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# Sustainability in Automotive Manufacturing

A Process-Stage Assessment of the State of the Art, Industrial Practice, and a Life Cycle Case Study

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# Abstract

As tailpipe emissions fall towards zero under regulations such as the EU "Fit for 55" package, the carbon footprint of a vehicle shifts upstream to its manufacture and its materials. The Carbon Border Adjustment Mechanism and the EU Battery Regulation make that shift economically concrete. This thesis assesses manufacturing-stage sustainability in the automotive industry from two complementary perspectives, the academic state of the art and actual industrial practice, and binds them together with a single analytical framework so that the two can be compared directly. A process-stage taxonomy is applied throughout: stamping and body-in-white, paint shop, powertrain and final assembly, with the powertrain stage divided into a thermal and an electrified branch of equal weight. Two cross-cutting levers, energy management and material circularity, complete it. Each technology is classified by Technology Readiness Level and by quantitative metrics. Every industrial claim is graded against a strict source-reliability hierarchy and against an explicit definition of terms such as carbon neutrality and offsetting, both designed to guard against greenwashing.

The academic assessment finds that the most mature process stages offer the least remaining headroom, while the high-impact levers split into two groups: some are deployable now, such as low-carbon electricity, reduced-stage painting and closed-loop aluminium, and others are still maturing, such as hydrogen-based steel, the electrification of process heat, dry-electrode cell manufacturing and battery recycling. Benchmarking of vehicle manufacturers, Tier-1 suppliers and the upstream materials industry, including the Italian Motor Valley, reveals four gaps between academia and industry: a diffusion gap that is closing at the leading manufacturers, a genuine scale-up gap, a verification gap between reduction and compensation that only third-party-verified disclosure makes visible, and a gap of attention around the manufacture of thermal powertrains. Treating both powertrain branches equally also shows that a hybrid vehicle carries the manufacturing burden of an engine and of a battery together, rather than an average of the two. A screening Life Cycle Assessment, anchored in the Motor Valley context, then quantifies the decisive material lever: substituting closed-loop recycled for primary aluminium reduces a structural component's cradle-to-gate global-warming impact by about 77 %, a result that applies to engine castings as much as to body parts. The work contributes a transferable method for turning parallel surveys into a structured, greenwashing-aware gap analysis.

**Keywords:** sustainable manufacturing; automotive; life cycle assessment; circular economy; decarbonisation; powertrain manufacturing; hybrid vehicles; green steel; recycled aluminium; Technology Readiness Level.

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# List of Acronyms

| | |
|---|---|
| **AHSS** | Advanced High-Strength Steel |
| **AGV** | Automated Guided Vehicle |
| **ASI** | Aluminium Stewardship Initiative |
| **BEV** | Battery Electric Vehicle |
| **BIW** | Body-in-White |
| **CBAM** | Carbon Border Adjustment Mechanism |
| **CDP** | Carbon Disclosure Project |
| **CFRP** | Carbon-Fibre-Reinforced Polymer |
| **$CO_2$** | Carbon Dioxide |
| **$CO_2$-eq** | Carbon-Dioxide Equivalent |
| **DRI** | Direct-Reduced Iron |
| **EAF** | Electric-Arc Furnace |
| **EmpCo** | Empowering Consumers for the Green Transition (Directive (EU) 2024/825) |
| **EPD** | Environmental Product Declaration |
| **ETS** | Emissions Trading System |
| **GHG** | Greenhouse Gas |
| **GWP** | Global Warming Potential |
| **HEV** | Hybrid Electric Vehicle |
| **HPDC** | High-Pressure Die Casting |
| **$H_2$-DRI** | Hydrogen-based Direct-Reduced Iron |
| **HVAC** | Heating, Ventilation and Air Conditioning |
| **ICE** | Internal Combustion Engine |
| **ISO** | International Organization for Standardization |
| **LCA** | Life Cycle Assessment |
| **LCI** | Life Cycle Inventory |
| **LCIA** | Life Cycle Impact Assessment |
| **LFP** | Lithium Iron Phosphate |
| **MILP** | Mixed-Integer Linear Programming |
| **MQL** | Minimum Quantity Lubrication |
| **NdFeB** | Neodymium-Iron-Boron (permanent magnet) |
| **NMP** | N-Methyl-2-Pyrrolidone |

| | |
|---|---|
| **OEM** | Original Equipment Manufacturer |
| **ORC** | Organic Rankine Cycle |
| **PCR** | Product Category Rules |
| **PGM** | Platinum Group Metal |
| **PHEV** | Plug-in Hybrid Electric Vehicle |
| **PV** | Photovoltaic |
| **RTO** | Regenerative Thermal Oxidiser |
| **SBTi** | Science Based Targets initiative |
| **SAC** | Spent Automotive Catalyst |
| **SPR** | Self-Piercing Riveting |
| **TES** | Thermal Energy Storage |
| **TRL** | Technology Readiness Level |
| **TWB** | Tailor-Welded Blank |
| **VOC** | Volatile Organic Compound |

CHAPTER 1

# Introduction

## 1.1 Context and motivation

The automotive industry is undergoing the deepest transformation in its history, driven simultaneously by electrification and by an increasingly stringent climate-policy environment. In the European Union, the "Fit for 55" package commits the bloc to a 55 % reduction in greenhouse-gas emissions by 2030 relative to 1990 and, for the automotive sector specifically, requires that all new cars registered from 2035 be zero-emission at the tailpipe [46]. The legal instrument is Regulation (EU) 2019/631, as amended by Regulation (EU) 2023/851. It sets fleet-average $CO_2$ reductions for new cars of 55 % by 2030 and 100 % by 2035, both measured against 2021 [46]. The two figures of 55 % should not be confused: the package's name refers to economy-wide emissions against 1990, while the car target is measured against 2021. A Commission proposal of December 2025, still under negotiation at the time of writing, would lower the 2035 car target to 90 % (Section 3.5) [58]. Manufacturers responsible for fewer than 10 000 new cars registered in the EU per year may apply for a derogation under Article 10 of the regulation until 2035, and the zero-emission requirement reaches them only in 2036; Ferrari falls into this category [58]. This regulatory trajectory has a consequence that is central to this thesis: as the use-phase (tailpipe) emissions of vehicles fall towards zero, the centre of gravity of a vehicle's carbon footprint shifts decisively *upstream*, towards the emissions embodied in its manufacture and, above all, in its materials. McKinsey estimates that material production accounts for about 18 % of vehicles' life-cycle emissions today, and that this share could exceed 60 % by 2040 [16]. The increase is a change in *share*, driven by two effects: battery-electric vehicles, which gain market share, have higher material emissions, and the energy used to drive vehicles is decarbonising.

Two further policy instruments make this shift a matter of direct industrial and economic consequence rather than of reputation alone. The EU Carbon Border Adjustment Mechanism (CBAM), whose definitive regime began in 2026, places a carbon price on the embedded emissions of imported carbon-intensive materials—iron and steel and aluminium among them—turning the carbon content of a vehicle's materials

into a line item in the cost of goods [47]. The EU Battery Regulation, Regulation (EU) 2023/1542, in parallel imposes rising recycled-content and material-recovery obligations, and makes a digital "battery passport" mandatory from February 2027 [19]. Together, these measures mean that the decarbonisation of manufacturing and of the materials supply chain is no longer optional, and that credible, quantified data on embodied emissions has become a competitive necessity.

It is against this background that manufacturing-stage sustainability—the environmental performance of the factory and its supply chain, as distinct from the vehicle in use—acquires its importance. This is the domain of the manufacturing engineer, and it is the subject of this thesis. The work is further situated in the specific industrial context of the Italian "Motor Valley," the Emilia-Romagna cluster of high-performance manufacturers whose small volumes, high vehicle value and intensive use of light metals and composites make the material-emissions question especially acute.

## 1.2 Problem statement and research gap

Despite the growing importance of factory-level sustainability, the literature and public discourse exhibit four gaps that this thesis addresses. First, the academic treatment of automotive sustainability has historically concentrated on the use phase and on tailpipe emissions; the process-level manufacturing perspective—what actually determines the energy and carbon intensity of stamping, painting, battery and assembly operations—is comparatively fragmented and rarely assembled into a single, maturity-aware picture. Second, industrial communication on sustainability mixes audited, quantified data with aspirational and marketing claims, creating a pervasive risk of greenwashing that is difficult to navigate without an explicit reliability discipline. Third, and consequently, the *gap* between what the academic state of the art considers achievable and what industry has actually deployed has not been examined systematically through a common analytical lens. Fourth, both the research literature and corporate reporting have followed the strategic shift towards electrification, so the manufacture of thermal and hybrid powertrains receives far less attention than battery production, even though most vehicles built today still contain an engine.

## 1.3 Research questions and objectives

To address these gaps, the thesis is organised around five research questions:

**RQ1** What is the academic state of the art in sustainable automotive manufacturing, organised by process stage, and how technologically mature is each identified

measure?

**RQ2** What have companies across the automotive value chain—vehicle manufacturers, Tier-1 suppliers and the upstream materials industry—actually deployed, as evidenced by verifiable disclosure?

**RQ3** Where does the gap between academic state of the art and industrial practice lie, and what is its nature?

**RQ4** For the material lever identified as decisive, what is the quantified environmental benefit, demonstrated through a concrete life-cycle case study?

**RQ5** How does the manufacturing footprint differ between thermal, hybrid and battery-electric powertrains, and what does that imply for manufacturers whose output is mixed?

The corresponding objectives are as follows. The first is to build a process-stage taxonomy and a technology-assessment framework, based on Technology Readiness Levels and quantitative metrics, that can be applied consistently to both the academic and the industrial analysis. The second is to establish a strict source-reliability protocol, together with a clear definition of the terms used in corporate climate claims, as a safeguard against greenwashing. The third is to survey and benchmark real industrial practice against the academic state of the art. The fourth is to quantify, through a screening Life Cycle Assessment anchored in the Motor Valley context, the manufacturing-stage carbon benefit of closed-loop recycled aluminium. The fifth is to compare the manufacturing burden of the three powertrain architectures on a common basis.

## 1.4 Scope and delimitations

The thesis addresses *manufacturing-stage* (cradle-to-gate) sustainability, with particular attention to greenhouse-gas emissions and energy. The use phase and end-of-life, although referenced where necessary to frame the life-cycle argument, are outside its scope. Breadth across the whole factory is retained—four process stages and two cross-cutting levers—but is governed by a quantitative framework rather than pursued descriptively, and the quantitative case study is deliberately bounded as a screening assessment. These delimitations are stated in full in Chapter 2.

A further delimitation concerns the vehicle powertrain. It is stated explicitly because it defines how far the results reach.

This thesis is not restricted to battery-electric vehicles. Most of the manufacturing footprint studied here does not depend on the powertrain at all. The body shop, the paint shop, final assembly and the two cross-cutting levers of energy and material

circularity are essentially the same for a combustion, a hybrid or an electric vehicle. They concern the factory and its materials, not the type of drive. The life-cycle case study of Chapter 5 is also powertrain-agnostic, because it examines a structural aluminium component.

Only one stage of the taxonomy depends on the powertrain. That is stage S3, which covers powertrain manufacturing. Chapter 3 therefore divides it into two parts of equal weight. The first, S3a, covers the *thermal* powertrain: the foundry, machining, heat-treatment and exhaust-aftertreatment operations that produce an engine and its driveline. The second, S3b, covers the *electrified* powertrain: battery cells, packs and e-drive components. A third part compares them.

Both branches are treated in full, for two reasons. First, the European $CO_2$ regulation limits *tailpipe* emissions only [46, 58]. The emissions released when *making* an engine fall outside it entirely, so they are neither measured nor reduced by it. Second, combustion and hybrid vehicles will be built in volume for many years, so their manufacture must be decarbonised now. This matters especially for the Motor Valley manufacturers examined in Chapter 4, whose current output is mostly hybrid and high-performance combustion rather than pure battery-electric.

## 1.5 Thesis structure

The remainder of the thesis is organised as follows. **Chapter 2** defines the research methodology: the process-stage taxonomy, the TRL-and-metrics assessment framework, the literature-review protocol, the company-selection and source-reliability procedures, and the framework of the LCA. **Chapter 3** establishes the academic state of the art for each process stage and cross-cutting lever, classifying every technology by maturity and quantified benefit and concluding with a maturity-versus-impact synthesis. **Chapter 4** surveys and benchmarks actual industrial practice across the value chain, constructs a deployment-maturity matrix, and derives the academia–industry gap analysis that is the analytical core of the work. **Chapter 5** develops the quantitative Life Cycle Assessment case study on primary versus closed-loop recycled aluminium, anchored in the Motor Valley context. **Chapter 6** draws the conclusions, answers the research questions, and sets out directions for future work.

CHAPTER 2

# Research Methodology

This chapter describes the methodological framework adopted to answer the research questions stated in Chapter 1. Because the thesis pursues two complementary perspectives—an *academic* assessment of the state of the art in sustainable automotive manufacturing (Chapter 3) and an *industrial* assessment of what companies have already deployed (Chapter 4)—the methodology is designed so that both perspectives are examined through a single, consistent analytical lens. This consistency is what allows the two views to be compared at the end of the work in the form of an academia–industry gap map, and it is what turns an otherwise descriptive review into an analytical contribution. The chapter also defines the framework of the Life Cycle Assessment (LCA) case study presented in Chapter 5 and, importantly, states its limitations explicitly.

## 2.1 Research design

The study follows a mixed, three-stage design. The first stage is a structured literature review that establishes the technological state of the art for each manufacturing process stage and classifies the maturity of each technology. The second stage is a structured industrial benchmarking exercise that maps the same technologies onto a sample of real companies spanning the automotive value chain, using publicly disclosed information filtered through a strict source-reliability protocol. The third stage is a screening LCA that applies the metrics discussed in the previous stages to a concrete, quantified example, thereby demonstrating their operational use rather than merely citing them.

The three stages are bound together by two shared instruments defined in this chapter: a *process-stage taxonomy* (Section 2.2), which provides the common vocabulary used throughout Chapters 3–5, and a *technology-assessment framework* (Section 2.3) based on Technology Readiness Levels (TRLs) and a catalogue of quantitative sustainability metrics. The deliberate re-use of the same taxonomy and the same metric set across the academic and industrial chapters is a methodological choice: it ensures that the gap analysis compares like with like.

## 2.2 Process-stage taxonomy

Sustainability in automotive manufacturing can be organised in several ways—by sustainability pillar, by emission scope, or by process stage. This work adopts a *process-stage* taxonomy because it maps most directly onto the physical reality of a vehicle plant and onto the competences of a manufacturing engineer. Four sequential process stages are complemented by two cross-cutting levers that act simultaneously across all stages. The taxonomy is summarised in Table 2.1 and is applied identically in Chapters 3 and 4.

**Table 2.1.** Process-stage taxonomy and cross-cutting levers used throughout the thesis.

| | **Stage / lever** | **Scope considered in this work** |
|---|---|---|
| S1 | **Stamping & body-in-white** | Sheet forming, blanking, joining and welding of the body structure; associated material yield and scrap flows. |
| S2 | **Paint shop** | Pre-treatment, e-coat, primer, base- and clear-coat application and, in particular, the curing ovens, historically the single largest energy consumer in the plant. |
| S3a | **Thermal powertrain** | Casting of engine blocks and heads, machining, heat treatment, transmission manufacture, engine testing and exhaust aftertreatment. |
| S3b | **Electrified powertrain** | Battery cell and pack manufacturing (electrode, assembly, formation) and e-drive component production. |
| S4 | **Final assembly & intralogistics** | Trim and final assembly operations, in-plant logistics and utility demand not attributable to S1–S3b. |
| L1 | **Energy & utilities management** | On-site generation, electrification of process heat, energy recovery and procurement of low-carbon electricity; cuts across S1–S4. |
| L2 | **Material efficiency & circularity** | Closed-loop material flows, secondary (recycled) materials, scrap reduction and remanufacturing; cuts across S1–S4. |

The two cross-cutting levers, energy management (L1) and material circularity (L2), are treated separately because the technologies that address them—for example on-site photovoltaic generation, or the substitution of primary with recycled metal—are not specific to one process stage but change the footprint of several stages at once. A third enabling dimension, digitalisation (digital twins and data-driven energy optimisation), is discussed within L1 where it acts as an efficiency multiplier rather than as an independent stage.

A point about the powertrain scope of the taxonomy should be made explicit, because it determines how general the results are. Three of the four stages (S1, S2 and S4) and both cross-cutting levers (L1 and L2) are *powertrain-independent*. They describe operations and material flows that are essentially the same whether

the vehicle uses an internal-combustion engine, a hybrid system or a battery-electric drivetrain.

Only stage S3 depends on the powertrain architecture. It is therefore split into two sub-stages of equal weight: **S3a**, the thermal powertrain (foundry, machining, heat treatment, transmission and exhaust aftertreatment), and **S3b**, the electrified powertrain (battery cells, packs and e-drive). Both are assessed in full in Chapter 3, which also compares them. The taxonomy thus covers the whole of current production, and the conclusions of Chapters 3–5 are not confined to battery-electric vehicles. This property is preserved deliberately, and it is revisited in the analysis of the Motor Valley manufacturers, whose output is at present largely hybrid and high-performance combustion.

## 2.3 Technology-assessment framework

Each technology identified in the literature is characterised along two axes: its maturity, expressed as a Technology Readiness Level, and its performance, expressed through one or more quantitative sustainability metrics. Reporting both axes is what distinguishes an assessment from a catalogue: a technology may be attractive on paper (low footprint) yet immature (low TRL), or fully industrialised yet only incrementally beneficial.

### 2.3.1 Technology Readiness Levels

The nine-level TRL scale, originally developed by NASA and adopted by the European Commission for its research framework programmes, is used here in the interpretation summarised in Table 2.2. TRLs are assigned on the basis of the evidence found in the literature and, for the industrial chapter, on the basis of the deployment maturity actually reported by companies (Section 2.5).

**Table 2.2.** Technology Readiness Level (TRL) scale as applied in this thesis.

| **Band** | **Interpretation adopted here** |
|---|---|
| TRL 1–3 | Basic principles and concept: laboratory-scale research; not yet demonstrated in a relevant manufacturing environment. |
| TRL 4–6 | Validation and demonstration: technology validated and demonstrated in a relevant or pilot production environment. |
| TRL 7–9 | Deployment: prototype to full commercial operation in an actual production plant; TRL 9 denotes a mature, industrialised process. |

### 2.3.2 Sustainability metrics

To keep the comparison quantitative, each technology is, wherever the evidence allows, evaluated against the metric catalogue in Table 2.3. The catalogue is intentionally compact and process-oriented; metrics are reported in the units most commonly used in the primary literature to preserve traceability.

**Table 2.3.** Catalogue of quantitative sustainability metrics used in the assessment.

| **Metric** | **Typical unit** | **Primary relevance** |
|---|---|---|
| Energy intensity | kWh per vehicle or per kWh of cell | S2, S3a, S3b, L1 |
| Carbon intensity | kg $CO_2$-eq per vehicle, per kg or per kWh | all stages |
| Embodied energy of material | MJ per kg | S1, L2 |
| Material yield / scrap rate | % | S1, L2 |
| Recycled content | % | L2 |
| Water intensity | L per vehicle | S2 |
| Renewable / low-carbon energy share | % | L1 |

## 2.4 Literature review methodology (academic strand)

The state-of-the-art assessment in Chapter 3 is built on a structured literature review. Peer-reviewed sources were retrieved primarily from Scopus and Web of Science, complemented by Google Scholar for citation tracking and for the identification of very recent pre-prints and conference contributions. Grey literature of a technical nature (standardisation bodies, national laboratories, sector agencies such as the International Energy Agency and the International Aluminium Institute) was admitted only as supporting evidence and always subordinated to peer-reviewed findings.

Search strings were constructed for each process stage by combining a process descriptor with a sustainability descriptor and a manufacturing qualifier. Representative strings include, for the paint shop, `("paint shop" OR "curing oven") AND (energy OR decarboni?ation) AND automotive`; for battery manufacturing, `("electrode" OR "cell manufacturing") AND ("energy consumption" OR "carbon footprint") AND ("dry coating" OR solvent)`; and, for the circularity lever, `(aluminium OR steel) AND ("closed-loop" OR recycled) AND automotive AND (LCA OR "carbon footprint")`. Retrieved records were screened in two passes—title/abstract, then full text—against explicit inclusion criteria: relevance to factory-level (as opposed to tailpipe) sustainability, presence of a

quantitative result or a clearly defined technology, and, as a rule, publication from 2015 onwards, with seminal earlier works retained where still authoritative.

## 2.5 Company selection and industrial benchmarking (industrial strand)

### 2.5.1 Sampling of companies

The benchmarking sample in Chapter 4 is designed to represent the automotive value chain rather than a single tier. It therefore spans three groups: vehicle manufacturers (OEMs), Tier-1 suppliers, and the upstream materials industry (steel, aluminium, battery and catalyst-metal producers). Companies were selected purposively against five criteria. The first is the materiality of their manufacturing operations to the sustainability question. The second is the availability of quantitative, verifiable public disclosure. The third is coverage of the process stages and levers of the taxonomy. The fourth, added so that the sample matches the powertrain scope of Section 2.2, is coverage of *both* powertrain branches: the sample must include producers of thermal powertrains and their catalyst metals (S3a) as well as of battery and e-drive components (S3b). The fifth is the inclusion of at least two Italian "Motor Valley" manufacturers, in keeping with the industrial focus of the work. The sample is not statistically representative and does not aim to be. It is an evidence-driven selection whose only purpose is to populate the taxonomy with real, documented practice.

### 2.5.2 Source-reliability hierarchy

The central methodological risk in the industrial strand is that corporate communication on sustainability mixes audited data with marketing. To guard against this, every claim admitted into the benchmarking is graded according to the reliability hierarchy in Table 2.4. A claim is retained only if it is quantified and, ideally, independently verifiable; unquantified or purely aspirational statements are excluded or, where contextually necessary, flagged explicitly as such. This protocol is the principal safeguard of the thesis against greenwashing and is the reason the industrial findings can be placed alongside peer-reviewed evidence. The hierarchy applies to sustainability claims. Ordinary business figures, such as shipment or delivery volumes, are used only to describe the industrial context and are taken as reported.

**Table 2.4.** Source-reliability hierarchy applied to industrial (corporate) data.

| Tier | Source type | Treatment |
|---|---|---|
| A | Third-party verified data: audited financial/ESG filings, ISO 14040/14044 critically reviewed LCAs, SBTi-validated targets, verified disclosure (e.g. CDP). | Admitted as primary quantitative evidence. |
| B | Company sustainability reports and environmental statements with quantified figures and stated methodology. | Admitted; cross-checked against Tier A where possible. |
| C | Corporate technical pages and supplier documentation with specific figures. | Admitted with attribution; used mainly for qualitative deployment evidence. |
| D | Press releases and marketing material. | Not admitted as quantitative evidence; used only to establish existence of a programme. |

### 2.5.3 Benchmarking matrix and deployment maturity

Evidence surviving the reliability filter is organised into a benchmarking matrix whose rows are companies and whose columns are the taxonomy stages and levers. Each cell records the maturity of deployment on the ordinal scale of Table 2.5. This ordinal coding, applied uniformly, is what makes the final academia–industry gap map possible: for each technology the industrial deployment level can be read against the TRL claimed in the literature, and the difference—if any—localised.

**Table 2.5.** Deployment-maturity scale used in the benchmarking matrix.

| Level | Meaning |
|---|---|
| None / n.d. | No public evidence of adoption, or not disclosed. |
| Announced | Publicly committed target or pilot announced, not yet operational. |
| Piloted | Operational at pilot or single-line scale. |
| Deployed | Operational in serial production at one or more sites. |
| Standard | Adopted as the plant-wide or company-wide standard. |

## 2.6 The vocabulary of climate claims

The reliability hierarchy grades *who* makes a claim and how well it is supported. A second problem remains: the words themselves. “Carbon neutral”, “climate neutral”, “net zero” and “$CO_2$-free” are not synonyms, are often left undefined, and can describe very different physical realities. Because a central finding of this thesis (Section 4.5) depends on these differences, the terms are defined here and used consistently in Chapters 4 to 6.

### 2.6.1 Emission scopes and the accounting boundary

Corporate claims follow the three scopes of the GHG Protocol [54]. *Scope 1* covers direct emissions from sources the company owns or controls; in a vehicle plant these are mainly natural gas burnt in paint-shop ovens, foundry furnaces and heat-treatment lines. *Scope 2* covers purchased energy, above all electricity. *Scope 3* covers the rest of the value chain; for a vehicle manufacturer it is by far the largest category, dominated by purchased materials upstream and by the use phase downstream.

A neutrality claim means little without its boundary. A claim that a company's *plants* are carbon neutral covers Scopes 1 and 2 only: it says nothing about the steel, aluminium and battery cells that may make up most of the vehicle's manufacturing footprint. This thesis therefore records which scopes each claim covers, and treats claims limited to Scopes 1 and 2 as partial.

Scope 2 can be reported in two ways [54]. The *location-based* figure uses the average carbon intensity of the grid that supplies the plant. The *market-based* figure uses the contracts the company has bought, such as guarantees of origin, renewable energy certificates or power purchase agreements, and can fall almost to zero while the electricity physically entering the plant is unchanged. Both are legitimate, but they answer different questions, and a "100% renewable electricity" claim is almost always market-based. Where the method is not stated, this thesis records it as a limitation.

### 2.6.2 Reduction, compensation and neutralisation

The key distinction is between emissions that are *not emitted* and emissions that are emitted and then *accounted for elsewhere*.

*Reduction* (or abatement) means that the emission does not happen: an electric oven on low-carbon power, a lower cure temperature, or recycled instead of primary metal. It changes the factory or the supply chain, and it is the subject of Chapters 3 and 4.

*Compensation* (or offsetting) means that the emission does happen and is balanced by buying credits for reductions or removals outside the company's value chain. *Avoidance* credits claim that an emission elsewhere was prevented, for example a forest that was not felled; *removal* credits claim that carbon was taken out of the atmosphere and stored, biologically or geologically, with very different durability. A credit is only as good as its additionality (would it have happened anyway?), its permanence (how long is the carbon stored?), its baseline and the absence of double counting. These points are contested, and voluntary carbon markets have well-documented quality problems.

*Neutralisation*, as used by the Science Based Targets initiative (SBTi), is narrower: only the small residual left after deep reduction is balanced, and only with permanent removals [55].

### 2.6.3 "Carbon neutral" versus "net zero"

The two terms are often used interchangeably, but the standards that define them differ.

*Carbon neutrality* (ISO 14068-1) means that the emissions of a defined subject, such as an organisation, a site or a product, over a defined period are balanced to zero within a stated boundary, through reduction and offsetting of the remainder [56]. It describes a *balance*, not a depth of reduction: a subject could be carbon neutral with little physical abatement and a large amount of purchased compensation.

*Net zero* (SBTi Corporate Net-Zero Standard) is much more demanding. It requires an absolute reduction of about 90 % to 95 % across all scopes against a base year, on a path consistent with limiting warming to 1.5 °C. Only the unavoidable residual may then be neutralised, and only with permanent removals [55]. Net zero is therefore mainly a statement about *reduction*.

In practice, "carbon neutral since year X" and "net zero by year Y" describe different achievements, and only the second says anything about how much physical decarbonisation has taken place.

### 2.6.4 Physical versus contractual material claims

The same distinction applies to materials, and Chapter 4 meets it in the steel and aluminium supply chain. A *physical* claim means that the metal in the vehicle was itself made by a low-carbon route: hydrogen-reduced iron, renewable-powered smelting or high recycled content. A *book-and-claim* or *mass-balance* claim means that low-carbon production somewhere in the producer's system has been allocated to the purchase by contract, while the metal delivered may come from a conventional route. Both can be audited and both help finance the transition, but only the first changes what is physically in the car. This thesis records which type a claim is whenever the disclosure allows.

### 2.6.5 The regulatory turn against offset-based claims

This distinction now has legal weight. Directive (EU) 2024/825 on empowering consumers for the green transition amends the Unfair Commercial Practices Directive. From 27 September 2026 it prohibits, in communication to consumers, any claim that

a product has a neutral, reduced or positive greenhouse-gas impact when the claim rests on offsetting emissions *outside the product's value chain*. Formulations such as "climate neutral", "$CO_2$ neutral certified" and "climate compensated" are named explicitly [57]. A product-level claim remains possible only if it reflects the actual life-cycle impact achieved through reductions within the value chain, and it must be substantiated.

Two consequences follow for this work. The distinction used here, between reduction inside the boundary and compensation outside it, is the one that regulation now draws. And some of the claims surveyed in Chapter 4, current at the time of writing, rest on a basis that European law is closing off for consumer communication.

### 2.6.6 The convention adopted in this thesis

Table 2.6 summarises the terms. Chapters 4 to 6 apply one rule: **the metric of interest is the absolute, offset-free emission attributable to manufacturing, per vehicle or per kilogram of product, within a stated scope boundary.** Compensation is recorded where companies disclose it; it is neither dismissed as illegitimate nor counted as physical decarbonisation. Where a claim cannot be split into reduction and compensation from public information, that opacity is itself reported as a finding.

## 2.7 LCA case study methodology

Chapter 5 develops a screening Life Cycle Assessment conducted in accordance with the principles of ISO 14040 and ISO 14044. These are the two international standards that govern life-cycle assessment, and they play complementary roles. **ISO 14040** sets out the principles and framework: it defines what an LCA is and divides it into four phases, namely the definition of goal and scope, the life cycle *inventory* of inputs and outputs, the life cycle *impact assessment* that converts those flows into environmental indicators, and the *interpretation* of the results [1]. **ISO 14044** sets out the requirements and guidelines, that is the rules for actually carrying the study out: how to draw the system boundary, how to judge data quality, how to allocate impacts when one process yields several products, and what independent critical review is required before a comparative assertion may be published [2]. The distinction matters for this thesis in one specific way. A study may follow the *principles* of both standards, as the present one does, without meeting the full requirements of ISO 14044 for a publicly disclosed comparative claim, which demands primary data and an external critical review panel. That is exactly the difference between the

**Table 2.6.** Terminology of climate claims as defined and applied in this thesis.

| **Term** | **Meaning adopted here** |
|---|---|
| Scope 1 | Direct emissions from owned or controlled sources (e.g. gas-fired ovens and furnaces). |
| Scope 2 | Indirect emissions from purchased energy; reportable location-based (physical grid) or market-based (contractual instruments). |
| Scope 3 | All other value-chain emissions; for vehicle manufacturing, dominated by purchased materials. |
| Reduction / abatement | The physical emission does not occur. Changes the factory or the supply chain. |
| Compensation / offsetting | The emission occurs and is balanced by credits from outside the value chain; avoidance and removal credits differ in durability. |
| Neutralisation | Counterbalancing of the residual only, after deep reduction, using permanent removals (SBTi sense). |
| Carbon neutral | A balance to zero within a stated boundary, reduction plus offsetting (ISO 14068-1). Implies no particular depth of reduction. |
| Net zero | Deep absolute reduction (∼90–95%) across all scopes, residual neutralised by permanent removals (SBTi Corporate Net-Zero Standard). |
| Physical material claim | The metal in the product was itself made by the low-carbon route. |
| Book-and-claim / mass balance | Low-carbon production is contractually allocated to the purchase; physical metal may differ. |

screening assessment presented here and a certified comparative LCA.

The goal of the assessment is to quantify, and to make transparent, the manufacturing-stage carbon benefit of substituting primary with closed-loop recycled aluminium in a representative structural component, using an Italian Motor Valley manufacturer as the anchoring context. The scope of the assessment is summarised in Table 2.7.

**Table 2.7.** Goal and scope summary of the LCA case study (Chapter 5).

| **Element** | **Definition adopted** |
|---|---|
| Goal | Quantify the cradle-to-gate GWP difference between primary and closed-loop recycled aluminium for a representative structural component. |
| Functional unit | One finished structural aluminium component of defined mass; results per kg. |
| System boundary | Cradle-to-gate: raw-material production, semi-fabrication and component manufacturing; use and end-of-life excluded. |
| Impact category | Global Warming Potential (GWP), kg $CO_2$-eq. |
| Foreground data | Company-disclosed plant energy mix and process information (Tier A/B). |
| Background data | Published, ISO-consistent emission factors for primary and secondary aluminium. |
| Benchmark | An externally certified, ISO 14040/14044 vehicle LCA from the Motor Valley segment, used to sense-check order of magnitude. |

Two points of methodological honesty must be stated at the outset. First, the assessment is deliberately labelled a *screening* LCA. A full, ISO-compliant comparative LCA intended for public comparative assertion requires primary, process-level inventory data that manufacturers do not publish in full; the present study therefore combines company-disclosed data as foreground context with secondary emission factors from the peer-reviewed literature and recognised databases for the life-cycle inventory. Second, the choice of the anchoring company and of the functional unit is driven by data availability, not by brand. The analysis is built so that its conclusions rest on transparent, cited emission factors and a clearly bounded system. They therefore remain valid as order-of-magnitude findings even under the uncertainty inherent in secondary data.

## 2.8 Limitations and validity

The methodology carries limitations that are acknowledged so that the findings can be read with the appropriate caution. The literature review, although structured, is not a formal meta-analysis and does not attempt statistical synthesis. The industrial

benchmarking depends on the completeness and honesty of corporate disclosure; the reliability hierarchy mitigates but cannot eliminate this dependence, and absence of evidence is recorded as such rather than interpreted as absence of practice. The LCA is a screening study bounded as described above. These limitations are revisited in Chapter 6 alongside the corresponding recommendations for further work.

CHAPTER 3

# State of the Art in Sustainable Manufacturing

This chapter establishes the academic state of the art. It surveys, for each stage and cross-cutting lever of the taxonomy defined in Chapter 2, the technologies that reduce the environmental footprint of vehicle manufacturing, and it classifies each of them by Technology Readiness Level (TRL) and by the quantitative metrics introduced in Section 2.3. The purpose is not encyclopaedic coverage but a structured, comparable picture that can later be set against actual industrial practice (Chapter 4) to reveal where theory and deployment diverge.

## 3.1 The energy and emissions anatomy of a vehicle plant

Before examining individual stages it is useful to fix the order of magnitude of the problem. The literature reports between about 700 kWh and 1290 kWh of energy per vehicle for a car assembly plant [3, 71, 4, 74, 72, 73]. The range is wide because plants are not all alike: they differ in size, product and climate, and they do not all carry out the same operations. It should therefore be read as an order of magnitude, not as a benchmark, and the same applies to the paint-shop shares given below. Energy typically represents 9 % to 12 % of production cost, so its reduction is pursued for economic as well as environmental reasons [72].

These values refer to the final assembly plant: body-in-white, painting and final assembly, with their utilities. They exclude powertrain manufacturing, because the foundries, machining lines and heat-treatment furnaces of Section 3.5.1 are usually separate facilities with much higher specific energy use. The standard energy-per-vehicle figure therefore says nothing about engine manufacturing, which is one reason why the thermal-powertrain blind spot of Chapter 4 is easy to overlook.

Within the plant, the distribution of energy use across process areas is markedly uneven, and this unevenness dictates where decarbonisation effort is best spent. The paint shop is consistently identified as the dominant consumer: it accounts for ap-

proximately 65 % of a plant's $CO_2$ emissions and is the single largest consumer of energy (below but close to 50 % of the total), water (above 40 %) and solvents (above 80 %) [5, 8]. In several German plants, paint shops alone have been reported to use 50 % to 60 % of the fuel consumed on site, essentially for heating, air conditioning of process air and thermal oxidation of volatile organic compounds. By contrast, the body shop, although electricity-intensive in its welding operations—resistance spot welding of a single body-in-white can require on the order of 90 kWh to 97 kWh—represents a smaller share of the total, and final assembly, being largely mechanical and manual, is the least energy-dense of the four stages. This anatomy is the reason the taxonomy weights the paint shop and the (increasingly important) battery stage so heavily in the discussion that follows.

A second structural observation concerns emission scopes. Direct (Scope 1) and purchased-energy (Scope 2) emissions of a modern vehicle plant are dominated by the thermal and electrical demand described above, and are therefore addressable through the process technologies and the energy lever discussed in this chapter. However, for most manufacturers the overwhelming majority of value-chain emissions is embodied in purchased materials and components (Scope 3), which is why the material-efficiency and circularity lever, and in particular the decarbonisation of steel, aluminium and battery cells, is treated here as a manufacturing concern and not merely a procurement one.

## 3.2 Review scope and evidence base

The evidence surveyed below was retrieved and screened following the structured procedure of Section 2.4. Peer-reviewed literature provides the assessment of maturity and of quantified performance; technical and standardisation sources are used to corroborate. Throughout, each technology is discussed in terms of *what problem it addresses*, *how mature it is*, and *what quantified benefit the literature attributes to it*, so that the closing synthesis (Section 3.10) can tabulate all technologies on a common TRL-and-metric basis.

## 3.3 Stage S1 — Stamping and body-in-white

The body shop turns coil and blanks into the vehicle's structural shell through forming, blanking and joining. Its footprint depends on two coupled factors: the electricity used by presses and joining equipment and, more significantly over the life cycle, the mass and type of material in the structure, which determine both the embodied emissions and the use-phase energy.

On the *process* side, the state of the art is mature. Servo-mechanical and servo-hydraulic presses tailor the stroke profile to the part, recover energy during deceleration and cut idle consumption; energy-oriented press control and the elimination of compressed-air waste are established measures. Better blank nesting and coil-line optimisation raise material yield and so reduce the scrap fraction, which is substantial in the body shop. These measures are incremental but well industrialised (TRL 8–9).

On the *material* side, the main lever is lightweighting: replacing mild steel with advanced high-strength steels (AHSS), aluminium and, in high-performance vehicles, carbon-fibre-reinforced polymers (CFRP). Lightweighting reduces use-phase energy but shifts, and often increases, embodied emissions, because aluminium and CFRP are much more energy-intensive to produce than steel. Its net benefit is therefore realised only together with the circularity measures of Section 3.8. Mixed-material bodies cannot be joined by resistance spot welding alone; they rely on cold and hybrid joining—self-piercing riveting, flow-drill screwing, structural adhesive bonding and laser welding—which is fully industrialised (TRL 9) in premium and volume production alike.

*Hot stamping* (press hardening) is a further mature but energy-relevant steel technology. A boron-alloyed blank, typically 22MnB5, is heated above its austenitisation temperature (around 900 °C) and then formed and quenched in a cooled die, giving components of about 1500 MPa that allow thinner, lighter structures with high crash performance [49]. Combined with *tailor-welded blanks*, in which press-hardening steel is laser-welded to a more ductile grade so that one part has hard, intrusion-resistant zones and softer, energy-absorbing zones, it is a cornerstone of lightweight body design. It is also a small version of the S1 trade-off: it reduces mass and hence use-phase energy, but the austenitisation furnace and the laser trimming make it more energy-intensive per part than cold forming. Its net benefit depends on the carbon intensity of the steel and of the electricity used.

In high-performance and luxury vehicles, typical of the Italian "Motor Valley", CFRP is used for monocoques and body panels. It gives the largest mass reductions but has the highest embodied energy of the common structural materials, because producing carbon fibre from its polymer precursor is extremely energy-intensive, and it is currently less recyclable than metals. CFRP is therefore the clearest case of the general S1 rule: a material that is advantageous in use can dominate the manufacturing footprint, and assessing it requires the life-cycle perspective of Chapter 5.

**Gigacasting: process consolidation and its carbon paradox.** *Gigacasting* (also megacasting or integrated die casting) uses very large high-pressure die-casting (HPDC) machines to produce single structural castings that replace dozens of

stamped and welded parts [20, 21]. Locking forces of 6000 t to 9000 t (up to about 92 000 kN) inject more than 200 kg of liquid aluminium into a die within milliseconds, and the largest machines now exceed 16 000 t [22, 21]. The pioneering application, a single rear-underbody casting that replaced some seventy parts, removed the related welding energy and quality operations and much of the scrap, and a single-alloy casting is easy to recycle. Gigacasting, however, carries a *carbon paradox* that is central to this thesis. Aluminium body *sheet* already has high recycled content, but structural die castings have traditionally been made from carbon-intensive *primary* alloys, so the net climate benefit depends on raising the recycled content of the casting alloy [21]. The process is mature (TRL 8–9) but not universally adopted, since its economics favour high volumes per die, and its sustainability case is conditional rather than automatic. It therefore links the process (S1) and material-circularity (L2) discussions.

Methodologically, S1 emissions are increasingly quantified with material-flow and energy-flow models of the body shop, which sum the energy of each forming and joining operation along the production route and, in recent work, predict it with data-driven (e.g. machine-learning) models. These models make the scrap fraction an explicit variable, which matters because less scrap lowers both process energy and the demand for carbon-intensive primary metal. The manufacturing-engineering conclusion is that S1 process emissions are largely a solved, incremental problem, whereas its material emissions are large, unavoidable at the body-shop boundary, and can only be reduced upstream (L2).

## 3.4 Stage S2 — Paint shop

The paint shop is the main battleground of plant decarbonisation, for the reasons quantified in Section 3.1. It uses energy in two places: the spray booths, whose large air flows must be heated, cooled and humidity-controlled, and the curing ovens, which must reach and hold high temperatures to cross-link the coatings. The state of the art addresses both.

**Overspray capture.** *Dry* separation systems capture overspray on cardboard or limestone-protected filters instead of in a water curtain. This removes the need to condition large volumes of scrubber water and recirculate booth air, cutting energy use and $CO_2$ emissions. Dry scrubbing is mature and widely deployed (TRL 9).

**Low-temperature and reduced-stage coatings.** The largest single opportunity is in the curing ovens. Low-cure clearcoats cross-link at markedly lower temperatures:

one supplier's technology cures at about 80 °C instead of about 140 °C, reducing the related energy use by up to 39 % [7]. Reduced-stage "wet-on-wet" processes remove intermediate bake steps altogether; the integrated multi-layer wet process being rolled out across a major manufacturer's plants is credited with up to 30 % energy saving per vehicle and a target of 321 kWh per vehicle [6]. Both are at the deploying end of maturity (TRL 8–9). The same principle, a lower oven temperature, is the coating innovation later documented in the industrial case study.

The size of the prize is clearest in absolute terms. Analyses by the Warwick Manufacturing Group, based on figures first published by General Motors, attribute more than 43 % of the toxic emissions of the whole manufacturing process to painting, and estimate that a conventional paint shop running at sixty vehicles per hour emits several hundred tonnes of $CO_2$ per day [8]. Against baselines of this size, the percentage savings above become large absolute reductions.

**Curing technology beyond convection.** Infrared and ultraviolet curing heat the coating directly rather than the surrounding air, shortening cure times and shrinking the dryer. Electrostatic application, in which charged paint droplets are attracted to the earthed body, raises transfer efficiency and reduces both overspray and the energy needed to capture it. These technologies are established but applied selectively, depending on body geometry and coating chemistry.

**Overspray-free application and the fully electric paint shop.** The most advanced commercial concepts combine these levers in an integrated, electrified system. Inside-out electric drying, which ducts hot air to heat the body from within, reaches the heavy reinforced sections of an electric-vehicle body more directly and cuts heating time by up to 30 % [48]. Coupling an electric oven to an *electric* regenerative thermal oxidiser removes a further fossil load: the oxidiser destroys the volatile organic compounds in the exhaust without an open flame, sustaining its temperature from the energy released by solvent oxidation. Running such a system on green electricity has been credited with cutting paint-shop $CO_2$ by about 40 % compared with a natural-gas shop [48]. *Overspray-free* application, in which a jet applicator puts paint only where needed, removes overspray separation and, for two-tone bodies, masking; it is credited with energy savings of up to 32 % across the painting line and up to 33 kg less $CO_2$ per body [48]. These technologies are at the deploying end of maturity (TRL 7–9) and embody the electrification-and-efficiency agenda at the highest-impact stage.

**Air management, electrification and digital control.** Recovering and recirculating booth exhaust air, linking booths to demand-controlled air-supply units and reducing oven airflow during downtime give further cost-effective savings. Digitalisation helps too: in-line optical inspection of coating thickness achieves the correct film build on the first pass, avoiding energy-wasteful rework, with reported savings of tens of kilowatt-hours per vehicle at plant scale; multi-objective optimisation of the coating line, balancing material, energy and emission flows, has been demonstrated in research. Looking forward, the complete electrification of paint-shop heat (replacing natural-gas burners with electric or heat-pump systems) is the pathway that finally removes Scope 1 emissions from the paint shop. It depends on low-carbon electricity. It is already in series production at a few plants, including a new fossil-free plant (Chapter 4), but the conversion of existing gas-fired paint shops is not yet documented; its maturity band is therefore TRL 7–9. The cumulative effect of a systemic paint-shop programme is illustrated by plants reporting reductions since 2010 of about 70 % in emissions, 55 % in water use and 78 % in waste.

## 3.5 Stage S3 — Powertrain manufacturing

Stage S3 is the only stage of the taxonomy whose content depends on the vehicle's powertrain architecture, and it is therefore treated here in two parallel parts of equal weight. Section 3.5.1 addresses the *thermal* powertrain—the foundry, machining, heat-treatment, transmission and exhaust-aftertreatment operations that produce an internal-combustion engine and its driveline. Section 3.5.2 addresses the *electrified* powertrain—battery cell and pack manufacturing and e-drive components. Section 3.5.3 then compares the two and examines the case that matters most for the manufacturers studied in this thesis: the hybrid, which carries both.

Treating the thermal branch in full is not a historical courtesy. Two considerations make it a live manufacturing-engineering problem. First, the European $CO_2$ regulation and its pending revision govern *tailpipe* emissions only [46, 58]. The emissions released in *making* an engine lie entirely outside that instrument, so they are neither measured nor reduced by it. Second, thermal and hybrid powertrains will be built in volume for many years. The Commission's December 2025 proposal would lower the 2035 target from a 100% to a 90% reduction. It would also allow plug-in hybrids, range extenders, mild hybrids and combustion vehicles to be registered after that date [58]. Small-volume manufacturers, those with fewer than 10 000 new EU registrations per year, can hold derogations that run to 2035, and the zero-emission requirement reaches them only in 2036. Ferrari falls into this category (Section 1.1). Whatever the outcome of that legislative process, the engines and transmissions built

in the intervening years carry a manufacturing footprint. That footprint is precisely what this thesis is about.

### 3.5.1 S3a — The thermal powertrain

Manufacturing an internal-combustion powertrain is dominated by high-temperature metallurgy and precision machining, and its material burden is concentrated in a few grams of very carbon-intensive catalyst metals. A study by the European Commission's Joint Research Centre puts the global-warming impact of a new internal-combustion engine at about 0.7 t of $CO_2$-eq on average: 69 % from materials, 24 % from manufacturing energy and 7 % from end-of-life shredding, so the cradle-to-gate part is about 0.65 t [64]. The figure covers the engine only; the transmission and the exhaust aftertreatment come on top. The pattern is the one found throughout this thesis: the material term dominates, while the smaller process term is the one the plant controls directly.

**Foundry: melting as the dominant process load.** Cylinder blocks, heads and housings are cast, and melting is the most energy-intensive operation in a cast house, typically 60 % to 75 % of a remelter's fuel and power budget [59]. The thermodynamic floor is well defined: heating aluminium from ambient to about 750 °C needs roughly $0.183\,\mathrm{kW\,h\,kg^{-1}}$, and the latent heat of fusion a further $0.108\,\mathrm{kW\,h\,kg^{-1}}$, giving a theoretical minimum of about $290\,\mathrm{kW\,h\,t^{-1}}$ to $330\,\mathrm{kW\,h\,t^{-1}}$. Real furnaces sit well above it, and the spread is the efficiency opportunity: an ageing single-pass reverberatory furnace with cold combustion air uses $700\,\mathrm{kW\,h\,t^{-1}}$ to $1100\,\mathrm{kW\,h\,t^{-1}}$, a modern shaft or well-tuned rotary furnace with heat recovery $500\,\mathrm{kW\,h\,t^{-1}}$ to $650\,\mathrm{kW\,h\,t^{-1}}$, and the best shaft designs have reached $489\,\mathrm{kW\,h\,t^{-1}}$ [59]. The shaft furnace works by counter-flow preheating: the exhaust gas leaving the melt warms the cold charge descending the shaft, recovering heat that a reverberatory furnace sends to the stack. Complementary levers are regenerative and low-$NO_x$ burners, charge preparation (dry, preheated, clean scrap), closed holding and dosing of liquid metal, and electrification of melting by induction or resistance heating, which is the pathway that finally removes Scope 1 emissions from the foundry. A second, less visible loss is metallurgical: oxidation and dross destroy 2 % to 5 % of the metal charged in a reverberatory furnace. That metal must be replaced by new primary or secondary aluminium, so melt loss is at once an energy, a cost and an embodied-carbon penalty. Efficient melting is mature (TRL 8–9); its diffusion, not its existence, is the constraint.

**Machining: the periphery, not the cut.** Blocks, heads, crankshafts and gears are then machined to tolerance. The machining-energy literature reports a counter-

intuitive central finding: the cutting itself takes only a small fraction of a machine tool's electricity. Most goes to peripheral and constant loads such as hydraulics, coolant pumps, chip conveyors, controls and standby. Energy must therefore be measured *per part* rather than per unit of material removed, and reducing non-productive time can matter more than optimising cutting parameters [60]. This framing, set by the early analyses of the environmental burden of machining and later extended to the embodied energy of cutting tools, makes machining energy a variable of the manufacturing system rather than a fixed physical constant.

The second axis is the cutting fluid. Flood cooling gives the best surface integrity but carries a substantial burden: mineral-oil emulsions need preparation, filtration, chilling and disposal, and pose a documented occupational-health issue. The state of the art is a ladder of decreasing fluid use: minimum quantity lubrication (MQL), MQL with vegetable-oil or nanoparticle-enhanced fluids, electrostatic MQL, cryogenic cooling with liquid nitrogen or carbon dioxide, and fully dry machining. Comparative life-cycle studies show that MQL has a markedly smaller carbon footprint than flood cooling, because it almost eliminates both fluid consumption and the related pumping energy [61]. The trade-off is real and process-specific: dry and near-dry machining can accelerate tool wear or worsen surface finish on difficult materials, so the choice is an engineering optimisation rather than a uniform substitution. These techniques are industrially mature (TRL 8–9) but unevenly adopted.

**Heat treatment, transmission and testing.** Crankshafts, camshafts and gears are case-hardened by carburising and quenching, with long furnace residence times under controlled atmospheres and therefore high specific energy use. The levers are the same as in the foundry and the paint shop: waste-heat recovery, better insulation and control, and progressive electrification of furnace heat (TRL 6–8, depending on temperature). Gear cutting, grinding and finishing add further machining load, to which the reasoning above applies. Finally, every engine is tested at the end of the line. *Cold* testing motors the engine electrically to verify assembly integrity; *hot* testing fires it on fuel. The choice is an energy and emissions decision in itself: cold testing avoids fuel combustion and its exhaust altogether, and regenerative test benches can recover part of the energy used.

**Exhaust aftertreatment: a small mass with a very large footprint.** The most distinctive material feature of the thermal powertrain is the catalytic converter. A three-way catalyst is a cordierite honeycomb carrying an alumina washcoat with platinum-group metals (PGMs): platinum and palladium oxidise carbon monoxide and unburnt hydrocarbons, while rhodium reduces nitrogen oxides. The quantities

are small, typically 2 g to 6 g of PGM in a passenger-car converter and 6 g to 30 g in larger vehicles, but their embodied carbon is extraordinary. Industry life-cycle data place primary platinum at tens of kilograms of $CO_2$-eq *per gram*, with palladium somewhat lower. The intensity is driven mainly by the coal-based electricity used in South African mining, beneficiation and smelting, which accounts for roughly 57 % of platinum's total emissions [62]. On these assumptions, the catalyst PGMs of a single vehicle embody an order-of-magnitude *one to two hundred kilograms of $CO_2$-eq*: a burden comparable to a substantial share of the rest of the powertrain's manufacture, concentrated in a few grams of material.

This is the thermal powertrain's analogue of the battery's cathode metals, and, as with the battery, the decisive lever is circularity. Recycled PGM has a footprint roughly two orders of magnitude below primary metal, and the recycling route is mature and thermodynamically favoured. A spent automotive catalyst assays at about 2000 g of PGM per tonne, against under $10\,\mathrm{g\,t^{-1}}$ in natural ore, so recovery uses about 90 % less energy than mining. Established processes recover more than 95 % of the contained metal, and more than 99 % for ceramic substrates [62, 63]. Two qualifications matter. First, metal-foil substrates are harder to process, with recovery nearer 80 %. Second, and more important, the *process* recovery rate is not the *system* collection rate: PGMs are abraded and lost to road dust during the catalyst's life, and converters that are never collected cannot be recycled at any efficiency. Since catalytic converters account for roughly 80 % of global PGM demand, and PGMs are EU critical raw materials, closing this loop is a supply-security question as much as a climate one.

**Reading of S3a.** The thermal powertrain is a mature manufacturing system whose remaining headroom lies in two places: the electrification and heat-recovery retrofit of its high-temperature processes (foundry and heat-treatment furnaces, the Scope 1 core of an engine plant), and the circularity of its catalyst metals, where the technology is mature and the constraint is collection. Neither is a research frontier; both are diffusion problems. This places S3a closer to S1 than to S3b on the maturity–impact map of Section 3.10.

### 3.5.2 S3b — The electrified powertrain

Electrification has shifted the centre of gravity of manufacturing emissions. In a battery-electric vehicle the battery is, for many models, the largest single contributor to cradle-to-gate emissions, and cell manufacturing is itself very energy-intensive. A detailed inventory of a research cell factory planned in Germany, with a theoretical output of 7 GWh per year, finds that three steps dominate: coating and drying,

formation, and the dry rooms together account for 76 % of the factory's energy use and 74 % of its greenhouse-gas emissions [9]. Cradle-to-gate, including the materials, current lithium-ion cells emit about 58 to 92 kg $CO_2$-eq per kWh of cell capacity, depending on chemistry and electrode design. The same study finds that optimised cell designs and production could cut this by up to 38 % in the short term, to about 37 kg $CO_2$-eq per kWh for LFP cells and 44 for NMC900 cells [10]. An earlier review by IVL gives 61 to 106 kg $CO_2$-eq per kWh at battery level [11]. Figure 3.1 summarises these values. At these values, the cells of a 60 kWh battery alone embody about 3.5 t to 5.5 t of $CO_2$-eq.

One of the dominant steps is electrode drying. Conventional wet processing coats a solvent-borne slurry, typically with N-methyl-2-pyrrolidone (NMP) for the cathode, which must then be driven off in long, gas-fired ovens and recovered. The state of the art targets this step directly:

- **Dry electrode coating** deposits a dry powder mix and consolidates it under heat and pressure, eliminating the solvent and the drying oven. Its benefit is therefore large at the level of the electrode line, but smaller at the level of the whole battery: a cradle-to-grave life cycle assessment of a 42 kWh NMC622 pack finds 4.8 % lower energy use and up to 47.5 % lower impacts in 12 of 13 impact categories [34]. The technology is still industrialising (TRL 6–8).
- **Electrification of drying** and the substitution of NMP with water-soluble binders reduce the emissions of the conventional wet route without abandoning it (TRL 6–7).
- **Low-carbon electricity supply** to the whole process is the most immediately available lever. In the factory study cited above, running the plant on electricity only, from the Swedish grid, would cut the emissions of cell production from 4.54 to 0.53 kg $CO_2$-eq per kWh of cell capacity [9]. These are factory emissions only; the materials are not included.

Two further points refine this picture. First, as the factory study shows, cell-manufacturing emissions are highly sensitive to the carbon intensity of the energy used: a cell made with decarbonised power is, in footprint terms, a different product from one made with coal-based power, even before any process innovation. Second, the cell *formation* and aging steps, the controlled first charge and discharge cycles that condition the cell, are time- and energy-intensive, and faster protocols and better scheduling are an active efficiency frontier.

**The dry room: the paint shop of the gigafactory.** A second, often-overlooked driver is the ultra-dry production environment. Electrode coating, calendering, cell assembly and electrolyte filling must take place at dew points between −40 and

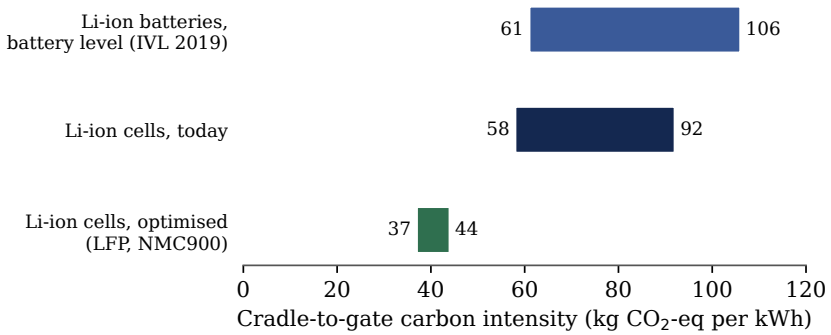



**Figure 3.1.** Cradle-to-gate carbon intensity of lithium-ion cells today and with optimised design and production (LFP and NMC900 cells) [10], and of lithium-ion batteries at battery level [11].

−65 °C, a relative humidity far below one percent, because tiny amounts of moisture degrade cell chemistry and safety. This requires continuous desiccant (adsorption) dehumidification rather than refrigeration, and the clean-and-dry-room HVAC systems take a remarkable share of factory energy: 29 % to 38 % in analyses of existing gigafactories and up to 43 % in some operators' reports, with dehumidification alone at 60 % to 70 % of dry-room energy [12, 13]. The dry room is the energy analogue of the paint shop in a vehicle plant, the single dominant thermal-management load, and a correspondingly large decarbonisation target. High-efficiency adsorption dehumidification has been reported to cut dry-room energy by up to 85 %; in one installation this equalled a 49 % reduction in whole-plant energy and about 7.8 % less embedded $CO_2$ in the batteries produced [13]. Since cell production accounts for roughly a fifth of the energy embodied in a finished pack [14], tackling both the electrode-drying and the dry-room loads is decisive for the whole S3b stage.

Two design trends further shape the footprint. On the *materials* side, the shift to lithium-iron-phosphate (LFP) chemistries, which avoid nickel and cobalt, lowers both the supply-chain footprint and the cost. Aqueous (water-based) processing of the cathode, which would replace the NMP route that dominates cathode energy, is an active research frontier; its main obstacle is corrosion of the aluminium current collector rather than any fundamental barrier [9]. On the *architecture* side, cell-to-pack and cell-to-chassis designs remove inactive module material and housing, raising the share of active material and so improving the energy and carbon embodied per usable kilowatt-hour. Both trends lower the stage's carbon intensity without a new process technology, and both are diffusing rapidly.

**Beyond the cell: the e-drive.** The battery dominates the electrified powertrain's footprint, but it is not all of it. The electric machine also carries a material bur-

den concentrated, as in the catalytic converter, in a small mass of critical elements: permanent-magnet synchronous motors use neodymium-iron-boron (NdFeB) magnets whose rare earths are energy-intensive to extract and separate and geographically concentrated, alongside electrical-steel laminations and substantial copper windings. The responses under development are the three that recur throughout this chapter: material substitution (externally excited and induction machines without rare-earth magnets, or magnets with less heavy rare earth), process efficiency in lamination stamping and winding, and circularity through magnet recovery and reuse. The e-drive is thus a smaller but structurally identical version of the battery problem, and it is at present less well characterised in the manufacturing literature than cell production.

S3b is therefore the sub-stage where the largest emissions reductions are still available but where the enabling process technology is least mature: the inverse of the situation in S1 and S3a.

### 3.5.3 Comparing the architectures: the hybrid dual burden

Setting the two sub-stages side by side yields a conclusion that is central to this thesis and that follows directly from the figures already established. The comparison uses the two components that differ between the architectures and for which published values exist: the engine, at about 0.65 t of $CO_2$-eq cradle-to-gate [64], and the battery cells, at 58 to 92 kg $CO_2$-eq per kWh [10]. With illustrative battery sizes, the cells of a 20 kWh battery embody about 1.2 t to 1.8 t of $CO_2$-eq, and those of a 60 kWh battery about 3.5 t to 5.5 t. On a manufacturing-stage basis, therefore, the electrified powertrain begins from a substantially higher footprint than the thermal one—which is precisely why the use-phase advantage of electrification must be earned back over the vehicle's life, and precisely why the manufacturing stage matters more, not less, as the fleet electrifies.

The consequence for the intermediate architecture is the point most often missed. A hybrid does not sit halfway between the two: it carries *both* an engine, transmission and exhaust aftertreatment *and* a traction battery with its e-drive. Its manufacturing footprint is therefore approximately *additive* rather than intermediate—a smaller battery than a comparable battery-electric vehicle, but a full thermal powertrain in addition to it. The arithmetic is straightforward. A plug-in hybrid with a 20 kWh battery carries about 0.65 t of $CO_2$-eq for its engine plus 1.2 t to 1.8 t for its battery cells, giving a total of about 1.8 t to 2.5 t. That is roughly three times the burden of the engine alone, and it is not an interpolation between the two pure architectures: it is the engine *plus* a battery. A battery-electric vehicle with a 60 kWh battery

still carries more in absolute terms, about 3.5 t to 5.5 t, because its battery is three times larger. All these totals are lower bounds: they leave out the transmission, the exhaust aftertreatment, the battery housing and electronics, and the e-drive, and a hybrid carries parts from both of these groups. The point is not that the hybrid is the worst case, but that its burden is built by addition rather than by substitution, so it does not inherit the manufacturing advantage of either architecture.

This finding has three implications that are pursued in the remainder of the thesis. Analytically, it means that a manufacturer's powertrain mix, not merely its electrification percentage, determines its manufacturing footprint. Industrially, it bears directly on the producers examined in Chapter 4. Hybrids made up 51 % of Ferrari's 13 752 shipments in 2024 [65], and since 2025 Lamborghini's entire range is hybrid, with 10 747 cars delivered that year [66]. Both manufacturers are thus exposed to both sets of process and material burdens at once. Methodologically, it reinforces the case for the cradle-to-gate perspective adopted throughout: an assessment framed only around tailpipe emissions would classify the hybrid as an unambiguous improvement, whereas the manufacturing-stage view shows that the improvement is conditional on the very foundry, machining, catalyst-circularity and cell-manufacturing measures catalogued in this section.

It should be stated plainly that these are order-of-magnitude comparisons built on published central values, not a like-for-like comparative assertion: powertrain masses, battery capacities, chemistries and electricity mixes vary widely, and a rigorous comparison would require the primary inventory data discussed in Chapter 5. The direction and the additive structure of the hybrid case, however, are robust to that uncertainty.

## 3.6 Stage S4 — Final assembly and intralogistics

Final assembly is the least energy-dense of the process stages, being dominated by manual and light-mechanical operations, but it is not negligible once utilities are attributed to it: heating, ventilation and air-conditioning, compressed air, lighting and in-plant logistics account for most of its demand. The state of the art here is largely one of good energy housekeeping enabled by digitalisation: demand-controlled HVAC, leak management and pressure optimisation of compressed-air systems, LED lighting, and energy-aware production scheduling. The electrification of intralogistics—battery-electric automated guided vehicles and tow trains replacing internal-combustion or inefficient fleets—removes local emissions and, when charging is scheduled against grid carbon intensity, reduces them further. These measures are mature (TRL 8–9); their contribution is real but bounded by the intrinsically low

energy intensity of the stage.

## 3.7 Lever L1 — Energy and utilities management and digitalisation

The energy lever cuts across every stage by changing how the plant sources and manages the energy the stages consume. Three families of measures define the state of the art.

**On-site generation and heat decarbonisation.** Rooftop and canopy photovoltaic generation, combined heat and power, and, increasingly, the electrification of process heat and the recovery of waste heat, allow a plant to displace purchased fossil energy. A notable trajectory in the sector is the retirement of gas-fired trigeneration in favour of electrified supply backed by renewables, together with the adoption of biogas or other low-carbon heat sources; such measures are mature (TRL 8–9) and are documented in the industrial chapter.

**Waste-heat recovery and heat-pump upgrading.** A complementary lever exploits the large quantities of low-grade waste heat a plant rejects—above all from the paint shop. High-temperature industrial heat pumps can upgrade such heat, for example from around 80 °C, to the temperatures other processes require, or to steam. Organic Rankine cycles convert low-grade heat into electricity, and thermal energy storage decouples supply from demand. Integrated with on-site photovoltaics, these technologies form the technical basis for electrifying and closing the plant's thermal loops [50]. The prize is large: bottom-up analyses of industrial process-heat electrification, including the automotive sector, estimate that heat-pump-based electrification could address a majority of process-heat $CO_2$ over the coming decades, though at additional cost and subject to the carbon intensity of the electricity used [50]. These technologies range from mature (waste-heat recovery, TRL 8–9) to maturing for the highest lift temperatures (TRL 6–7), and they are the natural partner of the paint-shop measures of Section 3.4.

**Renewable and low-carbon procurement.** Where on-site generation is insufficient, procurement of certified renewable electricity and, prospectively, of green hydrogen for high-temperature heat completes the decarbonisation of Scope 2.

**Digitalisation as an efficiency multiplier.** Industry 4.0 technologies do not by themselves generate energy, but they optimise its use. The *digital twin*—a synchro-

nised virtual replica of a line or plant fed by real-time sensor data—enables the simulation and optimisation of production and energy flows before physical change; a prominent example is the full digital twin of a major manufacturer's plant built on a real-time 3D collaboration platform to optimise line configuration. A more specialised and still-emerging variant, the *energy digital twin*, closes the loop by using bidirectional communication to optimise energy consumption at shop-floor level; demonstrations to date—for instance an energy-optimising twin of a heating tunnel with automated feedback—show measurable savings, but the literature notes that genuine energy digital twins remain rare in practice, placing this technology at TRL 5–7. Artificial-intelligence and operations-research methods for energy forecasting and process optimisation sit alongside it at TRL 6–8; recent work formulates plant energy management as a multi-objective mixed-integer program that schedules loads—including the charging of electric intralogistics fleets—against real-time grid carbon intensity, jointly minimising cost and emissions. Underpinning these technical measures is the organisational backbone of a certified energy-management system to the ISO 50001 standard, which institutionalises continuous energy-performance improvement and is a mature, widely adopted prerequisite for systematic decarbonisation [51]. Digitalisation is thus best understood not as a separate stage but as a cross-cutting multiplier that raises the achievable savings of every measure in S1–S4.

## 3.8 Lever L2 — Material efficiency and circularity

Because embodied material emissions dominate the value-chain footprint (Section 3.1), the circularity lever is, in aggregate, the most consequential of all. Its state of the art spans the three material systems that matter most to a vehicle.

**Steel.** Steel is the largest single material contributor to a vehicle's material-related emissions—on the order of one quarter for a typical car. The state of the art in its decarbonisation has two strands. The first replaces the coal-based blast furnace with hydrogen-based direct reduction ($H_2$-DRI) coupled to electric-arc melting. Using green hydrogen and low-carbon electricity, this route can cut steelmaking emissions by around 90 %, and in pilot operation it has reached essentially zero Scope 1 and 2 $CO_2$ per tonne of steel [27]. The second strand is the parallel use of high-quality scrap-based "recycled and reduced-$CO_2$" steels. In the $H_2$-DRI route hydrogen strips the oxygen from iron ore, yielding *sponge iron* (direct-reduced iron) with a high metallisation degree of 98 % to 99 % and, critically, water as the by-product in place of $CO_2$ [27, 28]. Against a conventional blast furnace's emission of more than two tonnes of $CO_2$ per tonne of steel, the reduction exceeds 95 %. These routes have

moved from demonstration to first commercial scale (TRL 7–8). A leading pilot has produced several thousand tonnes of hydrogen-reduced sponge iron, and is scaling to a demonstration plant targeting 1.3 to 2.7 million tonnes per year between 2026 and 2030 [28, 29]. In parallel, a dedicated commercial venture is commissioning the first industrial-scale hydrogen-DRI green-steel mill, with a capacity of about 2.5 million tonnes per year [30]. Near-zero and recycled-content steels are already being supplied to vehicle manufacturers under multi-year agreements [42, 40]. Because steel is such a large share of a vehicle's material emissions, even a partial substitution of conventional steel by these grades produces a first-order reduction in Scope 3, which is why it is one of the most consequential single measures available to the industry.

**Aluminium.** Aluminium exemplifies the lightweighting–circularity tension of Section 3.3. Primary aluminium is highly carbon-intensive, on the order of 8 to 16 kg $CO_2$-eq per kg depending on the electricity mix, whereas recycled (secondary) aluminium is on the order of 2 to 4 kg $CO_2$-eq per kg, about three-quarters lower (Figure 3.2) [23]. One technical nuance matters, however: the footprint of *primary* aluminium is itself dominated by the smelter's electricity. Primary metal produced with hydro- and wind-power can reach a third-party-verified footprint of about 4.0 kg $CO_2$-eq per kg, roughly a quarter of the global average, which approaches that of recycled metal. Premium recycled products with at least 75 % post-consumer scrap reach about 1.9 kg $CO_2$-eq per kg [24, 25]. The "primary versus recycled" comparison is therefore more precisely a comparison across the electricity mix and the scrap content together—a point quantified in the sensitivity analysis of Chapter 5. Closed-loop systems, in which process scrap and end-of-life aluminium are returned to the same grade of product, are the state of the art for capturing the recycling benefit and are well industrialised (TRL 8–9) [26]. This lever is quantified in detail in the case study of Chapter 5.

**Batteries.** Closing the loop on batteries reduces both the material footprint and supply-chain risk. It works through hydrometallurgical recovery of cathode metals such as lithium, nickel and cobalt, and, upstream, through designing cells for disassembly and recyclability. It also complements the manufacturing-energy measures of Section 3.5.2, because recovered active materials re-enter cell production with a fraction of the emissions of virgin extraction and refining. State-of-the-art hydrometallurgical processes recover more than 95 % to 99 % of nickel and cobalt and 85 % to 95 % of lithium from "black mass," markedly outperforming pyrometallurgy on lithium (which typically recovers below 60 %) [17, 18]. Industrial-scale recycling is maturing rapidly (TRL 7–8) as the first large end-of-life volumes approach, and it is

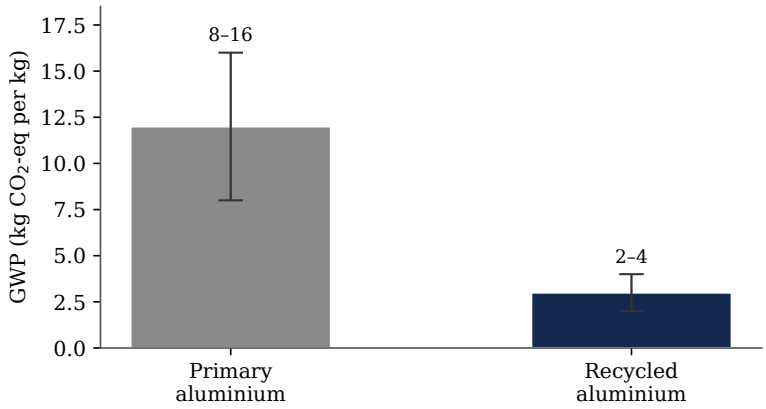



**Figure 3.2.** Cradle-to-gate global warming potential of primary versus recycled aluminium; ranges reflect dependence on the electricity mix. After published emission-factor data used in the case study of Chapter 5.

now being pulled forward by regulation: the EU Battery Regulation mandates rising recycling-efficiency and material-recovery targets (for example 95 % cobalt and nickel and 80 % lithium recovery by the early 2030s) together with a carbon-footprint declaration and a digital "battery passport" [19]. Recycling is estimated to be capable of cutting the supply-chain $CO_2$ of a battery pack by 30 % to 40 % [15]. Alongside recycling, the remanufacturing of powertrain and mechanical components—returning used parts to as-new condition—is a long-established circular practice (TRL 8–9). For an internal-combustion engine, the JRC study cited above finds that remanufacturing cuts the global-warming impact by about 66 % to 78 % relative to a new engine, depending on how many parts are reused [64]. The practice extends naturally to electrified-powertrain components.

Taken together, the circularity lever reframes the lightweighting dilemma of Section 3.3: the high embodied emissions of aluminium and, above all, CFRP are tolerable only to the extent that secondary material and closed loops are available to amortise them. Material choice and material circularity are therefore two halves of a single design decision, not independent levers.

## 3.9 Measurement, standards and verification

The metrics catalogued throughout this chapter are meaningful only if they are measured and reported comparably, and the same standardisation that makes them comparable is what allows an industrial claim to be trusted. It is therefore worth making explicit the standards framework that underpins both the academic assessment and the industrial benchmarking of the next chapter. Life-cycle results follow ISO 14040 and ISO 14044 [1, 2], and product-level footprints are increasingly published as En-

vironmental Product Declarations governed by Product Category Rules and verified by independent bodies—the mechanism, seen already for low-carbon aluminium, by which a figure becomes auditable rather than asserted. At the organisational level, corporate greenhouse-gas inventories are structured by the GHG Protocol's Scope 1/2/3 architecture and, where validated, by the Science Based Targets initiative, while energy performance itself is managed through certified ISO 50001 systems [51]. At the machine level, standards such as ISO 14955 provide methods for the environmental evaluation of machine tools, closing the loop from process to plant to product. This framework is not incidental to sustainability engineering: it is the infrastructure that distinguishes a quantified, verifiable reduction from an unsubstantiated claim, and it is the reason the source-reliability protocol of Chapter 2 can be applied at all.

## 3.10 Synthesis: technologies, maturity and metrics

Tables 3.1 and 3.2 consolidate the survey, the first covering the four process stages and the second the two cross-cutting levers. Figure 3.3 plots twenty representative technologies from both tables on a maturity-versus-impact map. On this map, a technology counts as *deployable now* when its whole TRL band lies at TRL 8 or above; a technology whose band reaches below TRL 8 counts as *still maturing*. Read together, they expose a pattern that frames the entire thesis. The stages with the most mature technology, S1, S4 and the process side of the thermal powertrain S3a, are also those with the smallest remaining emissions headroom. Where the headroom is large, the technologies split into two groups. Some are deployable now: reduced-stage and low-cure painting, low-carbon electricity for plants and cell production, on-site generation and closed-loop aluminium. Others are still maturing: hydrogen-based steel, the electrification of process heat in paint-shop ovens and engine-plant furnaces, dry-electrode cell manufacturing and battery recycling. Maturity and impact are therefore not simply opposed. The mature measures of the body shop and assembly have little left to give, but a large part of the high-impact agenda is already deployable, and the rest depends on technologies that are still being industrialised. The paint shop S2 shows both groups at once. Its largest levers are already at or near full deployment, placing them in the upper-right "high impact, deployable now" region, while the complete electrification of its heat is still spreading. This explains why the paint shop is the most active site of industrial decarbonisation and why it recurs throughout Chapter 4.

The practical implication for a manufacturer is a sequencing logic: the "deployable now" technologies (reduced-stage painting, closed-loop aluminium, low-carbon electricity procurement, on-site generation) are the near-term agenda, while the "still

maturing" high-impact technologies (green steel, oven and furnace electrification, dry electrode) define the medium-term investment and supplier-development agenda. This maturity-versus-impact map is the reference against which the industrial deployment evidence of the next chapter is compared, and it is the backbone of the academia–industry gap analysis presented there.

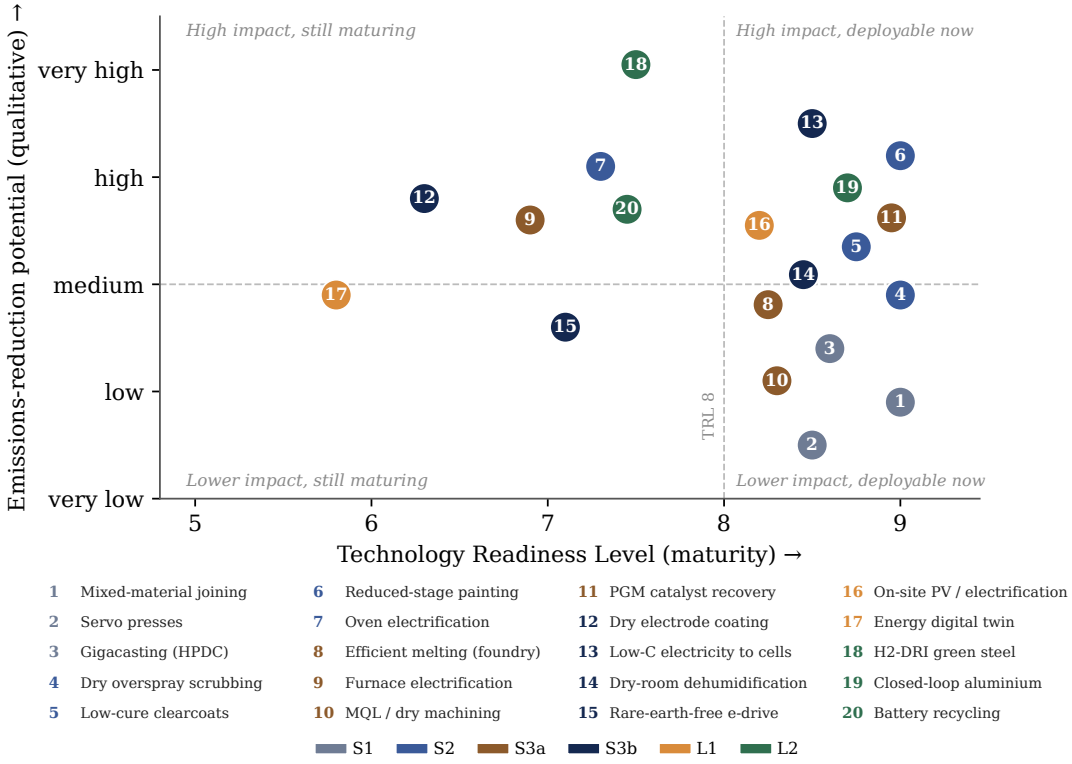



**Figure 3.3.** Maturity-versus-impact map of twenty representative technologies selected from Tables 3.1 and 3.2. The horizontal axis is the Technology Readiness Level: each technology lies within the TRL band given in those tables, and its exact position inside the band is chosen for legibility only. The dashed vertical line at TRL 8 separates the technologies that are deployable now (whole band at TRL 8 or above) from those still maturing. The vertical axis is the qualitative emissions-reduction potential. Colours denote the taxonomy stage or lever, with the thermal (S3a) and electrified (S3b) powertrain substages distinguished; numbers refer to the key below the plot. Final-assembly (S4) measures are not plotted: they are mature and offer little headroom.

**Table 3.1.** State-of-the-art technologies by *process stage* (S1–S4), with maturity and key quantified metric. The cross-cutting levers are given separately in Table 3.2.

| | **Technology** | **TRL band** | **Key quantified indicator (from literature)** |
|---|---|---|---|
| S1 | Servo presses, energy-oriented press control | 8–9 | Incremental electricity and idle-load reduction |
| S1 | Mixed-material joining (SPR, adhesive, laser) | 9 | Enables aluminium/CFRP bodies; mature |
| S1 | Hot stamping / press hardening (22MnB5) | 9 | ∼1500 MPa; enables lightweighting; furnace energy penalty |
| S1 | Blank nesting / scrap-yield optimisation | 9 | Higher material yield, lower scrap fraction |
| S1 | Gigacasting (integrated HPDC) | 8–9 | Part/joint consolidation; benefit contingent on recycled alloy |
| S2 | Dry overspray scrubbing | 9 | Removes scrubber-water conditioning load |
| S2 | Low-cure clearcoats | 8–9 | Up to 39 % curing-energy reduction (80 vs 140 °C) |
| S2 | Reduced-stage “wet-on-wet” painting | 9 | Up to 30 % energy/vehicle; target 321 kWh/veh. |
| S2 | Overspray-free application; electric oven + RTO | 7–9 | Up to −32 % line energy; ∼−40 % paint-shop $CO_2$ |
| S2 | Oven electrification / heat pumps | 7–9 | Removes paint-shop Scope 1; first plants in series |
| S3a | Efficient melting (shaft furnace, heat recovery) | 8–9 | 489–650 vs 700–1100 kW h $t^{-1}$; floor ∼300 |
| S3a | Foundry / heat-treatment furnace electrification | 6–8 | Removes engine-plant Scope 1 heat |
| S3a | MQL / dry / cryogenic machining | 8–9 | Near-eliminates cutting-fluid burden |
| S3a | Cold (vs hot) end-of-line engine test | 8–9 | Avoids test-fuel combustion and exhaust |
| S3a | PGM recovery from spent catalysts | 8–9 | >95% recovery; ∼90 % less energy than mining |
| S3b | Dry electrode coating | 6–8 | No solvent drying; −4.8 % pack energy |
| S3b | Electrified drying / aqueous binders | 6–7 | Removes NMP; cuts wet-route drying load |
| S3b | Low-carbon electricity to cell process | 8–9 | Cell-factory GHG 4.54 → 0.53 kg $CO_2$-eq/kWh (Swedish grid) |
| S3b | High-efficiency dry-room dehumidification | 8–9 | Up to −85 % dry-room energy; ∼7.8 % lower battery $CO_2$ in one plant |
| S3b | Rare-earth-free / reduced-REE e-drive machines | 6–8 | Avoids NdFeB magnet material burden |
| S4 | Demand-controlled HVAC / compressed air | 8–9 | Utility-load reduction in assembly |
| S4 | Electrified intralogistics (AGVs) | 8–9 | Removes local fleet emissions |

**Table 3.2.** State-of-the-art technologies for the *cross-cutting levers* (L1 energy, L2 material circularity), with maturity and key quantified metric.

| | **Technology** | **TRL band** | **Key quantified indicator (from literature)** |
|---|---|---|---|
| L1 | On-site PV, CHP-to-electrification | 8–9 | Displaces purchased fossil energy |
| L1 | Waste-heat recovery, heat-pump upgrading, ORC | 6–9 | Recovers/upgrades low-grade paint-shop heat |
| L1 | Energy digital twin | 5–7 | Shop-floor energy optimisation (rare in practice) |
| L1 | AI energy forecasting/optimisation | 6–8 | Multiplies savings of S1–S4 measures |
| L2 | $H_2$-DRI "green" steel | 7–8 | $\sim$90 % steelmaking-emission cut |
| L2 | Closed-loop aluminium | 8–9 | 2–4 vs 8–16 kg $CO_2$-eq/kg (about three-quarters lower) |
| L2 | Battery recycling (hydrometallurgy) | 7–8 | Recovers 95–99% Ni/Co; cuts material footprint |
| L2 | Component remanufacturing | 8–9 | Energy saving vs new manufacture |

CHAPTER 4

# Industrial Landscape and Benchmarking

This chapter turns from what the literature considers the state of the art to what the industry has actually put in place. Following the protocol of Chapter 2, it surveys a purposive sample of companies spanning the automotive value chain—vehicle manufacturers, three Tier-1 suppliers, and the upstream materials industry (steel, aluminium, battery and catalyst-metal producers)—and maps their disclosed practice onto the process-stage taxonomy of Section 2.2. Every quantified claim reported here has been graded against the source-reliability hierarchy of Table 2.4, and each measure is characterised by its deployment maturity on the scale of Table 2.5. The chapter culminates in a benchmarking matrix and in the academia–industry gap analysis that is the analytical core of the thesis.

A methodological note on scope applies throughout. The process stages are defined from the perspective of a vehicle plant. They map naturally onto vehicle manufacturers, but only partially onto suppliers and materials producers, whose own processes are different. Tier-1 and upstream companies are therefore assessed mainly on the cross-cutting levers of energy (L1) and circularity (L2), and on the decarbonisation of their own core process, rather than being forced onto stages that do not apply to them. A second point follows from the taxonomy of Section 2.2. Because stage S3 is split into a thermal branch (S3a) and an electrified branch (S3b), the benchmarking reports them as separate columns. A manufacturer that builds engines and a manufacturer that builds only battery packs are therefore not compared on a single, misleading "powertrain" score.

## 4.1 Vehicle manufacturers: volume producers

**BMW Group.** BMW frames its manufacturing decarbonisation through the "iFACTORY" strategy (*lean, green, digital*) applied across its global network. The company reports that its production facilities worldwide are supplied entirely with green electricity [36], that all plants in its production network have been operated as

$CO_2$-neutral since 2021, and that $CO_2$ emissions attributable to vehicle production have fallen by more than 70 % since 2006, with a target of reducing production emissions per vehicle by 80 % by 2030 against a 2019 baseline. Its most advanced site, the plant at Debrecen in Hungary, began series production in late 2025 and operates without fossil fuels in its processes [37]. Paint shops conventionally rely on gas to reach oven temperatures up to 180 °C; electrifying this one is credited with avoiding up to 12 000 t of $CO_2$-eq per year. About a quarter of the plant's power is to come from a 50 ha on-site photovoltaic array. On the material and supply side, BMW combines a "secondary first" approach with low-carbon procurement. Around 70 % of press-shop aluminium and steel offcuts are recycled. Agreements for hydrogen-based and $CO_2$-reduced steel are intended to cover more than 40 % of European steel demand and to save up to 400 000 t of $CO_2$ per year. Commitments on green electricity and secondary materials for battery cells are expected to cut the cell carbon footprint by up to 60 % [35]. BMW's disclosed practice is thus among the broadest in the sample.

**Volkswagen Group.** Volkswagen organises its environmental effort under the "goTOzero" mission and, since 2024, the broader "regenerate+" strategy. Its Scope 1 and 2 production targets are validated by the Science Based Targets initiative, with a confirmed absolute reduction of 50.4 % by 2030 against a 2018 baseline and net-carbon-neutral production sites targeted for 2040. The electric-vehicle plant at Zwickau is the reference case: producing the ID. family, it had already reduced $CO_2$ by 66 % against 2010 through energy efficiency, an on-site cogeneration plant and certified green electricity. All European production sites already draw renewable electricity, and battery-cell production for the ID. models is powered exclusively by green electricity. The Group operates a "goTOzero Impact Factory" programme structured around a checklist of some 143 environmental criteria, and steers progress with an internal decarbonisation index and a dedicated decarbonisation fund [39].

**Mercedes-Benz.** Under "Ambition 2039", Mercedes-Benz targets a net-carbon-neutral new-vehicle fleet across the entire life cycle by 2039, with an interim goal of at least halving $CO_2$ per car over the life cycle by 2030 against 2020. Its flagship is Factory 56 at Sindelfingen, operational since 2020. This net-carbon-neutral plant consumes about 25 % less energy than the preceding S-Class assembly. It uses an integrated energy concept combining rooftop photovoltaics, a direct-current grid and stationary storage built from second-life vehicle batteries. The company intends Factory 56 to serve as a blueprint for all its plants. Mercedes has purchased exclusively renewable electricity in Germany since 2022. It targets more than 70 % renewable

energy by 2030 and over 140 MWp of solar by 2025. It is decarbonising its steel supply chain through green-steel offtake and a closed-loop arrangement in which press-shop scrap is railed back to the steelmaker. Suppliers representing nearly 90 % of purchasing volume have signed an "Ambition Letter" committing to $CO_2$-neutral supply [40]. Importantly, the company is explicit that "net carbon-neutral" includes the compensation of residual emissions through certified offset projects—a definitional point revisited in Section 4.5.

**Toyota.** Toyota's "Environmental Challenge 2050" (first announced in 2015, SBTi-validated in 2022) includes distinct challenges for manufacturing and plant $CO_2$, targeting zero $CO_2$ at all plants worldwide by 2050. Its manufacturing philosophy emphasises the elimination of energy demand at source—simplifying and shortening processes and introducing, where possible, "processes that do not use energy"—alongside renewable and hydrogen-based supply; hydrogen fuel cells, for example, are used at the Honsha plant. Since 2018 Toyota has also used a hydrogen burner on a forging line at the same plant [38]. This is exactly the kind of furnace-fuel switch that Section 3.5.1 identifies for engine plants, but the source does not say which parts the line forges, so it is not coded as thermal-powertrain practice in the matrix below. The company reports that renewable energy reached about 79 % of factory electricity globally in fiscal year 2025, and interim milestones aim to cut process $CO_2$ per vehicle at new plants and lines to roughly half of 2001 levels by 2020 and about a third by 2030 [41].

**Volvo Cars.** Volvo's manufacturing decarbonisation is notable for its material-side depth. It is among the first automakers to take near-zero-emission steel from a hydrogen-based producer, and it operates a closed-loop aluminium system with its supplier in which press-shop scrap is remelted into the same automotive sheet—a system in which shifting sheet transport from road to rail alone cut the associated transport $CO_2$ by 68 %. Combined with its climate-neutral operations agenda and renewable electricity, Volvo exemplifies the circularity lever operating at serial scale [42, 26].

**Stellantis.** Stellantis illustrates focused excellence in the highest-impact process stage. Through its "Paint in Numbers" programme and the integrated multi-layer "4WET" painting process, it reports a 27 % reduction in paint-shop energy against 2021 with a target of 50 % by end-2025 and just 321 kWh per vehicle; at its Vigo plant the 4WET process cut energy by about 40 kWh per vehicle and paint-shop $CO_2$ by 25 % [6]. This makes Stellantis a benchmark specifically for S2, even where its disclosed practice in other stages is less prominent.

**A cross-manufacturer process trend: gigacasting.** Beyond individual company programmes, the diffusion of gigacasting (Section 3.3) is a structural shift in body manufacturing worth noting for its uneven, strategy-dependent adoption. The approach was pioneered by a single manufacturer and has since been taken up by others. Volvo, for instance, explicitly links its mega-casting project to its 2040 carbon-neutrality goal, on the grounds that a single, easily recycled alloy with high recycled content lowers the body's footprint. Several established suppliers and manufacturers remain sceptical, citing the very high per-die volumes needed for economic viability and concerns over reparability [21, 20]. Gigacasting thus illustrates, at the level of industrial practice, the same contingent sustainability logic identified in the academic assessment: the process consolidates parts and removes joining energy, but its net climate benefit is realised only if the casting alloy is drawn from recycled rather than primary metal.

**Paint-shop electrification in practice.** The paint-shop technologies identified as high-impact and deployable in Section 3.4 are now visible in concrete plant projects, often supplied by specialist equipment makers. A fully electric paint shop combining inside-out electric drying with an electric regenerative thermal oxidiser has been commissioned at a high-volume Volkswagen plant, where operating the ovens on green electricity is credited with cutting paint-shop $CO_2$ by about 40 % relative to a gas-fired shop [48, 39]. Overspray-free two-tone application has entered series production at a Renault plant, where—together with a high-transfer-efficiency coating—it is reported to have cut painting energy by around 25 % and avoided of the order of 300 t of $CO_2$ [48]. These deployments confirm that the paint shop is where the "deployable now" agenda is being most actively realised, consistent with its favourable position on the maturity–impact map.

## 4.2 Vehicle manufacturers: the Motor Valley

The two Italian high-performance manufacturers are treated separately, in keeping with the industrial focus of this thesis and because they anchor the case study of Chapter 5.

**Ferrari.** As a company listed on the New York and Milan exchanges, Ferrari discloses quantified, externally reported figures. It targets carbon neutrality across its value chain by 2030. On the energy lever its trajectory is concrete: in 2024 it shut down the gas-fired trigeneration plant that had powered Maranello since 2009, and it plans to double on-site photovoltaic capacity from 5 to 10 MWp by 2030, along-

side fuel-cell installations. In the paint shop it has introduced a coating that lowers oven temperatures from 150 to 100 °C for aluminium and carbon-fibre bodies simultaneously—the same physical principle (lowering cure temperature) identified as state of the art in Section 3.4, here applied to a high-performance, mixed-material context. Ferrari's aluminium-intensive body construction makes it a natural anchor for the aluminium life-cycle analysis of Chapter 5 [31].

Ferrari is also, for this thesis, the clearest industrial illustration of stage S3a. Almost uniquely among vehicle manufacturers, it still operates its own foundry on the Maranello site, as it has since the company was founded. The foundry employs more than a hundred skilled workers and casts cylinder heads, engine blocks and bedplates; aluminium ingots are melted in large furnaces and poured into sand or steel moulds, and the castings then move to an adjacent machining hall for milling, grinding and finishing [68]. Trade reporting adds that the engine castings use a near-eutectic aluminium–silicon alloy, poured at around 720 °C to 740 °C depending on whether shell or sand moulds are used, and that the steel crankshafts are made at the same Modena plant that produces the car bodies [68].

Two observations follow, and the second is a methodological one that the reliability protocol of Chapter 2 requires. First, the technical significance is direct: Ferrari performs in-house precisely the melting and machining operations that Section 3.5.1 identified as the dominant energy loads of thermal-powertrain manufacturing. Its melting furnaces are a Scope 1 load inside the plant boundary, not a supplier's emission, so the foundry sits squarely within the perimeter of the company's own decarbonisation programme. This also connects the two halves of the thesis: an aluminium engine block is a cast structural component, so the material logic quantified in Chapter 5 applies to it as directly as it does to a body part.

Second, the evidence for the foundry is corporate—the company's own magazine and trade press—and therefore Tier C under Table 2.4. It establishes, reliably, *that* the process exists and what it consists of. It does not establish any quantified figure for the foundry's energy use or emissions, and no such figure is publicly disclosed. This thesis therefore records the foundry as documented practice, but it codes no foundry-specific decarbonisation measure: the S3a cell of the matrix is left empty. The only measures that demonstrably reach the foundry are the site-wide energy actions described above, and these are counted under the energy lever L1. The gap this reveals is taken up in Section 4.5.

**Automobili Lamborghini.** Lamborghini published its first Sustainability Report in 2025 and has an unusually long operational track record on the energy lever. Its Sant'Agata Bolognese site has been certified carbon-neutral on an on-balance basis

since 2015, that is for ten consecutive years. On the company's own definition, residual emissions that remain after its reduction measures are compensated through offset projects, and the status is certified by DNV [33]. The status was maintained through trigeneration, photovoltaics, district heating and energy efficiency, even as the plant roughly doubled in size, and it is also recognised within its parent group's portfolio of early carbon-neutral facilities. Two features make Lamborghini distinctive for a manufacturing-engineering reading. First, it produces its carbon-fibre monocoques in-house, giving it direct control over one of the most energy-intensive material processes in the industry. Second, its Revuelto model obtained the company's first product Life Cycle Assessment certified to ISO 14040 and ISO 14044—an externally reviewed LCA that this thesis uses in Chapter 5 as an order-of-magnitude benchmark against which to sense-check its own screening assessment [32].

## 4.3 Tier-1 suppliers and the upstream materials industry

**Bosch (Tier-1).** Bosch is the reference Tier-1 case. Across more than 470 locations worldwide it reports carbon neutrality for Scope 1 and 2 since 2020, described as the first globally operating industrial enterprise to reach this status, against a 2019 footprint of about 1.94 million tonnes of $CO_2$ (Scope 1+2), some 90 % of which arose in production. Its strategy rests on four explicit levers—energy efficiency, self-generated renewable energy, purchased green electricity and, "as the last resort," carbon credits—and it targets a 30 % absolute cut in Scope 3 by 2030 against 2018, confirmed by the SBTi, backed by a one-billion-euro energy-efficiency programme and a 1.7 TWh efficiency target. The reliance on offsets for residual emissions is stated openly (of the order of half a million tonnes offset in 2025), which—as with Mercedes—places the "carbon-neutral" label in its proper, qualified context [43].

**ZF and Schaeffler.** Two further Tier-1 suppliers confirm that the pattern seen at Bosch is representative of the tier. ZF targets an 80 % reduction in Scope 1 and 2 emissions by 2030 (against 2018–2019) and full climate neutrality across all three scopes by 2040, underpinned by 100 % renewable electricity by 2030 and an annual efficiency improvement, with a Scope 3 target of −40 % per unit of sales by 2030 [44]. Schaeffler commits to climate-neutral in-house production by 2030 and a climate-neutral supply chain by 2040. Its measures include 100 % renewable purchased electricity and a three-quarter cut in its own production emissions by 2025. Like its peers, it offsets only genuinely unavoidable residual emissions. Its

CDP rating improved from D to A− within two years, which illustrates the role of third-party disclosure scoring in this tier [45]. Both firms identify the decarbonisation of purchased steel and aluminium as their principal Scope 3 challenge, which links the supplier tier directly to the upstream materials industry discussed next.

**Steel: SSAB and the hydrogen route.** On the materials side, steel decarbonisation has moved from pilot to first commercial supply. SSAB, developing hydrogen-based direct reduction through the HYBRIT initiative and commercialising near-zero "SSAB Zero" grades, has begun supplying automakers—including a closed-loop, near-zero steel supply to Volvo Cars from 2025 [27, 42]. Additional supply routes broaden the base and reveal a spectrum of strategies. ArcelorMittal offers two different products under its *XCarb* umbrella. The first is physically low-carbon steel: scrap-based electric-arc-furnace metal made with renewable electricity, already supplied in series to automakers and scaling through new furnace capacity. The second is a set of market-based "green-steel certificates" that allocate documented reductions to a customer's purchase [52]. thyssenkrupp, meanwhile, is building one of the world's largest industrial decarbonisation projects. Its hydrogen direct-reduction plant at Duisburg will have a capacity of about 2.5 million tonnes of DRI and is expected to save up to 3.5 million tonnes of $CO_2$ per year. The company also markets transitional *bluemint* grades with independently assured (DNV, TÜV) allocation [53]. Electrolysis-based approaches, such as that of the venture in which BMW has invested, add a further pathway [35]. This activity is being driven not only by voluntary commitments but structurally by policy: the EU Carbon Border Adjustment Mechanism and ETS carbon pricing raise the cost of carbon-intensive steel and thereby create a direct economic pull for the green grades [47]. Conventional primary steel emits more than two tonnes of $CO_2$ per tonne, and steel accounts for roughly a quarter of a vehicle's material-related emissions. These routes therefore address one of the largest single levers in the whole system. Their industrial volumes, however, are only now ramping up. A further distinction must also be kept in view: *physical* fossil-free product and *certificate*-based accounting coexist in this market, and the source-reliability discipline of this thesis treats them separately (Section 4.5).

**Aluminium: Novelis and closed-loop recycling.** In aluminium, the industrial state of the art is closed-loop recycling operated jointly with automakers. Novelis, described in its own securities filings as the world's largest closed-loop aluminium recycling partner to the automotive industry, operates programmes with, among others, Volvo, Jaguar Land Rover, a Porsche press-shop joint venture, BMW and Nissan, returning press-shop scrap to be remelted into the same automotive sheet.

The company quantifies the benefit consistently with the literature of Section 3.8: recycled aluminium uses about 5 % of the energy—roughly 95 % less—than primary, with commensurate $CO_2$ savings; one closed-loop partnership alone is projected to avoid up to 100 000 t of $CO_2$ per year. Novelis has raised recycled content from 33 % (FY2010) to 61 % (FY2019), targets a 75 % average by 2030 and aims to be the lowest-emissions flat-rolled-products supplier at below 3 t of $CO_2$ per tonne [26]. Complementing closed-loop recycling, primary producers now market third-party-verified low-carbon grades: renewable-powered primary aluminium at about 4.0 kg $CO_2$-eq per kg and premium recycled aluminium (at least 75 % post-consumer scrap) at about 1.9 kg $CO_2$-eq per kg, each documented through an Environmental Product Declaration and independent (DNV/ASI) certification [24, 25]. The existence of *verified* figures at this granularity is itself significant: it is the mechanism by which a claim can be graded Tier A under the protocol of Section 2.5, rather than accepted on trust. This directly underpins the case study of Chapter 5.

**Catalyst metals: the closed loop of the thermal powertrain.** The material lever of stage S3a has its own specialist industry, and it is a mature one. Two refiners dominate the recovery of platinum-group metals from spent automotive catalysts. Umicore processes both metallic and ceramic substrates, including silicon-carbide diesel particulate filters, and returns the recovered metal to the production of new converters [69]. Johnson Matthey describes itself as the world's largest refiner of secondary PGMs and operates an explicitly closed loop: a customer returns an end-of-life catalyst, the metal is extracted, and it is used to make a new catalyst [70].

Three points make this tier analytically useful. First, it is the structural counterpart of the battery-recycling industry discussed below, and it is considerably more mature: catalytic converters are already the largest secondary source of PGM supply [70], whereas battery recycling is only now reaching volume. Second, it confirms from the industrial side the conclusion reached in Section 3.5.1: for the thermal powertrain, the decisive material lever is circularity, and the constraint is collection rather than process capability. Third, and most relevant to the argument of this thesis, one of these refiners notes that internal-combustion vehicles will remain on the road for fifteen to twenty years and beyond, which is why they expect a continuous supply of recoverable catalyst metal [70]. That is an industrial statement of the same premise on which the thermal branch of this work rests: these vehicles, and the plants that build them, will be with us for a long time. For the battery stage, manufacturer disclosures show one dominant industrial lever: supplying cell production with green electricity and secondary materials. This is the route by which several manufacturers report cell-footprint reductions. It is complemented by the ramp-up of hydrometal-

lurgical recycling, where dedicated recyclers report recovery of more than 95 % to 99 % of nickel and cobalt and 85 % to 95 % of lithium. Such partnerships with vehicle manufacturers are increasingly common, and are being pulled forward by the EU Battery Regulation's recovery targets and battery-passport requirement [17, 18, 19]. The maturity of process innovations such as dry-electrode coating remains, as Chapter 3 noted, concentrated in a small number of producers.

Table 4.1 summarises the supplier and materials tier on the dimensions that apply to it.

**Table 4.1.** Benchmarking of the Tier-1 and upstream materials tier on the applicable dimensions.

| **Company** | **Core-process decarbonisation** | **Energy (L1)** | **Circularity / low-carbon product (L2)** |
|---|---|---|---|
| Bosch (Tier-1) | Efficiency + renewable supply (Deployed); residual offset | Renewable, self-generation (Standard) | Scope-3 target −30% by 2030 (Announced / Deployed) |
| ZF, Schaeffler (Tier-1) | Efficiency + 100% renewable electricity by 2030 (Deployed) | Renewable + self-generation (Deployed) | Scope-3 targets; low-C steel / Al sourcing (Announced) |
| SSAB (steel) | $H_2$-DRI & near-zero grades (first commercial) | Fossil-free process (Piloted / Deployed) | Near-zero and closed-loop steel to OEMs (Deployed, ramping) |
| ArcelorMittal, thyssenkrupp (steel) | XCarb EAF / bluemint; $H_2$-DRI plants building | Renewable EAF; $H_2$-DRI (Announced / Deployed) | Series low-C grades + certificates (Deployed); CBAM-driven |
| Novelis (aluminium) | Recycling-based melting (∼95% less energy) | Low-carbon target $<3\,\mathrm{t\,CO_2/t}$ (Deployed) | Closed-loop automotive recycling (Standard) |
| Hydro (aluminium) | Renewable-powered primary; recycled grades | REDUXA ≤4, CIRCAL ∼1.9 $\mathrm{kg\,CO_2}$-eq/kg (Deployed) | EPD / ASI-verified low-carbon products (Standard) |
| Battery cell & recyclers | Green-electricity cells; dry electrode nascent | Renewable supply (Deployed) | Hydromet recycling 95–99% Ni / Co (Piloted / Deployed) |
| Umicore, Johnson Matthey (catalyst metals) | PGM refining from spent catalysts (S3a material lever) | Refining energy far below primary route (Deployed) | Closed-loop catalyst recycling; largest secondary PGM source (Standard) |

## 4.4 The benchmarking matrix

Figure 4.1 consolidates the vehicle-manufacturer evidence into a single deployment-maturity matrix, coded on the ordinal scale of Table 2.5. Its seven columns are the seven categories of the taxonomy, so that it can be read directly against the state of the art of Chapter 3. Every coded cell rests on evidence stated earlier in this chapter, and Table 4.2 lists that evidence cell by cell, with its source and the tier of that source under Table 2.4. A dash means that no public evidence was found in the sources reviewed. Under the protocol of Section 2.5 it is recorded as such, and it is not read as proof that nothing is being done. Read horizontally, the matrix characterises each manufacturer's disclosed breadth; read vertically, it shows where a stage or lever has or has not been industrialised.

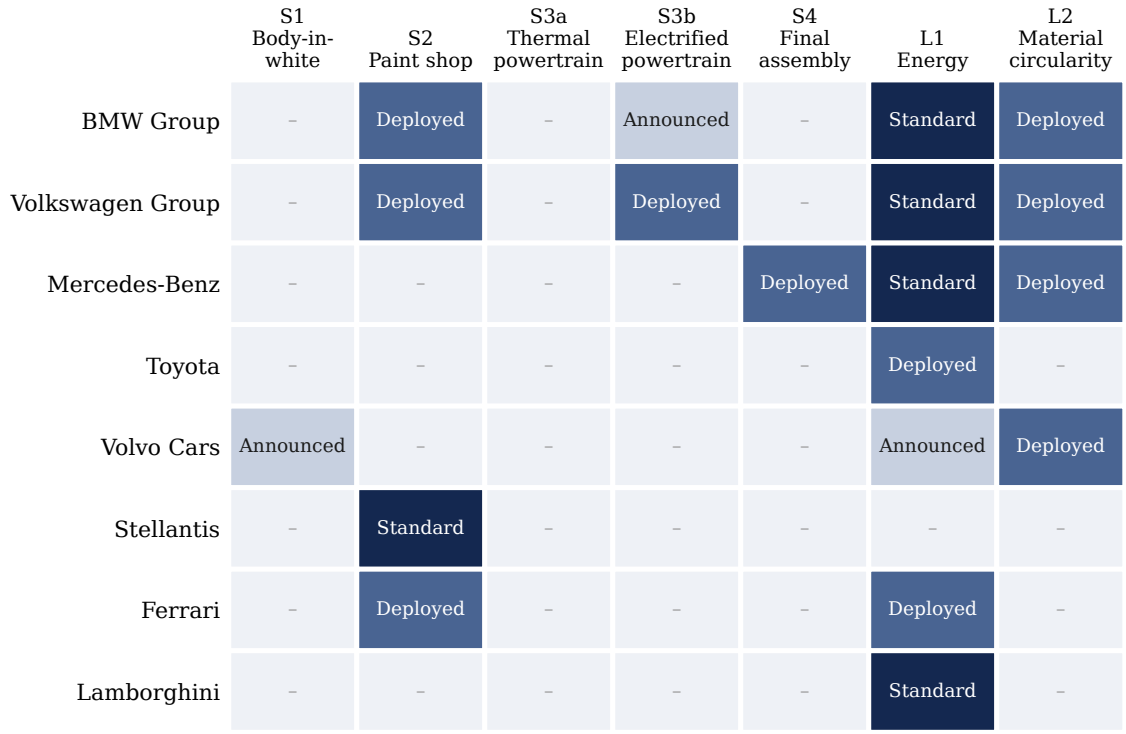



**Figure 4.1.** Deployment-maturity matrix for the sampled vehicle manufacturers across the seven categories of the taxonomy, with the thermal (S3a) and electrified (S3b) powertrain branches shown separately. Coding follows Table 2.5; the evidence for every coded cell is given in Table 4.2. Cells reflect an evidence-based assessment of publicly disclosed practice, not a company self-rating. A dash denotes that no public evidence was found in the sources reviewed, which under Section 2.5 is recorded as such rather than read as absence of practice.

Four readings stand out. First, the *energy lever* (L1) is the most mature column and the only one with evidence for almost every manufacturer. Renewable electricity and on-site generation are standard practice at BMW, Volkswagen and Mercedes-Benz, and deployed at Toyota. Strikingly, the two Motor Valley producers are among

**Table 4.2.** Evidence behind every coded cell of Figure 4.1. Tier refers to the source cited, graded under Table 2.4; press releases (Tier D) are used only to establish that a measure exists.

| Company | Cat. | Level | Evidence (as stated in this chapter) | Source (tier) |
|---|---|---|---|---|
| BMW Group | S2 | Deployed | Electric paint shop at the fossil-free Debrecen plant (series production since late 2025) | [35, 37] (C/D) |
| | S3b | Announced | Green-electricity and secondary-material commitments for battery cells (up to −60% cell footprint) | [35] (C) |
| | L1 | Standard | Production facilities worldwide supplied entirely with green electricity; 50 ha PV at Debrecen | [35, 36] (C/D) |
| | L2 | Deployed | About 70% of press-shop offcuts recycled; closed-loop aluminium with Novelis; low-$CO_2$ steel agreements | [35, 26] (A/C) |
| Volkswagen Group | S2 | Deployed | Fully electric paint shop (electric drying and electric RTO) at a high-volume plant, about −40% paint-shop $CO_2$ | [48, 39] (C) |
| | S3b | Deployed | Cell production for the ID. models powered exclusively by green electricity | [39] (C) |
| | L1 | Standard | All European production sites draw renewable electricity; Zwickau −66% $CO_2$ vs 2010 | [39] (C) |
| | L2 | Deployed | Closed-loop aluminium through a Porsche press-shop joint venture with Novelis | [26] (A) |
| Mercedes-Benz | S4 | Deployed | Factory 56 (S-Class assembly): about 25% less energy, rooftop PV, DC grid, second-life battery storage | [40] (C) |
| | L1 | Standard | Exclusively renewable electricity purchased in Germany since 2022 | [40] (C) |
| | L2 | Deployed | Green-steel offtake; press-shop scrap returned to the steelmaker by rail | [40] (C) |
| Toyota | L1 | Deployed | About 79% renewable factory electricity globally (FY2025); fuel cells at the Honsha plant | [41] (B) |
| Volvo Cars | S1 | Announced | Mega-casting project linked to the 2040 climate-neutrality goal | [21] (C) |
| | L1 | Announced | Climate-neutral operations as a stated goal (not quantified) | [42] (C) |
| | L2 | Deployed | Near-zero steel from a hydrogen-based producer; closed-loop aluminium with Novelis | [42, 26, 27] (A/C) |
| Stellantis | S2 | Standard | Company-wide “Paint in Numbers” programme: −27% paint-shop energy vs 2021; 4WET at Vigo | [6] (C) |
| Ferrari | S2 | Deployed | Coating that lowers oven temperature from 150 to 100 °C for aluminium and carbon-fibre bodies | [31] (B) |
| | L1 | Deployed | Gas-fired trigeneration shut down in 2024; 5 MWp on-site PV, 10 MWp planned by 2030 | [31] (B) |
| Lamborghini | L1 | Standard | Site carbon-neutral on-balance since 2015 via trigeneration, PV, district heating, efficiency | [32] (B) |

the leaders: Lamborghini's site has been carbon-neutral on-balance for a decade, and Ferrari has moved off gas-fired trigeneration. The paint shop (S2) is the second area of visible process practice, as the maturity–impact map of Chapter 3 predicted: a company-wide programme at Stellantis, fully electric paint shops at a Volkswagen plant and at BMW Debrecen, and lower-temperature curing at Ferrari.

Second, breadth tracks scale and disclosure. BMW and Volkswagen show evidence in four of the seven columns and Mercedes-Benz in three, whereas the smaller or more specialised producers show a single area of deployed practice: Stellantis in the paint shop, Volvo in circularity, Lamborghini in energy. The final-assembly column (S4) is almost empty. Its measures are mature and low-impact (Section 3.6), and only Mercedes-Benz, with Factory 56, reports an assembly plant as a decarbonisation project in its own right. Third, the *circularity* column (L2) is concentrated. Deployed practice appears only where a closed-loop or low-carbon supply agreement with a materials producer exists: BMW, Volkswagen (through a Porsche press-shop joint venture) and Volvo with Novelis for aluminium, and BMW, Mercedes-Benz and Volvo with steelmakers. Closed loops require a supplier relationship that not every manufacturer has built or disclosed.

The fourth reading concerns the thermal-powertrain column (S3a), and it is the most striking: the column is empty. Almost every manufacturer in the sample still builds thermal or hybrid powertrains, yet none discloses a decarbonisation programme specific to foundries, machining lines or heat-treatment furnaces. The nearest evidence is Toyota's hydrogen burner on a forging line, which the source does not attribute to the powertrain, and Ferrari's in-house foundry, which is documented but not covered by any disclosed foundry-specific measure. Elsewhere the engine plant is covered only by site-wide energy measures, which the matrix counts under L1. This is not evidence that nothing is happening; under the protocol of Section 2.5, absence of evidence is recorded as such. It is, however, a striking asymmetry against the reporting the same sample provides for battery manufacturing (S3b), where green-electricity supply and cell-footprint commitments are disclosed, and it is the basis of the fourth gap identified below.

## 4.5 Academia–industry gap analysis

The purpose of applying the same taxonomy in Chapters 3 and 4 was to make the two directly comparable. Setting the deployment matrix of Figure 4.1 against the maturity-versus-impact map of Figure 3.3 yields the central finding of this thesis, which can be stated as four gaps.

**Gap 1 — The diffusion gap: convergence where the technology is mature.** For most technologies that the literature places in the "high impact, deployable now" region of Figure 3.3, industrial practice has caught up at the leading manufacturers. Renewable-electricity procurement and on-site generation (standard or deployed at six of the eight manufacturers), reduced-stage and lower-temperature painting (Stellantis, Ferrari) and closed-loop aluminium (BMW, Volkswagen, Volvo) are all found at deployed-to-standard maturity in the matrix, and catalyst-metal recycling is standard practice in the supplier tier. In these areas academic state of the art and industrial practice coincide at the front of the industry, and the remaining constraint is diffusion to the rest of it, not invention. The one exception in this region, dry-room dehumidification, is discussed under Gap 2.

**Gap 2 — The scale-up gap: lag where the technology is high-impact but still maturing.** The largest divergence lies exactly where Chapter 3 predicted it would: in the "high impact, still maturing" technologies. Hydrogen-based green steel is assessed at TRL 7–8 and is offered by first commercial suppliers. In industrial practice, however, it appears only as supply agreements and as early, ramping deliveries: the first near-zero steel reached Volvo Cars in 2025, and BMW's agreements are intended to cover part of its European demand. The complete electrification of paint-shop heat is in series production at a few plants, BMW's new Debrecen plant and one Volkswagen plant, but not across existing plant networks. Dry-electrode cell manufacturing, rated TRL 6–8, does not appear in the disclosed practice of any manufacturer in the sample. Here the gap is not one of diffusion but of industrial maturation and supply-chain build-out: the technologies exist, but the volume does not yet. Two further technologies lag for different reasons. The energy digital twin (TRL 5–7) is rare in the literature and correspondingly rare in disclosed practice, but its expected impact is moderate rather than high. High-efficiency dry-room dehumidification, which Chapter 3 identified as decisive for cell manufacturing, is mature (TRL 8–9) but is found only among specialist adopters, not as a sector norm: its lag is one of diffusion, not of maturity.

**Gap 3 — The verification gap: reduction versus compensation.** A gap of a different kind emerges only when the source-reliability lens of Chapter 2 is applied to the language of the claims themselves. Several of the most prominent "carbon-neutral" statements—for a flagship plant (Mercedes-Benz Factory 56), a Tier-1 supplier (Bosch) and a Motor Valley site (Lamborghini)—are, on their own stated definitions, *net* of certified offsets [40, 43, 33]: residual emissions that have not been avoided or reduced are compensated. This does not make the claims false, but it

distinguishes genuine process decarbonisation from balance-sheet neutrality. For a manufacturing engineer the operative lesson is that the metric that matters is the absolute, offset-free emission per vehicle at the gate, and that part of the headline neutrality in the sample still rests on compensation rather than on the process and material changes catalogued in this work. Two observations sharpen this point. First, the reduction-versus-compensation distinction can only be drawn where disclosure is verifiable, and that is precisely what third-party certification provides. Independently audited Environmental Product Declarations and material certifications, for example for low-carbon steel and aluminium, are the concrete mechanism by which a claim earns Tier A status under Section 2.5. They are what allows the analyst to separate substantiated reductions from marketing. The same discipline must distinguish two kinds of material claim. A *physical* low-carbon material is fossil-free steel or high-recycled-content aluminium actually embodied in the vehicle. *Certificate*- or mass-balance-based accounting instead allocates a documented reduction elsewhere to a purchase. Both can be legitimate and independently assured, but they are not equivalent, and conflating them would understate the remaining physical decarbonisation task. Second, even a genuine process innovation can fail to reduce emissions if a material choice cancels it out. Gigacasting is the clearest case: consolidating parts is climate-positive only when the alloy is recycled. The gap analysis must therefore be read at the level of the whole cradle-to-gate balance, not of any single measure.

**Gap 4 — The attention gap: the blind spot of thermal-powertrain manufacturing.** A fourth gap appears only because this thesis assessed both powertrain branches with equal weight, and it runs in the opposite direction to the others. For stage S3b, evidence exists on both sides: the academic literature quantifies cell-manufacturing energy and emissions step by step, and the industrial evidence includes green-electricity cell production, cell-footprint commitments and recycling partnerships. For stage S3a, both sides are comparatively thin. The key machining-energy studies date from the 2000s and early 2010s, and the industrial disclosure surveyed in this chapter does not address engine plants as a decarbonisation target in their own right: the S3a column of Figure 4.1 is empty.

This asymmetry is easy to explain and hard to justify. Research attention and corporate reporting have both followed the strategic and regulatory shift towards electrification, which is where the new capital, the new processes and the political attention are. But most vehicles produced today still carry an engine: in 2025 about one quarter of new cars sold worldwide were electric, counting plug-in hybrids [67], so the other three quarters, and every plug-in hybrid, were built with a combustion engine. Moreover, the analysis of Section 3.5.3 showed that a hybrid carries *both*

powertrain burdens rather than an average of them. The consequence is a genuine blind spot: the emissions of melting, machining and heat-treating an engine are neither captured by the tailpipe regulation, which does not reach them, nor prioritised by the research and disclosure effort, which has moved on.

There is one important qualification, and it prevents this gap from being overstated. On the material side of S3a the picture is the reverse: catalyst-metal circularity is mature, industrialised and well documented, as Section 4.3 showed. The blind spot is therefore specific to the *process* side of thermal-powertrain manufacturing—the furnaces and machine tools—rather than to the thermal powertrain as a whole. That is a narrower claim than "industry ignores the engine plant," and it is the one the evidence supports.

## 4.6 Implications for the Motor Valley and bridge to the case study

The benchmarking places the two Italian high-performance manufacturers in a specific and instructive position. Their small volumes and high vehicle value make them less exposed to the battery-manufacturing emissions that dominate mass-market electric production. They are correspondingly more exposed to the embodied emissions of the light metals and composites from which their bodies and engines are built. At the same time, both are leaders on the energy lever.

The consequence is that, for a Maranello- or Sant'Agata-class vehicle, the decisive manufacturing-stage decision is not the electricity mix of the plant, which is already largely decarbonised. It is the origin of the structural material: primary or closed-loop metal. This applies twice over at Ferrari, because the same aluminium question governs both the body structure and the engine castings produced in the on-site foundry. That question is quantified, for a representative aluminium component and using Ferrari as the anchoring context, in the life-cycle case study that follows.

CHAPTER 5

# Life Cycle Assessment Case Study

The preceding chapters established, qualitatively and through the benchmarking, that the decisive manufacturing-stage lever for an aluminium-intensive, energy-decarbonised manufacturer is the origin of its structural material. This chapter tests that conclusion quantitatively. It develops a screening Life Cycle Assessment, conducted in accordance with the principles of ISO 14040 and ISO 14044 [1, 2], of the cradle-to-gate global-warming impact of a representative aluminium structural component, comparing primary and closed-loop recycled metal, and anchored in the Motor Valley context introduced in Section 4.6. Consistent with Section 2.7, it is explicitly a screening study: its role is to establish direction and order of magnitude transparently, not to make a certified comparative assertion.

## 5.1 Goal and scope

The *goal* is to quantify the difference in cradle-to-gate greenhouse-gas emissions between a structural aluminium component made from primary metal and the same component made from closed-loop recycled metal, and to attribute that difference between its material and its process origins so that the dominant lever is made visible.

The *functional unit* is one finished structural aluminium component of defined mass. Results are reported per kilogram of finished component, and are then scaled illustratively to a 20 kg component and to a 250 kg aluminium body-in-white. The body-in-white mass is a stated illustrative figure, not a manufacturer-specific one.

The component is deliberately defined by its *material and process class* rather than by its position in the vehicle, and this choice carries an important consequence for the reach of the results. The analysis applies to any cast or wrought aluminium structural part whose cradle-to-gate footprint is dominated by the metal it contains. A body panel or a subframe qualifies, and so does an *engine block or cylinder head*. The case study is therefore powertrain-agnostic in the same way the taxonomy is: it speaks to stage S1 and to the thermal powertrain stage S3a at once. This matters directly for the anchoring manufacturer, which casts engine blocks, heads and bedplates from aluminium in its own Maranello foundry (Section 4.2). For that company the question

quantified here—primary or closed-loop metal—is posed twice over, once for the body structure and once for the engine castings.

The *system boundary* is cradle-to-gate and comprises three contributions: the production of the input aluminium (primary or recycled), the semi-fabrication and component-manufacturing processing energy, and the plant electricity that drives it. The use phase and end-of-life are excluded, in keeping with the manufacturing-stage focus of the thesis. Recycled content is handled with a cut-off (recycled-content) allocation, in which secondary metal enters the system burdened only by its own recycling and re-melting emissions and not by the primary production of the scrap—a conservative and widely used convention for closed-loop systems. The single impact category assessed is Global Warming Potential, expressed in kg $CO_2$-eq.

Foreground context is taken from the disclosures of the anchoring manufacturer and graded Tier A/B under Section 2.5. It comprises the plant energy mix and the company's aluminium-intensive construction of both body and engine components. The life-cycle inventory of emission factors is taken from the ranges established in the literature of Section 3.8 and summarised below [23, 24, 25, 26].

## 5.2 Life cycle inventory

The inventory is deliberately compact and fully disclosed, so that every figure is traceable and the model reproducible. The cradle-to-gate GWP per kilogram of finished component is modelled as

$$G \;=\; \underbrace{\frac{1}{Y}\Big[r\,\mathrm{EF}_{\mathrm{rec}} + (1-r)\,\mathrm{EF}_{\mathrm{prim}}\Big]}_{\text{material production}} \;+\; \underbrace{E_{\mathrm{el}}\,\mathrm{CI}_{\mathrm{grid/ren}}}_{\text{processing energy}}, \tag{5.1}$$

where $r$ is the recycled content of the input metal, $Y$ the material yield (finished mass per input mass), $\mathrm{EF}_{\mathrm{prim}}$ and $\mathrm{EF}_{\mathrm{rec}}$ the emission factors of primary and recycled aluminium, $E_{\mathrm{el}}$ the processing electricity per kilogram of finished component, and CI the carbon intensity of that electricity. The central parameter values and the ranges used in the sensitivity analysis are given in Table 5.1. The two emission factors are taken from the literature ranges of Section 3.8. The material yield, the processing electricity and the grid carbon intensity are screening assumptions rather than measured values; Section 5.5 tests each of them over its range, and the primary-aluminium emission factor remains by far the most influential parameter.

**Table 5.1.** Life cycle inventory parameters (central values and sensitivity ranges).

| Parameter | Central | Range | Source basis |
|---|---|---|---|
| Primary Al $EF_{prim}$ (kg $CO_2$-eq/kg) | 12.0 | 8–16 | IAI; low-carbon primary ∼4 |
| Recycled Al $EF_{rec}$ (kg $CO_2$-eq/kg) | 3.0 | 2–4 | Secondary-Al literature |
| Material yield $Y$ (finished/input) | 0.70 | 0.60–0.85 | Screening assumption, tested in Section 5.5 |
| Processing electricity $E_{el}$ (kWh/kg) | 7.0 | 5–11 | Screening assumption, tested in Section 5.5 |
| Grid CI $CI_{grid}$ (kg $CO_2$-eq/kWh) | 0.35 | 0.25–0.45 | Screening assumption (European grid), tested in Section 5.5 |
| Renewable-plant $CI_{ren}$ (kg $CO_2$-eq/kWh) | 0.03 | – | On-site/renewable supply |

## 5.3 Impact assessment and scenarios

Three scenarios are defined to span the design space from worst to best case. Scenario A (primary, linear, grid) represents a component made entirely from primary aluminium in a linear supply chain with grid electricity. Scenario B (closed-loop, renewable) represents the best case of fully closed-loop recycled metal with renewable plant electricity. Scenario C (75% recycled, renewable) represents a realistic near-term configuration consistent with the 2030 industry recycled-content target and a decarbonised plant. The results are given in Table 5.2 and decomposed in Figure 5.1.

**Table 5.2.** Cradle-to-gate GWP results for the three scenarios (per kg of finished component, and scaled).

| Scenario | A: primary, linear, grid | B: closed-loop, renewable | C: 75% recycled, renewable |
|---|---|---|---|
| Material production (kg $CO_2$-eq/kg) | 17.1 | 4.3 | 7.5 |
| Processing energy (kg $CO_2$-eq/kg) | 2.5 | 0.2 | 0.2 |
| **Total (kg $CO_2$-eq/kg)** | **19.6** | **4.5** | **7.7** |
| Per 20 kg component (kg $CO_2$-eq) | 392 | 90 | 154 |
| Per 250 kg BIW (kg $CO_2$-eq)* | 4 900 | 1 120 | 1 930 |

* Illustrative body-in-white mass; a stated assumption, not a Ferrari-specific figure.

The headline result is unambiguous: moving from scenario A to scenario B reduces the cradle-to-gate GWP of the component by about 77 %, from roughly 19.6 to 4.5 kg $CO_2$-eq per kilogram. The realistic near-term scenario C already delivers about a 61 % reduction. Crucially, the decomposition shows *where* the reduction comes from. The material-production term falls from 17.1 to 4.3 kg $CO_2$-eq per kilogram, a 75 % reduction that accounts for the overwhelming majority of the total saving.

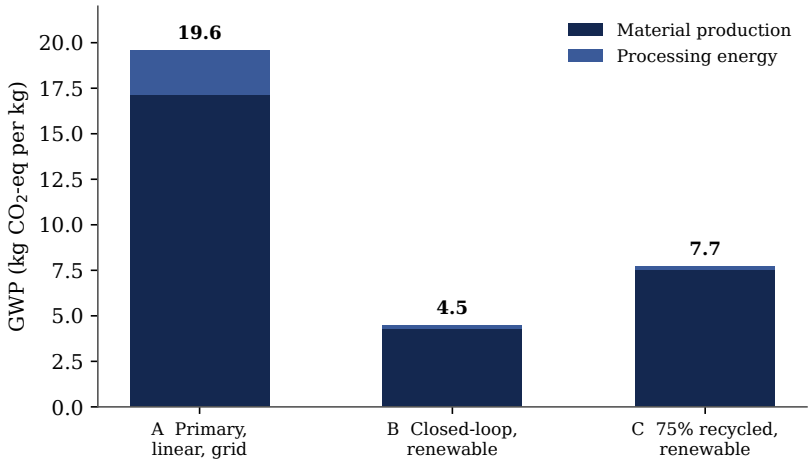



**Figure 5.1.** Cradle-to-gate GWP per kilogram of finished component for the three scenarios, decomposed into material production and processing energy.

The processing-energy term falls by an even larger proportion when the plant is decarbonised, from 2.5 to 0.2 kg $CO_2$-eq per kilogram, but it is small in absolute terms. This is the quantitative confirmation of the qualitative conclusion of Section 4.6: for an aluminium-intensive, already-decarbonised-plant manufacturer, the material origin dominates the manufacturing footprint.

## 5.4 Recycled content and electricity sensitivity

To generalise beyond the three discrete scenarios, Figure 5.2 traces the GWP as a continuous function of recycled content, for both grid and renewable plant electricity. Two features are salient. First, the strong negative slope with recycled content confirms that the material lever is the primary control on the footprint: increasing recycled content from zero to 100 % roughly quarters the material contribution. Second, the near-constant vertical gap between the two electricity curves—about 2.2 kg $CO_2$-eq per kilogram—represents the plant-electricity lever; it is real and worth capturing, but it is modest beside the range spanned by the material choice. The intersection of the two effects is the design message: the largest, most robust reductions come from securing high-recycled-content, closed-loop metal, with renewable plant electricity as a valuable but secondary complement.

## 5.5 Sensitivity analysis

Because the model of Equation 5.1 rests on secondary emission factors, its sensitivity to each parameter must be made explicit. Figure 5.3 is a tornado diagram showing

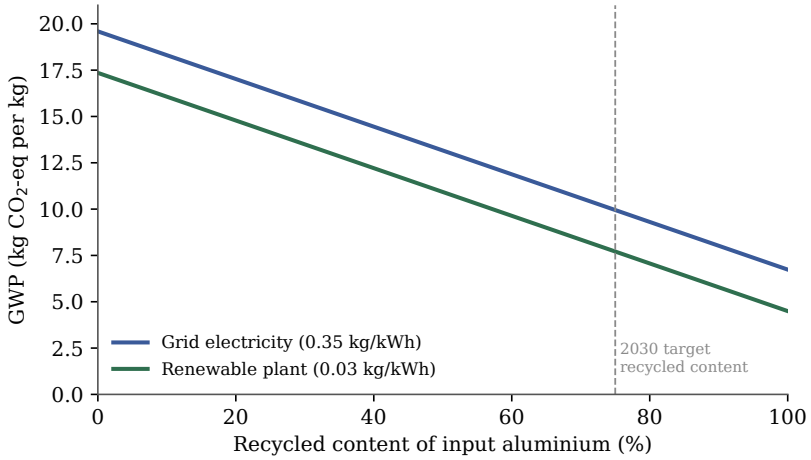



**Figure 5.2.** Cradle-to-gate GWP per kilogram as a function of recycled content, for grid and renewable plant electricity. The dashed line marks the 75% recycled-content industry target.

how the GWP of the worst-case scenario A varies as each parameter is swept across the range of Table 5.1. The result is decisive and, for the argument of this thesis, central: the GWP is by far most sensitive to the primary-aluminium emission factor, whose range alone moves the result across a wider band than all the other parameters combined. Material yield is the second most influential parameter; the processing-electricity quantity and the grid carbon intensity, which govern the process term, are comparatively minor. In other words, both the leverage and the uncertainty of the whole assessment reside in the primary-material term—the very term that closed-loop recycling removes. This simultaneously reinforces the headline conclusion and identifies the emission factor of primary aluminium as the parameter most in need of primary, verified data in any future full LCA.

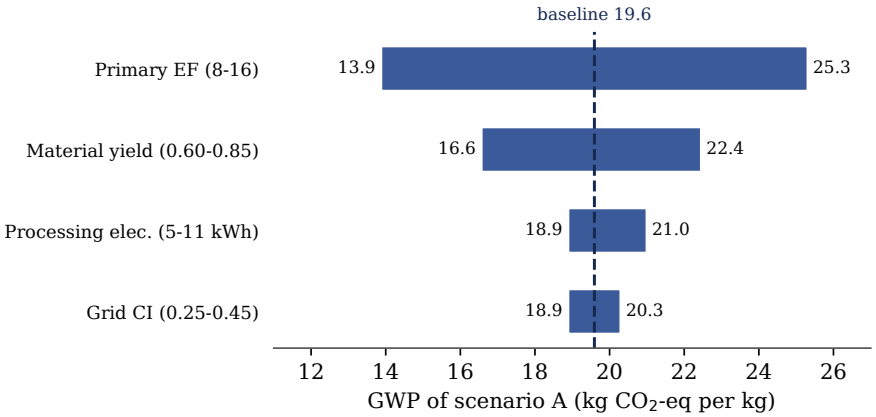



**Figure 5.3.** Tornado diagram: sensitivity of scenario A cradle-to-gate GWP to each inventory parameter, swept across the ranges of Table 5.1. The dashed line is the central-value baseline.

## 5.6 Interpretation, benchmarking and limitations

**Scaling and significance.** Scaled to a component or a body-in-white, the per-kilogram figures translate into substantial absolute differences: on the illustrative 250 kg aluminium body-in-white, the gap between the worst and best cases is of the order of 3.8 t of $CO_2$-eq per vehicle. For a manufacturer producing thousands of vehicles a year, the material-origin decision is therefore a multi-kilotonne annual lever, entirely within the manufacturing-stage boundary.

**Benchmarking against an external LCA.** As a sense-check of order of magnitude, the screening result can be read against the externally certified, ISO 14040/14044 vehicle LCA available in the Motor Valley segment (Section 4.2). The per-kilogram aluminium figures obtained here fall within the ranges implied by that certified study for the material contributions, which supports the use of the model for directional, order-of-magnitude conclusions while not claiming the precision of a full inventory-based assessment.

**Application to the thermal powertrain.** Because the functional unit was defined by material and process class rather than by vehicle position, the result transfers directly to engine castings. An aluminium cylinder block or head is a cast structural component whose cradle-to-gate footprint is likewise dominated by the metal it contains, so the same substitution—primary for closed-loop recycled alloy—yields a reduction of the same order. Two points make this more than a formality. First, it connects the quantitative core of this thesis to stage S3a, which Chapter 4 identified as the least well documented part of the industrial landscape. The material lever, at least, is measurable there, even where process-energy data are not disclosed. Second, it sharpens the carbon paradox of gigacasting discussed in Section 3.3. Large structural castings and engine castings share the same difficulty: cast alloys have conventionally been drawn from primary metal, and it is the recycled content of that alloy, not the casting process itself, that decides whether the part is a climate improvement. A foundry that melts secondary alloy and one that melts primary alloy perform the same operation to very different effect.

**Reconciliation of the recycling benefit.** A careful reader will note an apparent tension between the 75 % GWP reduction of the material term found here and the 95 % *energy* reduction commonly quoted for recycled aluminium (Section 3.8). The two are consistent: the 95 % figure refers to the process energy of remelting relative to primary smelting under best-case conditions, whereas the present figure is a *GWP*

reduction computed with central, average emission factors that also embed non-energy and collection-stage contributions. The verified supplier data of Section 4.3 reinforce the point. Renewable-powered *primary* aluminium, at about 4 kg $CO_2$-eq/kg, can approach recycled metal, whereas coal-powered primary approaches the top of the range. The dominant lever is therefore the combination of scrap content and smelter electricity, exactly as the recycled-content sweep and the tornado diagram indicate [24, 25]. Distinguishing the energy claim from the GWP outcome, and best-case from average, is itself part of the methodological discipline this thesis argues for.

**Transport.** Transport of metal and semi-finished parts was excluded from the core boundary as a minor contributor, but it is amenable to the same closed-loop logic. Where a closed loop is organised with low-carbon logistics, the transport term shrinks further: in a documented automotive closed-loop aluminium system, shifting sheet transport from road to rail cut the associated transport emissions by about 68 % [26]. Because the absolute transport contribution per kilogram of finished metal is small beside the material-production term quantified above, its inclusion would not change the direction or order of magnitude of the result; it does, however, reinforce the conclusion that circularity is a systemic property—of material, energy and logistics together—rather than a single substitution.

**Limitations.** The study's limitations follow directly from its screening nature and are stated plainly. It relies on secondary, average emission factors rather than primary supplier data. It assesses a single impact category, GWP, so trade-offs in other categories such as acidification, eutrophication and resource depletion are not captured, and recycling's benefit there is not verified. It uses a cut-off allocation, which is a conservative but not a unique choice. Finally, it uses the anchoring manufacturer for context and order-of-magnitude benchmarking, not for component-level primary process data. Within these bounds, the central finding—that closed-loop recycled aluminium reduces the cradle-to-gate GWP of a structural component by roughly three-quarters, with the material term dominating—is robust in both direction and magnitude, and it is the quantitative core of the thesis's conclusions.

CHAPTER 6

# Conclusions and Future Developments

## 6.1 Summary of findings

This thesis set out to characterise sustainable manufacturing in the automotive industry from two complementary perspectives—the academic state of the art and actual industrial practice—bound together by a single analytical framework, and to test its central conclusion quantitatively through a life-cycle case study. The unifying instrument was a process-stage taxonomy (stamping and body-in-white, paint shop, powertrain and battery, final assembly) complemented by two cross-cutting levers (energy management and material circularity), applied identically throughout so that theory and practice could be compared directly.

The academic assessment of Chapter 3 produced a clear structural picture, captured in the maturity-versus-impact map. The stages with the most mature enabling technology, namely the body shop, final assembly and the process side of the thermal powertrain, offer the smallest remaining emissions headroom. Where the headroom is large, the levers split into two groups. Low-carbon electricity, on-site generation, reduced-stage and low-cure painting and closed-loop aluminium are deployable now. Hydrogen-based green steel, the electrification of process heat, dry-electrode cell manufacturing and battery recycling are still maturing. The paint shop occupies a uniquely favourable position, with large headroom addressed largely by technologies already at or near full deployment.

The industrial benchmarking of Chapter 4 mapped real practice onto the same framework and yielded the analytical core of the thesis in the form of four gaps. Where technologies are mature and deployable—renewable electricity, on-site generation, reduced-stage painting, closed-loop aluminium—academic state of the art and industrial practice coincide at the leading manufacturers, and the binding constraint is diffusion and capital rather than invention. Where technologies are high-impact but still maturing—green steel, dry electrode, oven electrification—a genuine lag persists, one of industrial maturation and supply-chain build-out rather than of knowledge. A

gap of a different kind emerged once the source-reliability discipline was applied to the language of corporate claims. Part of the headline "carbon neutrality" in the sample rests, on the companies' own stated definitions, on compensating residual emissions through offsets rather than eliminating them. Only verifiable, third-party-certified disclosure allows an analyst to draw that distinction.

A fourth gap emerged only because the two powertrain branches were assessed with equal weight. For battery manufacturing, both the literature and corporate reporting are detailed. For the *process* side of thermal-powertrain manufacturing—foundry melting, machining and heat treatment—both are comparatively thin, even though most vehicles built today still contain an engine. Research attention and disclosure have followed the strategic shift to electrification, while the tailpipe regulation does not reach manufacturing emissions at all. The result is a blind spot. It is a narrow one, since catalyst-metal circularity is mature and well documented, but it sits precisely where the Motor Valley manufacturers operate.

The Life Cycle Assessment of Chapter 5 confirmed the thesis's central quantitative claim. Consider a representative aluminium structural component. Switching from primary metal in a linear, grid-powered configuration to closed-loop recycled metal in a decarbonised plant reduces the cradle-to-gate global-warming impact by about 77 %, from roughly 19.6 to 4.5 kg $CO_2$-eq per kilogram. The material-production term, not the plant electricity, accounts for the overwhelming majority of that reduction. Sensitivity analysis identified the primary-aluminium emission factor as by far the dominant parameter, confirming that both the leverage and the uncertainty reside in the material term that closed-loop recycling addresses.

## 6.2 Answers to the research questions

The five research questions of Chapter 1 can now be answered directly. **RQ1**: in the academic state of the art, organised by process stage, the most mature stages have the least remaining headroom, and the high-headroom areas split into levers that are deployable now and levers that are still maturing. **RQ2**: the leading manufacturers have industrialised the mature, deployable technologies—above all on the energy lever, where renewable electricity and on-site generation are standard or deployed at six of the eight manufacturers, including both Motor Valley producers—while high-impact emerging technologies appear only at a minority of front-runners, and no manufacturer discloses a decarbonisation programme for its engine plants. **RQ3**: the academia–industry gap is not monolithic. It comprises a diffusion gap, closing at the leading manufacturers; a scale-up gap, which is real for green steel, dry electrode and the electrification of process heat; a verification gap between reduction and com-

pensation, visible only through verified disclosure; and a gap of attention, in which the *process* side of thermal-powertrain manufacturing is under-researched and under-reported by both academia and industry. **RQ4**: the material lever is quantitatively decisive, with closed-loop recycled aluminium reducing an aluminium component's cradle-to-gate carbon by roughly three-quarters, an effect that decarbonised plant electricity complements but cannot substitute for. **RQ5**: the three powertrain architectures differ substantially at the manufacturing stage. An internal-combustion engine entails about 0.65 t of $CO_2$-eq from cradle to gate, while the cells of even a modest 20 kWh traction battery entail 1.2 t to 1.8 t, roughly two to three times that. The hybrid, however, is not an intermediate case: it carries a full thermal powertrain *and* a battery with its e-drive, so its manufacturing burden is closer to the sum of the two than to their average. A manufacturer's powertrain mix, not merely its share of electrification, therefore determines its manufacturing footprint.

## 6.3 Contributions

The principal contribution of the thesis is methodological as much as empirical: the demonstration that applying a *single* process-stage taxonomy and a *common* maturity-and-metrics framework to both the academic literature and industrial practice turns two otherwise separate surveys into a structured gap analysis. The explicit source-reliability protocol, together with the definitions of climate-claim terminology that accompany it, is a transferable safeguard against greenwashing: it is what allows substantiated reductions to be separated from balance-sheet neutrality. A further contribution follows from treating both powertrain branches with equal weight. It makes visible the additive manufacturing burden of the hybrid, and it exposes the asymmetry of attention between battery and engine manufacturing that neither branch of the literature had reason to notice on its own. The screening LCA, anchored in the Motor Valley context and benchmarked against an externally certified vehicle LCA, provides a concrete, reproducible quantification of the material lever and a worked demonstration of the metrics the framework defines.

## 6.4 Limitations

The findings must be read within the limitations set out in Chapters 2 and 5. The literature review, though structured, is not a formal meta-analysis. The industrial benchmarking depends on the completeness and honesty of corporate disclosure; the reliability hierarchy mitigates but cannot eliminate this dependence, and absence of evidence was recorded as such rather than interpreted as absence of practice. The

LCA is a screening study built on secondary emission factors, assessing a single impact category (global-warming potential) with a conservative cut-off allocation, and using the anchoring manufacturer for context rather than for component-level process data. Within these bounds, however, the direction and order of magnitude of the conclusions are robust.

## 6.5 Future developments

Several avenues would extend this work. The most immediate is to replace the screening LCA with a full, ISO-compliant assessment based on *primary*, supplier-specific and third-party-verified inventory data, above all a verified primary-aluminium emission factor. That assessment should also reach beyond global-warming potential to categories such as acidification, eutrophication and resource depletion, in which recycling may behave differently.

A second direction is to track, over time, the diffusion of the high-impact but immature technologies identified here: green steel, dry-electrode manufacturing, paint-shop oven electrification and the energy digital twin. This would allow the scale-up gap to be measured as it closes.

A third direction follows from the fourth gap. The process side of thermal-powertrain manufacturing needs current, primary data: measured specific energy consumption of foundry melting and of engine machining lines, and an assessment of how far furnace electrification and waste-heat recovery have actually penetrated engine plants. Much of the existing quantitative literature predates the electrification shift, and the corresponding corporate disclosure is thin. Closing that evidence gap would also make it possible to put the hybrid dual-burden comparison of Section 3.5.3 on a firm inventory basis rather than on published central values.

A fourth is to deepen the Motor Valley focus with plant-specific studies of aluminium, engine-casting and carbon-fibre processing. These should include the carbon paradox of gigacasting, where the sustainability of a promising process innovation hinges entirely on the recycled content of its alloy.

Finally, the reduction-versus-compensation distinction invites systematic, longitudinal scrutiny of corporate neutrality claims against verified, offset-free emissions per vehicle, which is the metric that this thesis has argued ultimately matters. This line of work is about to become considerably more consequential: from September 2026, European law prohibits consumer-facing product claims of climate neutrality that rest on offsetting outside the value chain [57]. Together with the Carbon Border Adjustment Mechanism and the Battery Regulation, which turn embodied carbon into a direct cost, these instruments make the analytical discipline developed

here—measuring maturity, demanding verified data, and quantifying the material lever—steadily more valuable in practice.

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