manufacturing processes if global emissions are to be curbed [3].

In the context of automotive manufacture, energy consumption not only drives direct (Scope 1) and indirect (Scope 2) emissions at individual supply chain stages, it contributes significantly to the embodied (Scope 3) carbon footprint of a final vehicle. Rigorous analysis of energy use and modelled energy reductions across supply chains reveals where energy efficiency interventions can have the greatest impact for cost (operating and product) and embodied emission reductions.

The project will:

- Model how energy efficiency improvements reduce emissions and costs for key materials and components.
- Identify where energy efficiency can have the greatest effect on embodied emissions reductions for finished vehicles.
- Provide practical, easy-to-implement guidance for OEMs and suppliers to improve energy efficiency and reduce emissions.

Critical assumption

The proposed work is based on the following critical assumptions:

1. Definitions for Scope 1, 2, and 3 emissions follow the GHG Protocol Corporate and Product Accounting Standards, and these definitions are consistently applied across all stages of the supply chain.
2. Due to time and funding constraints the analysis will be based on typical automotive supply chains derived from public (EPD & LCA) and benchmark datasets which sometimes vary in methodological details, rather than specific OEM or supplier datasets.

3. The analysis assumes modest but achievable energy efficiency improvements, reflecting actions that manufacturers could implement in practice, a range of energy efficiency scenarios will be assumed and presented.
4. Energy prices used in some stages are based on the UK grid mix for both electricity and natural gas.
5. Energy price and carbon intensity data reflect UK and international averages rather than site-specific data (as this is often confidential or difficult to obtain).
6. Cost calculations are assumed to include only fuel costs and exclude any carbon pricing or emissions-related costs.
7. Simplified supply chain steps will be assumed and considered in 2-3 steps for key components or materials.
8. The system boundary follows a cradle-to-OEM supply chain (cradle-to-gate). It includes only production-stage activities from upstream up to vehicle assembly and excludes the use phase, maintenance, end-of-life treatment, post-sale logistics, downstream distribution, and all inter-facility logistics beyond the defined manufacturing boundary.
9. OEM stage energy and emissions are purely for assembly line activities and proportional to mass within the vehicle, assuming a vehicle weight of 1,600 kg. These are equal for all components per kg of installed component mass. It is also assumed that energy used is purely electrical at this stage.
10. Energy efficiency measures are assumed to rely on commercially available technologies and to be implemented progressively and gradually across all supply chain stages.

Definitions for energy efficiency, Scope 1, Scope 2 & Scope 3

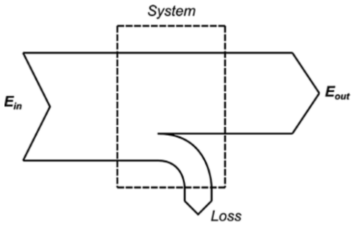
Scope 1: Direct emissions generated (from sources owned or controlled) during the production of the component at the supply chain tier being examined.

Scope 2: Indirect emissions from the generation of purchased electricity, steam, heat, or cooling consumed at the supply chain tier being assessed.

Scope 3: All emissions associated with upstream services indirectly linked to the component production at the supply chain tier being examined.

These are aligned with GHG guidance with adaptations to suit the specific application in this research [4].

Energy Efficiency (η): The ratio between useful energy output and energy input within a thermodynamic system. In terms of efficiency improvement, can be defined as the reduction of energy losses, either directly or indirectly (through upstream energy-related activities) [5].



$$\eta = \frac{E_{out}}{E_{in}} \qquad \eta = \frac{physical\,useful\,output}{E_{in}}$$

Figure 1: Energy efficiency definition.

Target materials and components in vehicles

This paper will concentrate on four representative materials and component areas commonly used in vehicle production:

- Metal component represented by cast aluminium wheel
- Glass component represented by laminated windscreen
- Plastics parts represented by injection-moulded interior trim component
- Seating materials represented by seat foam

A simplified automotive supply chain for each component is illustrated in Figure, spanning from cradle (raw material extraction and processing) through Tier 1 component manufacturing (and sometimes additional tiers) to final OEM vehicle assembly.

Energy consumption at each stage generates Scope 1 & 2 emissions, which accumulate along the supply chain and contribute to the embodied Scope 3 emissions of the finished vehicle.

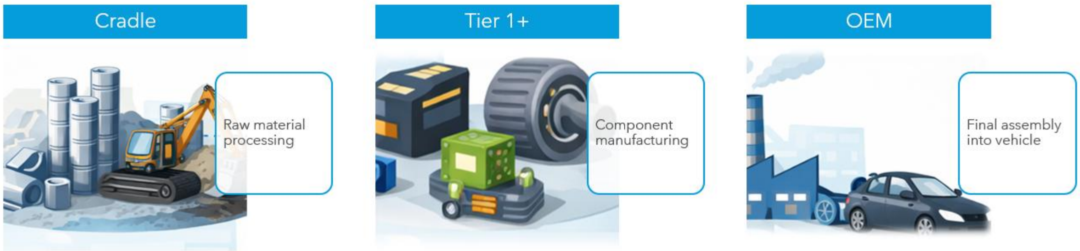


Figure 2: Simplified supply chain stages from Cradle to OEM.

Methodology

It is assumed that all components are assessed using consistent units, with energy expressed in kWh/kg, emissions in kg CO_2e/kg, and cost in £/kg, with each unit based on 1 kg of the studied material to ensure comparability across the analysis. Standardisation and proxy assumptions are applied where data gaps exist.

Energy consumption calculation

Energy demand associated with each component was represented by the energy consumed at each manufacturing stage throughout the different supply-chain tiers. Energy consumption values represent average industrial production conditions derived from multiple published sources to provide representative estimates for each manufacturing stage. To ensure consistency between different literature sources, all energy values were normalised into kWh/kg using: 1kWh= 3.6 MJ.

The reported energy values for plastics include both feedstock energy (inherent chemical energy embodied within the material), and processing energy (thermal and electrical energy consumed during manufacturing and conversion operations) represented as the primary energy. When calculating the associated emission and energy cost, only the process energy consumption was considered to be consistent with other components (glass and metal).

Carbon emissions calculation

Carbon footprints were evaluated separately for each supply-chain stage using published emission intensity data represented as emissions contribution from an individual manufacturing or supply-chain stage (kg CO_2e/kg). Where published embodied carbon data were available directly from EPDs, LCAs, or industrial databases, these values were adopted. In cases where direct emissions data were unavailable, emissions were calculated using process energy consumption values multiplied by activity-based carbon conversion factors obtained from UK DESNZ greenhouse gas reporting datasets: [6]

$$CO_2e\ Emissions = Fuel\ used \times Fuel\ activity\ factor$$

Energy mix assumptions

Because different manufacturing stages sometimes rely on different forms of energy, weighted energy mixes were applied to estimate realistic process energy costs. Energy prices are based on the 2026 UK grid mix, with electricity assumed at £0.2769/kWh and natural gas at £0.059/kWh [7]. The weighted energy price was calculated using:

(% gas × natural gas price 0.059/kWh) + (% electricity × electricity price 0.2769/kWh) = weighted price £/kWh.

Energy Cost calculation

Energy-associated manufacturing cost was applied independently to each manufacturing and supply-chain stage to determine stage-specific energy-related costs. Cost was estimated by multiplying the process energy demand by the energy (or sometimes weighted energy) price:

$$Cost_{energy} = E_{process} \times C_{energy}$$

Where:

- $Cost_{energy}$ = energy-related manufacturing cost (£/kg)
- $E_{process}$ = process energy demand (kWh/kg)
- C_{energy} = energy cost/ weighted energy cost (£/kWh)

OEM-stage contributions

Energy and emissions contributions at the OEM stage were taken based on assembly line automotive manufacture data [8], [9], assuming that all selected components would consume energy proportionally to their mass within the vehicle and that a full vehicle weighs 1,600 kg [10]. Energy consumed was taken to be purely electrical, and so cost contributions were calculated as described above. This was done as data for energy, emissions and cost consumption by component at OEM stage was not publicly available, and so a stage-level consumption is used as an estimate. This results in equal OEM stage values across all components within the report.

Plastics (injection-moulded interior trim and seat foam)

1. Target material and component selection

Plastics play a vital role in the modern automotive industry because they help manufacturers design vehicles that are lighter, safer, and more energy efficient. Today, an average car contains about 150–200 kg of plastic, roughly 15% of the vehicle's total weight, with around 2000 individual plastic parts making plastics one of the most widely used materials in vehicle production. Plastics are used in many components from lights and bumpers to engine components, dashboards, headrests, switches, clips, panoramic roofs, seats, airbags and seat belts as illustrated in Figure 3. Plastics are also valued for their versatility and durability. They can be easily moulded into complex shapes, allowing engineers to create innovative designs and integrate multiple functions into a single component. In addition, plastics contribute significantly to vehicle safety and comfort. Many safety systems, including airbags and energy-absorbing bumpers, rely on plastic materials to protect passengers during collisions. Plastics are also resistant to corrosion and chemicals, which improves the durability and lifespan of automotive components [11], [12], [13], [14].

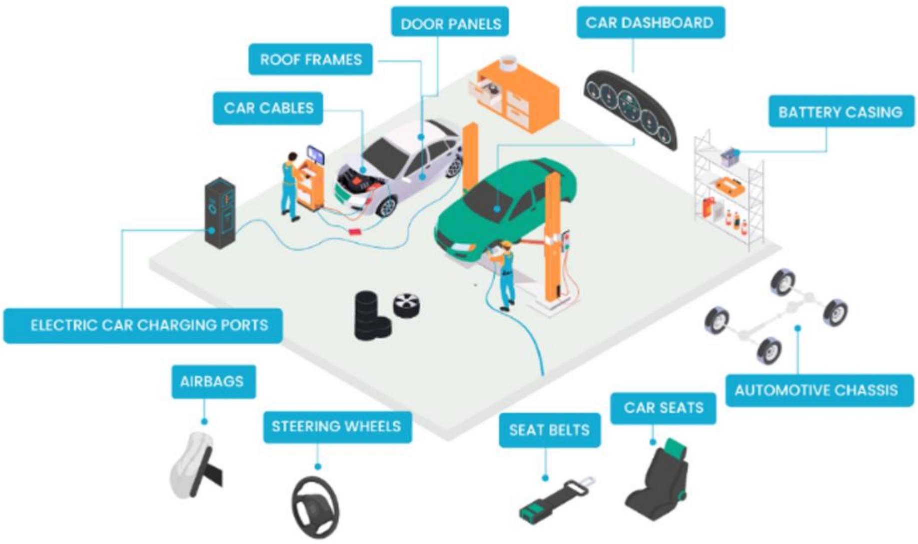


Figure 3: Examples of where plastics are used in automotive [12].

1.1. Selection justification for injection-moulded interior trim component

An injection-moulded interior trim component was selected as they constitute the highest percentage of plastic components in a vehicle. Interior applications dominate the use of injection moulded components, accounting for 53% of all plastics used, see Figure 4 [13], [15]. Interior trim components, including dashboard panels and door trims, are commonly produced through injection moulding, one of the most energy-intensive polymer processing methods. This technique enables high-volume manufacturing, making these parts well suited for assessing embodied emissions reduction at scale. In addition, seating systems account for nearly 40% of an interior's total weight, and the production of polyurethane precursors used in these systems is also energy intensive [16]. nearly 40% of an interior's total weight, and the production of polyurethane precursors used in these systems is also energy intensive [16].

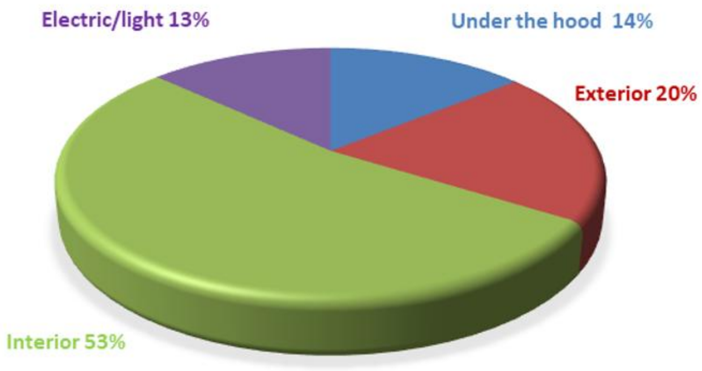


Figure 4: Plastics use in the European automotive sector, 2016 [14].

Four polymers are most used due to their impact resistance, surface finish quality, thermal stability, and recyclability: Acrylonitrile Butadiene Styrene (ABS), Polyvinyl Chloride (PVC), Polycarbonate (PC), and Polypropylene (PP). Polypropylene is the most widely used polymer, representing the highest percentage of all plastics employed, see Figure 5. For the purposes of this study, the representative trim component is assumed to be made from Polypropylene (PP) [17].

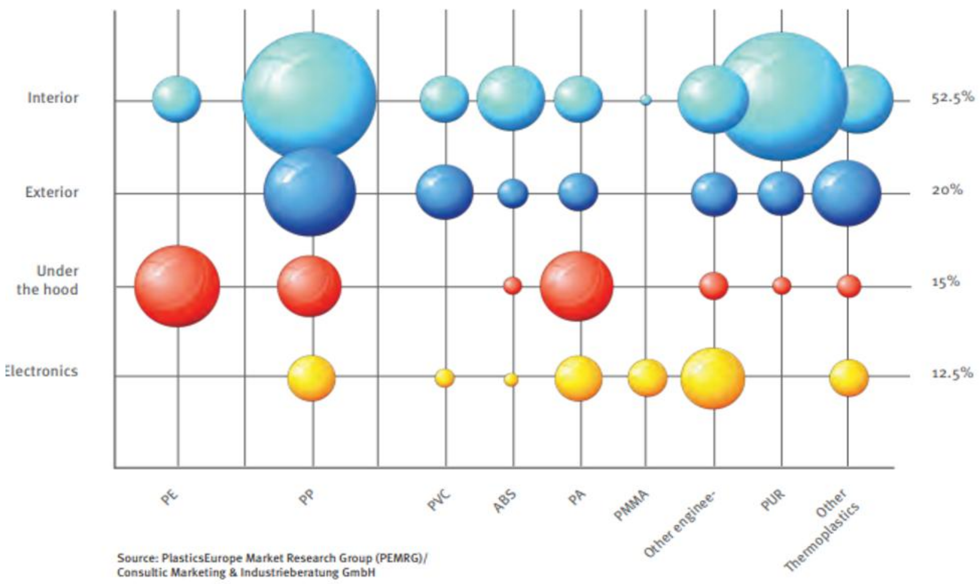


Figure 5: Use of plastics in the automotive industry by products and application [14].

1.2. Functional unit (typical masses for plastics)

The representative components selected are dashboard interior trim door and car seat, produced via injection moulding. The functional unit for this study is defined as:

- One kilogram of injection-moulded interior trim component delivered to the OEM assembly plant considering that typical injection-moulded PP door trim panel weight nearly 1.8 kg per door panel [18], [19].

- One kilogram of PU manufactured foam delivered to the OEM assembly plant considering that plastic materials used in seating systems total about 13 kg per vehicle. Assuming PU foam is the dominant material in seat cushioning and if distributed across 5 seating positions (front and rear), PU foam per car seat is almost 2.5-3 kg [20].

2. Supply chain mapping

Injection-moulded interior trim component (polypropylene, PP) and seating material (Polyurethane, PU) can be simply represented by the supply chain stages illustrated in Figure 6.

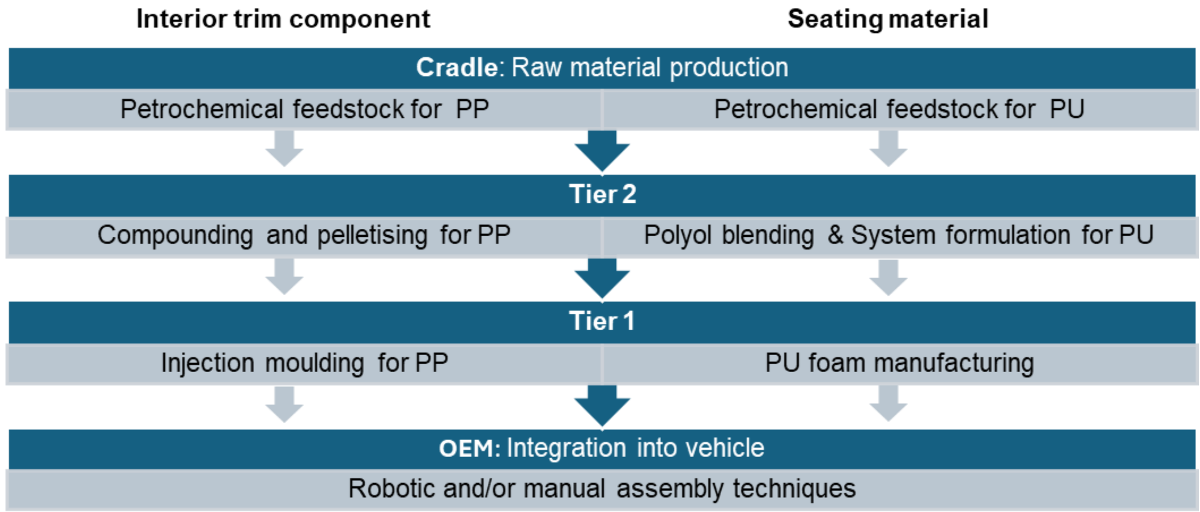


Figure 6: Simplified supply chain stages for PP and PU.

3. Baseline energy use, energy associated emissions and associated costs

While plastics can enable use-phase emission reductions, their production involves energy and emission intensive upstream processes. These upstream activities contribute to embodied greenhouse gas emissions within vehicle manufacturing. Cradle-to-gate polymer production and use is consistently identified as a significant contributor to Scope 3 emissions in automotive supply chains, accounting for 83% of the environmental impact, a large proportion of which is driven by embodied carbon emissions [13].

Baseline energy consumption has been defined using literature-reported energy intensities for polymer production and injection moulding. The baseline reflects current average industrial practice without additional energy optimisation or efficiency measures. Baseline for automotive plastic components can be divided into two routes:

Route 1: Polypropylene (PP) – Interior trim component
Route 2: Polyurethane (PU) – Seat foam

For both routes, the cradle stage for primary chemical production is highly energy intensive, with process energy accounting for just under 50% of total energy demand. This process energy consists of a combination of heat (thermal energy from fuel / steam) and electricity, with thermal energy typically dominating. In most cases, electricity contributes a relatively small share (around 15–30%), while the majority (70–85%) is supplied by fuels, mainly natural gas, used for steam generation and high-temperature processes. The exact energy demand varies significantly depending on factors such as plant age, level of heat integration, and operational efficiency. For example, differences in plant performance can lead to up to 50% higher energy consumption compared to best available technologies, although in well-optimized systems this gap may be as low as 10% [21].

All Tier-2 plastic compounders, Tier-3 polymer production, and injection moulding processes are represented by averaged or representative models to reflect typical industry conditions.

Route 1: Polypropylene (PP) – injection-moulded door components

Cradle / Tier 3 – Petrochemical feedstock

Production of propylene (from naphtha steam cracking or propane dehydrogenation) and polymerisation into polypropylene resin. The petrochemical sector primarily uses natural gas and oil for thermal energy, with electricity contributing a smaller but significant share. An energy grid mix of 80% gas and 20% electricity will be assumed at this stage [22], [23].

- Typical primary energy demand is on average 23.06 kWh/kg PP.
- Carbon footprint is nearly 2.3 kg CO_2e /kg PP.
- Energy-associated cost is £0.932/kg PP as UK energy grid mix.

Tier 2 – Polymer compounding

Addition of fillers, stabilisers, pigments, glass fibre (if reinforced), via extrusion and pelletising. These processes are driven mainly by electricity so we will assume the energy source here is 90% electricity for extruders motors, feeding systems, pelletising & cooling equipment and 10% gas for the heating barrels [22], [24], [25] [26].

- Typical energy demand on average is 1.50 kWh/kg PP.
- Carbon footprint is around 0.28 kg CO_2e /kg PP.
- Energy-associated cost is £0.38/kg PP.

Tier 1 – Injection moulding

Pellet drying, melting, mould clamping & cooling, see Figure 7 [24], [26], [27], [28].

- Typical energy demand ranges (1.48-3.62) kWh/kg PP, depending on the system type:
  - 3.62 kWh/kg for hydraulic systems.
  - 2.03 kWh/kg for hybrid systems.
  - 1.84 kWh/kg for all-electric systems.

- Carbon footprint/kg PP vary by system type as well:
  - 0.67 kg CO_2e/kg for hydraulic systems.
  - 0.38 kg CO_2e/kg for hybrid systems.
  - 0.34 kg CO_2e/kg for all-electric systems.

- Energy-associated cost/kg PP vary by system type as well:
  - £0.51/kg for hydraulic systems.
  - £0.56/kg for hybrid systems.
  - £1.00/kg for all-electric systems.

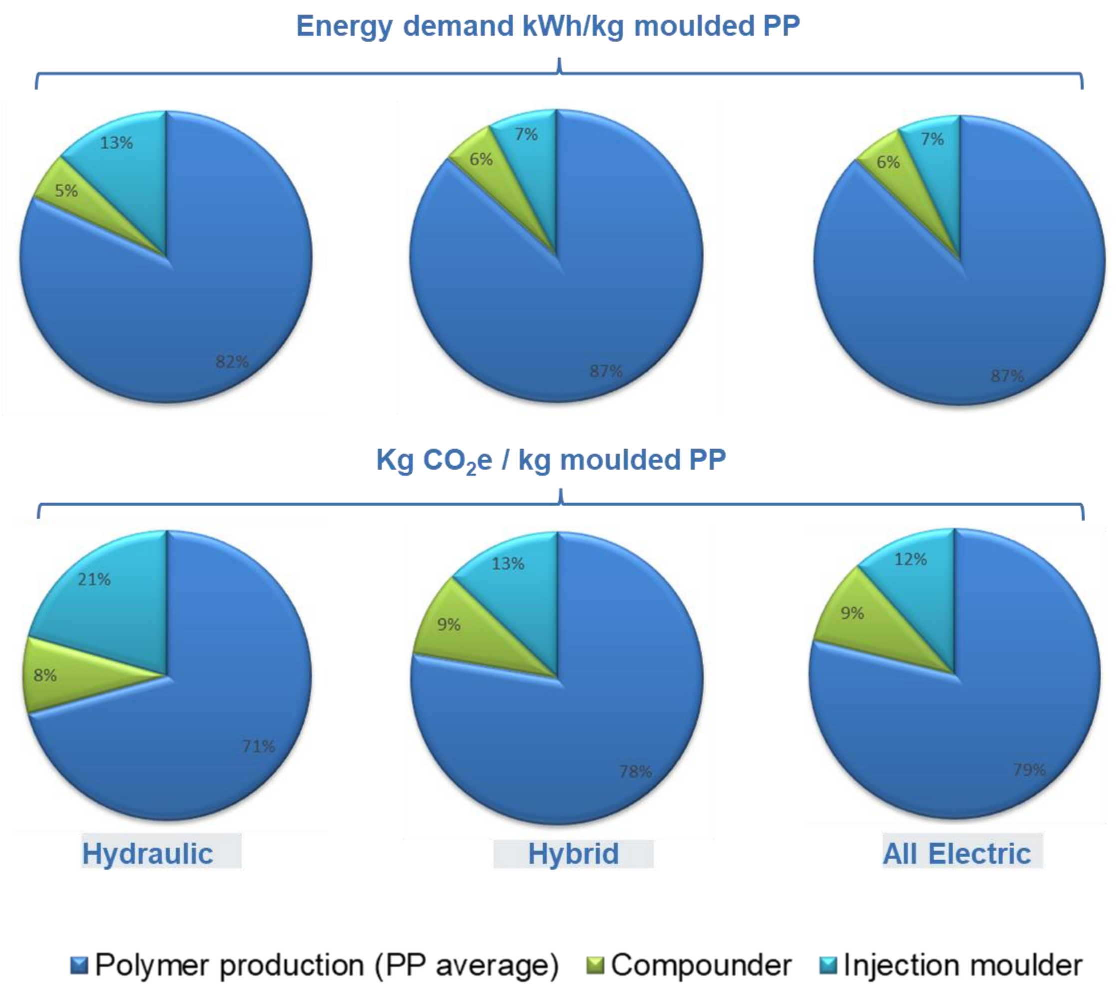


Figure 7: Difference in energy consumption and related emissions when changing the actuation system.

OEM- Final vehicle assembly

Assembly into vehicle, see methodology section for more details. Assumes based on electrical energy.

- Typical energy demand ~ 1.39 kWh/kg vehicle mass.
- Carbon footprint ~ 0.65 kg CO_2e/kg vehicle mass.
- Energy-associated cost ~ £0.38/kg vehicle mass.

Route 2: Polyurethane (PU) –Seat Cushion Foam

Polyurethane products can be manufactured either in integrated operations or across separate tiers in the value chain. In some cases, a single company performs both Tier 2 and Tier 1 activities within the same facility. Tier 2 involves formulating and reacting polyurethane systems from polyol and isocyanate, while Tier 1 focuses on shaping or moulding the final product. An example of this integrated approach is Getzner engineering [29].

In other cases, these stages are carried out by different companies. Tier 2 suppliers produce the formulated polyurethane systems, and Tier 1 manufacturers use these systems to produce the final products.

The data were taken from Plastics Europe and represent average values derived from European industries, based on information compiled across the region's manufacturing sector.

Cradle / Tier 3 – Petrochemical feedstock & chemical production

This stage is energy intensive and include the production of Polyols, Isocyanates (MDI/TDI)* and blowing agents / additives. Energy use in TDI and MDI production is dominated by thermal energy (steam), accounting for approximately 70–80% of total process energy due to distillation and heating requirements. Electricity contributes around 20–30%, primarily for pumps, compressors, and process operations [30]. An energy grid mix of 80% gas and 20% electricity have been assumed at this stage. For energy demand and associated emissions see Figure 8 and Figure 9.

- Typical energy demand is 28.05 kWh/kg foam [31], [32].
- Carbon footprint is on average 3.30 kg CO_2e kg/kg foam [31], [32], [33].
- Energy-associated cost is £2.03/kg foam as UK energy grid mix.

Tier 2 – Polyol blending & system formulation

At this stage, catalysts, surfactants, blowing agents, and other additives are blended to produce a customised polyol premix. The isocyanate, typically MDI or TDI, is stored separately and only combined with the polyol during the moulding process. A specialised company, commonly known as a PU systems house, sources raw materials and formulates customized polyurethane systems for specific applications such as automotive seating.

The energy demand at this stage is relatively low, around 1% of total primary process energy and consists of both thermal energy and electricity, mainly used for heating, facility operations, lighting, and auxiliary systems. An energy grid mix of 22% natural gas and 66% electricity have been assumed at this stage [33].

- Typical energy demand is 0.19 kWh/kg foam.
- Carbon footprint is 0.034 kg CO_2e /kg foam.
- Energy-associated cost is £0.039 /kg foam based on UK energy grid mix.

* TDI = Toluene Diisocyanate, MDI = Methylene Diphenyl Diisocyanate

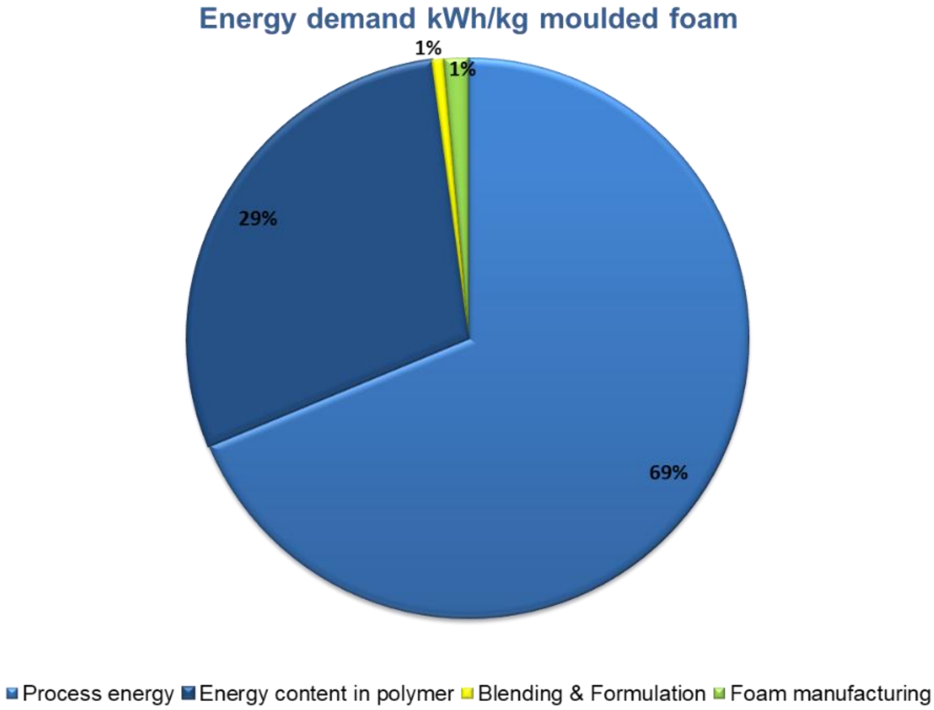


Figure 8: Energy consumption for foam manufacturing.

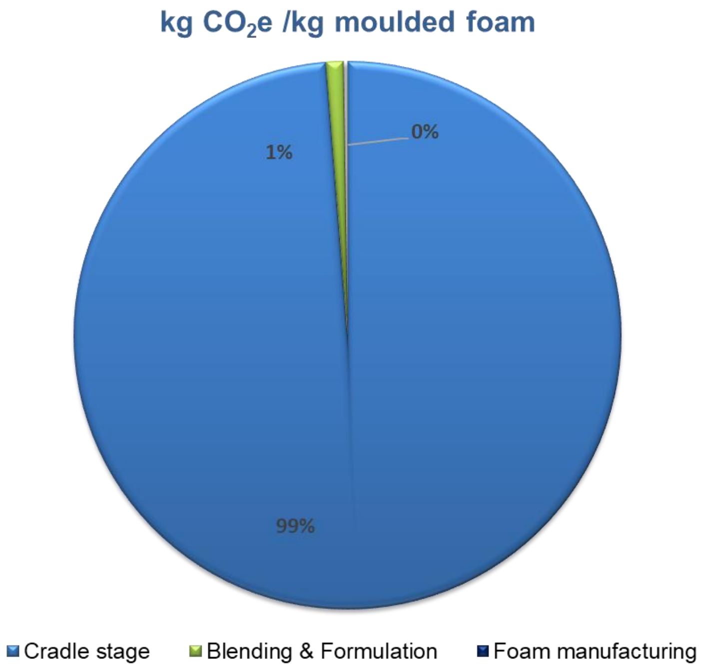


Figure 9: Emissions associated with foam manufacturing.

Tier 1 – Foam manufacturing - seat production

The foaming reaction occurs when polyol premix and isocyanate are combined in a high-pressure mixing chamber, requiring no external heating since the reaction is exothermic. The resulting liquid mixture is then injected into an aluminium seat mould, where the expansion (foaming) phase takes place. This is followed by curing and trimming of the final product.

The embodied energy is primarily associated with the electricity used to run the mixing and injection moulding equipment and is assumed in this study to represent approximately 2% of the total primary process energy, including both thermal energy and electricity. This energy also supports auxiliary functions such as heating, building operations, lighting, and other services, including IT systems and additional equipment.

Getzner engineering [29] reported the energy mix at their plant for a compound Tier 1 and Tier 2 stages as approximately 66% electricity and 22% natural gas, accounting for nearly 3% of the total primary process energy [33].

- Typical energy demand is 0.39 kWh/kg foam.
- Carbon footprint is 0.063 kg CO_2e /kg foam.
- Energy-associated cost is £0.077 /kg foam based on UK energy grid mix.

OEM - Final vehicle assembly

Assembly into vehicle, see methodology section for more details. Assumes based on electrical energy.

- Typical energy demand ~ 1.39 kWh/kg vehicle mass.
- Carbon footprint ~ 0.65 kg CO_2e/kg vehicle mass.
- Energy-associated cost ~ £0.38/kg vehicle mass.

4. Energy efficiency measures

Decisions can be made at OEM stage for both routes.

It is recommended that strategic decisions to be made at the OEM design stage, where the choice of starting materials (e.g. virgin or recycled) are defined in collaboration with suppliers. This stage is critical, as material selection strongly influences the energy used in manufacturing, effectively determining the emissions from all subsequent stages [34].

To maximise lifecycle benefits, OEM-led decisions can incorporate innovative solutions across aerodynamics, propulsion systems, structural lightweighting, and battery technologies. By integrating recycled and low-carbon materials, optimising product design, and prioritising energy-efficient manufacturing processes, OEMs can influence sustainability performance across the wider supply chain. These early-stage design and sourcing decisions not only improve operational efficiency and reduce lifecycle emissions but also encourage suppliers to adopt more energy-efficient production practices, reinforcing the critical role of OEMs in driving sustainable and resource-efficient supply chains [35].

Route 1: Polypropylene (PP) – Injection-moulded door components

<u>Tier 1: Energy efficiency improvement measures</u>

At this stage the compound is processed into the door component. Energy efficiency depends on machine efficiency, process parameters, thermal management, energy source and material choice. This can be improved by using efficient machine design, optimised processing and recycled materials [36]. Examples include:

- Mould system energy impact [23]

Mould systems can be improved using hot runner systems, which eliminate the need to manufacture and discard runners, unlike cold runner systems. Although they introduce an additional 0.42 kWh/kg of embodied energy into the product, hot runners significantly reduce waste from runners and sprues, resulting in an overall 15–20% reduction in the embodied energy of the moulding process.

- Actuation system and power transmission method [22]

Moving from hydraulic to all-electric systems enables significant energy savings, all-electric actuation systems are more efficient and have fewer losses than hydraulic systems, see Figure 10. At the injection moulding stage all-electric can have a ~50% efficiency improvement across key indicators such as energy process, emissions and costs.

All-electric, hybrid, and hydraulic injection moulding machines primarily use electricity as their external energy source but differ in how it is converted and applied within the system. All-electric machines use servo motors for all machine functions and are generally the most energy efficient, while also being capable of delivering high precision and high clamping forces. Hybrid systems combine electric drives with hydraulic components, balancing energy efficiency with high-force and high-power capability. Hydraulic machines rely most heavily on hydraulic systems driven by electric pumps, which can result in efficiency losses due to heat generation and fluid friction. Overall, the main distinction between these machine types is their energy conversion method and efficiency characteristics rather than differences in achievable force capability.

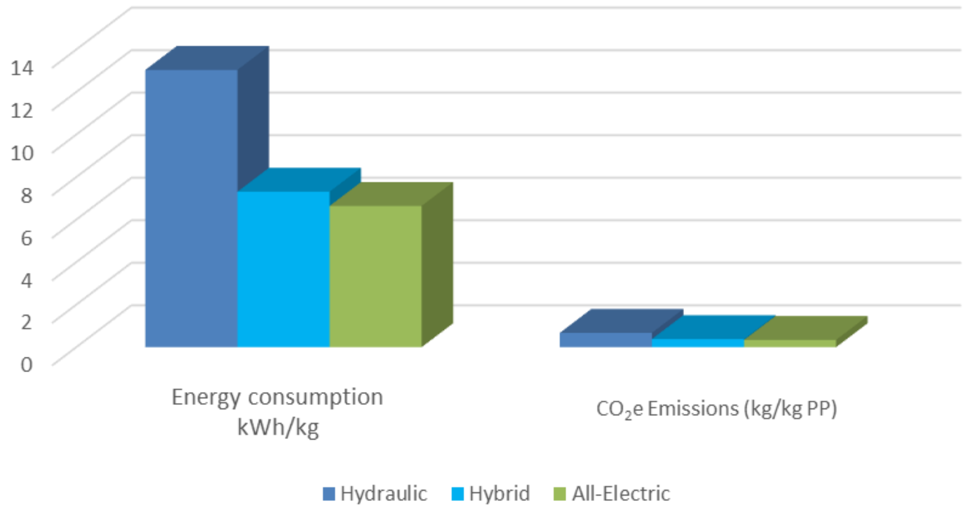


Figure 10: Energy demand and associated emissions between different actuation systems.

- Recycled materials or virgin materials substitutes

Using recycled PP instead of virgin PP can significantly reduce emissions at the material production stage as it avoids the highly energy-intensive processes associated with virgin polymer production (crude oil extraction, refining, and polymerisation) which dominate the material's embodied energy. Recycled PP is treated as a secondary material with minimal additional processing energy, leading to substantially lower overall energy demand. Furthermore, recycled PP typically has a lower molecular weight and viscosity, which improves flow during injection moulding and reduces the energy required for heating and screw operation. Overall, both material origin and processing conditions play a critical role in determining the magnitude of emission savings [23]

Tier 2: Energy efficiency improvement measures

At this stage polypropylene pellets are mixed with additives or reinforcements such as paper fibres or fillers to create the final compound used for manufacturing at Tier1. Energy efficiency depends on machine efficiency, thermal management, process optimisation and material choice [34], [22], [23].

An example of material choice, using recycled PP can reduce the energy consumption at the compounding stage, see Figure 11. Recycled PP has lower molecular weight from previous heat and processing history, which reduces molecular weight and melt viscosity, making it flow more easily and therefore requiring less mechanical energy during extrusion in compounding and pelletising [37], [38].

Cradle: Energy efficiency improvement measures

The dominant source of energy savings in using recycled PP arises from eliminating the need for virgin feedstock production, which is the most energy-intensive stage of the lifecycle. This stage is replaced by mechanical recycling processes, which lower energy demand and associated emissions by 30-70% [39]. This is evidenced by a life cycle assessment (LCA) study of polypropylene (PP), where the reported energy reductions across different recycling scenarios show that in a low recycling case (~12% recycled content), only a small portion of virgin production is displaced, resulting in a modest energy reduction of about 10.6%; in a medium scenario (~34% recycled content), greater substitution of virgin resin leads to a more substantial reduction of around 30%; while in a high recycling scenario (approaching 100% recycled content), the near-complete avoidance of virgin feedstock production drives a dramatic energy reduction of approximately 88%, see Figure 11 [40].

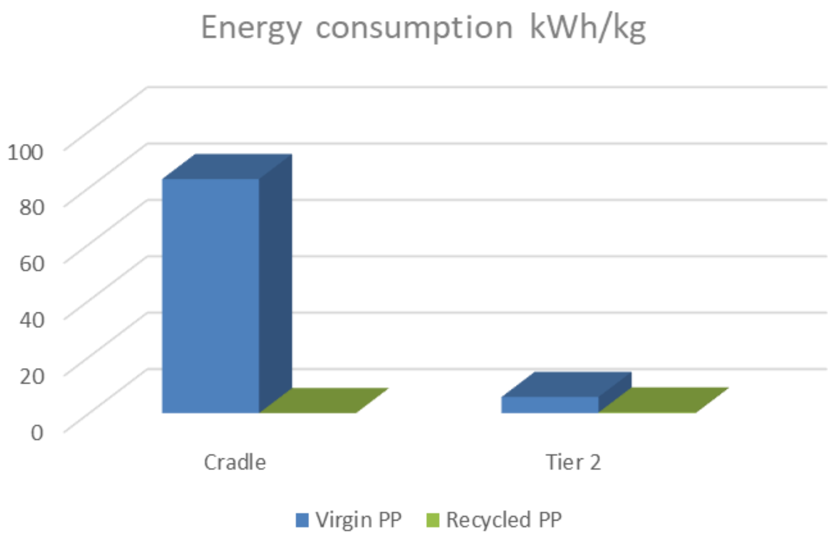


Figure 11: Comparison of energy consumption and emissions between virgin and recycled PP at the cradle and Tier 2 stages.

Route 2: Polyurethane (PU) – Flexible seat cushion foam

Tier 1 & Tier 2: Energy efficiency improvement measures

In Tier 1 and Tier 2 polyurethane (PU) manufacturing, several energy efficiency approaches can be used to reduce energy consumption and associated emissions while maintaining required mechanical performance and product quality. These strategies can be broadly grouped into operational-related approaches to reduce energy use during manufacturing, and material-related approaches which involve changes in material selection and product design.

For material-related approaches, energy efficiency is primarily achieved through the replacement of energy-intensive virgin materials with recycled or bio-based alternatives, thereby reducing embodied energy, processing requirements, and overall lifecycle impacts. Polyurethane foam remains the dominant material in automotive seating systems, particularly for cushions and backrests. However, it is increasingly being optimised through material substitution and lightweighting strategies such as:

- Expanded polypropylene (EPP) is increasingly adopted for structural seat components due to its significant lightweight potential, achieving 15–85% weight reduction while enabling integrated design features that can replace traditional materials such as steel.
- Thermoplastics and composites further contribute to weight and energy efficiency improvements, with up to 30% weight reduction in rear seat structures and the use of LFI PU composites for enhanced performance. Additionally, replacing foam with nonwoven PET in low-load areas improves recyclability, reduces VOC emissions, and lowers costs.
- Bio-based polyols (e.g., soya, castor oil) are used to reduce reliance on fossil-based materials, with adoption levels reaching up to 5% in TDI foams and 28% in MDI foams.

These materials can reduce petroleum-based polyol content by ~40%, see Figure 12 [16], [41].

Figure 12: Ford Mustang 2008 model is the first car to use soy-based PU seat foam [36].

For operations-related approaches, key measures include the use of energy management systems, smart metering, real-time process monitoring, and process optimisation to improve operational efficiency during formulation, moulding and casting operations. Temperature optimisation, particularly through improved control of mould temperature, curing, and post-curing phases, plays an important role in reducing unnecessary thermal energy use while ensuring proper chemical reactions. Studies and industrial applications have shown that process condition modifications and optimised moulding operations can reduce energy consumption by up to 60% in some systems. Reported production improvements indicate that optimised PU manufacturing can achieve emissions as low as approximately 0.1 kg CO_2 per kg PU, compared with benchmark values of around 3.3 kg CO_2 per kg PU in less efficient systems, representing a potential reduction of up to approximately 97% in production-stage emissions under best-in-class conditions [32], [42].

Additional measures include waste minimisation, closed-loop material handling, and the mechanical and chemical recycling of PU production scrap. Manufacturers also employ optimised granulation and moulded part technologies to reduce material losses during the conversion of polyols and isocyanates into PU foam components and improve overall resource efficiency.

Higher-capex measures involve the adoption of low-energy machinery, advanced processing technologies, and modern PU production systems with flexible and scalable configurations that integrate energy-efficient peripherals and automated controls. These technologies further reduce electricity demand and improve manufacturing sustainability, while also enabling manufacturers to estimate potential savings using customised energy assessment tools.

Although Tier 1 and Tier 2 processing stages are less energy-intensive than cradle-stage raw material production, they still contribute significantly to overall sustainability improvements.

<u>Cradle: Energy efficiency improvement measures</u>

At the cradle stage, the overall energy demand depends strongly on both the isocyanate type and the polyol chain length. MDI and TDI show slightly higher upstream fuel energy requirements at approximately 15.49 kWh/kg and 15.81 kWh/kg, respectively. In comparison, polyether polyols exhibit lower but still substantial energy demands, typically ranging from about 11.18 to 14.06 kWh/kg, depending on chain length and molecular structure [43], [44]

In automotive seating, different TDI/MDI and polyol formulations are used depending on the required performance and foam type. Flexible foams usually use TDI with long-chain polyols, while rigid foams are more often based on MDI with short-chain polyols (approximately 39% polyol to 60% MDI in 1kg foam). However, blended systems are also widely applied. Regional variation shows that the United States predominantly using T80 systems (80% TDI), Japan favouring higher MDI content (T20 systems), and Europe gradually transitioning toward more MDI-rich formulations [43], [45].

Introducing recycled polyols reduces dependence on virgin production, leading to a 17–18% decrease in primary energy demand for the polyol fraction and an associated 15% reduction in emissions, particularly at 50–75% replacement levels [41], [45].

Table 1 summarises key energy efficiency measures identified for automotive plastics manufacturing across different implementation scenarios. The measures are grouped according to process optimisation, machine and manufacturing efficiency, and material choice, highlighting their typical energy reduction potential and the applicable supply-chain tier stages where they can be implemented.

Table 1: Summary of energy efficiency measures by scenario level in plastics manufacturing.

Scenario	Measure	Typical energy reduction	Applicable tier stage
Scenario 1 – Process optimisation	PP-Improving mould system by using hot runner	15-20%	1
	PU- Optimised granulation and moulding processes	15-30%	2
Scenario 2 – Equipment and process upgrades	PP-Moving to all-electric actuation system and power transmission method	50%	1,2
	PU- low energy machinery	15-30%	1,2
Scenario 3 – Material choice/circularity	PP- Increasing recycled contents	10-88 %	1,2 and Cradle
	PU-Replacing virgin polyols with recycled polyols	15-17%	Cradle

Laminated automotive windscreen

1. Target material and component selection

Automotive glazing components, particularly laminated windscreens, represent a significant but often overlooked source of embodied energy and carbon emissions. Laminated windscreens are produced through a multi-stage manufacturing process comprising of raw material extraction, high-temperature float glass production (>1500°C), cutting and shaping, lamination with a polyvinyl butyral (PVB) interlayer, and autoclave curing. These processes are energy-intensive, relying on both thermal and electrical inputs, and contribute significantly to upstream (cradle-to-gate) emissions within the automotive supply chain.

1.1. Selection justification

Laminated windscreens were selected because they are the primary safety glazing system in passenger vehicles and therefore represent a high-volume, function-critical automotive glass product [46], [47].

From a manufacturing perspective, laminated windscreens are also a strong case study because they combine two major energy-intensive process group float glass production where glass precursors are melted to form flat glass at around 1600°C and downstream forming, where sheets of glass are formed into the right shapes and laminated together in processes using autoclaves operating at up to 600°C. For this study windscreens are a good example of a high-volume product produced using high energy processes over multiple stages [48], [49].

The selection of laminated automotive windscreens is justified from both economic and environmental perspectives. Flat glass manufacturing is highly energy-intensive, with natural gas accounting for approximately 75% of total energy use, while energy costs can exceed 30% of overall production costs in Europe. As windscreens are directly derived from this energy-intensive base and require additional energy for lamination processes, they provide a strong case study for assessing how improvements in process efficiency, energy sourcing, and energy management strategies can reduce both carbon emissions and manufacturing cost exposure [50].

1.2. Functional unit (typical masses for laminated windscreen)

Instead of analysing a full windscreen—which varies in size depending on the vehicle, this study uses 1 kg of laminated windscreen material as the basis for comparison.

Typical passenger car windscreen weighs roughly 10–15 kg [51]. Manufacturing costs are not reported in EPD, but industry estimates suggest production costs are typically in the range of £25–£55 per windscreen, while OEM prices are much higher depending on features such as coatings, sensors, or head-up display (HUD) compatibility.

2. Supply chains mapping

Figure 13 illustrates cradle-to-gate production of laminated automotive windscreens. Vehicle integration, use phase, and end-of-life stages are excluded, consistent with the focus on upstream embodied emissions.

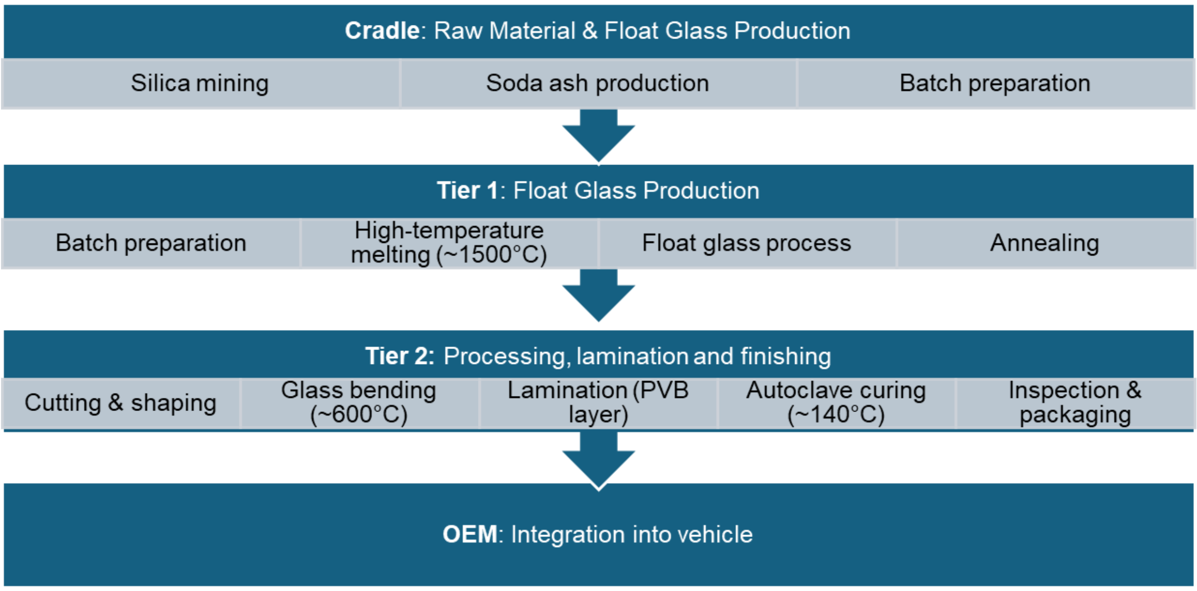


Figure 13: Cradle-to-Gate supply chain for laminated automotive windscreen.

3. Baseline energy use, energy associated emissions and associated costs

Literature studies and Environmental Product Declaration (EPD) datasets were used to establish baseline energy and emissions values for each supply chain tier of laminated automotive windscreen production. The cradle stage was further disaggregated into raw material extraction and float glass production, supported by literature indicating that 50–85% of total energy consumption in glass manufacturing is attributed to high-temperature melting processes (1200–1600 °C) [52]. See Figure 14 for supply chain tiers contributions towards energy, emissions and cost of windscreen production.

Cradle – Raw material extraction

Extraction and processing of silica, soda ash, and limestone used in glass batch preparation, with an assumed energy mix of 70% natural gas and 30% electricity [53].

- Typical energy demand ~ 1.16 kWh/kg.
- Carbon footprint ~ 0.32 kg CO_2e/kg.
- Energy-associated cost ~ £0.16/kg.

Tier 2 – Float glass production

Batch preparation, high-temperature melting (~1500°C), float process and annealing, with an assumed energy mix of 85% natural gas and 15% electricity [53].

- Typical energy demand ~ 3.49 kWh/kg.
- Carbon footprint ~ 0.95 kg CO_2e/kg.
- Energy-associated cost ~ £0.32/kg.

Tier 1 – Processing, lamination and finishing

Cutting, shaping, bending (~600°C), lamination (PVB), and autoclave curing (~140°C), with an assumed energy mix of 40% natural gas and 60% electricity [54].

- Typical energy demand ~ 10.19 kWh/kg.
- Carbon footprint ~ 2.01 kg CO_2e/kg.
- Energy-associated cost ~ £1.94/kg.

OEM – Final vehicle assembly

Final installation of the windscreen into the vehicle assembly line. Assembly into vehicle, see methodology section for more details. Assumes based on electrical energy [54].

- Typical energy demand ~ 1.39 kWh/kg vehicle mass
- Carbon footprint ~ 0.65 kg CO_2e/kg vehicle mass
- Energy-associated cost ~ £0.38/kg vehicle mass

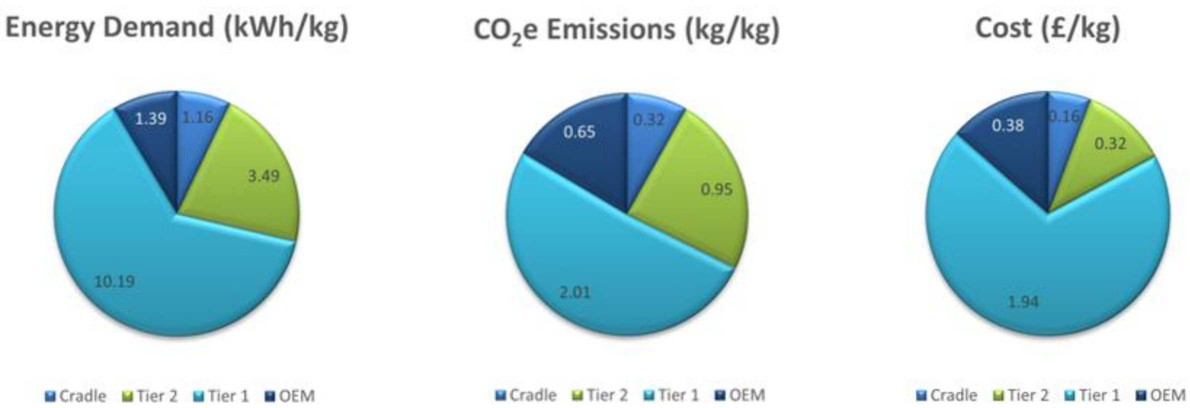


Figure14: Supply chain tiers contributions towards energy, emissions and cost of windscreen production.

4. Energy efficiency measures

The most significant opportunity for improvement lies in float glass production, which dominates overall energy demand due to continuous high-temperature furnace operation (~1500°C). Key interventions include increasing cullet (recycled glass) content, which reduces melting temperature and energy demand, and transitioning towards low-carbon or electrified furnace systems [52]. In addition, process-level improvements such as combustion optimisation and temperature control can reduce energy consumption by approximately 5–10% (up to 12%), while improvements in system efficiency, including reduction of thermal losses and leakage, can further enhance performance [55].

A second major intervention point is the manufacturing stage, particularly lamination and autoclave processes. These stages are electricity-intensive and represent the largest share of embodied emissions (~60%) in the analysed EPD dataset, driven primarily by operations such as glass bending and autoclave curing. As a result, emissions and energy reduction potential is strongly concentrated in this stage, where targeted optimisation can deliver the most significant impact. Improvements and reductions in emissions can be achieved through process optimisation (reduced cycle times and improved thermal efficiency) [56], thermal energy storage (TES) or battery ESS for load management (enabling more efficient

use of energy during peak demand periods), and renewable electricity integration, which directly reduces emissions associated with electricity-intensive processes such as lamination and autoclave curing [56].
Furthermore, waste heat recovery from furnace exhaust presents a strong opportunity, with studies indicating potential energy savings of approximately 10–15% through batch and cullet preheating [55]. Additional reductions can be achieved through fuel switching and improved burner control, enabling the use of lower-carbon fuels and more efficient combustion processes [57]. A more detailed breakdown of the identified improvement measures, including supporting data and references, is provided in the Appendix.

Emissions and cost reduction measures

Reduction scenarios were developed to evaluate the impact of realistic energy-efficiency improvements across float glass production and lamination stages. The analysis assumes proportional relationships between stage-level energy reductions and associated emissions, reflecting the dominance of operational energy within Scope 1 and Scope 2 impacts.

Based on the analysed datasets, the total embodied emissions for laminated automotive windscreens are approximately 2.65 kg CO_2e/kg, with a corresponding total primary energy demand of 11.11 kWh/kg. This indicates a tightly coupled manufacturing system in which energy consumption and emissions are strongly correlated, reflecting the combined influence of high-temperature thermal processes and electricity-intensive downstream operations.

To ensure realistic modelling, scenarios were developed based on documented industry interventions in glass manufacturing rather than arbitrary assumptions. Scenario modelling indicates that practical energy-efficiency measures can achieve up to ~20% reduction in embodied emissions, with the greatest impact arising from interventions in furnace operation and cost reduction in manufacturing processes.

Table 2 summarises key energy reduction measures applicable to laminated windscreen manufacturing. Measures are grouped by scenario level to reflect increasing implementation complexity and impact, with corresponding energy reduction potential and applicable supply chain stages identified. This provides a structured basis for evaluating realistic improvement pathways within the manufacturing process.

Advanced pathways, including furnace electrification and high renewable electricity integration, offer the largest long-term reduction potential in emissions. However, these approaches require significant technological development, infrastructure upgrades, and capital investment, highlighting the trade-off between immediate efficiency gains and long-term transformation of the manufacturing system.

The integration of TES and ESS as shown in Table 3 within the automotive windscreen manufacturing offers potential to reduce energy consumption, and lower carbon emissions; however, applicability varies significantly across process stages due to differing thermal and electrical demands. The float glass melting stage dominates energy use, accounting for approximately 70–80% of total plant energy, with typical consumption below 2222 kWh/t and strong dependence on natural gas (≈85–90%) and 10–15% electricity. Consequently, ESS deployment must be evaluated based on process temperature, energy type, and operational constraints, with the greatest potential in high-energy stages such as melting and heat recovery, and more limited application in low-demand processes.

Table 2: Summary of energy efficiency measures by scenario level in laminated windscreen manufacturing.

Scenario	Measure	Typical energy reduction	Applicable tier stage
Scenario 1 – Process optimisation (7.5%)	Process control & combustion optimisation (APC, air-fuel control)	5–10% (up to 12%)	Cradle
	Furnace maintenance & efficiency recovery (rebuild, leakage, insulation)	5–15%	2
	Operational optimisation (throughput, scaling, capacity)	5–10%	2, 1
	Raw material conditioning (batch preparation, moisture control)	~2–5%	Cradle
Scenario 2 – Equipment and process upgrades (15%)	Cullet utilisation increase	~2.5–3% per +10% cullet	Cradle
	Waste heat recovery & preheating (WHR, batch/cullet preheating, regenerators)	10–20% (up to ~35% heat recovery contribution)	Cradle, 2
	Thermal efficiency improvements (insulation, heat loss reduction)	Recovers part of 20–35% losses	Cradle, 2, 1
Scenario 3 – Advanced measures (25%)	Furnace electrification & hybrid systems	~20–40%+ reduction	Cradle
	Oxy-fuel & advanced combustion systems	10–20% efficiency gain	Cradle
	Process emission limitation (material chemistry constraint)	15–25% emissions unavoidable	Cradle

Table 3: ESS Implementation in glass manufacturing.

Stage	Recommended action	Expected benefit
Float furnace	Waste heat capture and storage + TES	10–15% energy reduction
Bending furnace	High-temp TES	Reduced peak energy demand
Autoclave	Steam / thermal storage	Stable operation + energy savings
Electrical systems	Battery ESS	Peak shaving + cost reduction

Cast aluminium wheel

1. Target material and component selection

Comprising over 70% of a vehicle body by mass [14], metals can be considered the most crucial materials within the automotive industry. Varying properties are sought depending on component characteristics, although generally metal use is due to a combination of strength, formability, and temperature resistance. Traditionally steels make up a significant proportion of the vehicle mass due to their manufacturability and affordability. Aluminium alloys are often used in areas where increased corrosion resistance is required or lightweighting is prioritised, as aluminium can save 30-60% [58] weight when compared to equivalent steel components.

Aluminium content in vehicles is expected to increase by 51.5 kg per vehicle before 2030, with both body-in-white (BIW) and electric vehicle (EV) specific uses increasing significantly [59]. Casting is also expected to increase in popularity [59] for BIW applications with the dawn of mega- and gigacasting processes [60]. A preference for reduced or single component castings over more complex multi-part assemblies is shown by adoption rates from various automotive OEMs including Tesla, Volvo, Mercedes and some Chinese OEMs. Given the high energy demands of casting processes when compared to other manufacturing methods, this expected increase in cast component use highlights an opportunity to improve energy efficiency in casting processes.

1.1. Selection justification

The use of aluminium for automotive applications is forecast to increase, aluminium production is energy and emission intensive making it a good example for energy efficiency.

Aluminium casting is the most energy intensive form of processing and may become a favoured process if megacasting becomes commonplace.

BIW and structural castings might be the most up-and-coming future technologies, wheel rims and hubs are currently the most common cast aluminium components in passenger vehicles with more than 90% of the European market share [61], and therefore have more readily available data sources. Hence, a cast aluminium wheel was selected as the component for this investigation.

1.2. Functional unit (typical masses for aluminium wheels)

The representative component selected is an aluminium wheel, produced using casting methods.

As with previous components, the functional unit for this study is defined as one kilogram of cast aluminium, used in a wheel delivered to a vehicle assembly plant.

On average, a 17-inch aluminium wheel has a 9.5kg mass [62], making an average of 38kg per vehicle containing four components.

2. Supply chains mapping

Cast aluminium components have a supply chain that can easily be grouped into two stages: extraction of ore and refinement into ingots [63], followed by the manufacturing of the cast component. For the purposes of this report the first stage will be separated into alumina production and then ingot manufacture, since these steps have significantly different energy demands and the benefits of secondary aluminium use (aluminium recycling) is more easier to consider.

Figure 15 below shows the supply chain tier categories and their associated manufacturing processes [62]

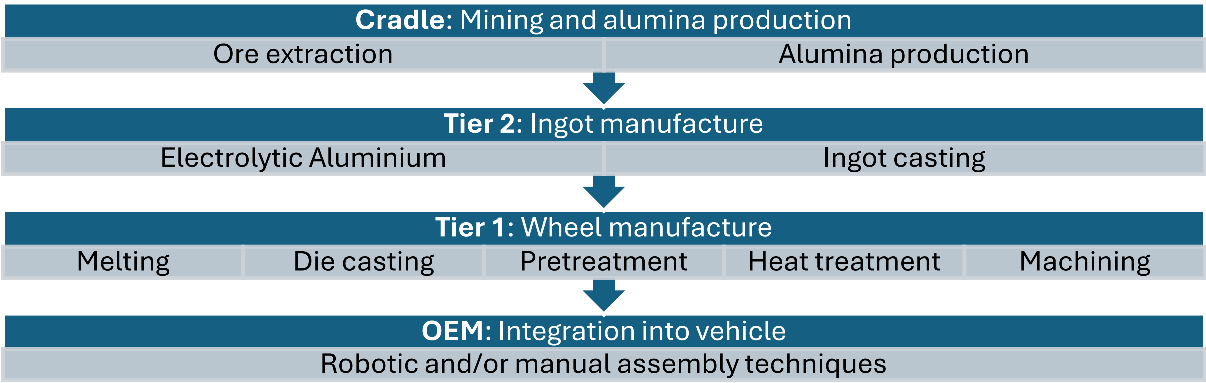


Figure 15: Supply chain tiers for cast aluminium wheel with description of manufacturing processes, adapted from literature LCA studies [62].

3. Baseline energy use, energy associated emissions and associated costs

A literature study was conducted to obtain baseline energy and emissions values for each supply chain tier. The energy mix of each supply chain tier has been accounted for [64]. See Figure 16 for supply chain tiers contributions towards energy, emissions and cost of cast aluminium wheel production.

Cradle – Mining and alumina production

Production of alumina from mined bauxite ore, assumes fully natural gas derived energy [65]

- Typical energy demand ~2.78 kWh/kg.
- Carbon Footprint ~1.7 kg CO_2e/kg.
- Energy-associated cost ~ £0.17/kg.

Tier 2 – Ingot manufacture

Smelting and casting of alumina into aluminium ingots, with a 30%/70% gas to electricity energy ratio [66]

- Typical energy demand ~52.78 kWh/kg aluminium ingot.
- Carbon footprint ~16.5 kg CO_2e/kg aluminium ingot.
- Energy-associated cost ~ £11.17/kg aluminium ingot.

Tier 1 – Wheel manufacture

Ingot melting, die cast manufacture, casting, heat treatment and finishing, with a 60%/40% gas to electricity energy ratio [67]

- Typical energy demand ~ 9.17 kWh/kg structural die-cast aluminium.
- Carbon footprint ~ 2.66 kg CO_2e/kg structural die-cast aluminium.
- Energy-associated cost ~ £1.35/kg structural die-cast aluminium.

OEM Integration

Assembly into vehicle, see methodology section for more details. Assumes purely electrical energy

- Typical energy demand ~ 1.39 kWh/kg vehicle mass.
- Carbon footprint ~ 0.65 kg CO_2e/kg vehicle mass.
- Energy-associated cost ~ £0.38/kg vehicle mass.

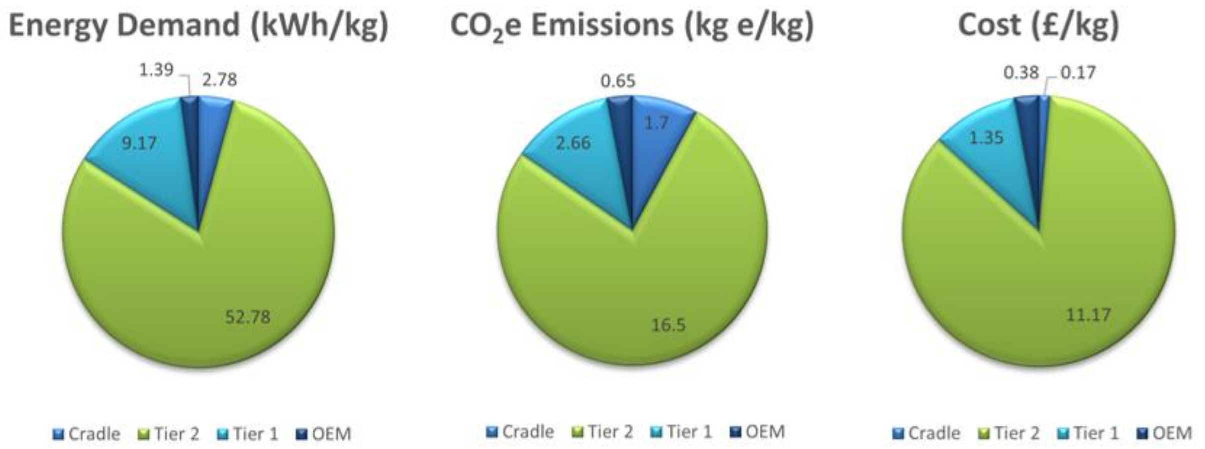


Figure 16: Supply chain tiers contributions towards energy, emissions and cost of cast aluminium wheel production.

4. Energy efficiency measures

There is an abundance of research into efficiency measures for cast aluminium production processes, but much of it contains limited details due to proprietary information. Straightforward methods include measures such as scheduling optimisation strategies, material substitutions and modifications, use of filters and/or scrubbers, and reduction of process waste [68], [69] [70], [71]. More advanced methods include improved burner technologies or furnace electrification, waste heat management and recovery, anode and cathode substitutions during electrolysis, or even receiving aluminium in molten form [69], [72], [73][74], [75].

The most energy intensive procedures within the supply cain are the electrolysis of alumina as well as melting furnaces for both ingot- and wheel die-casting. Thus, it is these points which require the most focus for energy reduction.

For electrolysis, the most energy and emissions saving methods include the use of inert anodes with wettable cathodes (up to 8 kWh/kg Al savings), vertical electrode cells (up to 9 kWh/kg Al savings), or substitution of the electrolysis process to direct carbothermic reduction (up to 11 kWh/kg Al savings), especially when using coal-based energy [76].

In foundries and melting processes, improved burner technologies and immersion heaters are prevalent energy efficiency methods, with substitution to newer induction furnaces (such as constrained rapid induction melting single shot up-casting – termed CRIMSON methods [77] – used to heat smaller batches and avoid larger holding furnaces) being the most effective but also most difficult in terms of setup costs and logistics. Improved burners have been shown to save up to 60% of emissions and 70% of costs [72].

Reduction scenarios were developed to evaluate the impact of realistic energy-efficiency improvements across aluminium wheel supply tiers. The analysis assumes proportional relationships between stage-level energy reductions and associated emissions, reflecting the dominance of operational energy within Scope 1 and Scope 2 impacts. Examples of possible measures to meet each scenario are given in Table 4, with associated energy reductions and supply chain tier stages applicable. These are intended to be an achievable, realistic set of targets for an average OEM's supply chain status, and therefore the figures stated are the lower end of the energy savings potentials described in some of the research findings discussed. Any of these scenarios may yield much greater efficiency improvements depending on a supplier's individual input and output parameters. This is particularly true of (especially when considering methods such as the use of secondary aluminium, for example).

Table 4: Summary of energy efficiency measures by scenario level in aluminium wheel manufacturing.

Scenario	Measure	Typical energy reduction	Applicable tier stage
Scenario 1 – Process optimisation (~7.5% reduction)	Schedule/loading optimisations	5-15%	2, 1
	Furnace maintenance & efficiency recovery	5-15%	2, 1
	Operational optimisation	5-10%	Cradle 2, 1, OEM
Scenario 2 – Equipment and process upgrades (~15% reduction)	Filters and scrubbers	5-30%	2, 1
	Waste heat recovery	10-20%	Cradle, 2, 1, OEM
	Upgraded burner systems	10-25%	2, 1
	Sophisticated anode/cathode designs	10-15%	2
Scenario 3 – Advanced measures and circularity (~25% reduction)	Molten aluminium supply	20-40%	1
	Use of secondary aluminium		
	Furnace electrification	10-30%	2, 1

Summary table and conclusions

Table 5 and Figure 17 compare the existing manufacturing supply chain with three proposed energy-efficiency scenarios for selected automation OEM components, including seat foam, plastic trim parts, windscreens, and aluminium wheel hubs. The analysis examines cumulative energy consumption (kWh/kg), embodied carbon emissions (kgCO_2e), and production costs (£/kg) across key supply chain stages: cradle, Tier 2, Tier 1, and OEM manufacturing.

Each scenario reflects incremental improvements in efficiency. Scenario 1 emphasises process optimisation, Scenario 2 introduces equipment and process upgrades, and Scenario 3 combines advanced efficiency measures with material circularity strategies. The findings highlight how these interventions can reduce energy use, lower emissions, and improve cost efficiency, providing valuable insights into enhancing sustainability in the automation OEM manufacturing sector.

The results presented in the table and figures demonstrate that improving energy efficiency across the manufacturing supply chain significantly reduces embodied emissions associated with the automotive OEM. Compared with the current manufacturing supply chain, all proposed scenarios result it cumulative energy, embodied emissions and overall cost reductions.

The figures show a consistent downward trend in emissions as energy use decreases along supply chains, showing the strong correlation between improved energy efficiency and lower embodied carbon. The reductions are particularly noticeable at Tier 2 and Tier 1 manufacturing stages, suggesting that supply chain optimisation and material efficiency contribute substantially to lowering the environmental impact of automotive production.

Table 5: Comparative assessment of energy consumption, embodied emissions, and cost across manufacturing supply chain scenarios for Automation OEM components.

	Energy Used (kWh/kg)					Emissions (kg CO_2e/kg)					Cost (£/kg)				
Current Manufacturing Supply Chains	**Cradle**	**Tier 2**	**Tier 1**	**OEM**	**Totals**	**Cradle**	**Tier 2**	**Tier 1**	**OEM**	**Totals**	**Cradle**	**Tier 2**	**Tier 1**	**OEM**	**Totals**
Seat Foam	28.05	0.19	0.39	1.39	30.02	3.30	0.03	0.06	0.70	4.10	2.03	0.04	0.08	0.38	2.53
Plastic Trim Part	23.06	1.50	2.03	1.39	27.98	2.30	0.28	0.38	0.70	3.66	0.93	0.38	0.56	0.38	2.25
Windscreen	1.16	3.49	10.19	1.39	16.23	0.32	0.95	2.01	0.70	3.98	0.07	0.21	0.60	0.38	1.26
Aluminium Wheel Hub	2.78	52.78	9.17	1.39	66.12	1.70	16.50	2.70	0.70	21.60	0.17	11.17	1.35	0.38	13.07
Cumulative Energy	55.05	113.01	134.79	140.35	140.35	7.62	25.38	30.54	33.34	33.34	3.20	15.00	17.59	19.11	19.11
Scenario 1															
Seat Foam 22%	21.88	0.15	0.30	1.29	23.62	2.57	0.03	0.05	0.65	3.30	1.58	0.03	0.06	0.35	2.03
Plastic Trim Part 17%	19.14	1.25	1.68	1.29	23.36	1.91	0.23	0.32	0.65	3.11	0.77	0.32	0.46	0.35	1.90
Windscreen	1.07	3.23	9.43	1.29	15.02	0.30	0.88	1.86	0.65	3.69	0.07	0.19	0.56	0.35	1.17
Aluminium Wheel Hub 7.4%	2.57	48.82	8.48	1.29	61.16	1.57	15.24	2.50	0.65	19.96	0.16	10.33	1.25	0.35	12.09
Cumulative Energy	44.66	98.10	118.00	123.16	123.16	6.35	22.73	27.46	30.06	30.06	2.58	13.45	15.79	17.19	17.19
Scenario 2															
Seat Foam 22%	21.88	0.15	0.30	1.18	23.51	2.57	0.03	0.05	0.59	3.24	1.58	0.03	0.06	0.32	2.00
Plastic Trim Part 40%	13.84	0.90	1.22	1.18	17.13	1.38	0.17	0.23	0.59	2.37	0.56	0.23	0.34	0.32	1.44
Windscreen	0.99	2.97	8.67	1.18	45.64	0.27	0.81	1.71	0.59	3.38	0.06	0.18	0.51	0.32	1.07
Aluminium Wheel Hub 15%	2.36	44.86	7.79	1.18	56.19	1.45	14.03	2.30	0.59	18.37	0.14	9.49	1.15	0.32	11.11
Cumulative Energy	39.07	87.94	105.93	110.65	142.48	5.67	20.71	25.00	27.36	27.36	2.35	12.28	14.33	15.62	15.62
Scenario 3															
Seat Foam 16%	23.56	0.16	0.33	1.04	25.09	2.77	0.03	0.05	0.52	3.37	1.71	0.03	0.07	0.28	2.09
Plastic Trim Part 50%	11.53	0.75	1.02	1.04	14.34	1.15	0.14	0.19	0.52	2.00	0.47	0.19	0.28	0.28	1.22
Windscreen	0.87	2.62	7.64	1.04	12.17	0.24	0.71	1.51	0.52	2.98	0.05	0.16	0.45	0.28	0.94
Aluminium Wheel Hub 25%	2.09	39.59	6.88	1.04	49.60	1.28	12.38	2.00	0.52	16.18	0.13	8.38	1.01	0.28	9.80
Cumulative Energy	38.05	81.17	97.03	101.19	101.19	5.44	18.70	22.45	24.54	24.54	2.35	11.11	12.92	14.05	14.05

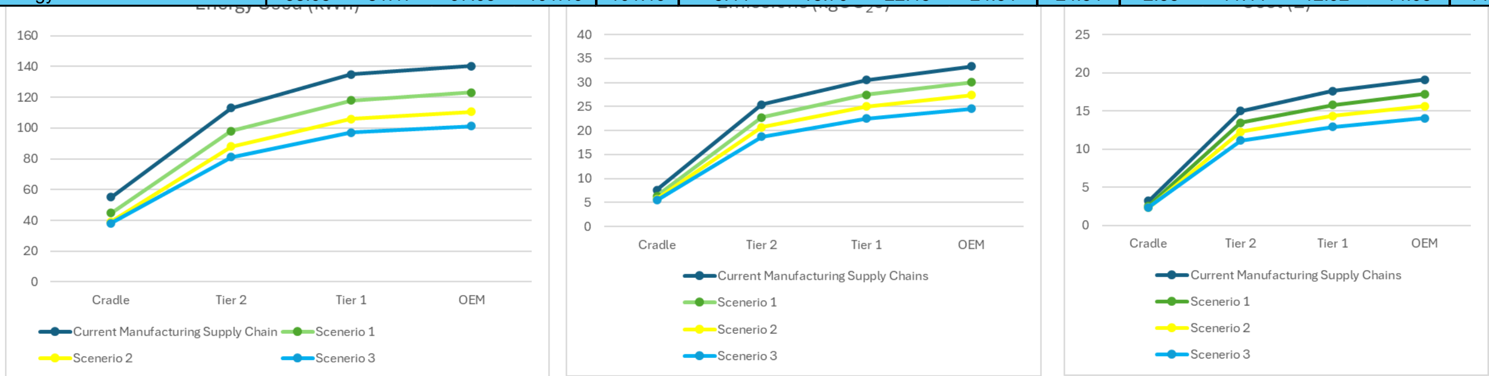


Figure 17: Energy use, embodied emissions, and cost trends across manufacturing scenarios.

In conclusion, to reduce embodied emissions effectively, two complementary strategies should be prioritised: a material-related approach and an operation-related approach.

The operation-related approach focuses on improving energy efficiency throughout supply chain activities using operational optimisation, data-driven energy management, and the adoption of best available technologies.

- Operational optimisation through low-capex measures provides practical, cost-effective pathways for near-term emission reductions. These actions are easier to implement than large-scale equipment upgrades, delivering rapid efficiency gains with minimal disruption to production. Examples include process optimisation, improved operational controls, preventative maintenance, energy monitoring, machine scheduling, refined production cycle times, regular energy audits and performance assessments, behavioural changes, and load management.

- Data-driven energy management enables the identification of hidden inefficiencies in manufacturing through continuous monitoring and analysis. This approach affects issues such as idle energy use, abnormal consumption patterns and performance variability. It allows organisations to implement targeted improvements and optimise energy use with relatively low investment.

- The adoption of best available technologies and advanced energy management systems includes high-efficiency electrical drives, advanced process control systems, improved thermal management, partial electrification of heating systems and manufacturing equipment, waste heat recovery, and digital energy optimisation technologies.

OEMs can play a key role in supporting supply chain decarbonisation by promoting structured energy audits, benchmarking performance, insetting, encouraging transparent emissions reporting and embedding energy-performance standards via purchasing agreements. Through these initiatives, suppliers can identify inefficiencies, monitor progress, and implement targeted improvements that contribute to lower operational emissions.

The material-related approach supports using more recycled materials which can significantly reduce energy use and carbon emissions as it requires less processing than virgin materials. At the same time, better additives and material innovations can improve material quality, processing efficiency thereby reduce energy consumption.

Overall, improving production efficiency and optimising materials offers a practical and effective way to reduce embodied emissions across supply chains. These strategies lower carbon emissions, improve resource use, strengthen operations, and support long-term cost savings.

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Appendix

Detail of improvement strategies in automotive glass manufacturing. The scenarios are supported by real industry practices:

- **Cullet increase (float glass stage)**
  Studies show that increasing recycled glass content reduces melting energy demand due to lower required furnace temperatures, every 10% increase in cullet usage leads to a roughly 2.5–3% reduction in furnace energy consumption and reduces related emissions by 250–300 kg per tonne of cullet. [78], [79], [80]
- **Regenerative heat recovery (combustion air preheating)**
  Regenerative furnaces recover heat from exhaust gases to preheat combustion air, supplying approximately 30–35% of total furnace energy input, significantly reducing fuel demand [81], [82].
- **Electric boosting / hybrid furnaces**
  Hybrid systems combining combustion and electrical heating can achieve up to 80% electric energy share, improving thermal efficiency and reducing fuel consumption [52].
- **Batch and cullet preheating (enhanced WHR integration)**
  Preheating raw materials using recovered waste heat improves thermal efficiency and reduces fuel consumption, with energy savings typically in the range of 10–20% depending on implementation [81], [82].
- **Oxy-fuel combustion (process intensification)**
  Replacing air with oxygen in combustion reduces inert gas heating losses, improving efficiency by approximately 10–20%, while also reducing NOx emissions by 70–90% [81], [83].
- **Furnace capacity and scaling effects**
  Larger, optimised furnaces operate more efficiently due to reduced relative heat losses, with regenerative furnaces achieving higher efficiency at large scales (e.g., ~300 t/day capacity), improving overall energy performance [81].
- **Furnace ageing and rebuild cycles**
  Studies show that as furnaces age, thermal losses increase due to refractory degradation and insulation wear, leading to measurable efficiency decline. Rebuilding or relining furnaces can restore efficiency and reduce energy demand by approximately 5–15% compared to aged furnaces [83], [84].
- **Production scaling and throughput optimisation**
  Increasing furnace throughput and operating closer to maximum capacity reduces specific energy consumption per unit product, as fixed thermal losses are distributed over larger output, improving efficiency significantly [85]
- **Raw material conditioning (moisture and pre-treatment)**
  Controlling batch moisture and temperature (e.g., raw material preheating to ~305 K) reduces combustion heat demand and improves melting efficiency, contributing to measurable reductions in specific energy consumption. [85]
- **Process emission awareness (non-energy CO_2)**
  Approximately 15–25% of total CO_2 emissions in glass production are process emissions (from raw material decomposition), meaning energy efficiency alone cannot eliminate total emissions. [86]