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Report on Material Stock Accounts for Buildings and Mobility

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Developing circular pathways for a EU low-carbon transition

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Executive Summary

The European Union (EU), in its ambition to achieve resilience and sustainability, faces the critical challenge of optimizing the resource management of its existing material stocks. Demand for buildings and infrastructure is the predominant driver of material extraction and production, causing greenhouse gas (GHG) emissions and environmental impacts along supply chains. These materials form the backbone of European society, providing essential functions including shelter and mobility. Yet, their efficiency in fulfilling these societal needs varies significantly across locations and provisioning systems.

In line with key policies and programs such as the Green Deal and the Circular Economy Action Plan, achieving greater material efficiency is a core goal of the EU. However, realizing this ambition through reduce, reuse and recycling strategies requires comprehensive understanding of where and how much material stocks already exist in buildings, transport infrastructure, and vehicles, and how they are currently utilized.

This report contributes to this understanding by providing detailed estimates of material stocks in buildings, transport infrastructure, and vehicles across the EU. Through high-resolution accounts distinguishing between building types, vehicle categories, and infrastructure locations, this report reveals the diversity of material stocks and utilization patterns across the EU's territory, providing essential evidence for policy development and strategic investment in the circular economy.

The following summary insights emerge from the European coverage as well as high spatial and thematic resolution on material stocks presented in this report:

- Residential buildings, local and tertiary roads and combustion-engine passenger cars cover more than half of material stocks in buildings, transport infrastructure and vehicles, respectively.
- More than 95% of concrete, wood, bricks and glass is contained in buildings rather than transport infrastructure or vehicles. Buildings also contain the majority of steel (82%, 3.2Gt), copper (72%, 15Mt) and plastics (54%, 99Mt). Yet, almost half of the plastics quantified in this report are in vehicles (84Mt), as well as two thirds of aluminum (77Mt) and critical materials such as lithium and cobalt.
- Building and transport infrastructure material stocks concentrate in cities. Yet, most building material stocks are located in regions that are projected to face population decline. Building material intensity per resident is particularly high in rural and suburban areas (132t/cap compared to 82t/cap in urban areas), even for residential buildings alone.
- Material stocks in transport infrastructure consist primarily of aggregates (sand, gravel, stones) and asphalt. Bridges and tunnels as present in the Alpine region and railways as particularly present in Central Europe contain 4-6% of highly GHG emissions-relevant concrete and steel stocks. Still, even accounting for bridges, tunnels and railways, more steel is contained in vehicles (443Mt) than in transport infrastructure (254Mt). Per capita material stocks in vehicles are particularly high in rural areas where large light-duty vehicles and heavy-duty vehicles are more prominent.
- Compared to previous work, the estimates presented in this study are on the larger end. Integration of cadaster, crowd-sourced and satellite-derived data in EUBUCCO allowed a more complete coverage of material stocks in buildings, whereas the consistent compilation

of vehicle material intensities (VMI) allowed for differentiation between various rail and road vehicles. While the aggregate total mass of material stocks indicated here needs to be evaluated against other estimating efforts, the particular value of this report lies in the detail it provides with regards to location, composition and type of structures that contain the materials.

Keywords

Material stocks, Geospatial data, Built environment, Vehicle material intensity

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Abbreviations

BE	Battery electric
BEV	Battery electric vehicle
CircEUlar	Developing circular pathways for a EU low-carbon transition
EPA	Environmental Protection Agency
EPD	Environmental product declaration
EU	European Union
EU27+3	30 European countries including all 27 European Union Members as of 2021, Norway, Switzerland and the United Kingdom
EUBUCCO	3D building cadaster of individual buildings across Europe
EV	Electric vehicle
FCV	Fuel cell vehicle
GEM	Global Exposure Model

Gt	Giga tonne
HDV	Heavy duty vehicle
HEV	Hybrid electric vehicle
HVAC	Heating, ventilation and air conditioning
IAM(s)	Integrated Assessment Model(s)
ICE	Internal combustion engine
LCA	Life cycle assessment
LDV	Light duty vehicle
LFP	Lithium iron phosphate battery
MI	Material intensity
Mt	Mega tonne
NCA	Lithium nickel cobalt aluminium oxides battery
NMC	Lithium nickel manganese cobalt oxides battery
NUTS	Nomenclature of territorial units for statistics
OEM	Original Equipment Manufacturer
OSM	OpenStreetMap
PHEV	Plug-in hybrid electric vehicle
RASMI	Regional Assessment of Buildings' Material Intensities
SUV	Sport utility vehicle
VMI	Vehicle material intensity
WP	Work Package
xl	Extra large

Report on material stock accounts for buildings and mobility

1. Introduction

In its ambition to achieve resilience and sustainability, the European Union (EU) faces the critical challenge of optimizing the resource management of its existing material stocks. Materials accumulating in buildings and infrastructure are the predominant source of anthropogenic resource use, and the production of such material has large energy requirements and environmental emissions along supply chains (Hertwich, 2021). Wiedenhofer and Streeck et al. (2024) estimate that more than three thirds of global material stocks are contained in buildings and transport infrastructure, and around 10% of emission-intensive metals are locked up in vehicles. 20% of global material is stored in the EU despite housing only 9% of the world population (Wiedenhofer and Streeck et al. 2024). These materials form the backbone of European society, providing essential functions including shelter and mobility. Yet, their efficiency in fulfilling these societal needs varies significantly across locations and provisioning systems.

In line with key policies and programs such as the Green Deal and the Circular Economy Action Plan, achieving greater material efficiency is a core goal of the EU. Reducing, reusing and recycling material that already exists would not only make the EU more independent of volatile raw material prices and those controlling critical raw materials (Baldassarre, 2025); it could also make room for countries that are yet to build up material capital in line with Sustainable Development Goals and global equity. However, realizing this ambition requires comprehensive understanding of where material stocks exist and how they are currently utilized.

This report contributes to this understanding by providing detailed estimates of material stocks in buildings, transport infrastructure, and vehicles across the EU member states, Norway, Switzerland and the United Kingdom (EU27+3). Through high-resolution accounts distinguishing between building types, vehicle categories, and infrastructure locations, this report reveals the diversity of material stocks and utilization patterns across the EU's territory, providing essential evidence for policy development and strategic investment in the circular economy.

Recent years have seen a significant increase in both the number and spatial resolution of estimates for construction material stocks and vehicle material stocks. Top-down approaches have disaggregated key sector accounts of the construction and manufacturing industry to trace materials from source to stock (Wiedenhofer and Streeck et al. 2024; Streeck et al. 2023; Yu et al., 2017; Chang et al., 2014). Statistical offices such as EUROSTAT provide estimates of existing buildings, road and rail networks and vehicles at the national level complementing economic accounts (EU Directorate-General for Energy, 2025; Eurostat, 2025). Researchers have harmonized material intensities from various case studies for relevant building, transport infrastructure and some vehicle archetypes (Fishman et al. 2024; Wiedenhofer et al. 2024, Pauliuk et al. 2021). Together these infrastructure and material intensity accounts have given rise to numerous studies estimating material in national building and infrastructure stocks.

Spatially explicit estimates of material stocks across the Europe are becoming more common, and the growth of higher resolution (open) descriptions of built environments through cadaster and remote sensing data enables stock estimates with increasing spatial resolution and higher accuracy. High resolution stock estimates at the building and block level were pioneered by (Tanikawa & Hashimoto, 2009) for sections of cities. More recently, high resolution estimates on spatial grids of down to 10m are available for entire countries and world regions, and down to 90m globally (Haberl et al., 2021; Wiedenhofer et al. 2024; Haberl et al. 2024; Peled & Fishman, 2021). High resolution material stock estimates finetuned to specific locations, often termed 'secondary resource cadasters' (Kleemann et al., 2017; Lanau & Liu, 2020; Miatto et al., 2019), can underpin better estimates of future inflows and outflows, and thereby circularity potential, especially when combined with information on infrastructure age and type (Wuyts et al., 2022). The mapping of material stocks across the entire EU as provided in this report further enables comparative analysis between places and provides essential information to local resource managers.

While estimates of future material inflows and outflows are necessary for assessing circularity potential, the circularity potential is further constrained by technical (e.g. material separation and recovery technologies), economic (e.g. labor costs and global trade), and regulatory restrictions (e.g. limits on the permitted use of recycled materials in different applications) which are beyond the scope of this report (Schiller et al., 2017).

This report builds on the existing research by offering block-level estimates of material stocks in residential and non-residential buildings and transport infrastructure, next to vehicle fleet material stock accounts based on individual models of different vehicle archetypes with various energy and drive train options, spanning cars, buses, trains and more to cover the broader rolling stock. The report is structured as follows: Section 2 summarizes the methodology applied to estimate the material stocks for each of the three material uses (buildings, transport infrastructure, vehicles). Section 3 presents the resulting material stock estimates for each of the uses for the entire EU27+3, at higher geographical detail, and highlighting notable differences at more granular resolution. Section 4 compares the estimates of this study to other approaches and offers future avenues for high-resolution material stock estimates.

2. Methods: Stock modelling approaches

The following section describes the specific procedures taken to construct the estimates of material stock in buildings, transport infrastructure and vehicles separately. Across the three stocks the approach is similar in that an estimate of the total stock of service units (*u*) such as buildings, transport infrastructure and vehicles by archetype (*i*) is combined with harmonized archetype-specific material intensities (*m*) to yield the total stock of material (*s*) in each of the archetypes of service units.

$$S = \sum s_i = \sum u_i \cdot m_i$$

2.1. Buildings

The approach to estimate and map material stocks in buildings at a high spatial resolution builds on 1) building stock mapping, 2) material stock mapping on top of 1) (Figure 1 Share of number of building footprints in EUBUCCO v1 by data source as used for this report at national scale (top) and by NUTS3 region (bottom).

). The entire workflow was written in Python, with additional visualization conducted in ArcGIS.

2.1.1. Building stock mapping

The building stock mapping is based on the scientific dataset EUBUCCO v1.0, a 3D building cadaster that describes 320 million individual buildings across Europe in terms of their footprint geometry, height, number of storeys, and functional use type. Functional use types are categorized as commercial, industrial, or residential, and residential buildings are further subdivided into single-family houses, terraced houses, and multi-dwelling apartment buildings (Table 1).

EUBUCCO v1.0 integrates official governmental cadaster data, volunteered OpenStreetMap data, and satellite-derived data from Microsoft Building Footprints using a novel machine learning–based conflation framework. In the first step, building footprints from different sources are spatially aligned and matched based on 87 geometric shape characteristics and contextual indicators. Subsequently, footprints and their attributes are systematically merged and validated across data sources. Missing values for height and usage type are imputed using the machine learning algorithm XGBoost, as detailed in Milojevic-Dupont et al., forthcoming. Compared to EUBUCCO v0.1, this version offers significantly improved completeness, with additional buildings incorporated from OpenStreetMap and Microsoft where gaps existed in government data (Milojevic-Dupont & Wagner et al., 2023).

Our analysis reveals that relying solely on governmental or OpenStreetMap (OSM) data leads to spatially incomplete and geographically biased inventories, which highlights the need for integrating satellite-derived data alongside robust conflation methodologies (Figure 1). Additionally, commonly used intersection-based matching approaches, without prior spatial alignment, omit approximately one-quarter of true building matches, causing duplicates, limiting attribute enrichment, and erroneously excluding numerous buildings. Compared to the earlier version (EUBUCCO v0.1), these methodological improvements yield a 59% increase in the number of buildings and a 6-33% increase in ground-truth building attributes. The integration of multiple sources allows for a transparent assessment of data completeness and supports validation of building attributes through cross-source comparison.

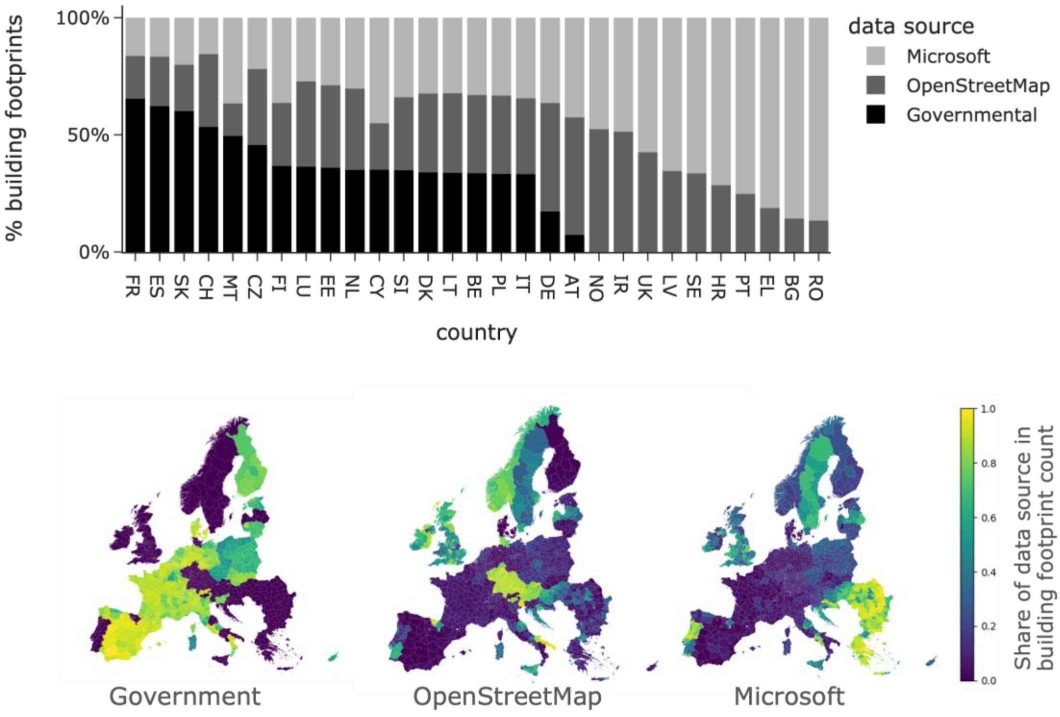

Figure 1 Share of number of building footprints in EUBUCCO v1 by data source as used for this report at national scale (top) and by NUTS3 region (bottom).

2.1.2. Material stock mapping

For the material stock mapping, we estimate material stocks in residential and non-residential buildings for eight major construction materials at building or block level in the 27 EU member states, and the UK, Norway and Switzerland. To do so, we combine the best available harmonized cadaster of European buildings at building level EUBUCCOv1.0 (Milojevic-Dupont & Wagner et al., 2023) with the recently developed globally harmonized database RASMI that provides material intensity per floor area for concrete, steel, bricks, wood, glass, copper, aluminum, and plastics (Fishman et al., 2024).

To attribute RASMI material intensities to the buildings in EUBUCCO, several steps are conducted. An overview of the workflow is presented in Figure 2*.* Except where number of floors are available from the official accounts that form part of EUBUCCO, floor area of buildings in EUBUCCO is based on the building footprint and the building height assuming an average floor height of three meters. RASMI operates as a multidimensional classification system: indicating material intensity per structural type, functional use type and the world region (Table 1). To attribute building material intensities from RASMI to the buildings in EUBUCCO, individual buildings are classified into structural types based on their geometry, location and use type as available in EUBUCCOv1.0. The classification is based on subnational regional counts of buildings by use type, structural type and height provided by the Global Exposure Model (GEM) which draws on local building practices and regulations (Yepes-Estrada et al. 2023).

Table 1 Overview of building typology across the three main data sources.

	EUBUCCO	GEM	RASMI
Spatial Resolution	Building level	Subnational regions	Country groups (EU15, EU12-High-income, EU12-Middle-income)
Functional Type	Residential detached single-family building	Residential	Residential single-family building
	Residential semi-detached duplex house	Residential	Residential single-family building
	Residential terraced house	Residential	Residential multi-family building
	Residential apartment block	Residential	Residential multi-family building
	Commercial building	Commercial	Non-residential building
	Public building	Commercial	Non-residential building
	Industrial building	Industrial	Non-residential building
	Agricultural building	Industrial	Non-residential building
	Other building	Industrial	Non-residential building
Structural Type		Unreinforced masonry	Masonry structure
		Confined masonry	Masonry structure
		Reinforced concrete	Concrete structure
		Precast concrete	Concrete structure
		Steel	Steel-frame structure
		Wood	Wood-frame structure
		Rammed earth	Wood-frame structure

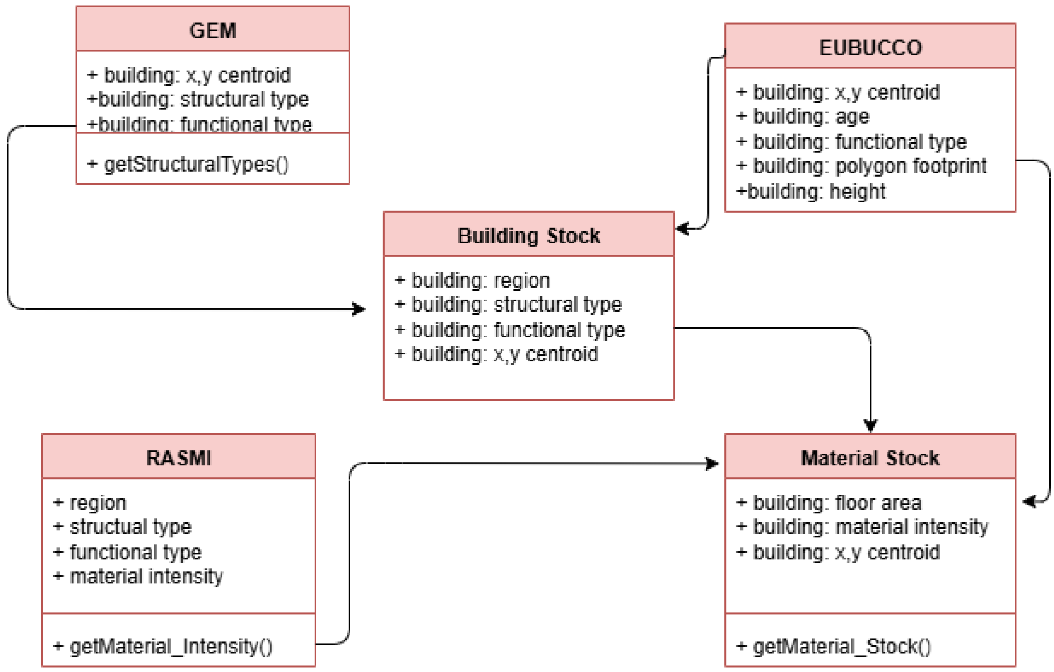

Figure 2 Process of determining material stock of a building.

While the output of this calculation has building level resolution, we present the results here at a 1km grid that aligns with EU population counts and allows to display material intensity per capita (EUROSTAT, 2025).

2.2. Transport Infrastructure

We designed a workflow to classify and process geographical features from crowd-sourced, publicly available data to map transport infrastructure networks, which together with material intensities per infrastructure types, are then used to estimate the respective material stocks.

2.2.1. Inventories of infrastructure

We primarily use data from OpenStreetMap (OSM), a collaborative project that provides free and editable maps of the world. OSM data includes various types of geographical features such as points (e.g., EV charging stations), lines (e.g., roads), and polygons (e.g., parking spaces). The data is unstructured in that each feature may possess one or more key-value pairs providing additional information. The use of tags and their values is not enforced but usually adheres to OSM conventions that allow to classify the data according to its properties. OSM data is available globally, but since it relies on users to add and update features, coverage and accuracy can vary substantially. North America and Europe have very active OSM communities, while Africa and the Middle East do not[1]. The data was downloaded in the course of August-September 2024 from the Geofabrik, BBBike and OSMfr mirrors[2].

To process and tile the data, the workflow uses the Global Administrative Boundaries (GADM) dataset version 4.1, released in July 2022[3]. The GADM dataset is compiled from various sources and includes territorial boundaries for 263 countries, autonomous regions and disputed territories. GADM distinguishes between countries and their autonomous regions at the top-level, consequently entities such as overseas departments (e.g., French Guiana) are not included in the national boundaries of France and the respective country statistics.

2.2.2. Infrastructure stocks workflow

The workflow was exclusively written in Python, with additional error checking and visualization conducted in QGIS. The workflow iterates over all administrative boundaries provided by the GADM dataset and processes data excerpts at a subdivision level, depending on availability and the boundaries size. This ensures that the processed data tiles are of roughly equal size, fit into the main memory, and can be processed in parallel. The QuackOSM library[4] was used to retrieve the raw data from the OSM mirrors (Figure 3a) and bring it into a Python compatible GeoParquet format. Initially, all features are pulled that possess a tag of any value that may be used in the classification.

[1] https://osmstats.neis-one.org/?item=countries
[2] https://download.geofabrik.de, https://extract.bbbike.org, https://tile.openstreetmap.fr
[3] https://gadm.org
[4] https://kraina-ai.github.io/quackosm

The features are classified into a specific category if their tags match the user provided scheme (see Table 2), while unclassified features are discarded.

Once classified, all features are transformed into polygons (Figure 3b). Line and point features, such as roads, rails, are buffered with a specific width to model the surface areas they occupy (see Table 2 for original shape types per infrastructure class). This provides a fairly accurate spatial representation of line features, while for point features this is necessarily a very crude approximation of their extent. To indicate this, point feature areas are represented as circles. The workflow differentiates assumptions about surface areas and widths by country, to account for local differences in construction. If no country specific values are set, global defaults are used.

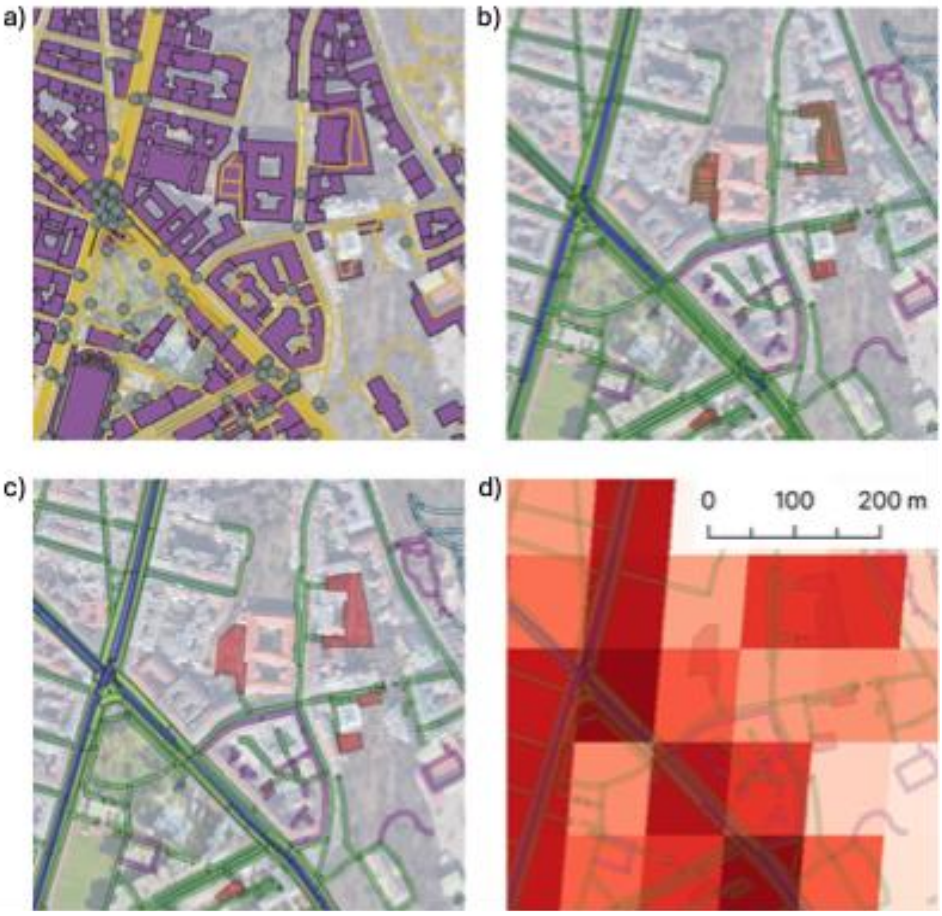

Figure 3 a) OpenStreetMap raw data; b) Classified mobility infrastructure with modelled areas; c) Classified data after conflict resolution; d) Stock raster after multiplying feature area with material intensity.

This creates explicit spatial extents for all features but introduces overlaps between the features that need to be removed. Overlaps exist primarily within each category, e.g., when local roads intersect at junctions, but can also exist between different feature classes that are mutually exclusive. The vast majority of these are overlaps between roads and parking surfaces, which are often mapped on top of each other in OSM data. Resolving these conflicts (Figure 3c; see Appendix for more details) is computationally expensive but improves overall accuracy of the surface estimates. The classified features with their modelled areas then serve as the model input data for the processing of various derived model output data products. For the EU27, the workflow creates ca. 65 million classified polygon features.

In some cases, such as buildings (railway station buildings, gas station buildings, parking garages), additional OSM information were used such as the number of floors. In that case, the area is multiplied by the number of floors. If, however, the floor number of a building is not available, an average number of floors is assumed. Consequently, for parking buildings an average of three floors is assumed, while for underground parking garages, an average of two floors is assumed. For all other building types (gas station buildings, station buildings), an average of one floor is assumed. These likely conservative assumptions are supposed to counterbalance the expected bias in tag use with structures with more floors being more likely to be tagged with information regarding the actual number of floors.

Based on combinations of OSM tags and definitions of those (Ramm, 2022; OpenStreetMap, 2024), 32 unique infrastructure classes were produced (see Table 2).

Table 2 Overview of final infrastructure categories based on OpenStreetMap tags.

Main category	**Infrastructure class**	**OpenStreetMap tags**	**Shape type**
Roads	Motorways	highway=motorway	line
		highway=motorway_link	
	Primary roads	highway=trunk	
		highway=trunk_link	
	Secondary roads	highway=primary	
		highway=primary_link	
	Tertiary roads	highway=secondary	
		highway=secondary_link	
	Local roads	highway=tertiary	
		highway=tertiary_link	
		highway=service	
		highway=residential	
		highway=living_street	
		highway=pedestrian	
		highway=footway	
		highway=cycleway	
		highway=unclassified	
		highway=unknown	
	Rural roads	highway=track	

Road infrastructure	Motorway bridge/tunnel	Same as 'Roads' category with tags: bridge=yes / tunnel=yes	
	Primary road bridge/tunnel		
	Secondary road bridge/tunnel		
	Tertiary road bridge/tunnel		
	Local road bridge/tunnel		
	Rural road bridge/tunnel		
Rail	Railway	railway=rail	
	Railway	railway=light_rail	
	Subway	railway=subway	
	Tram	railway=tram	
	Rail (other)	railway=funicular	
		railway=miniature	
		railway=monorail	
		railway=narrow_gauge	
		railway=rack	
Rail infrastructure	Railway bridge/tunnel	Same as 'rail' category with tags: bridge=yes / tunnel=yes	
	Subway bridge/tunnel		
	Tram bridge/tunnel		
	Rail (other) bridge/tunnel		
	Subway building	railway/public_transport=station & station=subway	point
	Railway building	railway=station/halt; public_transport=stop_position & train=yes	
	Railway building	building=train_station & train=*	polygon
	Railway building platform	train=yes & railway/public_transport=platform	
Parking	Parking surface	amenity=parking & parking=lane/street_side/surface	
	Parking building	amenity=parking & parking=multi-storey	
	Parking underground	amenity=parking & parking=underground	
	Parking garage	building=garage/garages & amenity=* & parking=*	
Fueling infrastructure	Gas station	amenity=fuel	
	Gas station	amenity=fuel	point
	Gas station building	amenity=fuel & building=*	polygon
	Gas station building	amenity=fuel & building=*	point
	Charging point	amenity=charging_station	

The workflow involves repeated geometry operations and relies on large amounts of unstructured, user-generated data. At various stages, invalid geometries and tag values must be expected and, if possible, repaired. Some errors such as invalid self-intersecting polygons, can often be repaired automatically. Others, such as misspellings in tags or erroneous double classifications (e.g., lines tagged as both road and rail) would require manual correction. Due to the scope of the project and the large number of features involved, this is not feasible. If automated repairs fail, erroneous data is therefore discarded. Discarded data is logged and retrievable from the workflow to ensure this does not impact the overall result.

2.2.3. Material intensity factors and widths

A database of material intensity (MI) factors and road widths that correspond to the hierarchical structure of infrastructure classes as reported in OSM (Table 2) was developed through a literature review. Many studies and reports were unusable for our use case because, for example, they define material composition of roads based on either traffic volume or pavement type and not on a hierarchical class from motorways to rural roads. Consequently, only studies were used that explicitly provide material composition information for individual road classes as defined above. In cases where no MI data was provided in the unit of kg/m^2 as required as input in our model but instead reported only base and surface layer thicknesses as shown in Figure 4a, a conversion was performed using standard material density factors (kg/m^3).

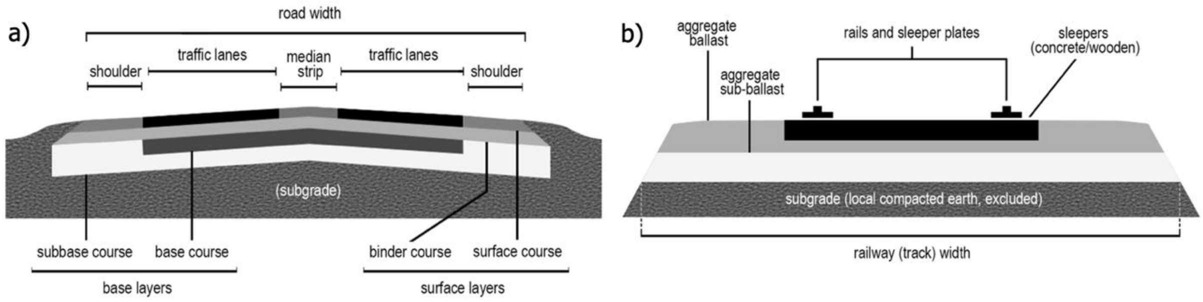

Figure 4 Simplified cross-section elements of roads (a) and railway tracks (b) used to derive material intensity factors and define road widths. Source: own visualization.

The original scope of the model is global. Consequently, MI factors and widths for all regions of the world were compiled, albeit many of the case studies utilized are from within the EU. Country-specific data was used for Germany, Austria, Slovakia (Haberl et al., 2021), France (Augiseau & Kim, 2021), Denmark (Lanau & Liu, 2020), and Sweden (Cruz, 2016). For countries or individual infrastructure classes where no country-specific MI or width data points were available, global averages across all regions were used that also include data from non-EU27 countries including the United Kingdom, United States of America (USA), China, Japan, Nepal, Turkey, United Arab Emirates, and South Africa. Only roads for the USA and China were not considered in global averages due to regional specific characteristics such as a relatively high share of concrete (rigid) pavements in roads.

Local and rural roads are quite heterogenous infrastructure classes with multiple function types for local roads (service roads, footways, cycleways) and multiple track grade types for rural roads (OSM tag grade=1-5). Based on our manual samples in Google Street View, we find that local and rural roads (tracks) vary in pavement type across specific road types and grades. Consequently, the rural road MI is weighted at the national level based on shares of each OSM track grade's length in the total length of tracks (see Appendix for more information).

2.2.4. Output products

The primary output of the workflow is the vector data of classified mobility infrastructure. From these, material stocks can be calculated by multiplying the material intensity per area unit with their surface areas (Figure 3d). For buildings, such as railway stations or parking garages, the area is multiplied by the number of building levels, if given by the OSM data. Otherwise, default values are used.

Summary statistics can be directly calculated for the administrative boundaries that were used to originally tile the data, but these are not heterogenous due to both data availability and differences in administrative structure for the various countries. For a spatially explicit representation of stocks, a raster product is generated from the vector geometries. The raster images are generated by burning the vector geometries material intensity per area on 2 x 2 m grid cells, which can then be coarsened to an arbitrary, user-defined resolution.

The rasterization of vector data onto a finite gridded space necessarily introduces some very small divergence between the area covered by the polygon features and their raster representations. To equalize the total stock sums, the resulting difference in mass is distributed or removed evenly from each raster tile.

2.3. Vehicles

This section presents the methodology used to quantify the material stock embedded in Europe's vehicle fleet and contains two main subsections. One for each of the key methodological components:

1. **Material- intensity determination** – We apply the Vehicle Material Intensity (VMI) model (introduced in the next section) to establish material composition and curb weight for each representative vehicle archetype.
2. **Fleet- inventory compilation** – We compile harmonized statistics on the number of vehicles in operation across all EU- 27 Member States and the United Kingdom for the period 2013 – 2023.

Multiplying the material intensity of each archetype by its fleet size yields country- and year- specific estimates of the in- use vehicle material stock. The next subsections describe the VMI architecture and the underlying fleet dataset in detail.

2.3.1. Vehicle material intensity model (VMI)

The VMI model is modular and adaptable. It constructs a representative ("average") vehicle for each combination of vehicle type, size/class, and powertrain as reported in Table 3. Unless otherwise stated, the base year is 2020; for light- duty vehicles (LDVs) we use 2005, reflecting the availability of longer historical series.

Figure 5 presents the overall workflow of the VMI. Data are sourced, prioritized, cleaned and harmonized as follows:

Primary data sources

- **Environmental Product Declarations (EPDs[5]):** component masses and material compositions of real vehicles.
- **Peer- reviewed LCA studies:** teardown inventories and cradle- to- gate intensities.
- **Established models (e.g. Argonne GREET):** reference distributions and cross- checks.
- **Technical specifications:** curb mass, battery capacity, engine power, etc., from OEM data, academic papers and government statistics.

Manufacturer data or EPDs are preferred; where gaps persist, we derive parameters from the most robust literature.

Table 3 Vehicle archetypes.

Type	Size/class	Power train
Light Duty Vehicles (LDV)	Mini	ICEg
	Small	ICEd
	Medium	HEV
	Large	PHEV
	Extra Large	BEV
		FCV
Heavy Duty Vehicles (HDVs)	Light Duty Truck (7,5t)	Diesel
	Medium Duty Truck (19t)	BEV
	Heavy Duty Truck (40t)	F-cells
	Coach bus 12m	Pantograph
	City bus 12m	
Rail vehicles	Passenger Regional Train	Diesel
	Passenger high speed train	Electric
	Locomotive freight	Battery Electric
	Railway freight wagons	
	Metro	Electric
	Trams	
Micromobility	Mopeds	ICE
		BE
	Motorcycles	ICE
		BE

Battery sub- module

For electric drivetrains the VMI contains an explicit battery model that translates battery capacity into cell- , module- and pack- level material splits. The sub-module is described in the next section.

[5] https://www.environdec.com/home

Scenario module

Although the current work focuses on the historical in-use stock, the VMI includes a dedicated scenario module designed for prospective analysis. This module enables the simulation of future vehicle material compositions under various technological development pathways. These scenario capabilities will be activated and expanded in the next phase of the Circular project to evaluate how material use in vehicles could evolve under differing assumptions for energy efficiency targets, regulatory frameworks, and technological adoption rates.

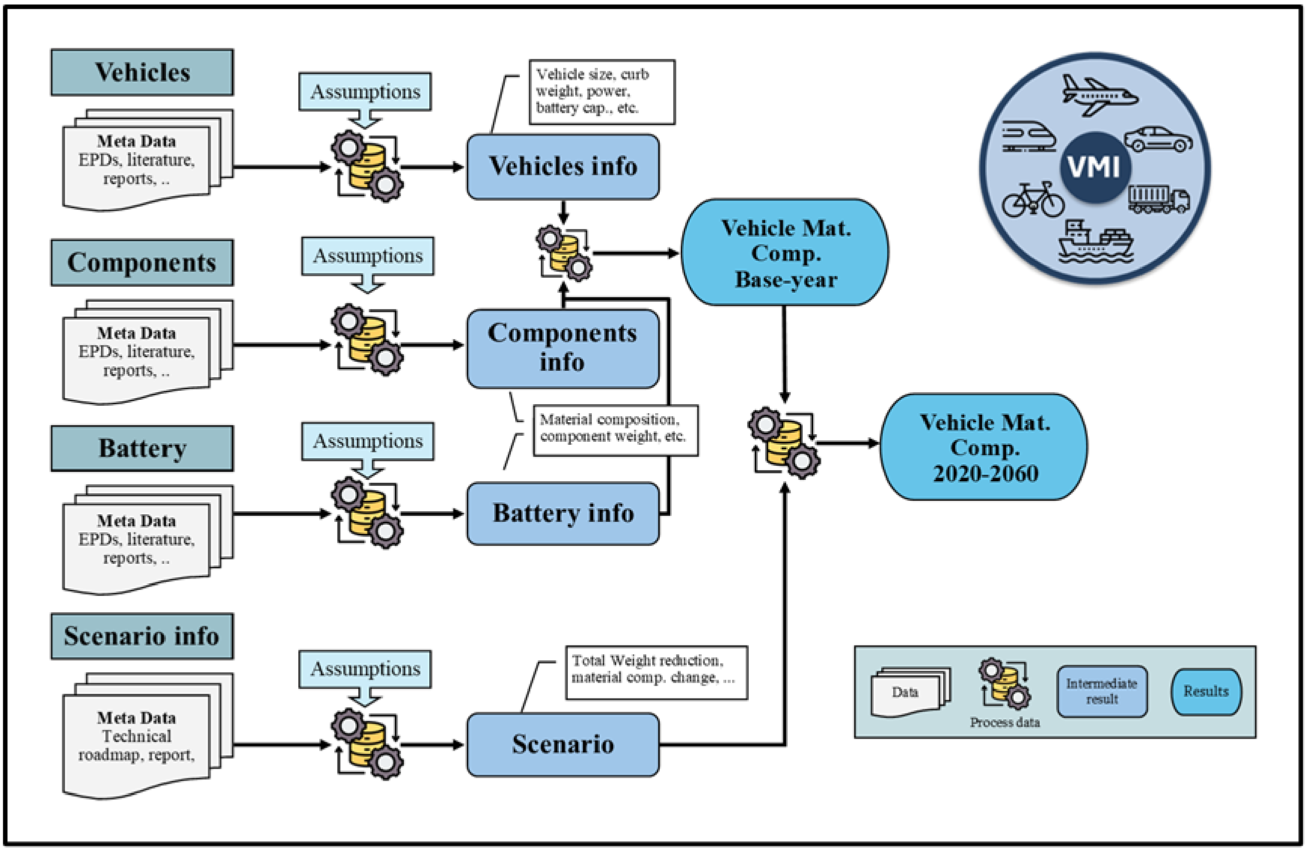

Figure 5 Overview of workflow to compile vehicle material intensities.

In the next section we introduce first the battery module, that is used across all the vehicles categories, and then we introduce all the different vehicles present in the VMI model and the relative results.

2.3.1.1. Battery module

Our analysis begins by specifying the mix of lithium- ion chemistries used in the base year 2020—NMC 622, NMC 811, NCA and LFP—together accounting for virtually the entire EV battery market. For each chemistry we extract a cradle- to- gate material bill of materials (kg material · kWh^{-1})as showed in Table 4 from peer- reviewed LCA datasets (Orangi et al., 2019); we then weight those intensities by the 2020 market shares to obtain the average composition.

Future chemistries are introduced through a scenario that tracks market- share trajectories from 2020 to 2060 (Figure 40). Consistent with the rapid uptake already observed in China[6], the scenario shifts gradually from today's Ni- and Co- rich cathodes toward an LFP- dominated landscape: NMC/NCA chemistries fall from \~60 % in 2020 to <15 % by 2060, while LFP grows to \~70 %. When the projected shares intensities yield the total battery material content used later in the vehicle- stock and material- flow calculations.

Table 4 Material intensity for different battery chemistries [kg/kWh].

	Battery chemistry						
Material	**NMC811**	**NMC622**	**NMC532**	**NMC111**	**NMC955**	**NCA80**	**LFP**
Lithium	1,45	1,59	1,75	1,94	1,39	1,41	1,12
Nickel	9,83	8,06	7,38	5,42	11,19	9,58	0
Manganese	1,15	2,51	4,15	5,07	0,33	0	0
Cobalt	1,23	2,7	2,97	5,43	0,24	1,81	0
Oxygen (NMC)	6,7	7,32	8,05	8,93	6,43	6,53	0
Aluminum	0	0	0	0	0	0,27	0
Iron	0	0	0	0	0	0	9,03
Phosphorus	0	0	0	0	0	0	5
Oxygen (LFP)	0	0	0	0	0	0	10,35
Graphite	14,7	14,4	14	13,5	14,8	14,8	13,8
PVDF	0,7	0,7	0,7	0,6	0,7	0,7	0,7
Copper	16,4	16	15,6	15,1	16,6	16,6	15,3
Wrought Aluminum	31,4	30,7	29,9	28,9	31,7	31,7	29,4
Cast Aluminum	0	0	0	0	0	0	0
LiPF6	1,1	1,1	1,1	1	1,1	1,1	1
Ethylene Carbonate	3	2,9	2,9	2,8	3	3	2,8
Dimethyl Carbonate	3	2,9	2,9	2,8	3	3	2,8
Polypropylene	1,2	1,2	1,1	1,1	1,2	1,2	1,1
PE	0,5	0,5	0,5	0,5	0,5	0,5	0,5
PET	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Steel	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Thermal insulation	0,8	0,8	0,8	0,7	0,8	0,8	0,7
Glycol	6	5,9	5,7	5,5	6,1	6,1	5,6
Electronic parts	0,5	0,5	0,5	0,5	0,5	0,5	0,5

Finally, typical battery capacities are assigned to each vehicle class (LDV, HDV, bus, etc.); multiplying capacity by the time- dependent average intensities yields the total battery material content used later in the vehicle- stock and material- flow calculations.

2.3.1.2. Light Duty Vehicles (LDV)

Light Duty Vehicles (LDVs) were classified into five size categories—mini, small, medium, large, and extra-large (xl)—based on a harmonized interpretation of European[7] and US[8] EPA standards. The

[6] https://www.iea.org/data-and-statistics/charts/share-of-battery-capacity-of-electric-vehicle-sales-by-chemistry-and-region-2021-2023
[7] https://alternative-fuels-observatory.ec.europa.eu/general-information/vehicle-types
[8] https://www.epa.gov/emission-standards-reference-guide/vehicle-weight-classifications-emission-standards-reference

classification allows for a structured differentiation of vehicles by physical dimensions, weight, and functional equivalence.

Each size class is associated with specific physical thresholds, including maximum vehicle length (ranging from 4 to 10 meters). Weight thresholds were also set separately for BEVs and ICEVs, acknowledging their structural and powertrain differences. For instance, while the maximum weight of a mini-BEV was set at 1500 kg, the equivalent ICEV was capped at 1100 kg.

Table 5 Specifications of vehicle categories.

VMI Category name	mini	small	medium	large	xl
European equivalence	A	B	C,D	E,F, M	pick-up, M, Small truck
US EPA equivalence	Minicompact	Subcompact	Compact, Mid-size	Large, SUV	Largest SUV, Minivan + small trucks
Max length [m]	4	4.7	5	8	10
Max BEV weight [kg]	1500	2000	2500	2750	3500
Max ICEV weight [kg]	1100	1400	1800	2500	6000
Average BEV weight 2020-2025 [kg]	1063	1667	2150	2500	2750
Average ICEV weight 2020-2025 [kg]	900	1300	1500	1950	2200

Average vehicle weights were derived from a combination of market data, manufacturer specifications (AUDI AG. 2014,AUDI AG. 2015, AUDI AG. 2016a-b, AUDI AG. 2018, BMW Group. 2023a-b, Changan Automobile. 2023, Lynk & Co. 2021, Mercedes-Benz Group. 2009, Mercedes-Benz Group. 2022, Mercedes-Benz Group. 2023, Nissan Motor Corporation. 2022, Polestar. 2020, Volkswagen AG. 2019, Hyundai Motor Company. 2021), and literature sources (Green NCAP. 2024, Gui, G. 2019, Oliveira, F. B. de. 2023, International Copper Association. 2022, Weiss, M. 2021). BEVs showed consistently higher weights across all size classes due to battery systems and structural reinforcements, with average values ranging from 1063 kg in the mini class to 2750 kg for extra-large vehicles. ICEVs ranged from 900 kg to 2200 kg in the same period and classes.

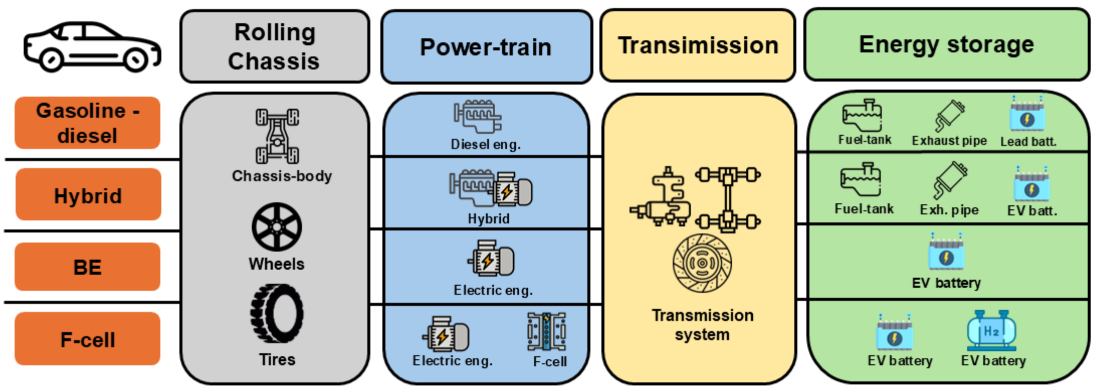

Figure 6 Light Duty Vehicles components.

Each vehicle class and powertrain was modeled using a modular structure encompassing body and interior, powertrain, chassis, tires, auxiliary systems, and where applicable, battery systems. As shown in Figure 7**Errore. L'origine riferimento non è stata trovata.**, the share of total vehicle mass across these components varies by powertrain type. ICEVs typically allocate more weight to the powertrain (combustion engine, gearbox, exhaust), while BEVs and fuel-cell vehicles shift weight toward the battery and associated electrical systems. Dedicated EV platforms, such as skateboard architectures, show a different internal distribution, with a significant structural shift compared to converted ICE-based EVs.

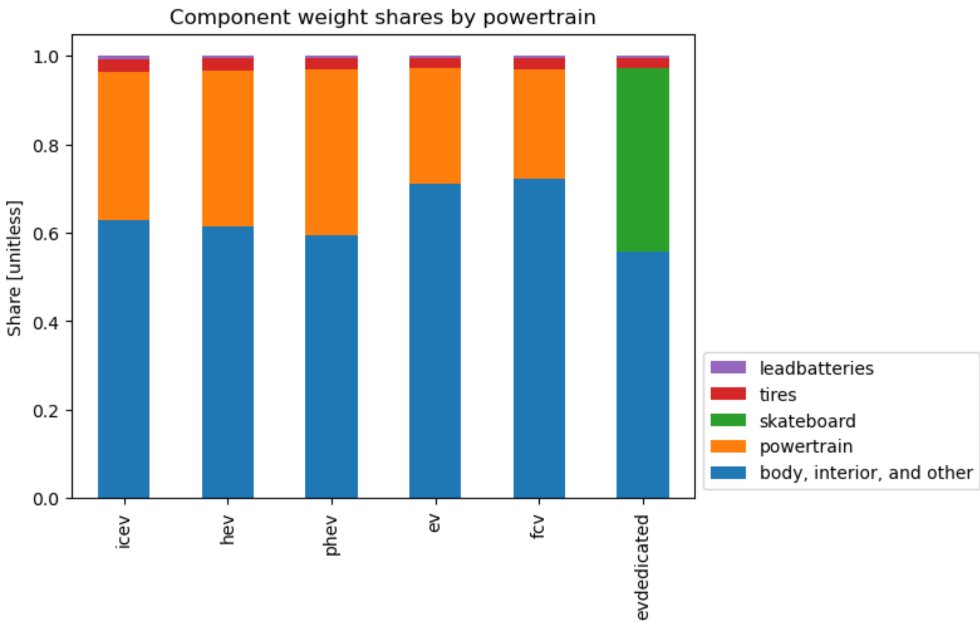

Figure 7 LDVs component weight shares by powertrain

Further insights into the detailed material composition of LDVs are presented in Figure 8 and **Errore. L'origine riferimento non è stata trovata.**. Here, our modeled archetypes for the year 2015 are compared with existing reference datasets from **RECC v2.4**[9] and **GREET2**[10] **(2023)** (Figure 8). The updated VMI archetypes for LDVs yield heavier, more powertrain-differentiated bills of materials—especially for BEVs, where battery, aluminum structures, and copper increase total mass and shift composition—while ICEVs retain relatively higher cast iron and automotive steel shares. VMI reproduces observed vehicle weights and material splits across a broad set of real models (Figure 9) (from compact ICEVs to large BEVs), with steel dominant, aluminum (cast and wrought) rising in larger and electric vehicles, and plastics and electrical-grade copper. Overall, the results align with empirical vehicle data in both weight and composition and are systematically higher than the previous model, indicating that earlier datasets underestimated vehicle mass, particularly for larger vehicles and electric powertrains.

In Figure 10 the results for LDVs by size and powertrain are showed.

[9] https://www.industrialecology.uni-freiburg.de/odym-recc
[10] https://www.energy.gov/eere/greet

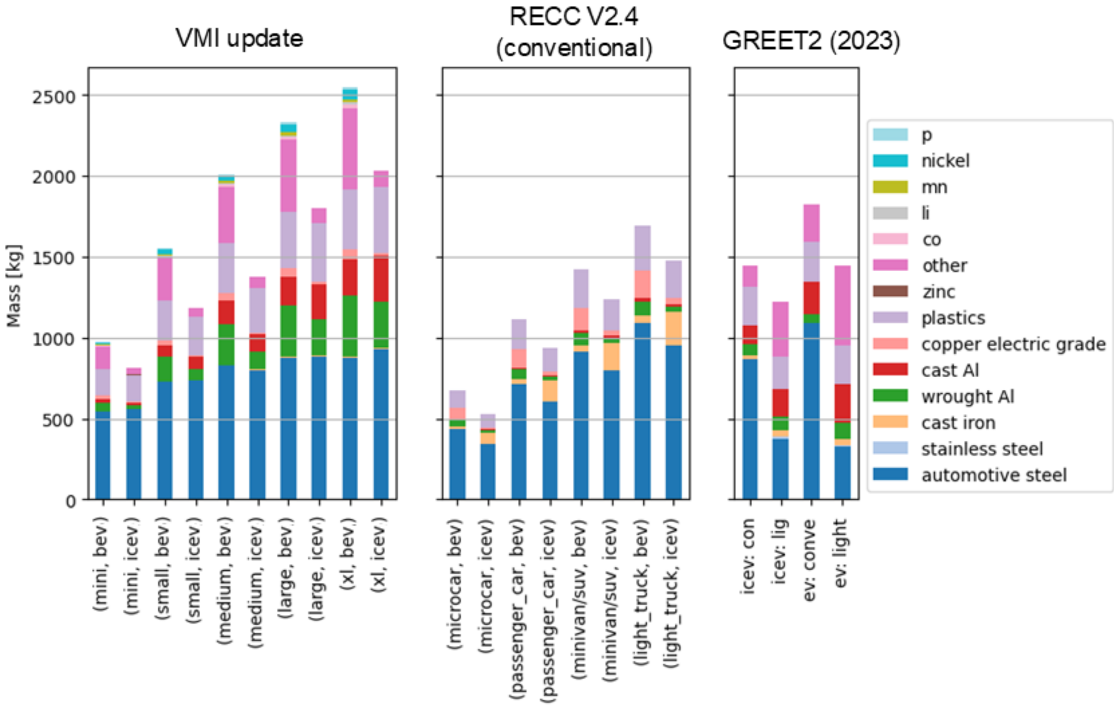

Figure 8 Material composition of material intensities per vehicle type.

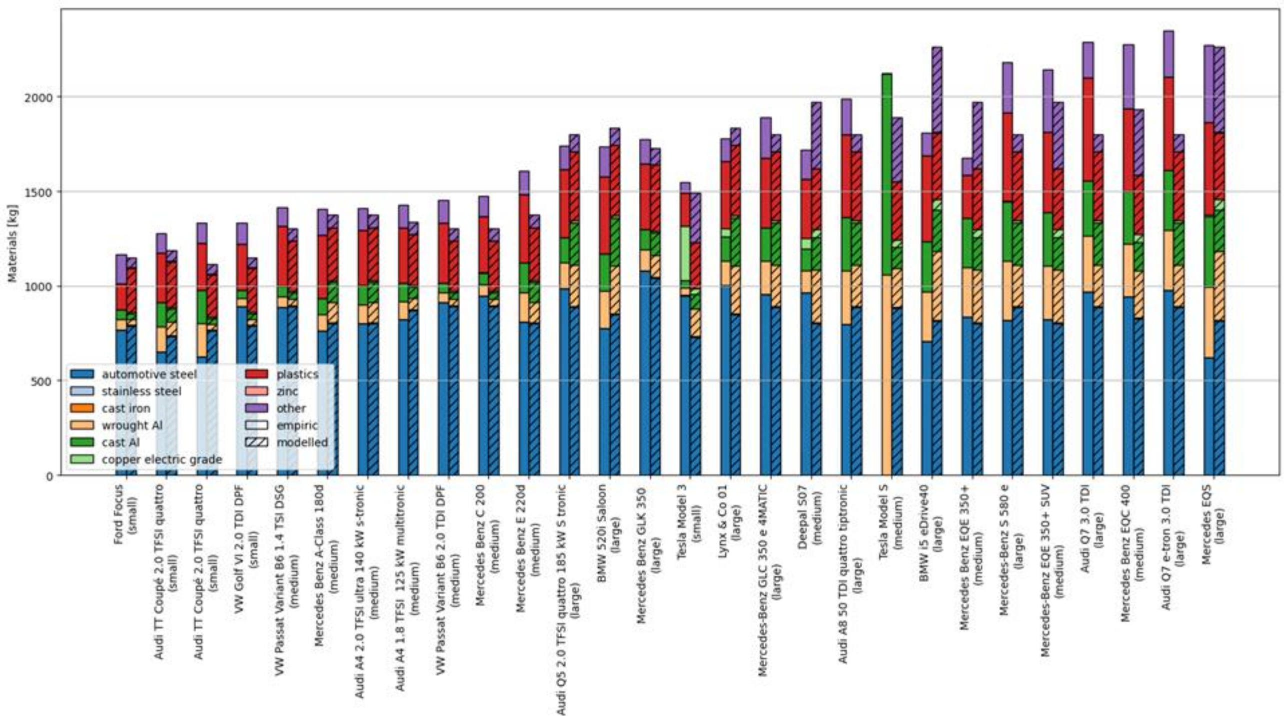

Figure 9 Modelled result vs. real data for LDVs.

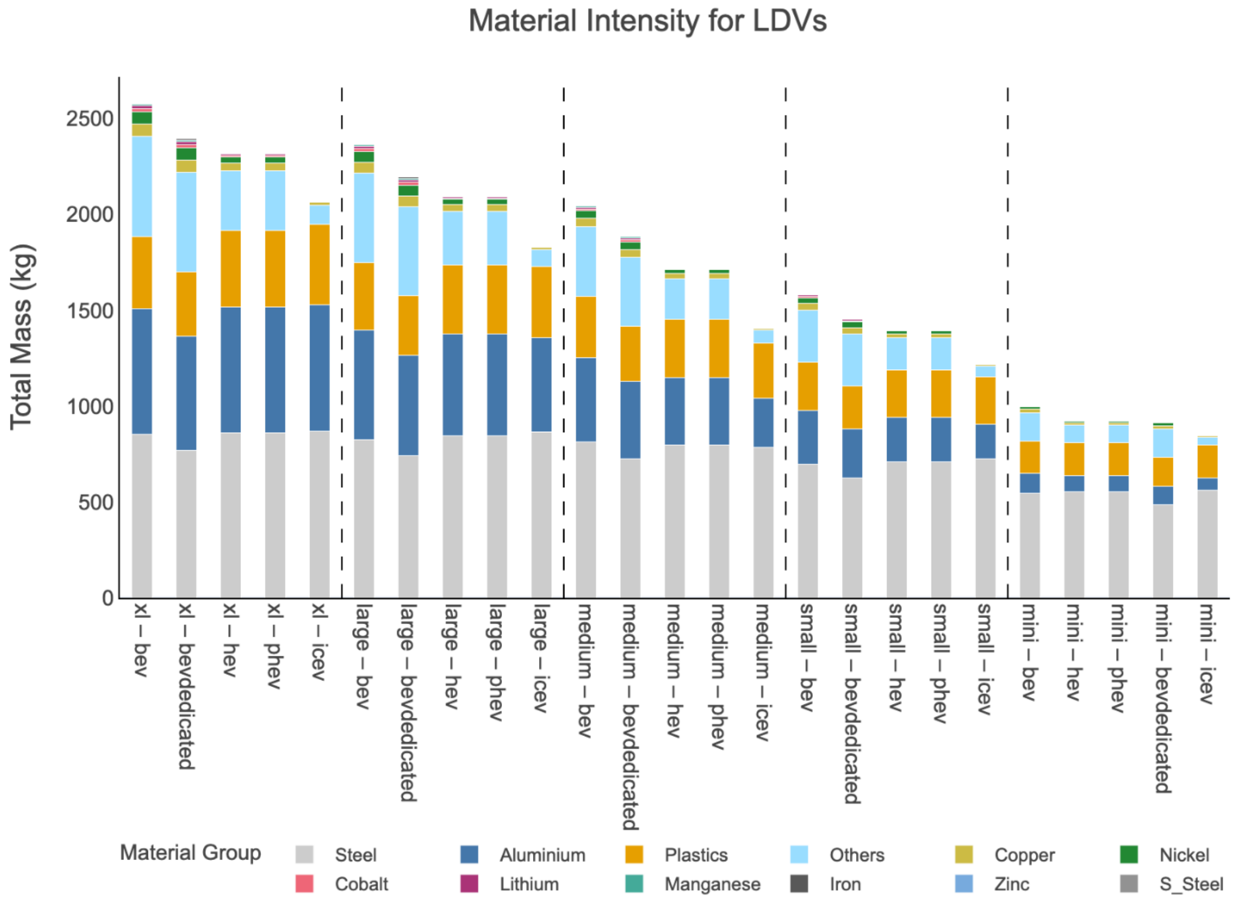

Figure 10 LDVs material composition by size and powertrain.

2.3.1.3. Heavy Duty Vehicles: Trucks

Heavy Duty Vehicles (HDVs) were modeled by distinguishing between two main types: trucks and buses. While structurally similar in their modular architecture, these vehicles differ substantially in function—trucks are designed for cargo transport, whereas buses are designed for passenger movement. These differences are reflected in the component configuration and the resulting material composition.

Trucks were classified into **three weight-based categories** to reflect typical commercial vehicle segments:

- **Light-duty truck (7.5 tonnes)** – modeled on the *FUSO Canter*[11]
- **Medium-duty truck (19 tonnes)** – modeled on the *Volvo FE*[12]
- **Heavy-duty truck (40 tonnes)** – modeled on the *Volvo FH*[13]

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[11] https://www.fuso-trucks.com/product/canter/
[12] https://www.volvotrucks.com/en-en/trucks/models/volvo-fe.html
[13] https://www.volvotrucks.com/en-en/trucks/models/volvo-fh.html

Each truck configuration was assigned a specific set of technical parameters and component sizes based on manufacturer specifications (ICCT. 2021, Volvo Trucks. 2020, Scania. 2021, Renault Trucks. 2020a-b) and other sources (Simons, S., & Azimov, U. 2021, Celedón Cruz, L. I. 2020, ACEA 2021), scaled to reflect real-world vehicle mass and use cases.

Both trucks and buses were analyzed using a consistent, component-based modelling framework, as shown in Figure 11, while the results are reported in Figure 12. The system includes:

- **Rolling chassis** (which comprises the structural frame, wheels, and tires)
- **Powertrain** (diesel engines, electric motors, fuel-cell stacks, hybrid systems, or pantograph connections)(Cummins Inc. 2019a-d, Granlund, O. 2020, Mareev, I., & Sauer, D. U. 2018, Remy International. 2018, Siemens Mobility. 2019, Volvo Trucks. 2016b,)
- **Transmission system** (including gearbox, drivetrain, and clutch)(Volvo Trucks. 2008, Volvo Trucks. 2016a, Volvo Trucks. 2022, Volvo Trucks. 2023, Mercedes-Benz. 2021c-d)
- **Energy storage system** (comprising fuel tanks, exhaust systems, EV battery packs, and hydrogen tanks).
- **Cargo-specific components** such as the box, trailer, or liftgate, depending on the vehicle type and intended use. (Dhollandia. 2018a-c, Dautel. 2019, Morgan Truck Body. 2023, Schmitz Cargobull. 2011, Schmitz Cargobull AG. 2013, Schmitz Cargobull AG. 2020, Schmitz Cargobull AG. 2021)

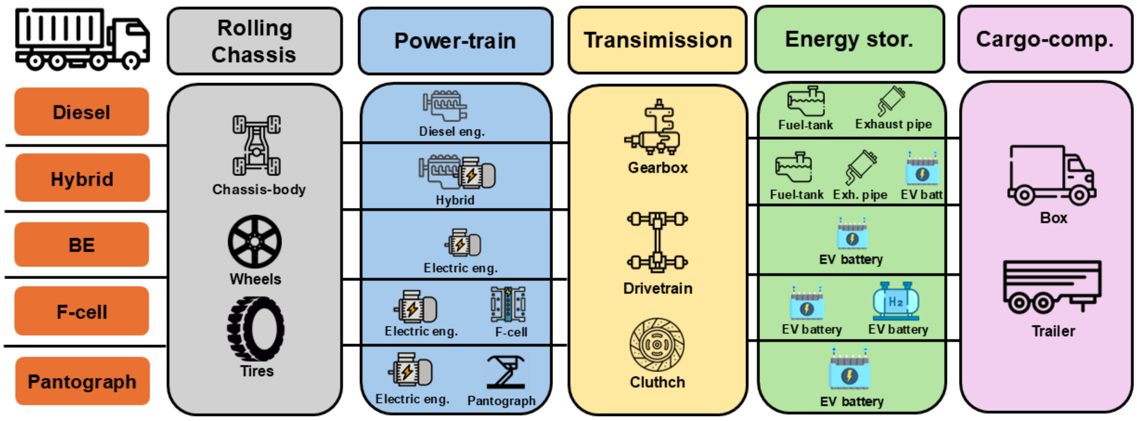


Figure 11 Truck components breakdown.

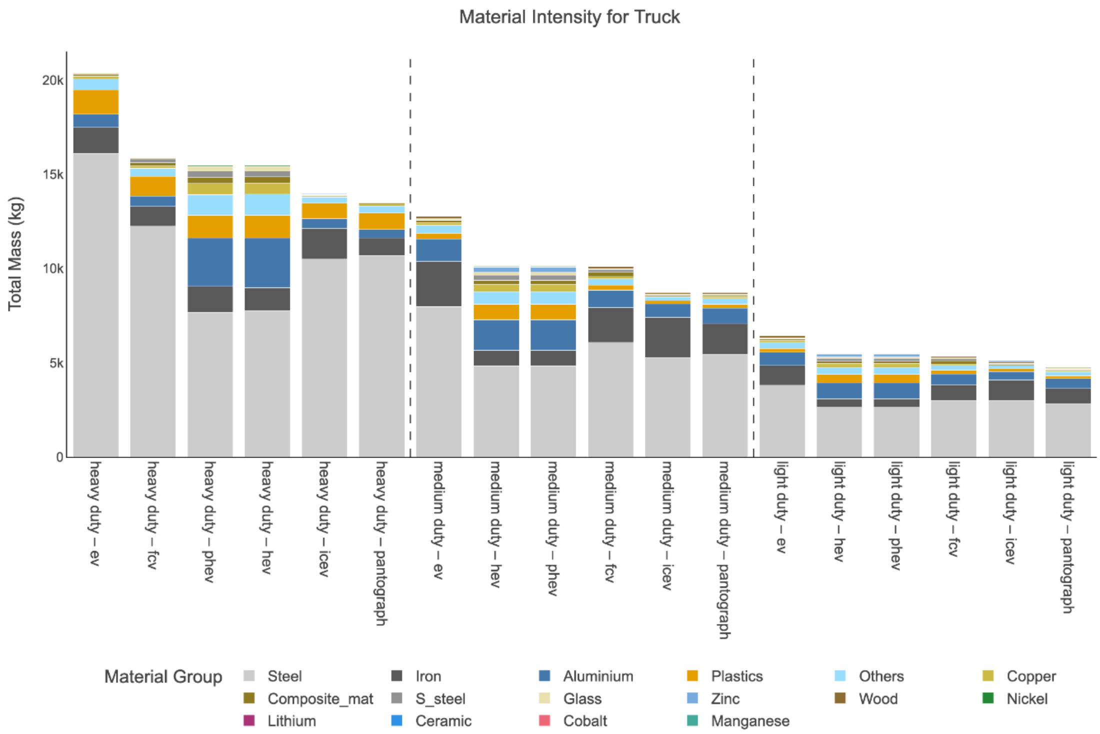


Figure 12 Truck material intensity.

2.3.1.4. Heavy Duty Vehicles: Buses

Buses were modeled in **two main categories**, based on vehicle type and length:

- **City bus (12 meters)** – typical for urban public transport
- **Coach bus (12 meters)** – used for intercity and long-distance travel

For both trucks and buses, we modeled five powertrain technologies: diesel, hybrid (including both HEV and PHEV systems), battery electric (BEV), fuel-cell electric, and pantograph-electric systems (light trucks and coach bus excluded). Each configuration was assigned a distinct set of components and material parameters.

The modeling was informed by multiple data sources, including technical specifications from leading vehicle manufacturers such as Volvo[14], Scania[15], and Mitsubishi FUSO[16], as well as environmental product declarations for city bus (BYD Auto Industry Co., Ltd.. 2023a,b, BYD Auto Industry Co., Ltd.. 2024a-b, CaetanoBus. 2024a,b, Ebusco B.V.. 2024, Volvo AB, Business Area Buses, 2023, Irizar e-mobility. 2021, IVECO France 2024, MAN Truck & Bus SE. 2022, Irizar. 2019, Solaris Bus & Coach. 2022, Xiamen Golden Dragon Bus Co., Ltd.. 2025a, Zhongtong Bus Holding Co., Ltd.. 2025), and coach (Xiamen Golden Dragon Bus Co., Ltd.. 2025b, Irizar. 2024, Yutong bus Co., Ltd.. 2023a,b, Yutong bus Co., Ltd.. 2025)

[14] https://www.volvotrucks.com/en-en/
[15] https://www.scania.com/
[16] https://www.mitsubishi-fuso.com/en/

life cycle assessment databases such as the GREET model, and relevant scientific and industrial literature (Simons and Azimov, 2021; Cullet et al., 2021). These sources were used to derive the mass and material composition of each component, scaled appropriately for the vehicle class.

The resulting model enables a detailed estimation of material intensities across HDV categories and powertrains.

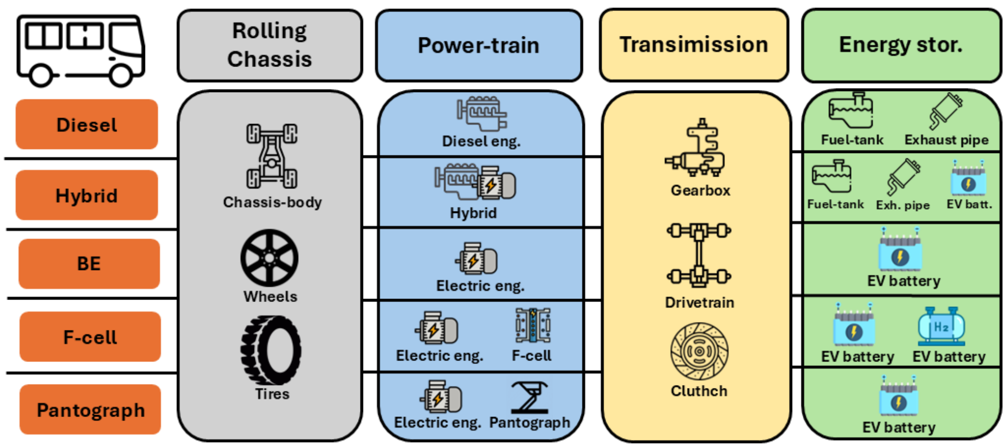


Figure 13 Bus component breakdown.

Figure 13 below present the component configuration adopted in the model for trucks and buses. Figure 14 shows the results of the total material composition for each configuration, illustrated through stacked bar charts.

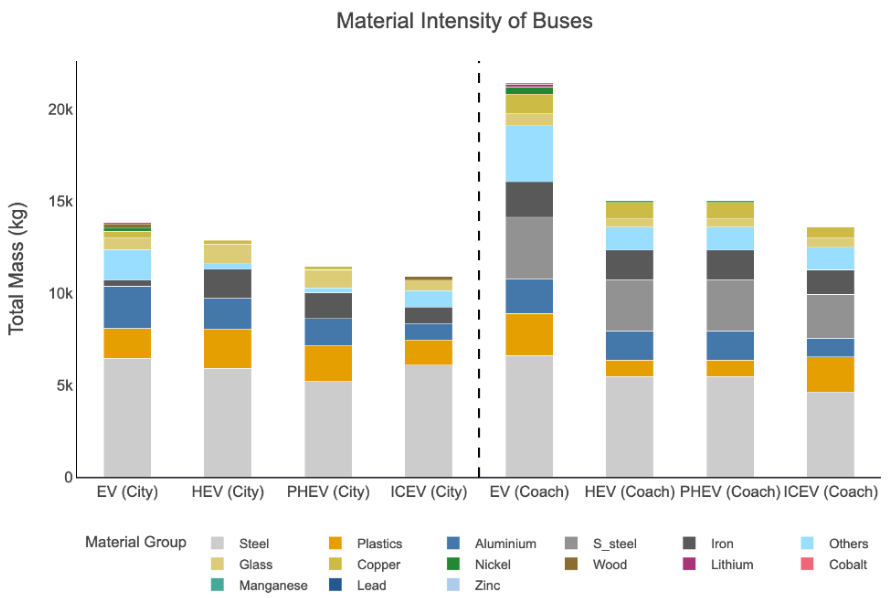


Figure 14 Bus material intensity.

2.3.1.5. Trains

For rail vehicles—including trains, metros, and trams—we modelled the main subsystems based on data from EPDs (Alstom. 2006, Alstom. 2015, Alstom. 2018a,b, Alstom. 2022, Alstom. 2023, Bombardier. (2010a,b), Bombardier. 2012, Bombardier. 2014, CAF. 2014, CRRC Qingdao Sifang Co., Ltd.. 2023, Hitachi Rail Italy. 2013, Hitachi Rail. 2019, Hitachi Rail. 2022, Railconnect NSW. 2020, Patentes Talgo S.L.U. 2022, Stadler. 2023), LCA studies (Sexauer, M. 2019), and the GREET model. These sources consistently identify key structural and functional modules of rail vehicles, which we adopted in our classification.

The following components were modelled, each with an approximate share of the vehicle's total weight (ranges may vary depending on vehicle type and configuration):

- Car body (35–45%): This includes the external shell and load-bearing structure of the rail vehicle. It is typically made of steel or aluminum and represents the largest single component by weight.
- Interior (10–20%): Encompasses internal fittings such as windows, doors, flooring, seating, and panels. Materials include plastics, glass, and composites, with substantial variation depending on comfort and service requirements.
- Bogie and Running Gears (20–30%): This group includes the wheelsets, axles, suspension systems, and bogie frames. Usually manufactured from high-strength steel, this subsystem plays a critical role in load transfer and stability.
- Propulsion and Electric Equipment (10–20%): Covers all drivetrain-related elements such as electric motors, inverters, transformers, and pantograph systems (where applicable), as well as wiring and control units.

Comfort Systems (5–10%): Includes HVAC (heating, ventilation, and air conditioning), lighting, and infotainment systems. These elements are crucial for passenger comfort and typically consist of electrical components and polymers.

Different train configurations use various propulsion strategies, including:

- Diesel engines
- Electric motors powered by overhead lines or third rail
- Hybrid systems with onboard battery storage

This modular approach allows flexibility in modelling different rail vehicle types while maintaining consistency in the structure of material intensity estimates.

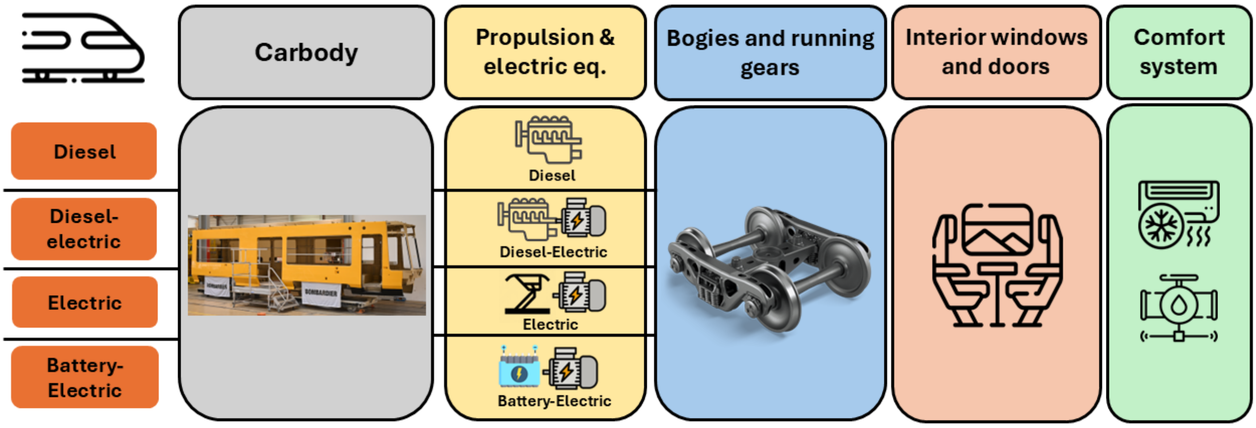


Figure 15 Train components breakdown.

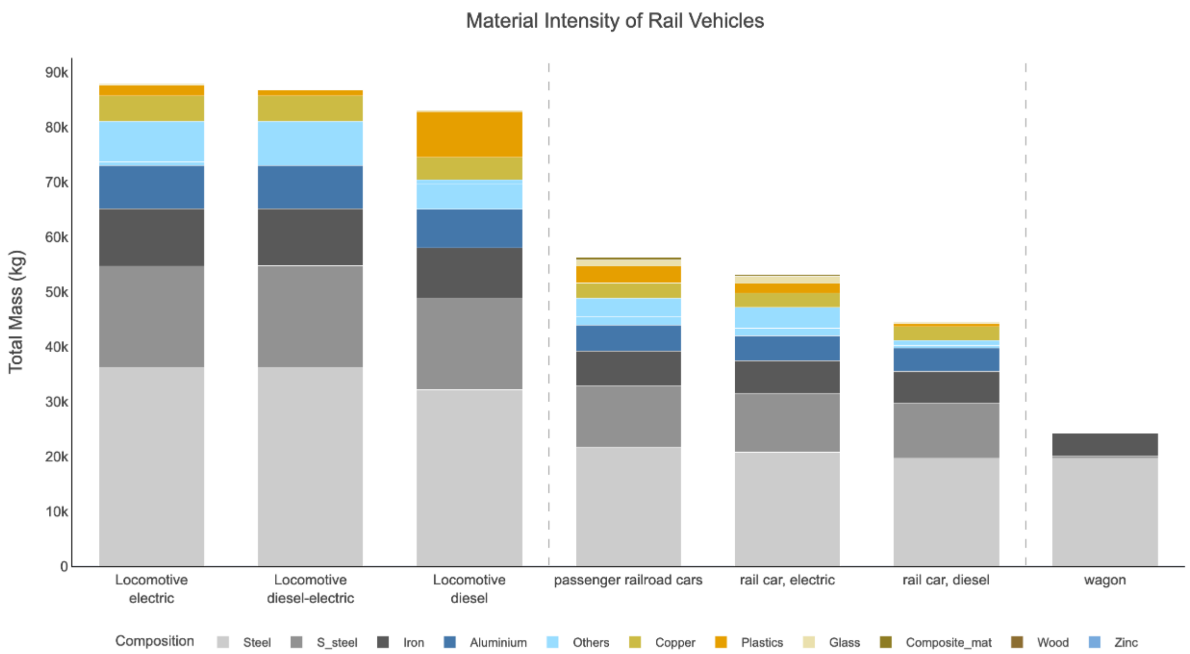


Figure 16 Train material composition.

2.3.1.6. Motorcycles and Mopeds

The micromobility category includes a broad range of lightweight personal transport vehicles. In our model, we considered the following types:

- Motorcycles (equivalent to 125cc ICE)
- Mopeds (typically equivalent to 50cc ICE)

These vehicles are important in both urban and rural mobility systems. They and characterized by relatively low weight and compact size compared to other modes of transport. They are available in both internal combustion engines (ICE) and battery electric vehicle (BEV) configurations.

However, due to difficulties in harmonizing available data and limited detail in technical documentation, these vehicles were not disaggregated by components. Instead, we adopted a simplified modelling approach based on total material intensity per vehicle, using estimates from product declarations from main manufacturers (Piaggio[17], Honda[18], Yamaha[19], Vespa[20], Super Soco[21], Niu[22]) and scientific literature (KTH / CAKE project 2023, Schelte, N. et al. 2021, Felipe-Falgas et al. 2022).

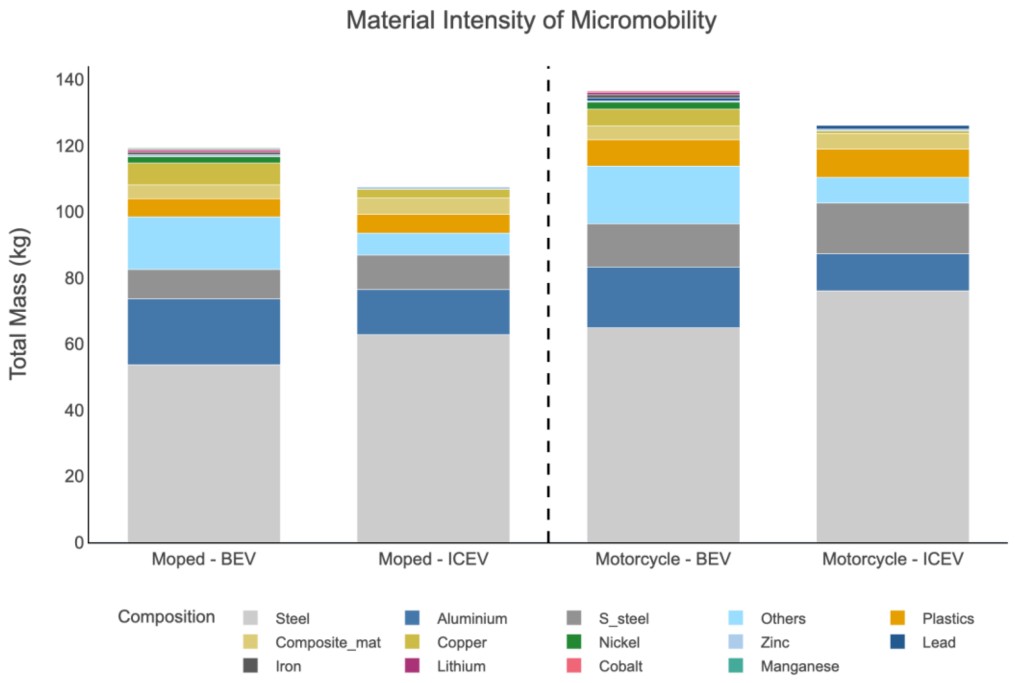


Figure 17 Micromobility vehicles' material composition.

For electric variants, we further refined our estimates by separating the vehicle body and the battery: the non-battery vehicle body composition was estimated from literature and adjusted where needed.

The battery system was modelled separately, based on the average battery capacity for each vehicle type. We derived the corresponding battery weight and material composition as explained in the previous section.

[17] https://www.piaggio.com/us_EN/
[18] https://powersports.honda.com/
[19] https://yamaha-motor.com/land
[20] https://storeusa.vespa.com/
[21] https://shop.vmotosoco.com/
[22] https://global.niu.com/en-us

The final material intensity (Figure 17) for each electric micromobility vehicle is the sum of the non-battery vehicle mass and the separately modelled battery. In general, the electric variants are 10-15 % heavier than their fossil counterparts.

2.3.2. Vehicle stock data

We assembled a harmonized vehicle stock dataset for the EU- 27 + UK by integrating official counts from Eurostat's transport statistics[23] with registration records reported by ACEA[24] and, where gaps existed (e.g., two- wheelers or zero- emission buses), supplemental national sources and manufacturer disclosures. Raw records were first mapped to a common classification that distinguishes light- duty vehicles (LDVs), heavy- duty vehicles (HDVs), rail, and micromobility, and further subdivides each mode by size class (e.g., mini, small, SUV for LDVs; rigid < 18 t, articulated > 40 t for HDVs) and by powertrain (ICE, HEV, PHEV, BEV, FCEV). Duplicates and reporting lags were reconciled by cross- checking year- over- year growth against ACEA's aggregated registrations, and missing observations were linearly interpolated only when consecutive reporting covered at least three out of five years.

Table 6 Total vehicles stock EU27 + UK.

Million unit	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Cars	237.10	246.43	250.80	256.02	261.76	266.51	265.83	268.26	271.80	274.50	278.15
Trucks	30.08	31.83	32.42	32.10	32.64	33.36	34.08	34.62	35.40	35.80	36.45
Busses	0.82	0.66	0.83	0.84	0.86	0.88	0.85	0.81	0.82	0.82	0.82
Trains	0.72	0.71	0.70	0.69	0.68	0.66	0.66	0.65	0.64	0.63	0.64
Motorcycles	35.86	36.60	37.12	37.75	38.34	38.80	39.61	40.47	41.38	42.60	43.32

The time series data in Table 6 2013–2023) highlights distinct trends in vehicle fleet dynamics, with further details provided in the annex section. First, the car fleet experienced steady growth, increasing from 237.10 million to 278.15 million units, a moderate rise of approximately 17%. However, further analysis is required to understand the underlying factors driving this growth, which may include variations in the share of populations living in rural versus urban areas, the availability and usage of public transportation (e.g., buses and trains), or differences in economic activities across regions. Second, the truck fleet grew modestly from 30.08 million to 36.45 million units, potentially reflecting increased demand for freight transport or regional differences in industrial activity, though this requires deeper investigation. Buses and trains remained relatively stable, with buses fluctuating slightly around 0.82 million units and trains declining marginally from 0.72 million to 0.64 million units. Motorcycles saw consistent growth, rising from 35.86 million to 43.32 million units, possibly due to their affordability and use in densely populated or less infrastructure-dependent regions. These fleet totals serve as inputs for further modeling, such as material-stock assessments, by combining vehicle counts in each category with their respective material intensities.

[23] https://ec.europa.eu/eurostat/web/transport
[24] https://www.acea.auto/

3. Findings: Material Stocks in Buildings, Transport Infrastructure and Vehicles

3.1. Buildings

In this section, building material stocks are disaggregated, looking at materials, building types, as well as the spatial distribution across the 27 EU member states, Norway, Switzerland and the UK (EU27+3).

3.1.1. Total Stocks and Types of Materials

We find total material mass in buildings – including residential, commercial and industrial buildings – in the EU27+3 amounting to about 94Gt. 65% of that mass is concrete, bricks cover 29%, whereas wood and steel cover around 3%. Glass, plastics, aluminum and copper - despite having high carbon intensities - make only less than 0.03% of the mass of material stored in buildings (Figure 18).

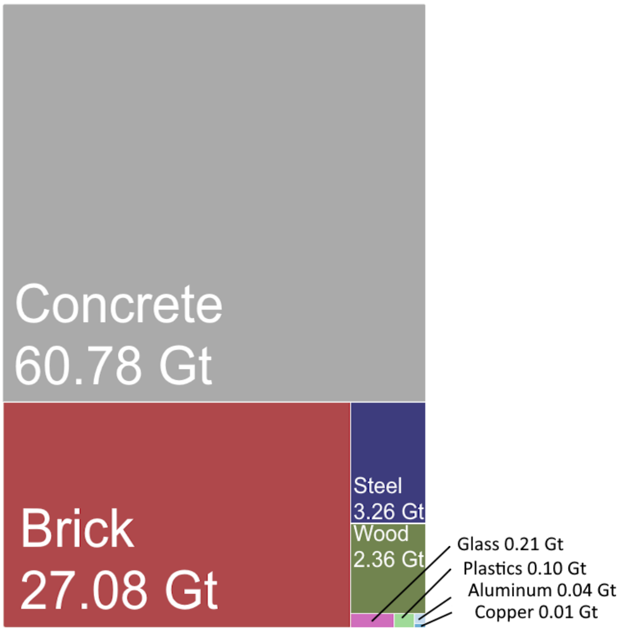


Figure 18 Material composition of the total building material stock in the EU27 + Norway, Switzerland and the UK.

The majority of these materials is stored in buildings with a predominantly residential function (Figure 19**a**). 83% of bricks can be found in residential buildings, with only very few industrial buildings containing bricks. Also wood is primarily used in residential buildings (71%). In contrast, while still 55% of steel and concrete can be found in residential buildings, a relevant share of these materials is also found in industrial buildings. This is the case since industrial buildings are often steel-frame or reinforced concrete constructions. Around a fifth of material is found in commercial buildings including shops, restaurants, hotels, but also administrative buildings and care institutions.
The majority of material stocks in buildings are located in urban centers of the EU27+3 (Figure 19**b**). Urbanity is here defined according to the Degree of Urbanization (Eurostat, 2025) which is a compound measure of population density and population size in contiguous grid cells. In particular, bricks and wood are more prevalent in urban centers (62-63%) where residential buildings dominate.

Steel and concrete, on the other hand, are slightly more common in sparsely populated rural and suburban locations (43-44%) where industrial steel-frame buildings reside.

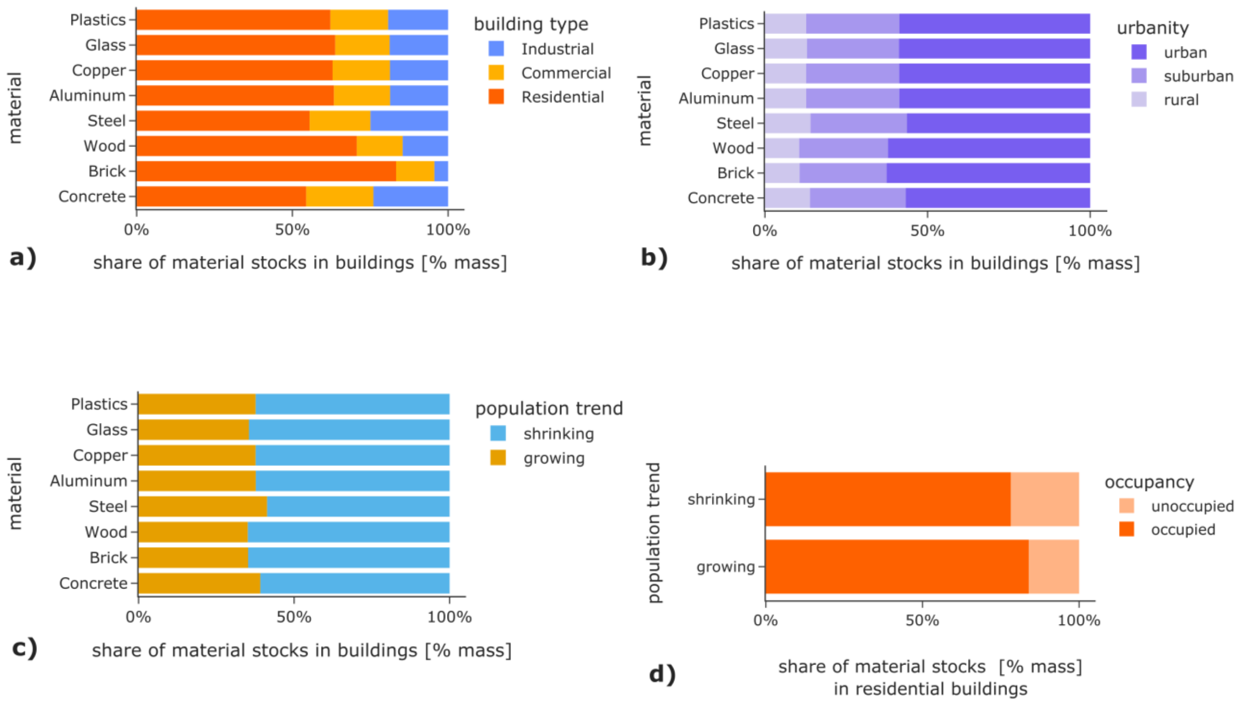


Figure 19 Distribution of building material stocks by a) functional type of building, b) degree of urbanisation of the 1km grid cell, c) expected regional population trend from 2020 to 2060 in the NUTS3 region, and d) occupancy status of residential buildings in the NUTS3 region.

To better understand the future use of these available material stocks and the potential exploitation of these materials for reuse and recycling, we can differentiate material stocks by those lying in growing or shrinking regions (Figure 19**c**). This distinction reveals that across materials the majority of material stocks in buildings lies in regions with expected population decline. Already today, 22% of material stocks in residential buildings in shrinking regions remain unused due to building vacancy; and even in growing regions 16% of material stocks hibernate as part of unoccupied dwellings (Figure 19**d**). To keep these material stocks in use, abandoned material stocks could be exploited via disassembly and made available for reuse in construction in growing regions. Notably, there is some mismatch between those materials particularly present in growing regions (concrete and steel) and those present in shrinking regions (bricks, wood, glass). Thus, to fully leverage this disassemble-and-reconstruct-elsewhere approach would require a shift in construction practices. An alternative strategy would be to bring abandoned material stocks to new life via place-based policies that incentivize reuse of under-occupied buildings.

3.1.2. Geographical Distribution of Material Stocks

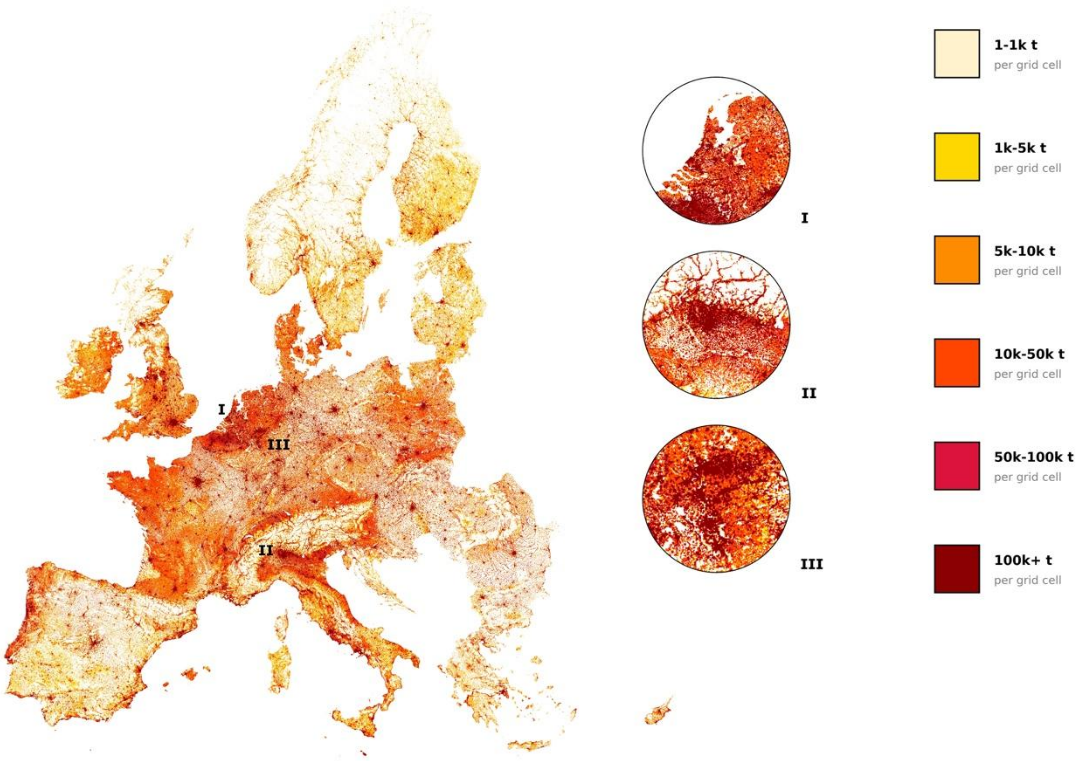


Figure 20 Total material stocks in buildings across the EU27, Norway, Switzerland and the UK.

Figure 20 presents the total amount of material stored in European buildings at a 1km grid scale. At first glance, regions that have a high degree of urbanization stand out such as the Netherlands (I), the Po valley in Italy (II) and the Ruhr region in western Germany (III). This large amount of material stocks of more than 100,000 tonnes per square kilometer can be explained by the high density of building stocks (Figure 21). High building count values are also present for major European cities such as Paris, Berlin, Hamburg, Warsaw, Prague and Budapest. Not only can one identify these cities due to their high-building count values relative to their hinterland, but even more so due to their well-defined morphological characteristics. For example, the distinct urban sprawl of the Banlieue surrounding Paris is captured within this map (Figure 21 I). Contrary to regions with a high degree of urbanization, Figure 21 shows that low building counts and with that also low material stocks are found in the sparsely populated woodlands of northern Sweden, the arid steppes of Spain (Figure 20 II) and the Scottish Highlands. The relative absence of buildings is even more evident for mountain ranges such as the Alps and the Pyrenees, the latter clearly separating the Iberian Peninsula from mainland Europe. Furthermore, the Apennine mountains contrast sharply with the urbanized areas of Northern Italy (Figure 21 III).

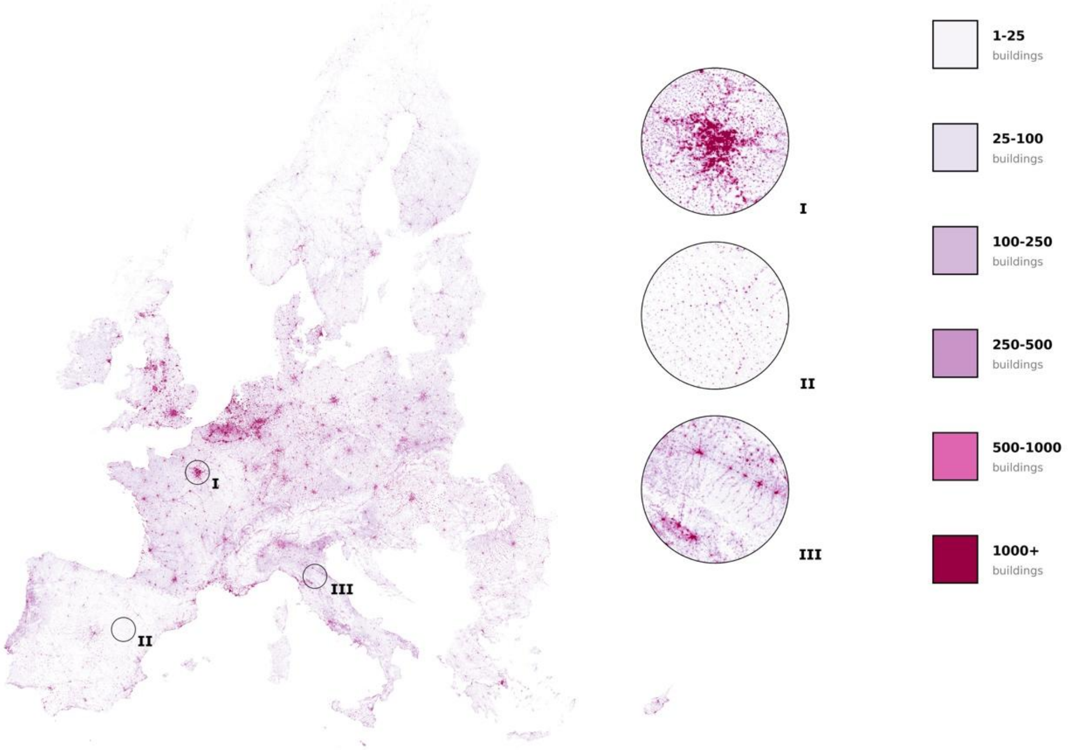


Figure 21 Building stocks across the EU27, Norway, Switzerland and the UK.

While buildings concentrate -together with population- in cities (Figure 21), material stocks per capita are particularly high in sparsely populated rural locations (Figure 23). Across residential, commercial and industrial buildings, rural and suburban locations show on average a 61% higher material intensity per resident than urban areas (Figure 22). High material per capita values either reflect a relative abundance of building material, or a relative absence of people that permanently live there, or both. Low values indicate that there is a relatively strong presence of people living for the building material present. Hence, the high amount of material per capita in sparsely populated rural locations can be explained by the higher presence of industrial buildings including factories, greenhouses, and warehouses in locations where none or few people are registered. In line with this interpretation, we observe particularly high material intensities of more than 10 kilotonnes per capita in locations with airports. For example, the airport Flughafen Hamburg and the port facilities within the city of Hamburg are clearly recognizable (Figure 23 I).

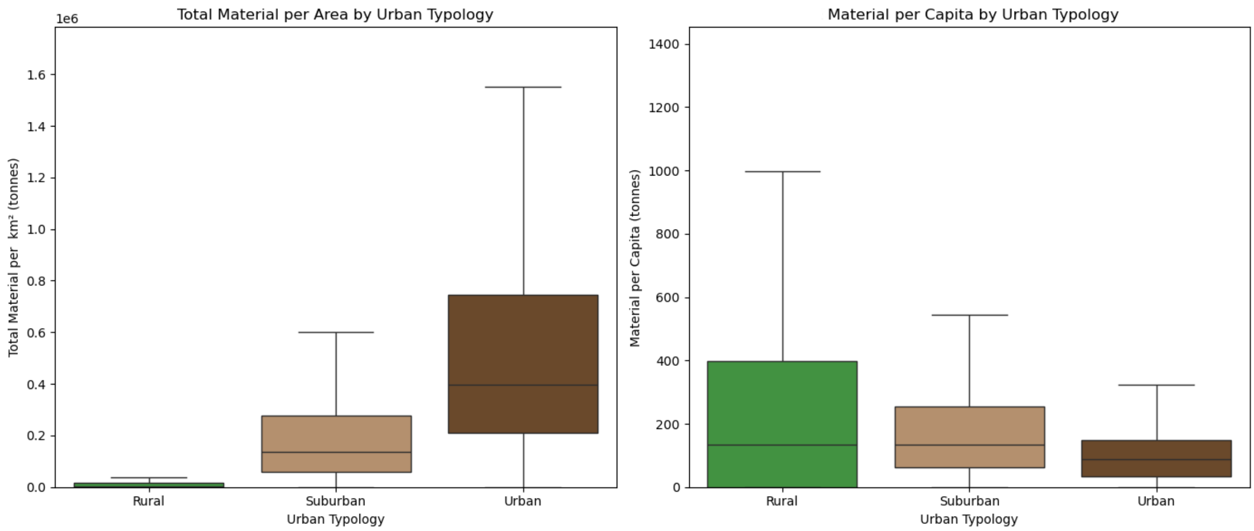


Figure 22 Building material stock per area (left) and per capita (right) by urban typology according to the Degree of Urbanization classification of 1km grids.

Yet, even material stocks in only residential buildings show higher material intensities per capita in rural locations than urban locations (Figure 24). This may be explained by larger residential units and abandoned, under-occupied building stocks in shrinking areas. Moreover, areas that depend heavily on tourism are prominently visible on the map due to their large building stocks despite the low number of registered residents. This is particularly visible in coastal Spain, on the Balearic Islands (Figure 24 II), and the Hungarian Balaton Lake (Figure 24 III), of which the shorelines are heavily built-up to accommodate tourism.

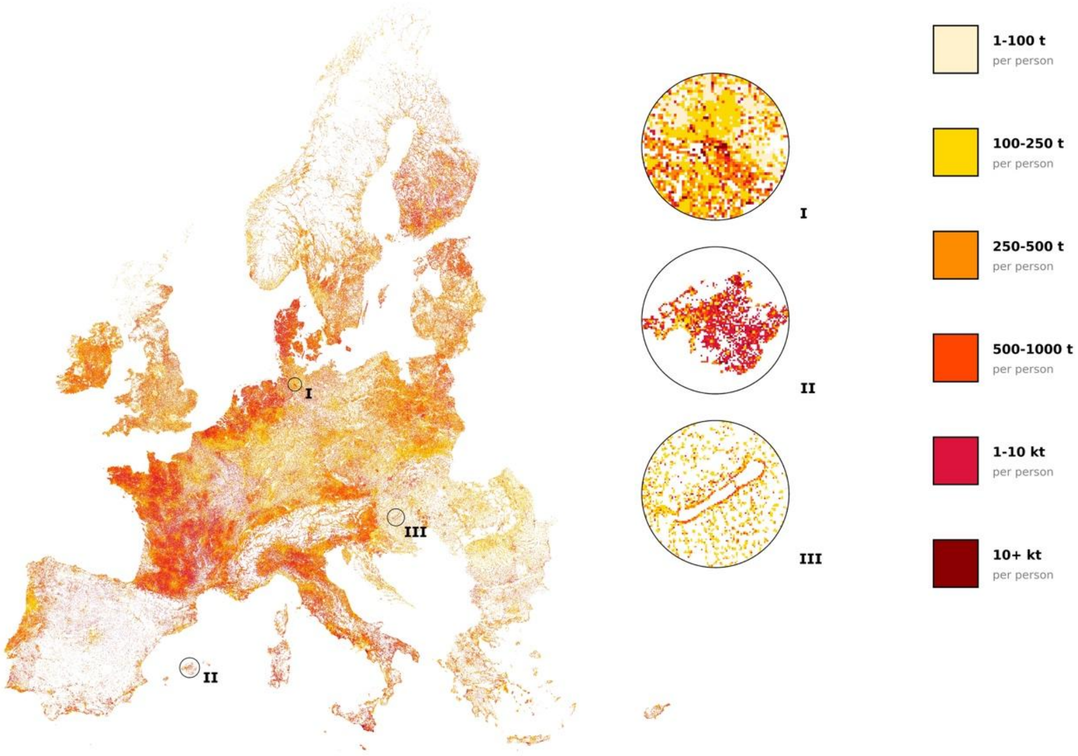


Figure 23 Material stocks in buildings per capita across the EU27, Norway, Switzerland and the UK.

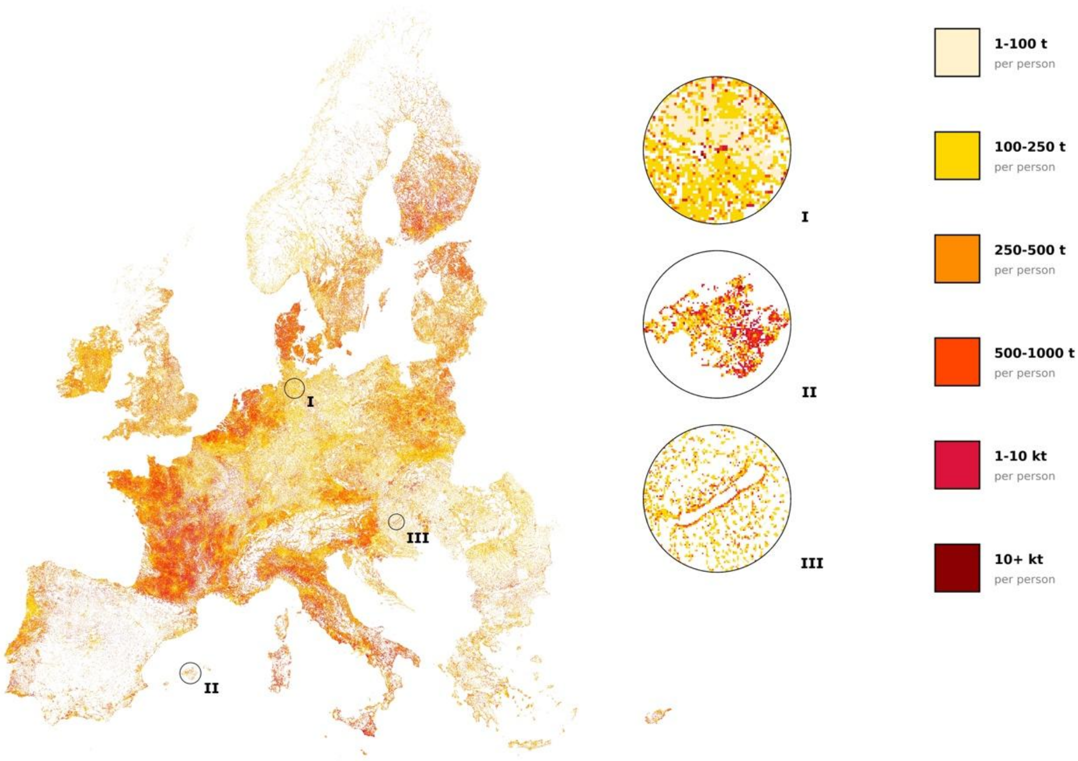
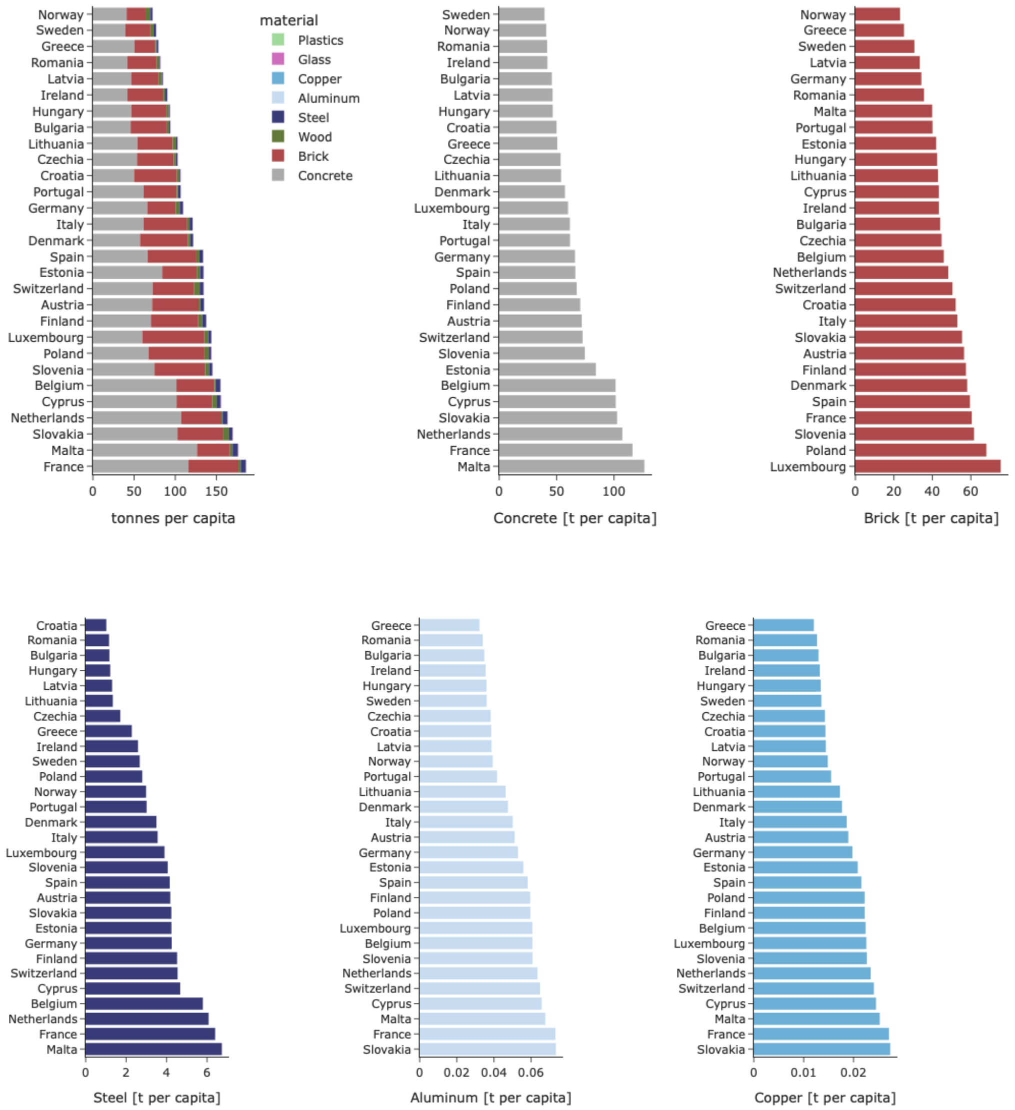


Figure 24 Material stocks in residential buildings per capita across the EU27, Norway, Switzerland and the UK.

3.1.3. Diversity of Material Stocks

A national-level view on material stocks per capita shows some diversity in material stocks between regions (Figure 25). For instance, while countries such as France, Slovakia and Cyprus appear to have a high per-capita material intensity related to larger building stocks in general, per-capita wood stocks are highest in the Scandinavian and Alpine region.



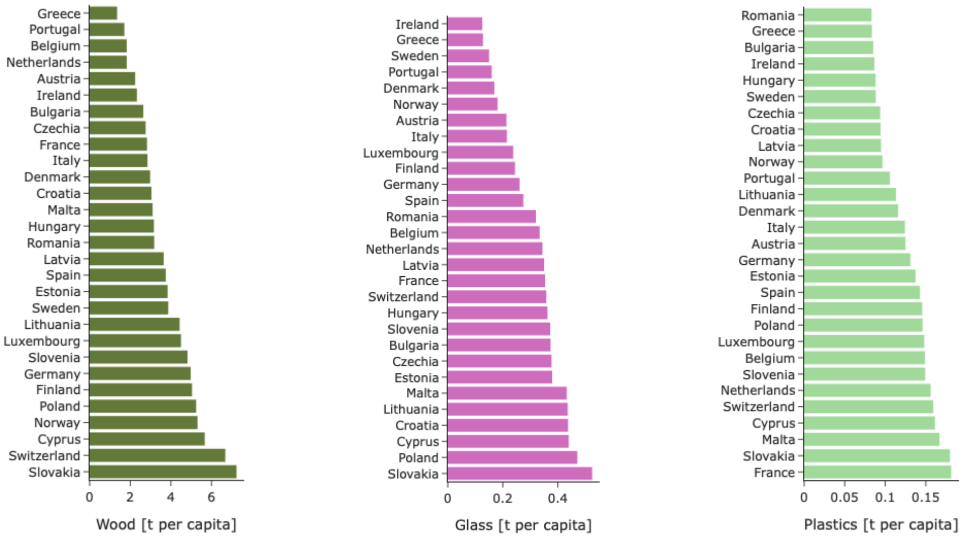


Figure 25 Per-capita material stocks in buildings by country.

A higher spatial resolution reveals that the composition of material stocks in buildings also varies at subnational scale across Europe. Figure 26 shows where materials are particularly more present in local material stocks than in the European average square kilometer (Figure 18). For instance, wood appears to be more prevalent in Scandinavia, Germany, Switzerland, Slovenia and Cyprus, but also in the mountainous regions between Slovakia and Poland, in Romania, and the Italian Appennine, as well as in Galicia. In contrast, bricks are used more than European average in Ireland, the UK, Denmark, Portugal, Italy, Luxembourg and the rural regions Greece and France. Concrete and steel are more common inland of Western Europe including Spain, France, Northern Italy and Flanders, and in major cities of Eastern Europe. Also steel is particularly dominant in densely urbanized areas in Western Europe such as the Netherlands, Flanders, Paris, Hamburg and Berlin. Plastics is only in very few locations (0.3% of grid cells) the material that deviates most from average values. One cluster can be identified in the agriculturally dominated Greek peninsular of Peloponnese.

Some of the patterns revealed by Figure 26 are not quite intuitive to explain and relate to the specific estimates used to calculate material stocks in Europe. For instance, much of Eastern Europe appears to have a considerably higher share of glass in the building material stocks. This is likely explained by the higher glass intensity indicated in the RASMI database. Similarly, one would expect wood to be particularly present in Austrian buildings. Yet, the underlying Global Exposure Model assumes Austria to be dominated by masonry construction.

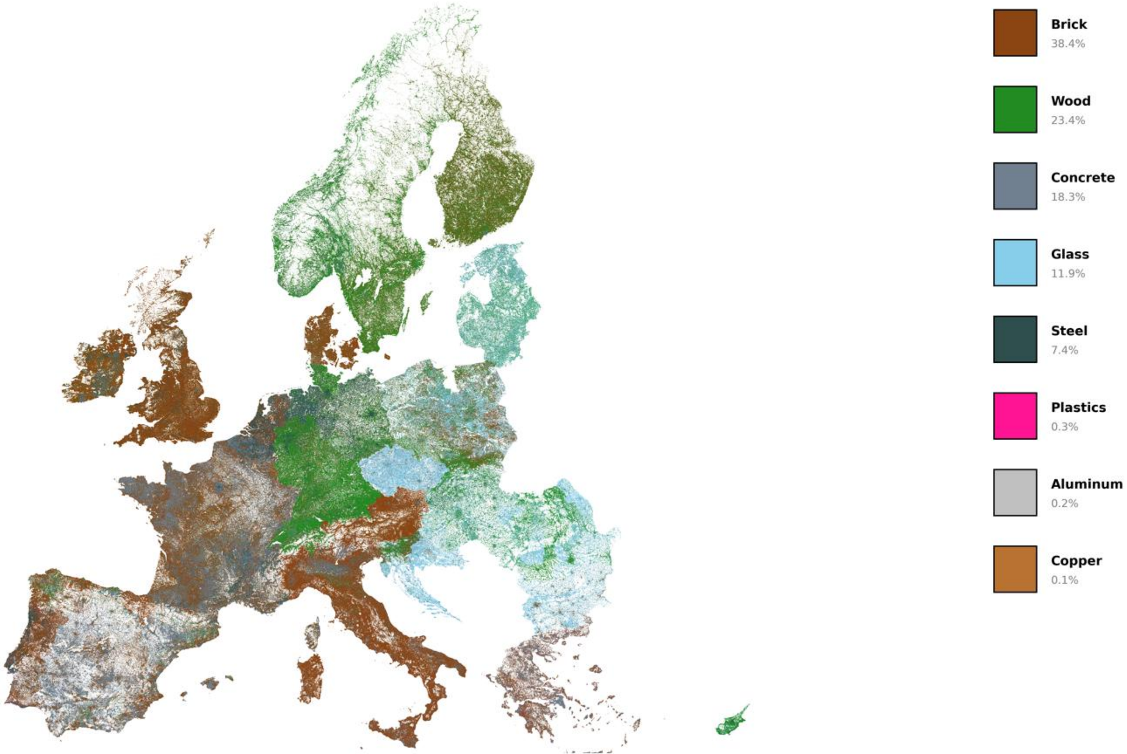


Figure 26 Building material diversity across the EU27, Norway, Switzerland and the UK. Each 1km-grid cell is colored by the material that shows the highest positive deviation from average material composition.

3.2. Transport Infrastructure

We find total material stock of transport infrastructure – including road- and rail-based infrastructure, bridges and tunnels, parking infrastructure, and fueling infrastructure – amounting to 59 Gt in 2024. In this section, material stocks are disaggregated, looking at materials, infrastructure types (categories), as well as the spatial distribution across E27+3 countries.

3.2.1. Total Stocks and Types of Materials

Material stocks of transport infrastructure per region can be seen in Figure 27a. The countries with the highest individual share in material stocks in European transport infrastructure are Germany (8.4 Gt), France (8.3 Gt), and the United Kingdom (5.5 Gt). Collectively, the three countries account for 38% of total stocks.

Roads (excluding bridges and tunnels) dominate infrastructure in the EU27+3 region, accounting for little more than 51 Gt, or 85% of total material stocks. While per kilometer of road, low-class roads (tertiary, local and rural roads) are significantly less material intensive than higher-class roads due to widths and pavement thicknesses, the sheer extent of low-class road networks makes them dominate over high-class roads, accounting for 37 Gt, or 62% of the total stock (Figure 27b).

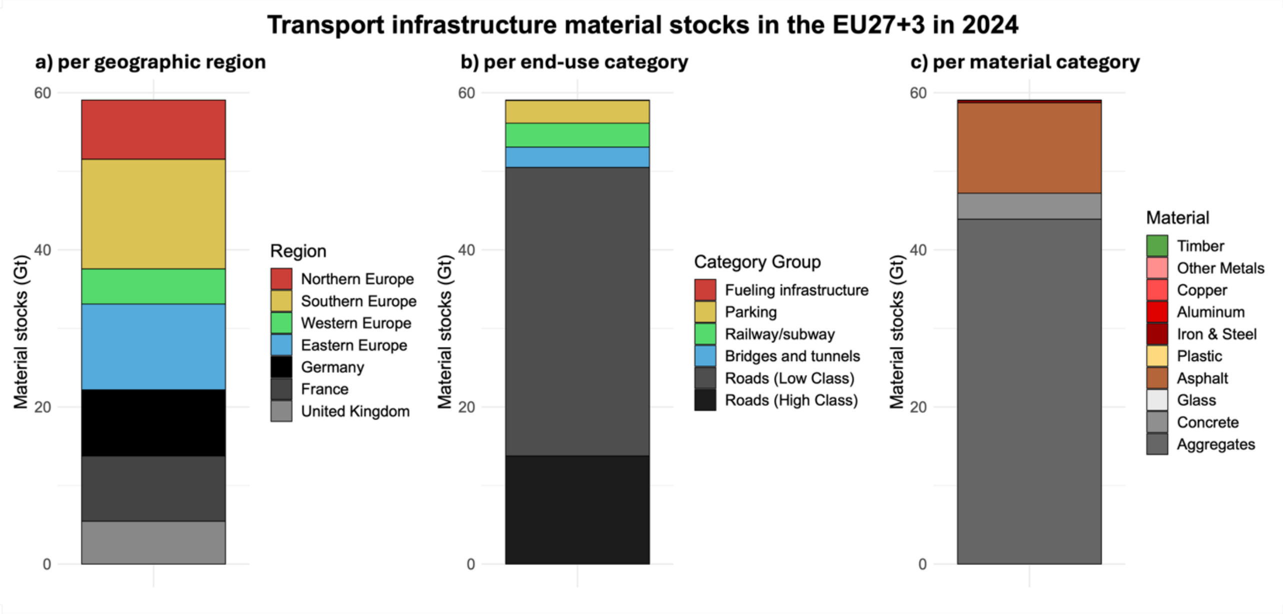


Figure 27 Material stocks of total transport infrastructure in the EU27+3 region by region, end-use category, and material. Note that for regions, Eastern Europe refers to Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia. Western Europe refers to Austria, Benelux, Ireland, Liechtenstein, Switzerland. Northern Europe refers to Finland, Denmark, Sweden. Southern Europe refers to Cyprus, Greece, Italy, Malta, Portugal, and Spain. Low-class roads include tertiary, local and rural roads, while high-class roads include motorways, primary and secondary roads. Railway/subway includes all rail-based infrastructure including station buildings and platforms. Parking includes parking lots, buildings, and garages. Fueling infrastructure includes conventional fuel stations and e-charging points.

Non-metallic minerals determine the material composition of transport infrastructure stocks (Figure 27c). With aggregates (e.g., sand, gravel, stones) used in sub-base layers of roads, and as rail track ballast, they account for 44 Gt – more than 74% of total material stocks. Due to the high share of roads in transport infrastructure, asphalt is the second most widely used material category, accounting for 12 Gt (19% of total stock). It should be noted that while other materials only have a small share in total material stocks, the share of their embodied carbon footprint can be expected to be significantly higher, as the production of steel and concrete in particular are associated with high energy requirement compared to aggregates which are mostly sources locally and with comparably low energy inputs.

3.2.2. Geographical Distribution of Material Stocks

Deriving material stocks from OpenStreetMap data allows for a detailed mapping of material stocks Figure 28). This allows for an analysis of spatial patterns of mobility infrastructure. We find that mobility infrastructure is highly unevenly distributed across regions of Europe with urban areas showing high density in transport infrastructure stocks of more than 75,000 t/km^2 while rural and more remote regions such as Lapland and Southern Spain, as well as mountainous regions such the European Alps, the Pyrenees, and the Scottish Highlands exhibiting very few to no tonnes per square kilometer. Major transportation routes and industry hubs are clearly visible in the map, particularly in the Rhine-Ruhr metropolitan in Germany and the neighboring Netherlands, Southern England, and the Parisian metropolitan region, and Northern Italy.

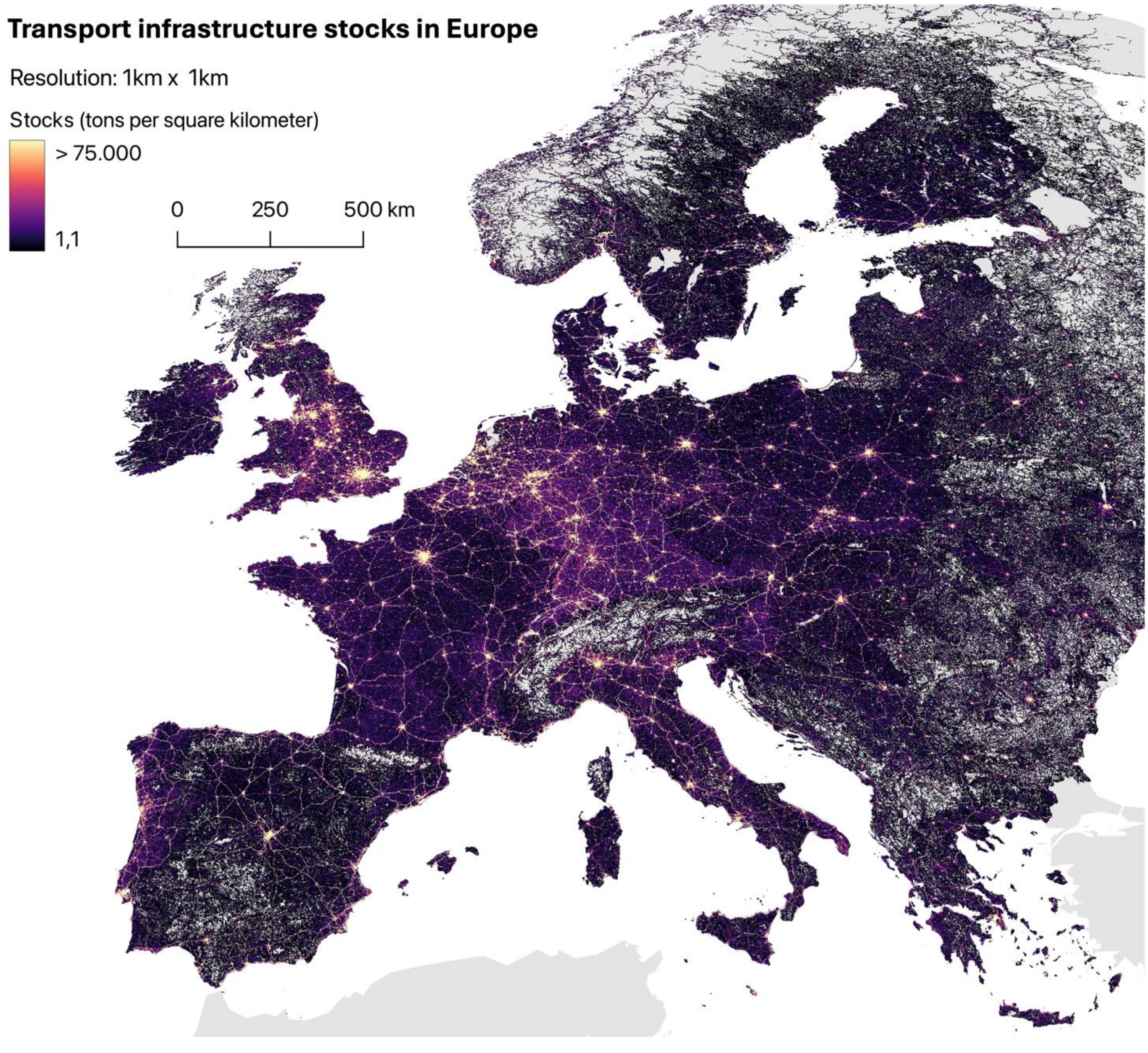


Figure 28 Total transport infrastructure stocks in Europe in 2024, as derived from OpenStreetMap data, in tonnes per 1x1km grid cell. Total stocks include road- and rail-based infrastructure, bridges- and tunnels, and parking and fueling infrastructure.

The map in Figure 28 provides only a continental-scale overview of European material stocks in transport infrastructure. However, the scalable resolution of the full OpenStreetMap-derived data product allows for a further investigation of finer spatial patterns, e.g., at urban or regional level, and an analysis of the spatial co-occurrence or interaction of different transport infrastructure types. In addition, an integration with spatially-explicit building stock data (see section 3.1.) would enable an analysis of how the building and transport infrastructure stocks interact, in turn allowing for insights to be gained regarding urban form and spatial configurations of material stocks (Creutzig et al., 2016) – aspects which are highly relevant for service provisioning and climate change mitigation.

3.2.3. Diversity of Material Stocks

The composition of material stocks in transport infrastructure varies across EU27+3 countries, both in terms of materials and end-use categories, as seen in Figure 29a. Though aggregates and asphalt account for the majority of material stocks in all countries as roads dominate end-uses across regions, the precise shares in totals can vary significantly (see Figure 29b). For example, asphalt accounts for 26% of total stocks in the United Kingdom (GBR), but for only 16% in Switzerland (CHE). The share of timber, an indicator for railway infrastructure due to its use in railway sleepers, is highest in the Czech Republic (CZE) and Slovakia (SVK), both with shares between 0.16%, and lowest in Cyprus (CYP) with 0.006%, where active railway lines are currently close to non-existent.

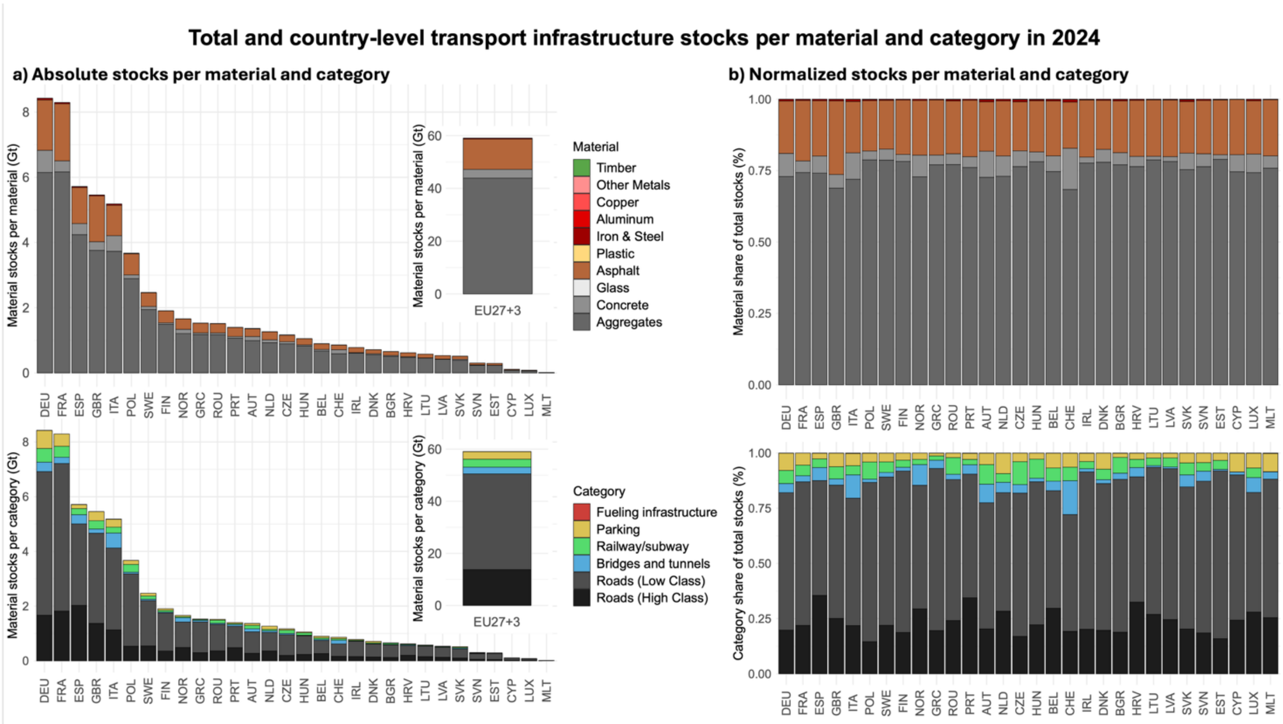


Figure 29 Material stocks of transport infrastructure in the EU27+3 in 2024 per country (ISO3 country codes), stacked by material (top bars) and end-use category (bottom bars). Insert figures represent EU27+3 material stock disaggregation, as shown in Figure 27. Note that low-class roads include tertiary, local and rural roads, while high-class roads include motorways, primary and secondary roads. Railway/subway includes all rail-based infrastructure including station buildings and platforms. Parking includes parking lots, buildings, and garages. Fueling infrastructure includes conventional fuel stations and e-charging points.

Because material stocks are defined by their use, disaggregating end-uses per country allows for further insights (Figure 29b). The share of *low-class* roads is highest in Estonia with 76%, and lowest in Spain (ESP) with 52%. Poland has the lowest share of high-class roads in total material stocks, with only 15%, while the share of high-class roads is highest in Spain (35%). The highest share of overall roads in total transport infrastructure stocks was found to be in Lithuania (LTU) with 94%, while the total roads were found to have the least share in Switzerland (73%). With 15%, Switzerland is also the country with the by far highest share of bridges and tunnels in total stocks, as opposed to

Estonia, where these account for less than 1% of total stocks. Rail-based infrastructure is highest in the Czech Republic, with more than 10% and lowest in Cyprus with less than 0.1%.

3.3. Vehicles

3.3.1. Total Stocks and Types of Materials

Figure 28 present the evolution of total material stock embedded in the rolling stock across the EU27 and the United Kingdom from 2013 to 2023. The total material stock in vehicles has steadily increased throughout the observed period, reaching more the 600 million tonnes, reflecting the continuous growth of the vehicle fleet and gradual shifts in vehicle composition.

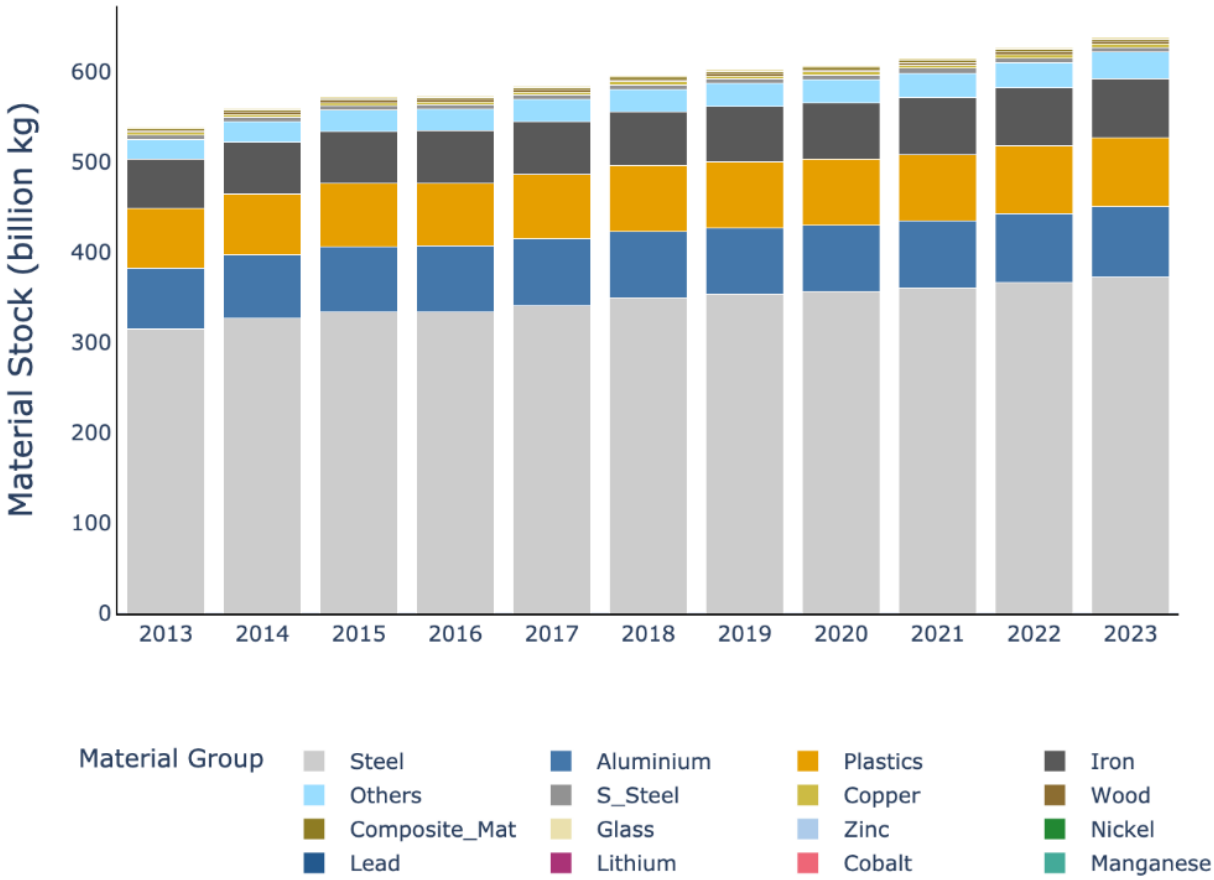


Figure 28 Total vehicle material stock in the EU27 + UK by material (2013-2023).

When analysing the stock by material composition (**Errore. L'origine riferimento non è stata trovata.**), steel remains by far the dominant material, accounting for approximately 50% of the total rolling material stock throughout the period. It is followed by aluminium, plastics, and iron, which together with steel represent over 80% of the total stock. This composition reflects the structural and functional roles these materials play in conventional vehicle manufacturing, with gradual shifts occurring as lightweighting strategies and new vehicle technologies are adopted. In 2023 our modelling suggests that the total rolling stock contained ca 350 Million tonnes of steel and 77 Million tonnes of plastics and aluminum.

Figure 29 shows that internal combustion engine (ICE) vehicles dominate the material stock throughout the decade. In particular, gasoline-powered passenger cars represent the single largest contributor, followed by light commercial vehicles (lorries ≤3.5 tonnes, diesel), diesel passenger cars, heavy-duty lorries (>3.5 tonnes, diesel), and diesel-powered road tractors. Combined, these ICE vehicle categories account for approximately 80% of the total stock, highlighting the still-prevailing dominance of conventional technologies in the EU+UK vehicle fleet.

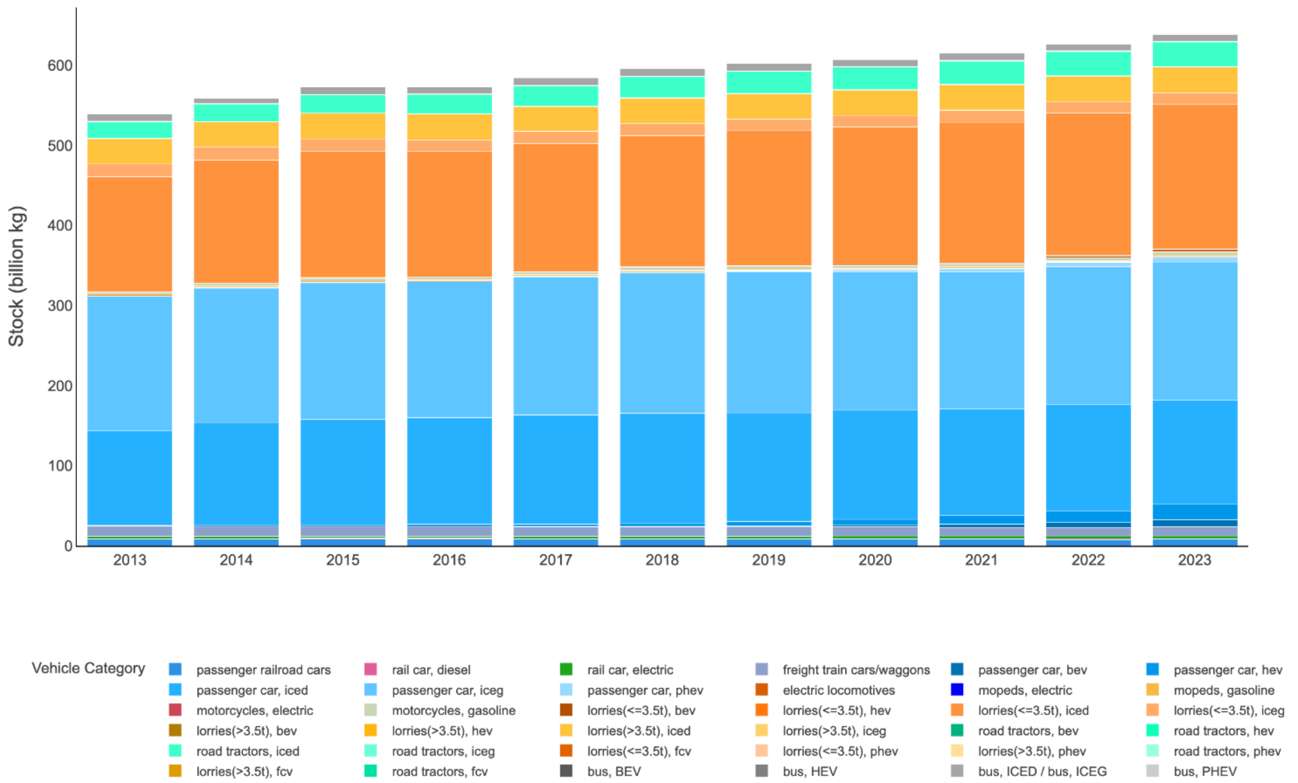


Figure 29 Total vehicle material stock in the EU27 + UK by vehicles type (2013-2023).

Nonetheless, the data also indicate a visible emergence of alternative powertrains in recent years. Electrified vehicles—particularly hybrid electric vehicles (HEVs)—have begun to accumulate a growing share of the total material stock. This trend reflects the ongoing transition toward lower-emission transport technologies, with HEVs currently forming the majority of non-ICE vehicles in stock. Battery electric and plug-in hybrid vehicles are also expanding, though their contribution remains relatively modest at this stage.

3.3.2. Geographical Distribution of Material Stocks and Vehicles

The geographical distribution of vehicle-related material stocks in the EU27 and the United Kingdom reveals significant heterogeneity across countries. As shown in Figure 30, the largest absolute stocks are concentrated in a few populous major economies. Germany, France, the United Kingdom, Italy, Spain, and Poland together account for the majority of the total vehicle material stock in the region. This reflects both the size of their vehicle fleets and the structural composition of their transport systems, including a higher presence of heavy-duty vehicles and long-distance transport modes.

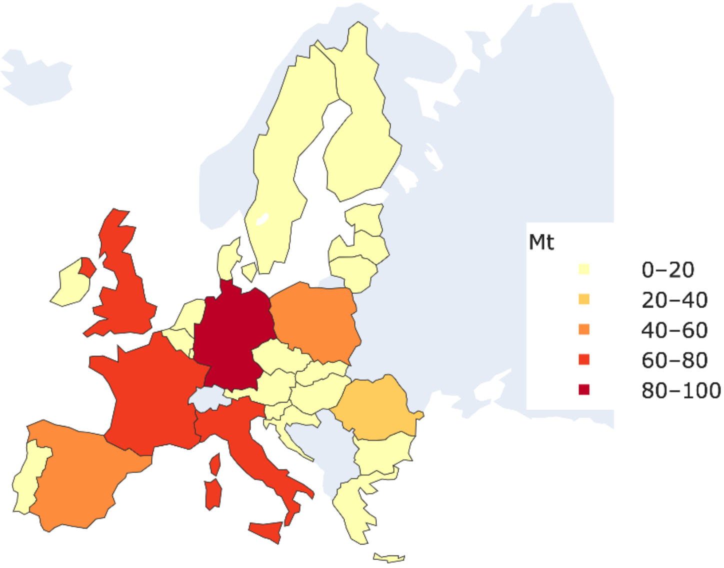


Figure 30 Map of total vehicle material stock by country in 2023.

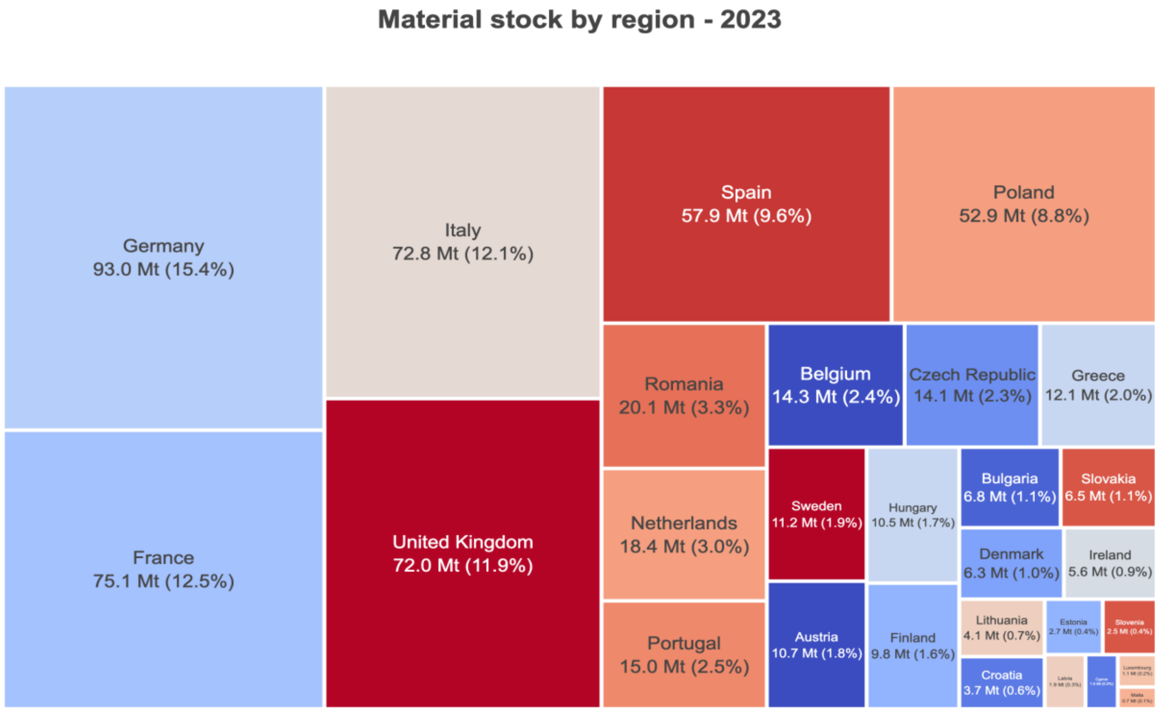


Figure 31 Total vehicle material stock in the EU27 + UK by country in 2023.

The same pattern is confirmed in Figure 31, which visualizes the total material stock by country. The highest values are observed in Germany (over 90 Mt), followed by France, Italy, the UK, and Spain. Eastern and smaller European countries show lower total stocks, reflecting their smaller populations and vehicle fleets.

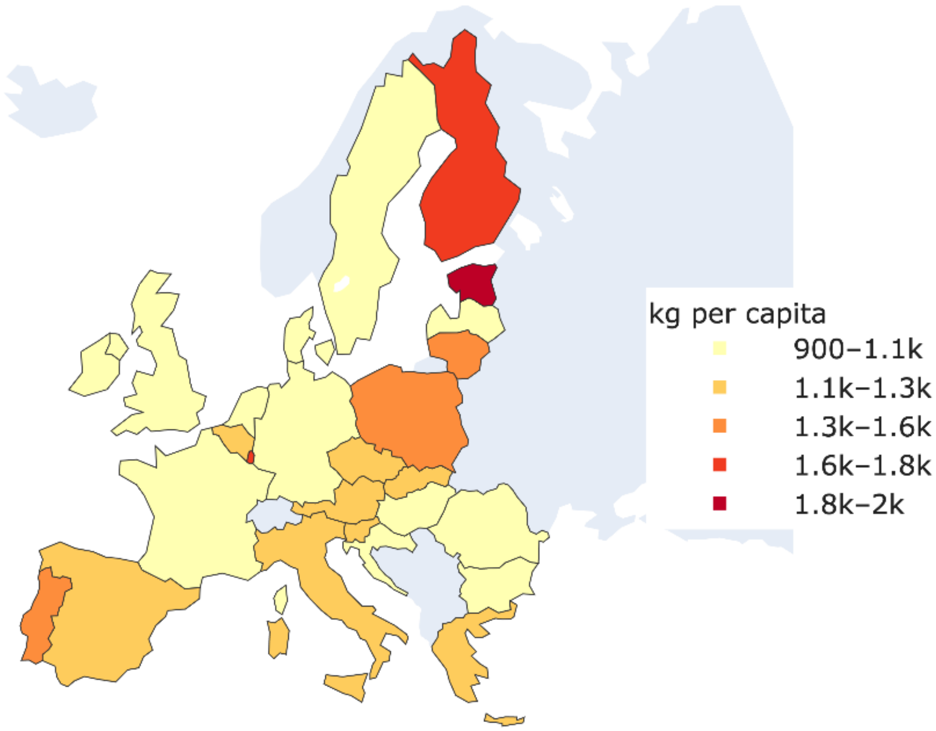


Figure 32 Map of total vehicle material stock per capita by country in 2023.

However, when the stock is normalized by population (Figure 32), a different picture emerges. The per-capita material stock highlights countries with relatively high levels of vehicle-related material intensity per resident. In 2023, Estonia and Finland exhibit the highest per-capita values—exceeding 1,800 kg per person—followed by several Baltic and Central European countries. This pattern indicates variations in mobility demand, vehicle ownership rates, and fleet structure across countries. However, further analysis is needed to understand the underlying causes, which may include the proportion of the population living in rural areas, the availability and quality of public transportation (e.g., buses and trains), and the prevalence of trucks, potentially influenced by country-specific factors such as economic activities or infrastructure.

Figure 33 shows that cross-country patterns largely mirror those in the previous figure. Differences across countries are mainly explained by fleet composition (share of SUVs vs. small cars), vehicle ownership per capita, and powertrain mix (ICEV/HEV/PHEV/BEV), which shift both total mass and the relative shares of materials.

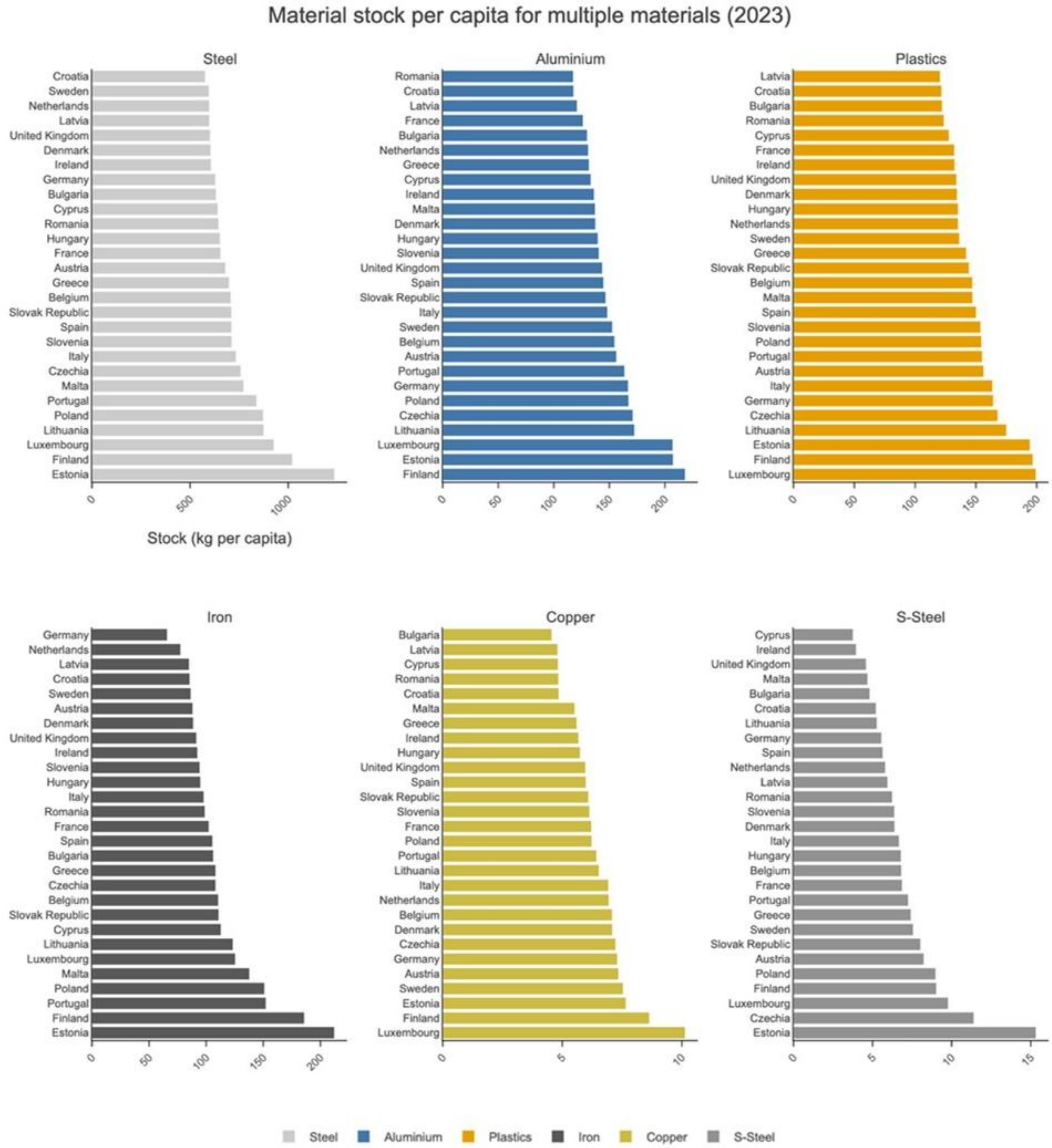


Figure 33 Vehicle material stock per capita by material in 2023

The evolution of per-capita material stock over time is presented in Figure 34, where the countries with the top 5 countries with the highest material vehicles stock are colored, shows a gradual and consistent increase across all countries from 2013 to 2023. This suggests that even in countries with slower vehicle growth, the material intensity per person is rising—likely due to ongoing shifts toward larger vehicles (e.g., SUVs, vans), an increase in the motorization rate, and the introduction of new vehicle technologies that require heavier vehicles.

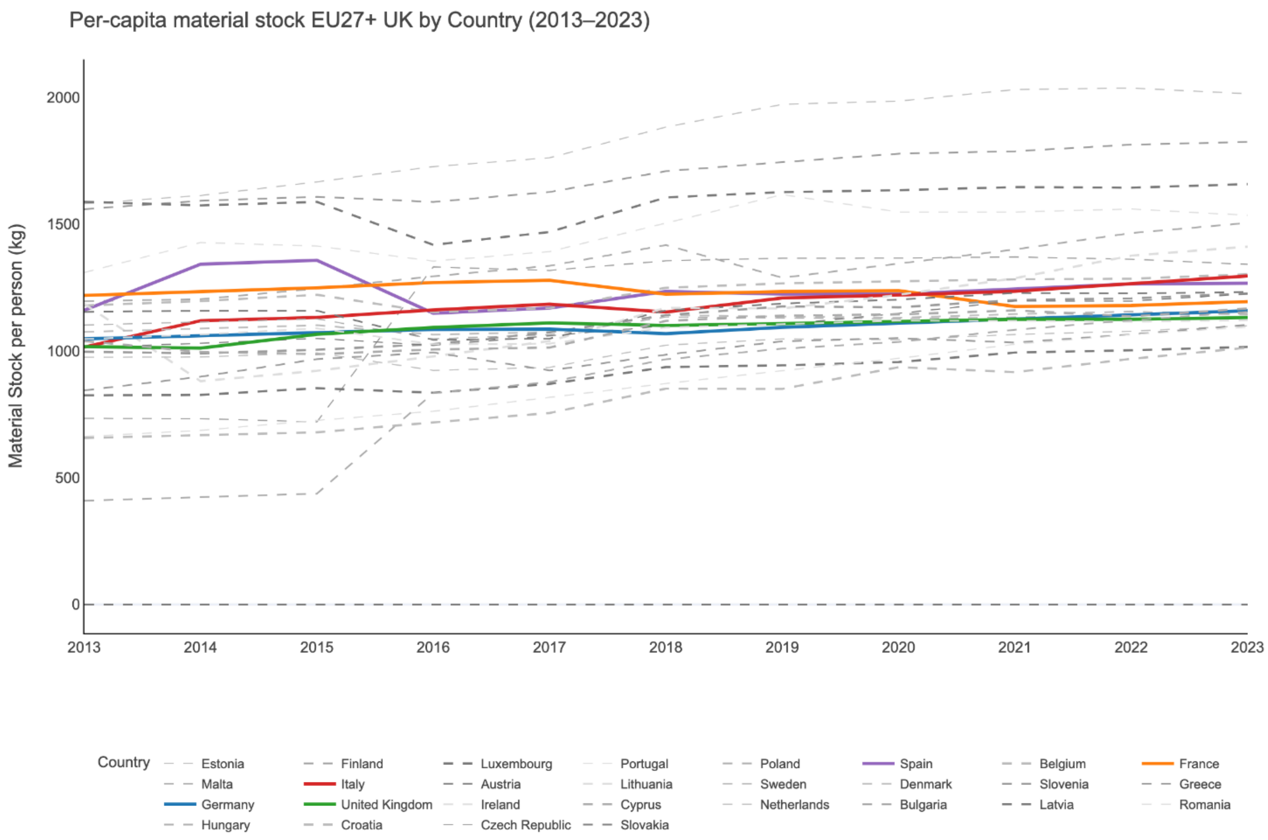


Figure 34 Total per-capita material stock in vehicles by country (2013-2023).

Together, these figures highlight the spatial disparities in vehicle-related material accumulation and underline the importance of tailoring circular economy and decarbonization strategies to national contexts.

3.3.3. Diversity of Material Stocks

Figure 35 presents the distribution of total vehicle material stock across European countries in 2023, disaggregated by material category. The data illustrate how different materials are allocated geographically, largely reflecting the total stock per country but also revealing differences in material mix intensity.

Unsurprisingly, the countries with the largest total vehicle stock—Germany, France, the United Kingdom, Italy, Spain, and Poland—also account for the highest absolute quantities of materials such as steel, aluminum, plastics, iron, and lead. These five materials dominate across all countries, with steel being the largest contributor in every case, typically accounting for more than half of the total stock mass per country.

Secondary materials such as copper, zinc, glass, wood, and various critical raw materials (e.g., lithium, cobalt, nickel, manganese) appear in smaller quantities but are increasingly relevant in countries with higher shares of electric vehicles. For instance, countries such as France, Germany, and the Netherlands exhibit slightly higher stocks of battery-related materials like lithium, cobalt, and nickel, indicating a greater penetration of electrified vehicle technologies.

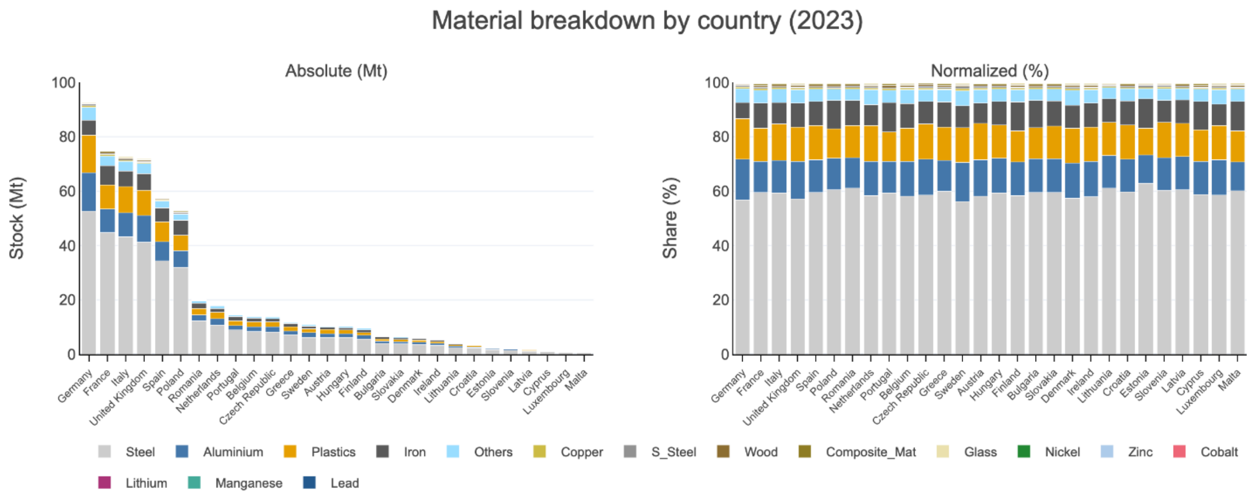


Figure 35 Breakdown of vehicle material stocks in the EU27 + UK by material in 2023

Overall, the figures highlight both the concentration of materials in high-population and high-motorization countries and the underlying homogeneity in material composition, driven by the predominance of internal combustion vehicles. Nevertheless, emerging differences in material types—especially critical metals—may become more pronounced in future years as electrification progresses.

4. Results in Perspective

4.1. Robustness of evidence on material stocks across sectors

Compared to previous estimates of material stocks in buildings and vehicles in the EU27 (Figure 36), the estimates presented in this report are on the larger end. While the estimate for material stocks in residential buildings comes close to the largest previous estimate (12% more than Haberl et al., 2024), the estimate for material stocks in non-residential buildings is more than double that of Haberl et al. (2024) and 45% larger than the inflow-driven estimate by Wiedenhofer et al. (2024a). Total building volume accounted for in this study is within a 10% range of that of satellite-derived Haberl et al. (2024), which indicates that the discrepancy in material stock is related to higher material intensities applied in this study and potentially different functional and structural composition of the building stock. Compared to previous studies that rely on nighttime light or officially reported occupied building stocks (Pauliuk et al., 2024; Peled & Fishman, 2021; Wiedenhofer et al., 2015), the combination of governmental cadasters with crowd-sourced and satellite-derived data allows for a more complete and more accurate representation of material stocks in buildings that stretches residential, commercial and industrial buildings irrespective of occupancy status. While alignment of derived material flows with trade and production accounts is desirable, different from inflow-driven studies, this study also allows accounting for material stored in buildings parts predating national accounting efforts for material use.

Also the vehicle material stock in motorized road vehicles calculated here is 53-100% larger than previous estimates (Pauliuk et al., 2021; Wiedenhofer et al., 2024a). A comprehensive comparative decomposition of the results from the different studies has not been performed, but some key insights can be deduced from the results in section 2.3. In particular, the subsection on LDVs demonstrates how the VMI yield higher vehicle weights across different size segments than previous studies. The benchmarking of the VMI model with manufacturer data gives confidence to those estimates. This report also provides detail on different power engines and weight classes of vehicles, which is particularly relevant as material intensities can vary significantly. Another key factor is how different vehicle segments are matched with fleet stock data. Variations in this across studies may yield significant differences in outcomes.

Material stocks in roads and railways reported here, largely align with previous studies which take a similar stock-driven approach relying on OpenStreetMap to estimate infrastructure stocks. The major difference to van Engelenburg et al. (2024) lies in this study assuming higher concrete material intensities for roads and railways compared to aggregates and asphalt.

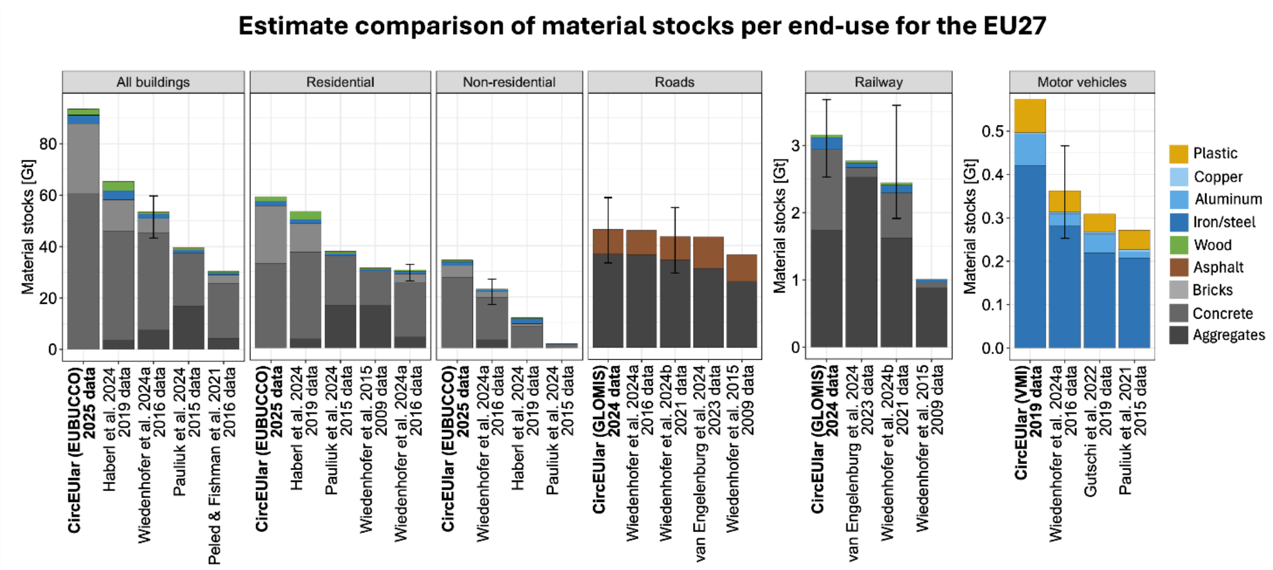


Figure 36 Comparison of material stock estimates for buildings, roads, railways and motor vehicles in the EU27.

The estimates provided here also differ from inflow-driven estimates, which rely on annual production and trade statistics on material flows together with lifetime distributions to derive material stocks. Inflow-driven estimates have difficulty accounting for the historical accumulation of long-lived material stocks such as building base layers, as well as base courses of roads and railways, requiring strong assumptions to model such often underreported flows (Wiedenhofer & Streeck et al. 2024), as well as for attributing material inflows into stocks to end-use product groups (Streeck et al., 2023a; Streeck et al. 2023b). Overall, while the total mass of material stocks indicated here needs to be evaluated against other estimating efforts to understand overall stock amounts (Streeck et al. 2025), the particular value of this report lies in the detail it provides with regards to location, composition and type of structures that contain the materials.

4.2. Future use of detailed stock accounts for circularity pathways

The high resolution of material stocks provided by the approaches presented in this report can inform further modelling efforts towards climate change mitigation and a circular economy. High value lies in integrating the key insights yielded from these detailed accounts into Integrated Assessment Models (IAM) which form the basis of international scenario analysis. For instance, to understand urban mining and circularity potentials in the construction sector at large scale, it will be relevant to differentiate the specific composition of material stocks by local population dynamic and account for un-occupied building stocks as well as un-used transport infrastructure. While vehicles occupy a smaller share of total material stocks, their higher turnover rate and metal-intensity make them highly relevant for circularity and climate change mitigation scenarios. This report showed that transport modules in IAMs need to pay particular attention to differentiating weight classes for heavy duty vehicles which have notably different material intensities as well as differentiating power trains for light duty vehicles for which a shift towards electric vehicles is ongoing. Further, analysis should also be conducted to integrate material stock accounts in buildings, transport infrastructure and vehicles to understand how these stocks interact with regards to urban form and use patterns (Creutzig et al., 2016) – aspects which are highly relevant for service provisioning and climate change mitigation.

4.2.1. Integration with MESSAGEix-Buildings

Future developments will focus on integrating the insights provided by the enhanced stock estimation in IAM-based sectoral modelling to improve the representation of material stock and flows in prospective circular economy scenarios. For the building sector, the granular buildings data in EUBUCCO will inform the scenario assessment in the MESSAGEix-Buildings model (Mastrucci et al., 2021), part of the MESSAGEix-GLOBIOM integrated assessment model (Huppmann et al., 2019). Incorporating the detailed information from EUBUCCO will enable enhancing the accounting of building stocks from national up to sub-national level and further characterizing buildings by location, such as urban, suburban, and rural, and by more detailed building types. These improvements can significantly improve the accounting of geographical distribution and building characteristics that are key to a more comprehensive assessment of circular strategies for the building sector.

4.2.1. Integration with MESSAGEix-Transport

For the transport sector, adaptation of the Vehicle Material Intensity (VMI) model and the vehicle-stock accounting model towards MESSAGEix-Transport offers opportunities for enhanced representation of material demand, stocks and flows associated with the transition of the mobility and transport sector. Specifically, VMI may be coupled to provide time series of vehicle material intensities, enabling MESSAGEix-Transport to track how fleet composition drives primary material demand, embodied emissions, and end-of-life scrap supply. Such a linkage will support technology scenarios in which VMI endogenously varies mass and composition through light-weighting (e.g., shifts toward aluminum, magnesium alloys, and selected composites) and explores battery pathways (chemistry shares, pack sizing), quantifying implications for critical materials and total demand.

Appendix

Transport Infrastructure

OpenStreetMap tags

The main tags used were highway and railway, each denoting the hierarchical class or more precise type of an infrastructure class. For roads, a Geofabrik product description (Ramm, 2022) provided guidance for matching OSM tags with road classes ('motorway' to 'rural roads') and based on manual samples from Google Street View for various regions, as well as by consulting the OSM online encyclopedia entry for each tag (OpenStreetMap, 2024), each OSM tag was matched with one of the 32 infrastructure classes based on characteristics such as road width, pavement type, etc. While most infrastructure classes are made up of only one or two OSM tags, 'local roads' are compilations of multiple road types spanning a variety of functions that broadly share a common width and pavement type. Analogously, rail-based infrastructure types were matched with the rail infrastructure classes 'railway', 'subway', 'tram', and 'other rail'.

For each road and rail infrastructure class, associated bridges and tunnels were distinguished using the additional OSM tag 'bridge=yes' or 'tunnel=yes', respectively. In the case of subway lines, the latter refers to underground sections, while the former or the lack of either tag refers to above-ground, elevated sections, respectively. Additional infrastructure classes include railway or subway station infrastructure, parking infrastructure (parking lots and buildings, as well as underground garages), as well as fueling infrastructure (conventional gas stations and electric charging points). These infrastructure classes predominantly make use of the OSM tags 'amenity', 'building', 'parking', and 'public_transport'.

Material intensity factors for mobility infrastructure

Table 7 provides an overview of global average MI factors for the main material categories (biomass, metals non-metallic minerals, and fossil fuel-based materials) as well as road width for each infrastructure class defined above. Actual MI factors distinguish timber, plastics, various metals (iron/steel, copper, aluminum, other metals), non-metallic minerals (concrete, aggregates, glass), and asphalt (a mixture of 5% bitumen and 95% aggregates). In the case of bridges and tunnels, MI factors were combined with the pavement of each corresponding road class.

Table 7 Global average material intensity factors. Note that categories may not sum to total due to rounding.

Infrastructure class	Material intensity (kg/m^2)					Width (m)	Data sources
	Biomass	Metals	Minerals	Fossil	Total		
Motorways roads	–	–	1.76	0.02	**1.79**	22.6	(Alzaim et al., 2020; Alzard et al., 2019; Augiseau & Kim, 2021; Chen et al., 2017; Cruz, 2016; CSIR, 2000; DMR, 2014; DMT, 2016; Frantz et al., 2023;
Primary roads	–	–	1.44	0.02	**1.46**	15.0	
Secondary roads	–	–	1.27	0.02	**1.29**	11.6	

Tertiary roads	–	–	1.07	0.01	**1.08**	9.2	Haberl et al., 2021; Henderson & van Zyl, 2017; Lanau & Liu, 2020; Miatto et al., 2021; Özgenel, 2016; Wiedenhofer, Baumgart, et al., 2024; Wiedenhofer, Schug, et al., 2024)
Local roads	–	–	0.56	0.01	**0.56**	5.7	
Rural roads	–	–	0.29	<0.01	**0.29**	5.0	
Motorway bridges	–	0.14	3.17	0.02	**3.33**	21.5	(JICA, 2018; Haberl et al., 2021; Wiedenhofer, Baumgart, et al., 2024)
Primary bridges	–	0.16	2.64	0.02	**2.81**	11.7	
Secondary bridges	–	0.16	2.47	0.1	**2.64**	10.9	
Tertiary bridges	–	0.16	2.30	0.01	**2.47**	9.1	
Local bridges	–	0.16	2.13	0.01	**2.30**	4.7	
Rural bridges	–	0.16	2.13	<0.01	**2.30**	4.7	
Motorway tunnels	–	0.12	5.14	0.02	**5.29**	21.5	
Primary tunnels	–	0.12	4.79	0.02	**4.93**	11.7	
Secondary tunnels	–	0.12	4.63	0.1	**4.77**	10.9	
Tertiary tunnels	–	0.12	4.43	0.01	**4.57**	9.1	
Local tunnels	–	0.12	4.25	0.01	**4.38**	4.7	
Rural tunnels	–	0.12	4.25	<0.01	**4.38**	4.7	
Railway	0.01	0.02	0.45	–	**0.48**	11.0	(Antoniou et al., 2023; Bai et al., 2019; Frantz et al., 2023; Haberl et al., 2021; Schmied & Mottschall, 2013; Wiedenhofer, Baumgart, et al., 2024)
Railway bridge	0.01	1.14	0.86	–	**2.00**	10.8	
Railway tunnel	0.01	1.14	4.49	–	**4.64**	10.8	
Subway ground-level	–	0.20	2.27	–	**2.46**	10.0	
Subway elevated	–	0.28	3.98	–	**4.25**	10.0	
Subway underground	–	0.55	10.56	–	**11.20**	10.0	
Tram and other rail	0.01	0.02	0.45	–	**0.47**	6.3	
Railway station	–	–	4.40	–	**4.40**	[1]500.0	
Railway platform	–	–	4.80	–	**4.80**	–	
Subway station	–	–	6.05	–	**6.05**	[1]1.500.0	
Gas station	–	0.28	0.06	–	**0.34**	[1]1.000,0	(Haberl et al., 2024; Lucas et al., 2012; Mulrow & Grubert, 2023; Zhang et al., 2019)
Gas station buildings[2]	0.04	0.05	1.03	<0.01	**1.12**	[1]500.0	
Charging station	–	0.17	0.82	0.07	**1.06**	[1]1.0	
Parking, surface	–	–	0.72	0.01	**0.73**	[1]1.000,0	

Parking building	–	0.05	2.52	–	**2.56**	[1]1.000, 0	(Cruz, 2016; Eliassen et al., 2019; Rebello, 2022; Zeitz et al., 2019)
Parking, underground	–	0.01	1.25	–	**1.25**	[1]1.000, 0	

[1] Width refers to assumed area in m^2 if infrastructures are provided by OpenStreetMap as points instead of polygons.
[2] General commercial building MI factors have been used as proxies for fuel station buildings.

MI factors for rural roads were weighted at the national level based on shares of each OSM track grade's length in the total length of tracks. While track grade types 1 is assumed to be asphalted, the remaining track grades are assumed to be 50% gravel roads and 50% so-called dirt roads (i.e., merely consisting of compacted local earth or other local materials). Because for dirt roads no material is extracted, transported, or otherwise moved, they do not fall within our socio-metabolic system boundary and their MI factor is effectively zero. Track roads without a grade information tag are weighted according to the shares of the reported grade types per region. For local roads, we assume that 50% are paved and 50% are unpaved with 75% of unpaved local roads being compacted local material (MI = 0).

Conflict resolutions for overlapping infrastructure classes

To resolve some of the conflicts stemming from class overlaps, we defined a set of conflict resolutions. While some infrastructure class overlaps may be realistic (e.g., bridges above or tunnels below roads and railway lines), other overlaps are less reasonable. This is especially true for overlaps of polygons and lines. In the raw OSM data, roads often run through parking infrastructure areas. This is likely due to the use of OSM maps for navigational purposes. However, in reality, it is more likely that a parking lot is made up of a single pavement type. In cases of such overlaps, our conflict resolutions allow the model to select one infrastructure class over the other based on a predefined order: In the case of roads and parking lots (surface parking), motorways, primary and secondary roads are to be selected over parking lots, as it is less likely, that these major road types are interrupted by parking infrastructure, and more likely, the parking infrastructure is located to both sides of these roads. For tertiary, local and rural roads, however, the opposite is assumed and the conflict is set to be resolved to parking infrastructure. All other infrastructure classes follow the former rule (i.e., parking lots are to be prioritized). The same logic is used for the paved area of gas stations. All building types (gas station buildings, railway station buildings and platforms, as well as subway stations) overwrite all other infrastructure classes (i.e., overlapping road or rail sections are removed). The conflict of overlapping road segments is resolved by always prioritizing the hierarchically higher class (e.g., motorways over primary roads, tertiary over rural roads).

Vehicles

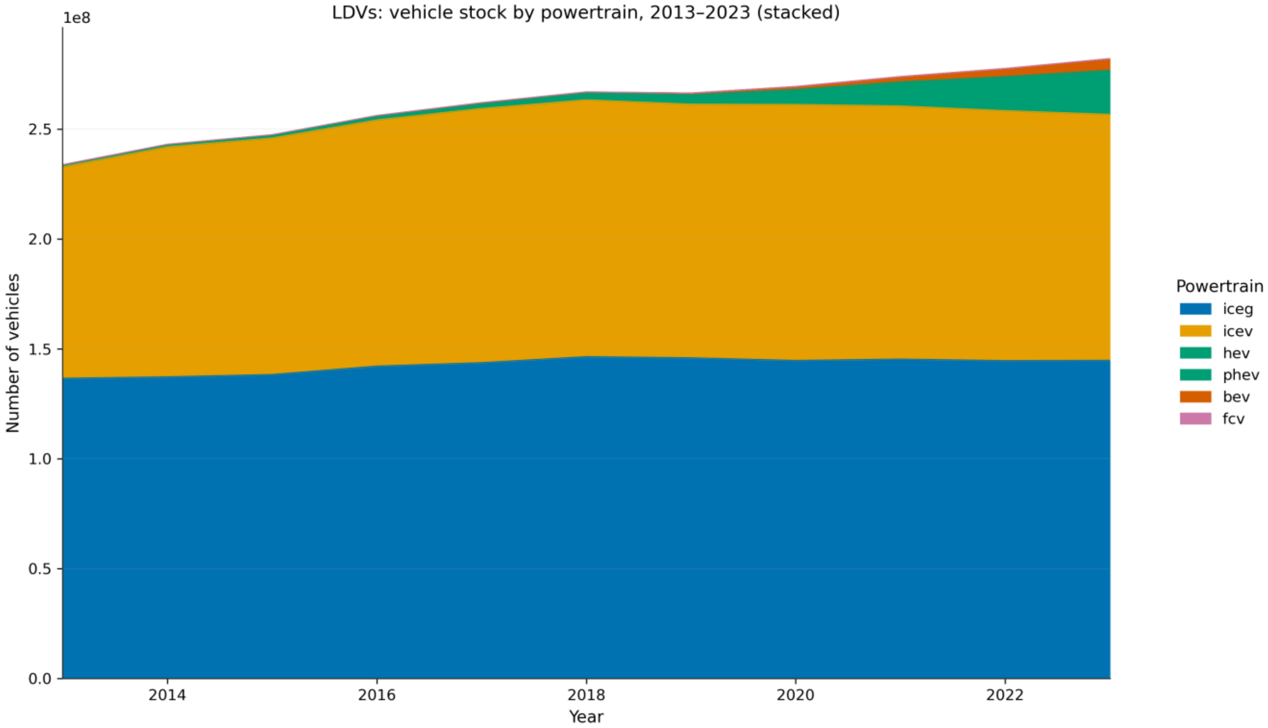


Figure 37 LDVs fleet stock EU27 – UK – 2013-2023.

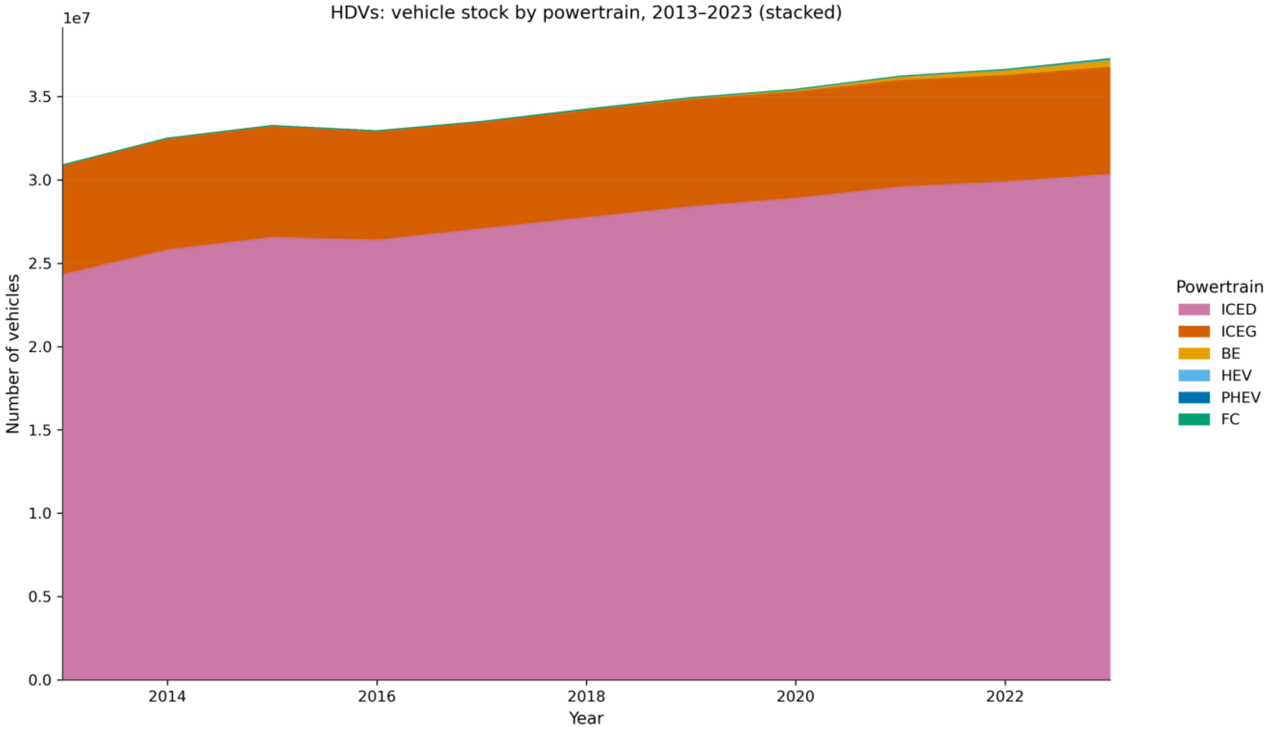


Figure 38 HDVs (truck + bus) fleet stock EU27 – UK – 2013-2023.

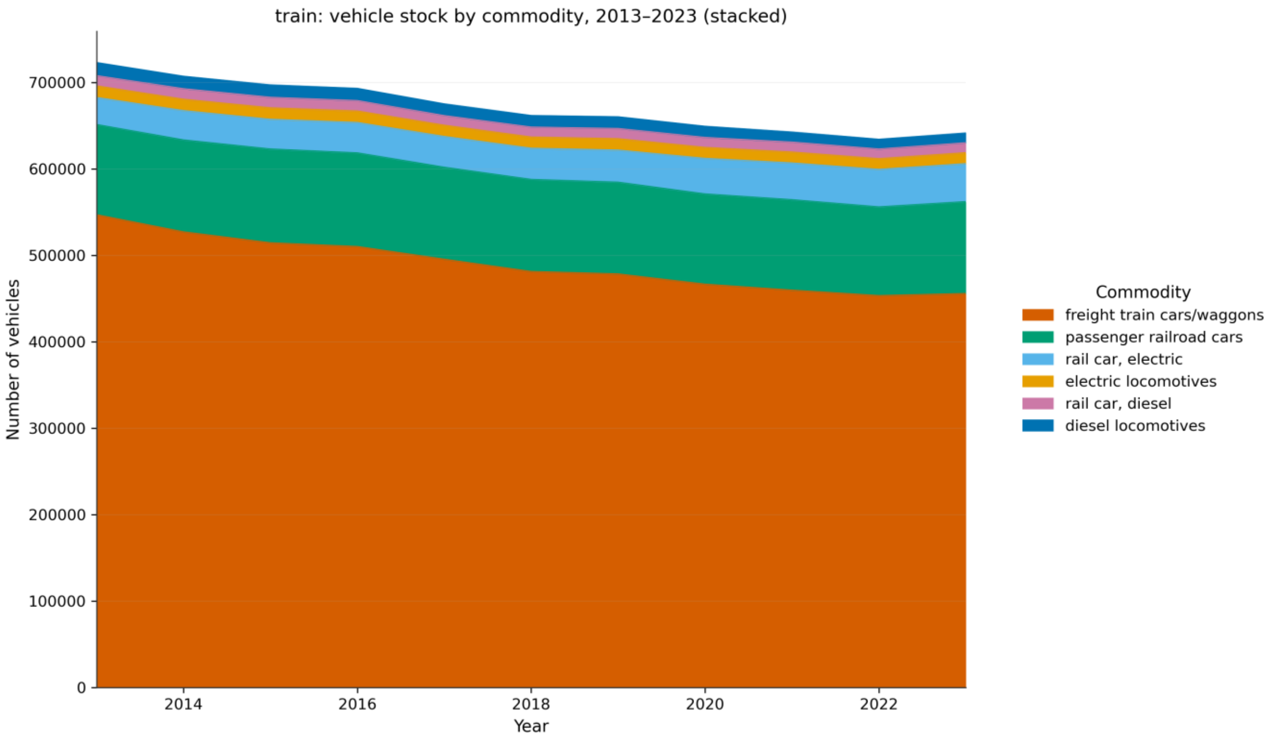


Figure 39 Train fleet stock EU27 – UK – 2013-2023.

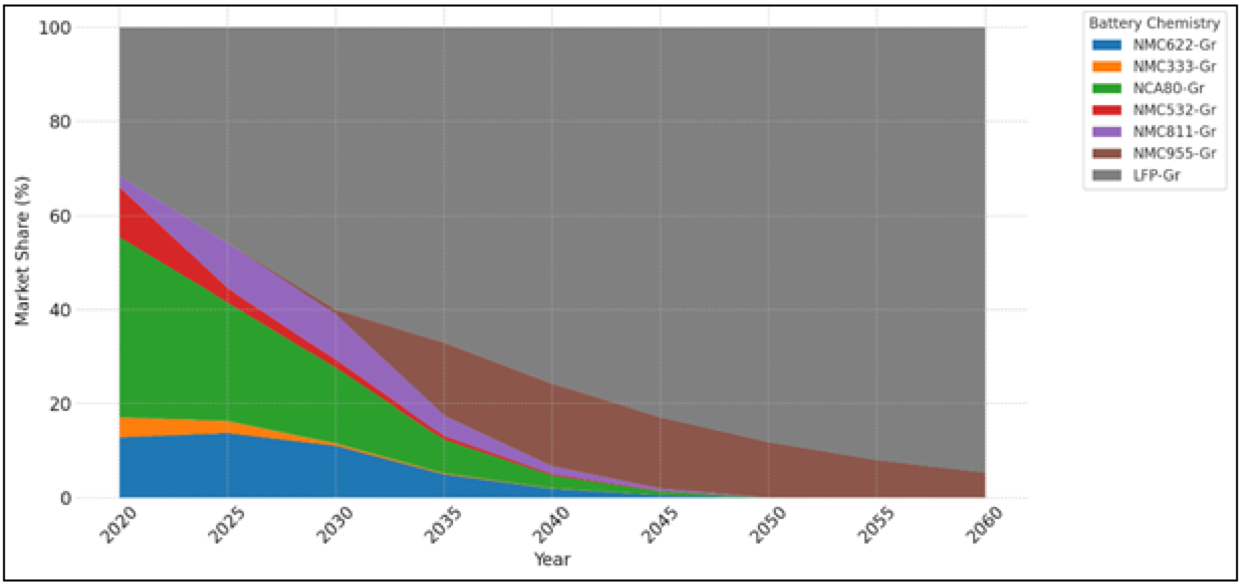


Figure 40 Projected battery market share 2020-2060

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