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Beyond Green Growth: Evaluating the Biophysical Feasibility of Rail-Centric Transport Systems in the European Union

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Abstract

Achieving the European Union's (EU-27) 2050 climate neutrality goal requires a drastic reduction in transport emissions. This study utilizes the pymedeas2 integrated assessment model to evaluate trade-offs between technology-led and structure-led transitions under both continuous growth and steady-state economic paradigms. Our results reveal that relying primarily on private vehicle electrification falls short of emission targets. The baseline REF-G scenario—following current institutional roadmaps centred on rapid technological substitution and sustained economic growth—maintains a high final energy demand and requires a cumulative extraction of 2.35 Mt of lithium by 2050, claiming nearly 6.4% of current global proven reserves solely for European mobility. Conversely, combining a modal shift toward electrified rail with macroeconomic stabilization (RAIL-SSE) reduces transport final energy demand by 68% relative to the projected 2024 peak and decreases lithium requirements by 57%. This sufficiency-driven pathway achieves the deepest absolute climate mitigation, dropping residual transport emissions to approximately 90 $MtCO_2$/year. Furthermore, despite the front-loaded costs of rail expansion, RAIL-SSE emerges as the least capital-intensive pathway, requiring a total investment of USD 19.83 trillion—a systemic saving of USD 7.27 trillion relative to the REF-G baseline. We conclude that reaching absolute sustainability in the EU transport sector necessitates a policy shift away from resource-intensive green growth strategies toward demand sufficiency and durable public infrastructure.

Keywords: transport transition; biophysical limits constraints; transport modal shift; stationary economy

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1. Introduction

The transport sector currently stands as the primary source of greenhouse gas (GHG) emissions in the European Union, accounting for approximately 25% of the total as of 2024 [1]. While other economic sectors have collectively achieved a 44% reduction since 1990, transport emissions have increased by 21% over the same period, structurally plateauing as efficiency gains are consistently offset by rising activity [2]. This persistent decoupling failure is driven by a combination of increasing road freight, growing car ownership, and a shrinking share of rail, leaving the sector 93% dependent on oil products [3,4].

To reverse this trajectory, current EU policy, anchored in the Green Deal and Fit for 55 packages, mandates a 90% reduction in transport-related emissions by 2050 [5,6]. This institutional strategy is predicated upon a green growth paradigm that seeks to achieve

absolute decoupling through accelerated technological substitution. Such a transition is propelled primarily by mass electrification and systemic efficiency gains; yet, it largely overlooks the structural challenges posed by the continuous growth in mobility demand [7]. However, recent literature raises significant concerns regarding the biophysical feasibility of this techno-centric approach [8,9]. These studies argue that the rates of decoupling required are historically unprecedented and unlikely to be sustained, while the massive material requirements for battery production and renewable infrastructure pose severe risks of supply-chain bottlenecks and ecological shifting.

García-Olivares et al. [10,11] propose a strategic shift toward electrified collective transport as a primary mechanism to remain within absolute biophysical limits, arguing that high-capacity rail can provide essential mobility services with significantly lower energy and material demand compared to private road transport. Following this framework, this study operationalizes and quantifies the feasibility of a large-scale modal transition from road transport to electrified rail systems within the EU-27. Our primary objective is to quantify how prioritizing electrified rail can mitigate systemic constraints frequently overlooked in mainstream policy pathways, such as critical raw material bottlenecks in Lithium and the intensification of peak energy demand associated with universal private car electrification [12,13].

Finally, we investigate the frontier of sufficiency and post-growth strategies as a necessary complement to technological and modal shifts. As defined in the IPCC Sixth Assessment Report (AR6), sufficiency encompasses policy measures that avoid the demand for energy and materials while ensuring well-being within planetary boundaries [14]. To operationalize this, we explore scenarios specifically testing the impacts of a post-growth strategy where GDP per capita growth gradually decelerates to reach zero by 2040, remaining constant thereafter. We frame both continuous economic expansion and post-growth stabilization as distinct hypotheses to be objectively tested against the biophysical, material, and energy constraints of the European transport system.

To address these complexities, we integrate a new detailed transport module into the pymedeas2 framework [15]. While widely used institutional optimization tools like PRIMES or TIMES focus on cost-effective pathways, they frequently treat critical raw material availability as an exogenous factor, thereby ignoring potential supply-chain bottlenecks in Lithium, Nickel, or Platinum group metals [12,16]. Furthermore, empirical analysis suggests that mass electrification could induce non-negligible spikes in peak energy demand and operational costs, potentially exceeding current power grid capacities [13,17,18]. By contrast, pymedeas2 explicitly internalizes biophysical limits and dynamic feedback loops linking the economy, energy, and environment. This architectural design directly connects our theoretical framing to our methodology, allowing us to quantitatively stress-test the green growth paradigm by evaluating whether continuous economic expansion remains feasible when strict material and energetic constraints are endogenized. We first assess a Reference Scenario aligned with current institutional roadmaps, adopting the projections from the Clean Energy Technology Observatory (CETO) [19]. We contrast this with a Rail Scenario grounded in the material feasibility analysis of García-Olivares et al. [11], which prioritizes electrified collective rail systems over individual road transport to minimize the overarching mineral footprint.

This study makes three primary contributions to the fields of Integrated Assessment modeling (IAM) and Ecological Economics. First, it establishes a transparent framework for assessing transport decarbonisation within an IAM that treats material availability as a binding constraint. Second, it quantifies the trade-offs between a technology-led transition and a structure-led transition, specifically regarding energy demand, the related CO_2 emissions, and critical material requirements. Finally, it derives policy-relevant insights

for the EU, identifying the necessary conditions—such as managed GDP stabilization and structural modal shifts—under which a high-well-being mobility system can remain compatible with climate neutrality targets.

2. Materials and Methods

The methodology of this study is designed to quantify the biophysical and economic implications of structural transport shifts within the EU-27 through 2050. We employ a simulation-based framework to evaluate how different modal configurations and macroeconomic trajectories interact with finite material and energy resources. To achieve this, we define divergent decarbonization pathways—contrasting electrification-centric and rail-centric approaches—and subsequently test their robustness against material and energetic constraints. The stability of these results and the influence of key input parameters are further validated through a global sensitivity analysis, detailed in Appendix A.

The quantitative execution of these scenarios is performed using an upgraded version of the pymedeas2 modeling framework [15,20]. This tool internalizes the non-linear feedbacks between economic activity, transport demand (pkm and tkm), and the resulting mineral requirements for battery and infrastructure stocks. Specifically, the framework couples sectoral economic outputs with energy intensities to determine the total fuel consumption and subsequent CO_2 emissions associated with each transport mode. While the model provides the computational core, the specific mathematical formulations of the transport module, the updated 49-sector economic aggregation based on EXIOBASE v3.9.6 [21], and the detailed causal chains are documented in Appendix B.

2.1. Scenarios Definition

To evaluate the trade-offs between technology-oriented and structure-oriented transition strategies, we define two primary decarbonization pathways: the Reference Scenario, which follows institutional technology-substitution roadmaps, and the Rail Scenario, which prioritises structural modal shifts to mitigate biophysical constraints. To further isolate the impact of economic scale, each pathway is evaluated under two macroeconomic variants: a continuous growth case, aligned with official projections, and a Steady-State case, characterized by a transition toward macroeconomic stabilization. This dual-track approach allows for a rigorous assessment of how technological choices and macroeconomic paradigms interact to shape energy requirements, CO_2 emissions, monetary costs, and material demand through 2050. The fundamental differences in modal partition between the institutional paradigm and the rail transition are summarized in Figure 1. These configurations serve as the end-state targets for our simulations through 2050.

2.1.1. Reference Scenario: Institutional Green Growth (CETO 2025)

To establish a baseline trajectory compliant with institutional ambitions, we define a reference scenario based on the POTEnCIA model [22] and the CETO 2025 scenario [19], which operationalizes the targets of the European Climate Law [23,24]. As a proxy for the "Green Growth" paradigm, this pathway assumes absolute decoupling through rapid technological substitution and efficiency gains, projecting a 38% reduction in final energy consumption by 2050 despite continued economic expansion. While the strategy relies on pervasive road electrification—with battery electric vehicles exceeding 90% of the light-duty fleet—and the scale-up of renewable fuels, projections indicate a significant decarbonization lag where emissions do not fall below 1990 levels until 2032. We construct this reference within the pymedeas2 framework by adopting CETO technological and activity outputs as exogenous drivers, ensuring alignment with current EU climate policy while internalizing biophysical feedbacks for direct comparison with alternative structural pathways.

Figure 1. Structural archetypes for the 2050 transport system. Panel **A** illustrates the passenger modal split (pkm), highlighting the transition from private vehicle dominance in the Reference Scenario to a rail-centric collective system. Panel **B** displays the freight modal split (tkm), where the Rail Scenario applies an "all-rail" logic to long-haul logistics, reserving road transport (LCV) primarily for capillary distribution. Note that while absolute activity volumes vary between Growth (-G) and Steady-State (-SSE) variants, these modal shares define the structural logic of each pathway.

The Reference Scenario integrates institutional fuel-switching mandates for aviation and maritime sectors from ReFuelEU Aviation [25] and FuelEU Maritime [26] as projected in the CETO 2025 report [27]. Inland transport follows an electrification roadmap implementing the 2035 internal combustion engine phase-out, resulting in battery electric vehicles (BEVs) exceeding 90% of the passenger fleet by 2050. Freight dynamics reflect a heterogeneous transition with near-total electrification of Light Commercial Vehicles (LCVs) and a 2050 Heavy Goods Vehicle (HGV) mix of 66% BEVs and 20% hydrogen fuel cells [28]. Finally, rail activity growth is aligned with TEN-T expansion projections—84% for passengers and 68% for freight—to establish a consistent baseline for comparison with alternative modal shift strategies [29].

2.1.2. Alternative Pathway: Rail Scenario

The Rail Scenario operationalizes a structural shift from individual road mobility to electrified collective rail, building on the framework established by García-Olivares et al. [11]. Unlike technology-led substitution, this pathway targets the "decarbonization lag" inherent in the slow turnover of the European vehicle stock, which currently averages 12.5 and 14 years for passenger cars and heavy-duty vehicles, respectively [30]. The scenario simulates a fundamental reallocation of activity, projecting a 50–60% contraction of the private car fleet by 2050. Inland logistics follow an "All-Rail" logic, where road transport is capped at 15% of total ton-kilometers, reserved for last-mile distribution, while inter-urban freight is absorbed by electrified rail networks.

By 2050, rail transport reaches 100% electrification via overhead catenary systems, minimizing the need for large-scale battery storage. The remaining road fleet transitions

entirely to electric propulsion for light-duty vehicles and buses. The freight transport segment (the 15% of activity remaining on road) operates on a mix of 90% battery or catenary-electric and 10% hydrogen fuel cells, with the latter strictly capped to preserve Platinum-group metal reserves.

2.1.3. Macroeconomic Variants: Growth vs. Steady-State Economy

To isolate the impact of structural modal shifts from the influence of total economic volume, each pathway described above is evaluated under two distinct macroeconomic trajectories. This dual-track approach generates four distinct scenarios (REF-G, REF-SSE, RAIL-G, and RAIL-SSE), allowing the pymedeas2 framework to capture the dynamic feedbacks between economic output, energy demand, and material constraints in a system-dynamics approach.

The first variant, the Growth trajectory (REF-G and RAIL-G), adopts the official macroeconomic projections aligned with the CETO 2025 and EU reference scenarios [31]. In this case, GDP per capita is assumed to follow a sustained growth trajectory through 2050. This variant serves as a "stress test" for technological and structural solutions: it evaluates whether deep electrification or radical modal shifts can remain biophysically feasible if the total volume of economic activity—and its associated mobility demand—continues to expand, as posited by proponents of green growth paradigms [7].

The second variant, the Steady-State Economy trajectory (REF-SSE and RAIL-SSE), implements a shift away from the paradigm of perpetual expansion [32]. In this trajectory, GDP per capita growth is parametrized to gradually decelerate, reaching zero by 2040 and remaining constant thereafter. This variant operationalizes the concept of sufficiency by reducing the activity pressure on the transport system, moving beyond mere technological efficiency [33]. By running the Rail Scenario under steady-state conditions (RAIL-SSE), we investigate the synergies between structural efficiency (trains) and demand-side sufficiency (macroeconomic stabilization), identifying the conditions necessary to stay within absolute planetary boundaries [34,35].

2.2. Modeling Framework

To analyze these scenarios, a new transport module has been integrated into the pymedeas2 model, employing a hybrid top–down and bottom–up approach to maintain metabolic consistency with the broader economy. Its structural logic follows a sequential causal chain: macroeconomic output drives aggregate demand for passenger (pkm) and freight (tkm) activity; this demand is subsequently disaggregated by mode and fuel share according to specific policy scenarios. Finally, these modal splits are coupled with technology-specific energy intensities and material intensity factors to quantify mineral requirements, total energy demand, and its associated CO_2 emissions, as detailed in Appendix B.1.

2.2.1. Transport Data Preprocessing and Demand Projection

Future transport activity trajectories are derived from econometric correlations with macroeconomic drivers, calibrated using historical data from the JRC-IDEES database [3]. We adopted a per-capita specification for passenger mobility and a GDP-centred model for freight to ensure mathematical consistency in the mature EU-27 economy. The projections follow a Constant Elasticity of Demand (CED) specification. To account for systemic inertia and temporal autocorrelation, the model incorporates a first-order autoregressive process (ε_{t-1}) derived from historical residuals. The resulting equations used for the system dynamics projections are:

$$\mathrm{PKM}_t = \mathrm{PKM}_0 \cdot \exp\left[\gamma \ln\left(\frac{\mathrm{GDP}_{\mathrm{pc},t}}{\mathrm{GDP}_{\mathrm{pc},0}}\right) + \phi\varepsilon_{t-1}\right] \quad (1)$$

$$\mathrm{TKM}_t = \mathrm{TKM}_0 \cdot \exp\left[\beta \ln\left(\frac{\mathrm{GDP}_t}{\mathrm{GDP}_0}\right) + \phi\varepsilon_{t-1}\right] \quad (2)$$

where γ and β represent the estimated income and freight elasticities, respectively. Parameters were estimated via Ordinary Least Squares (OLS) with Cochrane–Orcutt corrections, filtering pandemic-related anomalies (2020–2021) as exogenous shocks. The detailed regression framework, statistical diagnostics, and complete parameter tables are provided in Appendix C.

2.2.2. Material Demand and Economic Evaluation

The estimation of material requirements follows a two-step logic that translates transport demand into physical stocks. The required vehicle fleet size is first determined by applying vehicle intensity factors to the projected activity, accounting for historical occupancy rates and annual mileage. Subsequently, the modeling framework distinguishes between the active material stock in use and the annual demand required for maintenance and expansion. This mass-balance formulation, detailed in Appendix D.1, captures the total material throughput by accounting for both net fleet expansion and the replacement of degraded battery packs. Material intensity factors evolve dynamically through 2050 to reflect technological shifts, such as the transition toward Lithium Iron Phosphate (LFP) chemistries in passenger segments and the prioritization of high-nickel NCM 811 for heavy-duty logistics [36].

To evaluate the economic burden of the transition, we apply a physical capital replacement framework that disaggregates total annual investment into vehicle acquisition, charging infrastructure, and rail network expansion [11]. Vehicle investment covers both net expansion and the replacement of stock reaching the end of its operational life. The deployment of charging systems is parametrized following a high-utilization shared model that prioritizes fast-charging units to reduce the total material and spatial footprint of the network [37]. Finally, the structural shift toward rail necessitates significant investment in electrifying the remaining 46% of the current EU-27 network and constructing new tracks to absorb transferred road activity. The specific equations for material throughput and infrastructure costs across calculation methodology are documented in Appendix D.2. Crucially, our investment accounting captures only direct capital costs (fleet acquisition and primary track expansion). We explicitly exclude secondary expenses—such as maintenance, grid upgrades, and land acquisition—which require high-resolution spatial modeling outside our scope.

2.3. Data Integration and Calibration

The transport module is calibrated for the EU-27 using the JRC-IDEES 2023 database [3]. We aligned the model's last historical year (2020) with empirical records of transport activity (pkm, tkm), vehicle stocks, and final energy demand (EJ). The calibration disaggregates the system by mode (m), fuel carrier (f), and technology (j).

2.3.1. Modal and Fuel Classification

Transport activity is disaggregated into passenger and freight sectors across the categories summarized in Table 1. Energy demand is partitioned into four primary carriers: liquids (gasoline, diesel, LPG, and biofuels), gases (natural gas and bio-methane), electricity, and plug-in hybrids (PHEV). For PHEVs, the liquid and electric components are isolated to facilitate accurate energy substitution accounting. Within the freight sector, we maintain a structural distinction between Light Commercial Vehicles (LCVs $\leq$ 3.5 t) and Heavy Goods Vehicles (HGVs $>$ 3.5 t) to account for their divergent energy intensities and load-optimized efficiencies [30].

Table 1. Classification and scope of transport modes included in the model.

Category	Mode	Scope and Inclusions
Passengers	Private Road	Individual cars and light-duty passenger vehicles
	Collective Road	Urban and interurban bus services
	Rail	High-speed, regional, and metropolitan networks
	Domestic Air	Internal flights within the modeled region
	Maritime	Regional ferries and passenger shipping
Freight	Road Heavy	Heavy goods vehicles (>3.5 t)
	Road Light	Light commercial vehicles ($\leq$3.5 t)
	Rail	Electric and non-electric cargo trains
	Maritime	Short-sea shipping and inland waterways
	Air	Domestic cargo and logistical flights

2.3.2. Model Calibration and Performance Parameters

The module is calibrated for the EU-27 using the JRC-IDEES 2023 database [3]. We aligned the model's base year (2020) with empirical records of transport activity (A), vehicle stocks (V), and energy demand (E) for each mode (m) and fuel (f). From this dataset, we derive the fuel-specific energy intensity ($e_{m,f}$) as the ratio of consumption to transport work:

$$e_{m,f} = \frac{E_{m,f}}{A_{m,f}} \tag{3}$$

To link transport demand with material requirements, we calculate the annual vehicle productivity ($P_{m,f}$), representing the transport work performed per physical vehicle unit:

$$P_{m,f} = \frac{A_{m,f}}{V_{m,f}} \tag{4}$$

The derivation of $P_{m,f}$ enables differentiated stock estimations based on specific battery capacities—such as 80 kWh for LCVs versus 600 kWh for HGVs—providing a more granular assessment of mineral requirements than fleet-wide averages [11].

3. Results

The simulation of the various decarbonization pathways reveals that technological shifts alone are insufficient to meet the EU's 90% transport emission reduction target. Our analysis indicates that deep decarbonization requires a combined strategy of significant modal shift, high electrification, and substantial reduction in total activity volumes.

3.1. Passenger and Freight Metabolic Transition

The transition matrices (Figures 2 and 3) illustrate the divergent structural logic between institutional roadmaps and sufficiency-oriented strategies. In the passenger sector (Figure 2), Reference scenarios maintain a mobility system structurally reliant on individual vehicles, even with a near-total electrification of the light-duty fleet by 2050. In contrast, the Rail scenario implements a fundamental reallocation of activity, resulting in a 50–60% contraction of the private car fleet relative to baseline trends. By prioritizing high-speed electrified networks, rail becomes the primary carrier for medium-to-long distance travel by 2040.

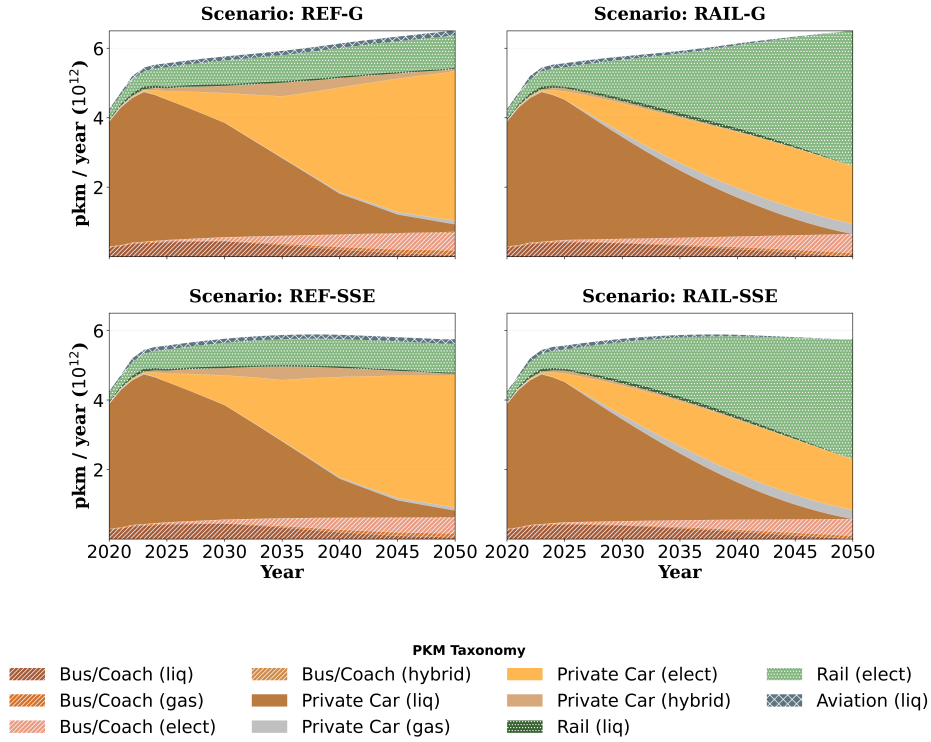


Figure 2. Evolution of Passenger Transport Demand and Modal Share (2020–2050). The projections illustrate distinct transition pathways, contrasting institutional technology substitution with structural modal shifts under two macroeconomic paradigms.

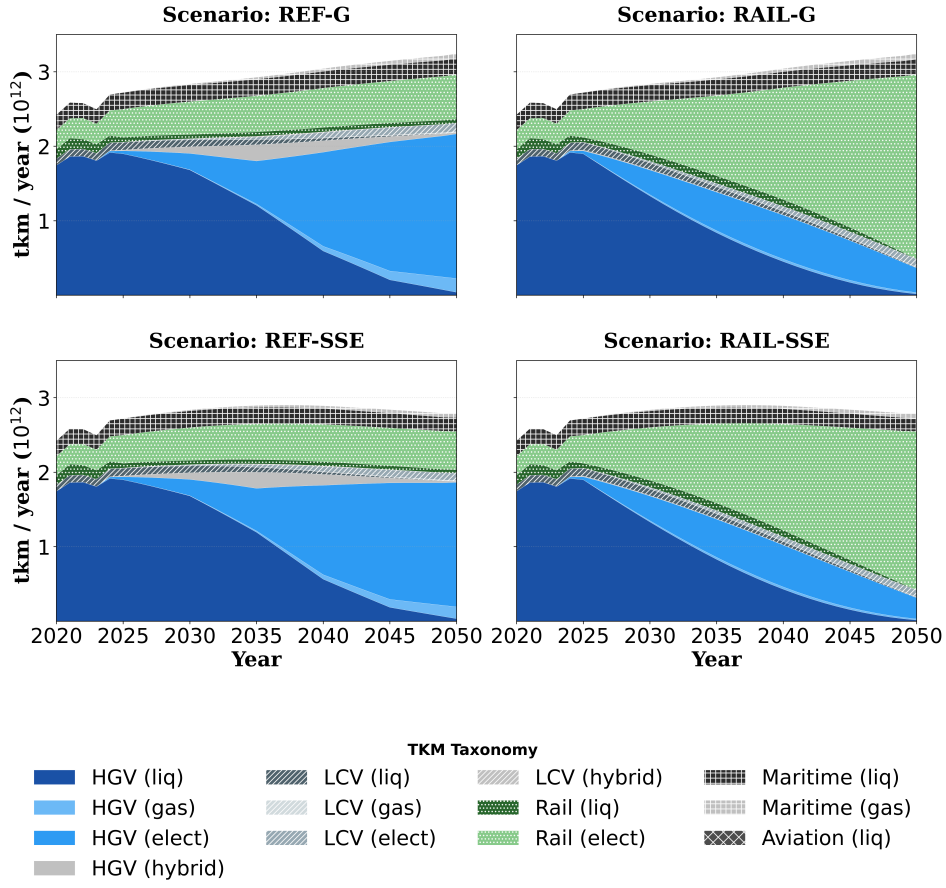


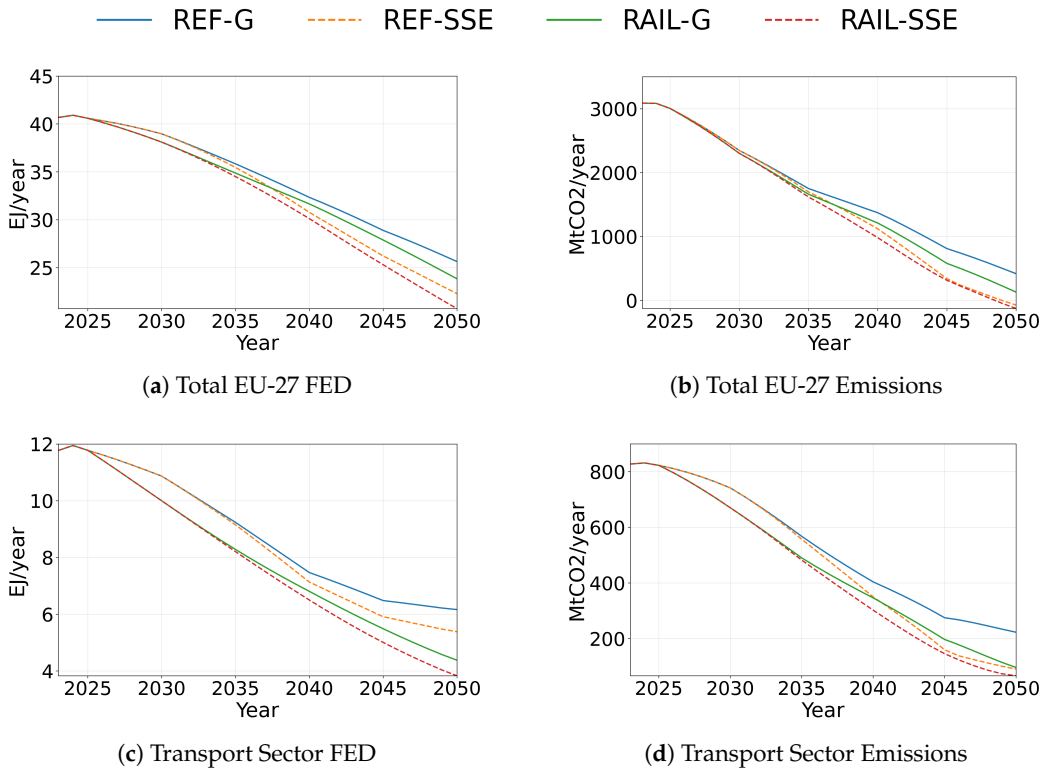
Figure 3. Evolution of Freight Transport Demand and Modal Share (2020–2050). The projections illustrate a structural shift, replacing road-based long-haul freight with electrified rail networks under the two macroeconomic scenarios.

Regarding freight logistics (Figure 3), the Reference pathways sustain high activity levels for heavy goods vehicles (HGVs), which continue to dominate long-haul transport. The Rail scenario applies an "All-Rail" logic to inland logistics, effectively phasing out HGVs from the strategic bulk of inter-urban cargo. Under this framework, road transport is strictly reserved for capillary and last-mile distribution, limited to approximately 15% of total tkm.

The vertical differentiation across both matrices highlights the impact of macroeconomic scale. While structural shifts improve systemic efficiency, the Steady-State (SSE) variants effectively mitigate the demand-side pressure, preventing the activity growth projected under continuous economic expansion.

3.2. Transport Final Energy Demand

The simulation of Final Energy Demand (FED) reveals a clear divergence between the transport sector's metabolism (Figure 4c) and the total EU-27 energy footprint (Figure 4a). From a common 2024 peak of 11.8 EJ in transport and approximately 41 EJ for the total socio-economy, the Reference Scenario pathways demonstrate the inherent limitations of a transition centered exclusively on technological substitution. While the superior thermodynamic efficiency of electric power-trains helps reduce transport demand to 6.2 EJ in the growth variant or 5.4 EJ under demand stabilization, these sectoral gains are partially neutralized by sustained mobility growth, resulting in a total EU-27 FED that remains as high as 26 EJ in the REF-G case. This trend underscores that maintaining an individual road-based mobility paradigm, even when electrified, sustains a metabolic inertia that significantly limits the overall reduction potential of the total economy.



(**a**) Total EU-27 FED

(**b**) Total EU-27 Emissions

(**c**) Transport Sector FED

(**d**) Transport Sector Emissions

Figure 4. Evolution of Final Energy Demand (FED) and CO_2 emissions (2020–2050). (**a**) Total EU-27 FED, capturing the systemic effects of transport modal shifts and macroeconomic stabilization; (**b**) Total CO_2 emissions, showing the synergy between modal shifts and macroeconomic stabilization; (**c**) Transport sector's FED evolution, contrasting the gradual reduction in Reference pathways with the Rail variats; (**d**) Transport-related emissions, highlighting the decarbonization lag of technology-centric scenarios.

In contrast, the Rail Scenario pathways illustrate how structural modal shifts fundamentally reshape both sectoral and systemic energy trajectories. The RAIL-SSE variant achieves an accelerated contraction, reaching 3.8 EJ in the transport sector—a 68% reduction from the 2024 peak—which in turn drives the total EU-27 FED to a systemic low of approximately 21 EJ by 2050. This deep reduction suggests that prioritizing high-capacity electrified rail over road-based alternatives acts as a superior thermodynamic leverage point, where modal substitution provides higher energy savings.

3.3. Decarbonization Trajectories and Emissions

The emission figures reported in this assessment represent operational and upstream energy CO_2 emissions, capturing direct vehicle operation and the carbon intensity of energy supply chains, while explicitly excluding the embodied carbon from vehicle manufacturing and large-scale infrastructure construction.

While all primary pathways achieve significant decarbonization by 2050, the trajectories for transport (Figure 4d) and the total EU-27 socio-economy (Figure 4b) diverge based on their specific structural and growth paradigms. In the transport sector, both Rail Scenario variants (RAIL-G and RAIL-SSE) achieve early action mitigation by bypassing the multi-decadal decarbonization lag inherent in private fleet turnover. However, the reduction in RAIL-G is partially limited by continued economic expansion, while the reference scenarios—even with the demand-side benefits of REF-SSE—remain fundamentally hampered by the high energy intensity of individual road-based mobility.

Consequently, the deepest absolute mitigation is achieved in the RAIL-SSE variant, where aggressive sectoral shifts and systemic sufficiency operate concurrently. Over the 2025–2050 time-frame, the institutional baseline (REF-G) results in cumulative transport emissions of 13.1 Gt CO_2, while the RAIL-SSE scenario restricts them to 10.6 Gt CO_2, reaching the lowest residual transport footprint of approximately 90 $MtCO_2$/year. This sectoral result is matched by the total socio-economic trajectory, which reflects the broader impact of a steady-state economy where GDP per capita growth reaches zero by 2040. Ultimately, the RAIL-SSE profile demonstrates that absolute sustainability requires reducing the physical scale of the entire economy alongside technological and modal transitions.

3.4. Cumulative Material Requirements: The Lithium Wall

The biophysical feasibility of the evaluated pathways is primarily differentiated by the cumulative demand for Lithium (Figure 5). Under REF-G, the transition to a universal electric vehicle fleet, incorporating passenger cars, light commercial vehicles (LCVs), and heavy goods vehicles (HGVs), requires a cumulative extraction of approximately 2.35 million tons (Mt) of Lithium by 2050 [38]. These values represent the cumulative demand for metallic lithium. We acknowledge that the EU Battery Regulation (2023/1542) mandates ambitious lithium recovery targets of 50% by 2027 and 80% by 2031 [39]. However, due to the current lack of commercial-scale, high-efficiency closed-loop lithium recycling within the EU, and the inherent temporal lag between initial battery deployment and EoL availability, we explicitly frame our projections as a deliberately conservative upper bound for primary demand. Conversely, RAIL-SSE demonstrates a strategy for mineral parsimony, requiring only 1.02 Mt of Lithium over the same period, representing a 57% reduction relative to the baseline. By prioritizing catenary-powered rail and contracting the absolute volume of the private vehicle stock, this structural transition remains within safer biophysical boundaries while achieving superior decarbonization outcomes.

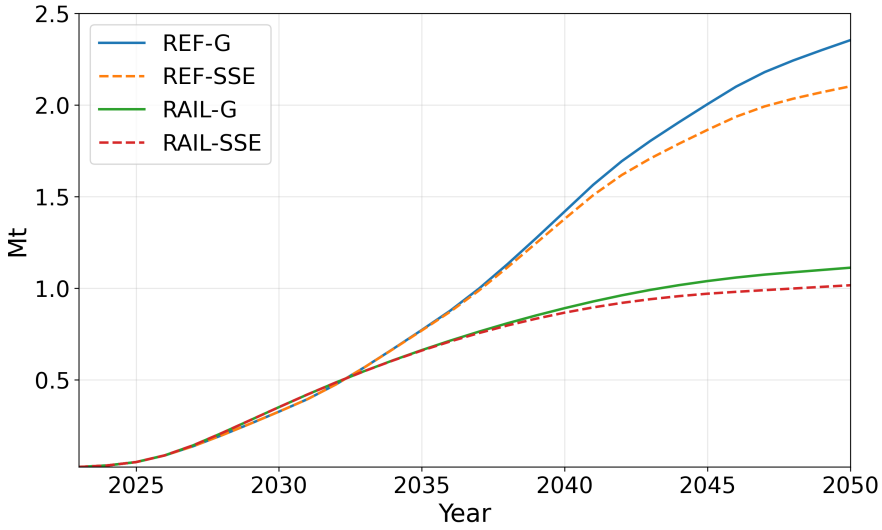


Figure 5. Cumulative Lithium requirements for EV batteries through 2050. The results contrast the material intensity of private fleet electrification (REF-G and REF-SSE) with the mineral parsimony of structural modal shifts (RAIL-G and RAIL-SSE).

3.5. Economic Valuation: Capital Investment and Infrastructure Deployment

The economic assessment, summarized in Table 2, reveals a profound structural divergence in capital allocation strategies between the evaluated pathways. Total cumulative investment is governed by a fundamental trade-off: the high-volume, continuous renewal of short-lived private vehicle fleets in the Reference Scenarios versus the infrastructure-intensive expansion of a durable rail network in the Rail Scenarios. In the REF-G scenario, capital expenditure is primarily driven by the private passenger fleet, which requires an investment of USD 17.20 trillion. Even under demand stabilization (REF-SSE), maintaining an individual mobility paradigm necessitates massive financial outflows totalling USD 15.71 trillion for private cars alone.

Table 2. Summary of cumulative investment and physical infrastructure deployment (2025–2050).

Indicator (Total 2025–2050)	REF-G	REF-SSE	RAIL-G	RAIL-SSE
Capital Investment (Trillion USD)				
Private Vehicles	17.20	15.71	8.13	7.50
Buses	0.78	0.71	0.78	0.71
Freight Vehicles (LCV + HGV)	7.12	6.39	4.14	3.78
Rail Rolling Stock (Locomotives)	0.20	0.17	0.96	0.86
Charging Infrastructure (I_{charge})	1.67	1.52	0.88	0.81
Rail Infrastructure (Tracks) (I_{rail})	0.14	0.14	7.60	6.16
Total Investment (I_{total})	27.10	24.64	22.50	19.83
Physical Deployment				
New Rail Lines (km)	0	0	451,322	364,032
Rail Electrification (km)	108,784	108,784	108,784	108,784
AC Charging Posts (Millions)	91.82	83.68	48.39	44.43
DC Fast Chargers (Millions)	19.74	17.99	10.41	9.56

Conversely, the Rail Scenarios facilitate a substantial reduction in total vehicle-related capital by redirecting investment from individual machinery to high-capacity collective assets. The 50–60% contraction of the private car fleet and the phase-out of long-haul road freight effectively offset the increased investment required for electrified rail rolling

stock. While investment in locomotives increases to between 0.96 and 0.86 trillion in these scenarios, the total capital required for road-based freight vehicles is nearly half that of the REF-G. Physical deployment further illustrates this shift; the RAIL-G requires planned public investment to construct 451,322 km of new high-speed and standard tracks, or 364,032 km in the more efficient RAIL-SSE variant.

Energy infrastructure costs further reflect the efficiency gains of the high-utilization shared model implemented in the Rail Scenarios. While the Reference Scenarios necessitate a fragmented network of nearly 112 million charging posts to support universal private electric vehicle ownership, the Rail Scenarios optimize expenditure, requiring fewer than 59 million units. Cumulatively, the RAIL-SSE variant emerges as the most economical pathway over the simulation period with a total investment of USD 19.83 trillion. This represents a systemic saving of USD 7.27 trillion relative to REF-G, demonstrating that the savings from avoided private vehicle acquisition and optimized charging networks compensate for the multi-trillion dollar costs of new track construction.

4. Discussion

This study applied the latest release of the pymedeas2 framework to assess the biophysical implications of the transport sector transition in the EU-27, aiming to evaluate which decarbonization pathways are most effective at minimizing structural dependencies on critical materials and overall energy demand. To achieve this, we contrasted four distinct scenarios: the institutional baseline (REF-G) focused on green growth and private fleet electrification; a rail-centric growth pathway (RAIL-G); a steady-state economy pathway maintaining road dominance (REF-SSE); and a sufficiency-driven pathway combining macroeconomic stabilization with rail expansion (RAIL-SSE). While all modeled pathways achieve significant decarbonization by 2050, the results demonstrate that institutional strategies like Reference Scenario remain unable to achieve the absolute decoupling of energy demand from transport activity. Although the superior thermodynamic efficiency of electric power-trains drives a downward trajectory in energy consumption across all scenarios—a trend consistent with official projections like the Clean Energy Technology Observatory [19]—these gains in Reference Scenario are partially neutralized by the sustained growth in transport volume. This confirms that a transition centred exclusively on fleet electrification maintains a high energy demand due to the metabolic inertia of persistent private vehicle usage, effectively limiting the scope of energy reduction to the efficiency of the delivery mechanism rather than the scale of the service provided.

In contrast, the RAIL-SSE scenario demonstrates that the integration of demand stabilization and structural modal shifts, specifically the transfer of long-distance activity to rail, acts as a superior thermodynamic leverage point. By bypassing the inherent energy intensity of individual road transport, these sufficiency-oriented pathways achieve an additional reduction in total energy consumption of approximately 39% relative to the reference. This divergence reveals that while technological substitution achieves a relative improvement, only the structural changes in Rail Scenario facilitate the absolute metabolic contraction required for biophysical sustainability. This outcome reinforces the theoretical critiques of the green growth paradigm offered by [7,8] while aligning with the demand-side mitigation strategies recently emphasized by the UNEP [40] and the European Scientific Advisory Board on Climate Change [41]. Both bodies increasingly emphasize that reaching climate neutrality necessitates structural reductions in energy service demand alongside rapid electrification.

The temporal dynamics of CO_2 mitigation reveal a persistent decarbonization lag in Reference Scenario pathways, highlighting the tension between market-led technological change and climate urgency. In these scenarios, the rate of emission reduction is fundamen-

tally constrained by the physical inertia of the vehicle stock—an effect directly linked to the 12.5-year average age of the European passenger fleet [30]. This constraint implies that even if sales of internal combustion engines (ICEs) were phased out rapidly, the existing fleet would continue to consume the remaining carbon budget for over a decade. To contextualize the severity of this lag, deducting 2020–2024 historical emissions from the sector's 1.5 °C-aligned budget [42] leaves a remaining allocation of strictly 6.4 to 8.3 Gt CO_2 from 2025 onward. Our modeling reveals that the REF-G trajectory drastically overshoots this biophysical limit by generating 13.1 Gt CO_2 in cumulative transport emissions, whereas the RAIL-SSE scenario restricts them to 10.6 Gt CO_2. While institutional frameworks often assume a near-linear decarbonization based on the market penetration of new electric vehicles [43], our results suggest that such projections frequently underestimate the "lock-in" effect of the current stock. This finding aligns with the warnings of Brand et al. [44], who argue that technological substitution alone is too slow to meet the 1.5 °C target, and reinforces observations by the European Environment Agency [45] that the ageing European fleet is becoming a structural barrier to rapid emission cuts; while other economic sectors are successfully decarbonizing, transport emissions remain high largely due to the slow turnover of the existing vehicle stock.

In contrast, the Rail Scenario serves as a temporal shortcut by decoupling decarbonization from the slow process of machine replacement. By enabling an immediate shift to existing electrified rail and reducing high-impact activities such as aviation, these pathways achieve deep systemic reductions long before the total electrification of the road fleet is physically possible. This structural intervention bypasses the multi-decadal turnover cycles that hamper Reference Scenario, delivering the early action mitigation [46] as essential for staying within biophysical limits. Although meeting the strictest 1.5 °C targets remains highly challenging even under the 10.6 Gt CO_2 trajectory, this structural pathway converges significantly closer to biophysical sustainability than technology-led green growth. Consequently, our analysis indicates that structural and demand-side measures likely play a fundamental role in achieving the rapid mitigation required by the Paris Agreement, suggesting that a technology-only approach may face significant temporal risks that these interventions could help mitigate.

Beyond the temporal and energetic risks, the physical feasibility of a technology-centric transition is challenged by extreme mineral intensity, creating a significant material bottleneck in the Reference Scenario pathways. Our results indicate that the cumulative lithium requirement for the EU-27 passenger fleet in the REF-G scenario reaches 2.35 million tons by 2050. While this constitutes approximately 6.4% of the 37 million tons of current global proven reserves [47], the fact that a single region representing less than 6% of the global population would claim this entire "fair share" solely for its domestic mobility calls into question the geopolitical and biophysical viability of a global green growth strategy [48]. Although circular economy strategies, including hydro-metallurgical recycling and secondary material recovery, are often proposed to mitigate these constraints, their current industrial scalability remains highly uncertain [49]. Furthermore, due to the inherent temporal lag between the initial deployment of battery stocks and their eventual EoL availability, secondary supply can only satisfy a fraction of the rapidly growing demand through 2050 [36]. Thus, while essential for long-term sustainability, circularity serves as a complementary improvement rather than a systemic solution to the resource-intensive requirements of the REF-G pathway, justifying a conservative assessment of primary demand.

This disproportionate appropriation becomes even more critical when accounting for competing cross-sectoral demands. Industry forecasts project that electric mobility will directly compete for lithium with the rapidly expanding stationary energy storage sector, which is indispensable for stabilizing renewable grids and relies heavily on

lithium-intensive LFP chemistry [43,50]. Furthermore, this techno-centric dependence offshores significant environmental burdens; the energy-intensive extraction and refining processes generate substantial CO_2 emissions and ecological degradation outside the EU's borders—typically in the Global South—a factor frequently externalised in institutional green growth accounting [38]. The aggressive electrification of private vehicles under REF-G effectively monopolizes the lithium required for both the EU's own renewable grid and the basic energy needs of the rest of the world, suggesting that 1:1 vehicle replacement is structurally incompatible with a globally equitable transition. In contrast, the RAIL-SSE variant mitigates this risk by reducing cumulative lithium demand by 57%—to 1.02 Mt. This demonstrates that sufficiency and modal shifts act not only as transport mitigation strategies but as vital cross-sectoral resource-buffering mechanisms, essential to align the sector with the planet's finite geological reality [38].

4.1. The Rail Transition as a Limit Case: Feasibility, Materiality, and Implementation Barriers

Despite the clear lithium demand advantages of the RAIL scenarios, the scale of infrastructure expansion required to absorb 60% of passenger and 76% of freight traffic presents profound real-world feasibility challenges. Our model indicates this shift would require an estimated 364,032 to 451,322 equivalent line-kilometers of new rail infrastructure. We explicitly frame these scenarios not as predictive forecasts, but as "limit cases" designed to analytically quantify the absolute biophysical boundaries of replacing road-dominated transport. While our macroeconomic framework captures the overarching capital and energy requirements, it does not account for micro-level operational factors such as traffic management, network capacity or specific operating modes. Furthermore, it does not account for protracted construction rates, specific land-use demand, or the complex spatial planning required to deploy new corridors. Absorbing such a massive reallocation of traffic would inevitably clash with protracted land-use planning processes and face significant hurdles regarding the social acceptance of extensive new construction projects [51].

Furthermore, this infrastructure-heavy pathway fundamentally shifts the material burden of the transition. While a rail-centred approach significantly reduces dependence on battery-grade lithium, it necessitates immense volumes of structural materials, such as copper for electrification and steel and cement for large-scale track construction. The associated embodied carbon represents an upfront emission penalty that may temporarily offset short-term climate gains [52,53]. However, this trade-off must be contextualized: the road-centric baseline is not exempt from these impacts, as it demands significant material inputs for highway maintenance and structural adaptation to accommodate heavier electric fleets. Consequently, rail expansion can trade the global supply-chain risks of battery metals for the localized, high-volume ecological impacts of heavy construction.

In light of these institutional, social, and physical barriers, our comparative analysis highlights the limitations of relying exclusively on either technology substitution or macro-structural modal shifts. While our aggregate EU-27 model abstracts from spatial specificities to identify absolute biophysical boundaries, realizing this transition requires unprecedented alignment across EU Member States [54]. In practice, transcending the binary between Green Growth and post-growth trajectories is essential. Policy must integrate sufficiency with systemic efficiency, optimizing transport architecture, dynamic flow management, and infrastructure utilization, alongside robust logistics reorganization and absolute transport demand reduction [55,56].

4.2. Macroeconomic Implications and Capital Reallocation

Finally, the divergence between these pathways translates into different macroeconomic requirements, where the Reference Scenarios represent a high capital expenditure

transition that risks exacerbating the investment gap recently identified in assessments of European competitiveness [57]. By maintaining a growth-oriented activity model, this strategy necessitates a constant flow of capital into short-lived consumer goods—with the REF-G variant requiring USD 17.20 trillion for private vehicles alone, effectively crowding out investments in more durable public infrastructure.

In contrast, the Rail Scenarios suggest a shift in economic logic: by reducing the total volume of required machinery and prioritizing high-capacity rail, the transition moves from a consumption-heavy model toward a service-oriented one. While rail infrastructure investment rises to USD 6.16 trillion in the RAIL-SSE variant to support the construction of 364,032 km of new tracks, this expenditure is offset by the reduction in private vehicle acquisition costs to USD 7.50 trillion. Consequently, the RAIL-SSE pathway emerges as the most efficient strategy, requiring a total cumulative investment of USD 19.83 trillion, which represents a systemic saving of USD 7.27 trillion relative to the REF-G baseline. This alignment with post-growth frameworks [8,58] suggests that absolute sustainability is only achievable if the European economy is reoriented away from resource-intensive GDP growth and toward the provision of essential services with minimal biophysical and capital overhead.

5. Conclusions

This study demonstrates that, under the modeled assumptions of high-growth baselines, conventional technology-led pathways succeed in improving relative efficiency but face significant challenges in achieving the absolute energy reduction required for sustainability due to the metabolic inertia of transport demand within the EU-27. We frame our RAIL-SSE scenarios as normative limit-cases rather than predictive forecasts, designed to analytically quantify the biophysical boundaries of a post-growth transition. Consequently, our analysis indicates that transport decarbonization likely requires more than technological substitution; an absolute reduction in the physical scale of activity, quantified as the aggregate annual volume of *pkm* and *tkm*, appears to be a fundamental factor in achieving biophysical sustainability.

First, the temporal dynamics of CO_2 mitigation reveal a persistent decarbonization lag, where the 12.5-year average age of the European passenger fleet acts as a structural barrier to rapid emission cuts. Assuming this current lifespan remains constant, the high average age of the European fleet creates a multi-decadal lag that market-driven electrification cannot overcome in time to meet climate targets. Only a large-scale modal shift toward electrified rail and demand-side management can bypass these vehicle turnover cycles, providing the immediate emission reductions necessary to remain within biophysical limits.

Second, universal private electrification presents significant challenges regarding resource equity under current demand growth assumptions and life-cycle material intensities. An EU-27 private electric fleet would require 2.35 million tons of lithium by 2050, claiming 6.4% of global reserves for only the transport sector of a region with only 6% of the world's population. This concentration of resources is structurally incompatible with a globally equitable transition. Conversely, the RAIL-SSE scenario reduces cumulative lithium demand by 57%, aligning the sector with the reality of finite geological endowments.

Third, when assessed within the defined system boundaries that focus on direct capital requirements for fleet and basic network expansion, a structure-led transition proves to be economically superior to technology-led green growth. Despite the massive upfront capital required to expand and electrify the European rail network, the RAIL-SSE pathway emerges as the least capital-intensive strategy. By drastically reducing the continuous, high-volume acquisition of short-lived private vehicles and optimizing charging infrastructure,

this sufficiency-driven scenario yields a systemic saving of over USD 7.27 trillion relative to the institutional baseline.

From a policy perspective, the divergence in metabolic and economic pathways indicates that absolute sustainability necessitates aligning EU policy with post-growth frameworks, prioritizing durable public infrastructure and service provision over resource-intensive GDP expansion. Future policy should integrate sufficiency as a core pillar alongside efficiency and renewables to mitigate the identified temporal and material risks and ensure a resilient transition within the sector's absolute biophysical limits. To advance this paradigm, future research must expand this integrated framework to assess the socio-economic distributional impacts of sufficiency-based transitions, particularly concerning employment shifts and equity. Furthermore, deepening the analysis of circular economy strategies—such as secondary material recovery and alternative battery chemistries—is essential to further refine the mitigation of the material constraints identified in this study.

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Abbreviations

The following abbreviations are used in this manuscript:

AR6	Sixth Assessment Report
BEV	Battery Electric Vehicle
CED	Constant Elasticity of Demand
CETO	Clean Energy Technology Observatory
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CRM	Critical Raw Material
EJ	Exajoule
EU	European Union
FED	Final Energy Demand
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HGV	Heavy Goods Vehicle
IAM	Integrated Assessment Model

IEA	International Energy Agency
IOT	Input–Output Table
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCV	Light Commercial Vehicle
LFP	Lithium Iron Phosphate
Mt	Million Tonnes
NMC	Lithium Nickel Manganese Cobalt Oxide
PHEV	Plug-in Hybrid Electric Vehicle
PKM	Passenger-kilometer
RES	Renewable Energy Sources
SSE	Steady-State Economy
TEN-T	Trans-European Transport Network
TKM	Ton-kilometer
TPES	Total Primary Energy Supply

Appendix A. Global Sensitivity Analysis (GSA)

Appendix A.1. Methodology: The Morris Method

To ensure the robustness of the results presented in this study, we conducted a Global Sensitivity Analysis (GSA) following the Method of Elementary Effects, commonly known as the Morris Method [59]. This screening technique allows for the identification and ranking of input parameters that most significantly influence the model's critical outputs, distinguishing between direct linear impacts and complex non-linear interactions or dependencies [60].

The analysis was implemented using the `SALib` library in Python [61]. Following the standard Morris design, we generated $r = 50$ trajectories with $p = 4$ grid levels. For each of the seven input parameters analyzed ($k = 7$), the total computational cost followed the Morris equation $N = r(k + 1)$, resulting in 400 simulations. This sample size was selected to ensure the convergence and stability of the sensitivity indices μ^* (mean absolute elementary effect) and σ (standard deviation) [60].

Appendix A.2. Input Parameters and Configuration

Seven key exogenous drivers were selected to capture the primary dimensions of uncertainty within the transport transition pathways. For each parameter, a variation range was established around the baseline value, consistent with uncertainty ranges used in similar biophysical modeling studies [20,62].

- GDP Sensitivity Factor (gdp_sens): Variation in annual GDP growth rates.
- Activity Demand ($sens_pkm_tkm$): Scaling factor for total passenger (pkm) and freight (tkm) activity.
- Passenger Efficiency ($sens_pkm_eff$): Energy intensity improvements for passenger transport.
- Freight Efficiency ($sens_tkm_eff$): Energy intensity improvements for freight transport.
- Renewable Expansion ($sens_res$): Scaling factor for the deployment of renewable energy infrastructure.
- Vehicle Efficiency ($sens_veh_eff$): Specific efficiency in the number of vehicles for tkm and pkm transport activity.
- Rail Mode Share ($sens_rail_mode_share$): Additive variation to the baseline percentage of transport activity shifted to electrified rail systems.

Appendix A.3. Results and Interpretation

The sensitivity of four primary output variables was assessed: Transport CO_2 Emissions, Cumulative Lithium Requirements, Total Primary Energy Supply (TPES), and Total Final Energy Demand (FED). Table A1 summarizes the resulting indices for the most influential parameters in each category.

Table A1. Morris sensitivity indices (μ^* and σ) for the key transport output variables.

Target Variable	Input Parameter	μ^*	σ
CO_2 Emissions	*sens_tkm_eff*	1.056	5.801
	sens_pkm_eff	0.703	3.007
	sens_pkm_tkm	0.624	2.957
	gdp_sens	0.431	0.286
	sens_res	0.231	0.187
Lithium Requirements	*sens_veh_eff*	1.046	0.183
	sens_pkm_tkm	0.960	0.220
	sens_rail_mode_share	0.614	0.142
	gdp_sens	0.562	0.209
	sens_res	0.215	0.206
TPES (EJ)	*gdp_sens*	23.062	9.810
	sens_res	8.787	10.282
	sens_pkm_eff	5.545	2.619
	sens_pkm_tkm	4.456	2.456
	sens_tkm_eff	2.558	2.310
Total FED	*gdp_sens*	9.036	3.713
	sens_pkm_eff	6.472	1.187
	sens_res	4.818	3.908
	sens_tkm_eff	3.096	0.902
	sens_pkm_tkm	2.124	1.000

The results identify the metabolic scale and systemic efficiency as the paramount drivers of environmental and material impacts. For CO_2 emissions and Total FED, improvements in transport efficiency (*sens_tkm_eff* and *sens_pkm_eff*) alongside overall GDP growth exhibit the highest influence, confirming that the interplay between demand-side volume and energy intensity dictates the broader energy transition limits. For TPES, the *gdp_sens* parameter remains the overwhelmingly dominant driver ($\mu^* = 23.06$) with a high σ (9.81), suggesting strong non-linear interactions within the energy-economy feedback loops.

Crucially, the analysis of Cumulative Lithium Requirements validates the core thesis of this study regarding material bottlenecks. The mineral demand is heavily dictated by the specific manufacturing efficiency of vehicles (*sens_veh_eff*, $\mu^* = 1.04$) and the absolute volume of transport demand (*sens_pkm_tkm*, $\mu^* = 0.96$). However, the Rail Mode Share parameter emerges as the third most critical driver ($\mu^* = 0.61$), surpassing even the influence of total GDP growth. This statistically confirms that structural interventions, specifically the degree to which mobility is shifted toward catenary-powered rail, directly and significantly determine the feasibility of staying within safe planetary boundaries for critical minerals. These findings reinforce the conclusion that achieving a sustainable transition requires prioritizing demand-side sufficiency and structural modal shifts over exclusive reliance on technological substitution [20,63].

Appendix B. pymedeas2 Improvements

Appendix B.1. Transport Module Architecture and Causal Logic

The transport module employs a hybrid top–down/bottom–up approach to internalize the biophysical and economic feedbacks of mobility within the system dynamics framework. The modeling sequence follows a four-stage causal chain:

1. Demand Generation: Aggregate transport demand (pkm and tkm) is driven endogenously by macroeconomic variables: GDP and population. These variables are calibrated using econometric elasticities.
2. Modal and Technological Allocation: Total demand is disaggregated into specific modes (road, rail, air, and maritime) and powertrain technologies (BEV, ICE, and Hydrogen) according to scenario-specific policy pathways.
3. Metabolic Accounting: The model applies technology-specific energy intensities and material factors to calculate final energy demand, its associated greenhouse gas emissions, and critical raw material requirements (e.g., lithium for battery stocks).
4. Systemic Feedback Loops: Variations in energy availability or climate impacts can retroactively constrain economic output, internalizing the biophysical limits to transport growth.

Appendix B.2. Economic Framework Integration

The economic module of pymedeas2 has been updated to work with the EXIOBASE database [21] for more detail in the economic sectors. The improved economic model consists of 49 sectors (see Table A11), including the land transport sector independently from the other transport categories (i.e., air transport and maritime transport).

The pymedeas2 model works with the sectoral energy consumption from the IEA world energy balances [64], which are published with low industrial resolution. To increase the resolution of the energy data to match the updated detail of the economic model, we implemented an adapted version of the methodology from [65]. It estimates the energy flows for each sector based on the EXIOBASE supply-and-use (SUT) tables. The IEA database energy sources are aggregated into five final fuel categories in pymedeas2: solid, liquid, gas, electricity and heat (see Table A13). The energy consumption for the transport sectors excludes international bunkers, which are not accounted for in this study.

Appendix C. Econometric Estimation and Statistical Analysis

To establish the empirical foundation for Equations (1) and (2), we developed an econometric framework to estimate the structural drivers of transport activity. All variables were normalized relative to the base year ($t_0 = 2000$) to ensure dimensional homogeneity. The year 2020 served as the historical calibration year to validate the model's baseline physical and energy outputs. To ensure continuity between historical trends and projected pathways, 2023 acts as the projection anchor (integrating the latest available statistical data). Projections for the 2024–2050 period (with 2024 marking the starting point for our forward-looking scenario simulations) were calculated by applying the estimated income elasticity to the relative growth of GDP per capita, using the 2023 anchored activity levels as the starting point for the extrapolation.

Appendix C.1. Econometric Specification

For passenger transport, a log-log per-capita regression model was fitted to the historical data:

$$\ln\left(\frac{PKM_t}{PKM_0}\right) = \gamma \ln\left(\frac{GDP_{pc,t}}{GDP_{pc,0}}\right) + \varepsilon_t \quad \text{(A1)}$$

where PKM_t and $GDP_{pc,t}$ represent passenger-kilometers and GDP per capita, respectively. For freight transport, activity was modeled relative to total GDP:

$$\ln\left(\frac{TKM_t}{TKM_0}\right) = \beta \ln\left(\frac{GDP_t}{GDP_0}\right) + \varepsilon_t \quad \text{(A2)}$$

The residuals (ε_t) were modeled as a first-order autoregressive process (AR(1)) to capture temporal autocorrelation: $\varepsilon_t = \phi\varepsilon_{t-1} + u_t$ [66].

Appendix C.2. Estimation Results and Diagnostics

The parameters were estimated using historical time-series (2000–2023) bound by the database limits. To isolate long-term structural elasticities from severe macroeconomic shocks, the anomalous COVID-19 pandemic years were identified using a standardized residual threshold of 2σ. The income elasticity for passenger transport (γ) was estimated at 0.652 ($p < 0.001$, adjusted $R^2 = 0.96$), reflecting the saturation of individual mobility in high-income regions. For freight transport, the elasticity (β) was found to be 0.774 ($p < 0.001$, adjusted $R^2 = 0.92$), consistent with the relative decoupling of logistics from economic growth observed in the EU-27. Complete regression diagnostics are summarized in Table A2.

Table A2. Econometric regression parameters for passenger-kilometer (*pkm*) and ton-kilometer (*tkm*) demand projections in the EU-27.

Parameter	Value	Description/Diagnostic
Passenger Transport (*pkm*)—GDP Per Capita Model		
γ (Elasticity)	0.6517	Income elasticity of mobility
pkm_0	4747.18	Base year activity (billion *pkm*, 2000)
$GDP_{pc,0}$	22,032.08	Base year GDP per capita (1995USD, 2000)
R^2	0.9490	Coefficient of determination
p-val (γ)	4.71×10^{-13}	Statistical significance of elasticity
ϕ_{AR1}	0.4803	First-order autoregressive coefficient
Freight Transport (*tkm*)—GDP Model		
β (Elasticity)	0.7737	Freight-income elasticity
tkm_0	1973.57	Base year activity (billion *tkm*, 2000)
GDP_0	9.4402	Base year total GDP (trillion 1995USD, 2000)
R^2	0.9209	Coefficient of determination
p-val (β)	1.56×10^{-11}	Statistical significance of elasticity
ϕ_{AR1}	0.2964	First-order autoregressive coefficient

Appendix D. Material and Economic Formulations

Appendix D.1. Vehicle Stock and Material Demand

The estimation of material demand follows a two-step sequential logic that translates transport demand into primary material requirements. First, the required vehicle fleet size ($N_{m,f}$) for each mode and technology is determined by applying the inverse of the productivity coefficient, defined here as the vehicle intensity ($\sigma_{m,f} = 1/P_{m,f}$). This coefficient implicitly accounts for historical vehicle occupancy rates, load factors, and average annual mileage:

$$N_{m,f}(t) = A_{m,f}(t) \cdot \sigma_{m,f} \quad \text{(A3)}$$

where $N_{m,f}$ is the number of vehicles for mode m and technology f, and $A_{m,f}$ is the mode-specific transport activity.

Second, the material modeling framework distinguishes between the active *Material Stock in Use* and the *Annual Material Demand* required for fleet maintenance and expansion. The total installed energy capacity of the fleet is calculated by assuming an average battery capacity per vehicle ($C_{avg,m}$) in kWh. The aggregate stock for a specific material k is

then derived using material intensity factors (I_k), expressed in kg of material per kWh of battery capacity:

$$S_k(t) = \sum_m \left(N_{m,elec}(t) \cdot C_{avg,m} \cdot I_k \right) \quad \text{(A4)}$$

The material intensity factors (I_k) are technology-specific and reflect the chemical composition of the prevailing battery architectures, such as Lithium-ion Lithium Nickel Manganese Cobalt Oxide (NMC) or Lithium Iron Phosphate (LFP) (see Table A10). These shares evolve dynamically through 2050 following projected technological trends. For instance, the model simulates a transition in the passenger car segment toward LFP alternatives, reaching a 60% market share by 2050, while high-nickel chemistries like NCM 811 are prioritised for heavy-duty segments to meet specific energy density requirements [36] (see Table A6).

To accurately capture material throughput, the model calculates the *Annual Primary Material Demand* ($D_k(t)$) by isolating gross physical inflows from net stock dynamics. Relying on net stock changes ($\Delta S_k(t)$) would artificially underestimate primary resource requirements when vehicle retirements exceed new additions.

Consequently, the total annual primary material demand for a specific material k is defined strictly as the sum of materials required for gross new vehicle additions ($Inflows_k(t)$) and the maintenance of the existing active fleet ($Replacements_k(t)$):

$$D_k(t) = Inflows_k(t) + Replacements_k(t) \quad \text{(A5)}$$

Gross inflows are driven by the required new vehicle sales ($Sales_{m,elec}(t)$) and their corresponding material intensity (I_k):

$$Inflows_k(t) = \sum_m \left(Sales_{m,elec}(t) \cdot C_{avg,m} \cdot I_k \right) \quad \text{(A6)}$$

Replacements are calculated based on the existing stock and a technology-specific battery lifetime (L_{batt}):

$$Replacements_k(t) = \frac{S_k(t-1)}{L_{batt}} \quad \text{(A7)}$$

The physical retirements of vehicles ($Outflows_k(t)$) are determined by the fleet size and the average mechanical vehicle lifetime (L_{veh}):

$$Outflows_k(t) = \frac{S_k(t-1)}{L_{veh}} \quad \text{(A8)}$$

The net change in the active fleet stock is the balance of these flows:

$$\Delta S_k(t) = Inflows_k(t) - Outflows_k(t) \quad \text{(A9)}$$

Because this assessment models a primary-extraction-dominated pathway, circularity mechanisms are not endogenised. Therefore, $Outflows_k(t)$ are routed to an EoL scrap pool and do not provide a secondary supply stream to offset $D_k(t)$. Even when $\Delta S_k(t)$ is negative due to intentional fleet contraction, $D_k(t)$ remains a strictly positive function of necessary fleet turnover and maintenance, ensuring that primary material bottlenecks are accurately represented [36,67].

Appendix D.2. Economic Valuation of the Transition

To evaluate the economic burden of the proposed transition, we follow the physical capital replacement framework established by [11], disaggregating total annual investment ($I_{total,t}$) into vehicle fleet acquisition, charging infrastructure deployment, and rail network

expansion. The investment in new vehicles ($I_{veh,t}$) accounts for both the net expansion of the fleet to meet growing transport demand and the replacement of existing stock reaching the end of its operational life. The cost is calculated as:

$$I_{veh,t} = \sum_{m,f} \left(S_{m,f,t} \cdot P_{m,f} \right) \tag{A10}$$

where $S_{m,f,t}$ represents the units sold for mode m and technology f at time t, and $P_{m,f}$ is the unit purchase price (see Table A3).

The deployment of the electrical charging system ($I_{charge,t}$) is modeled based on the required density of charging points to ensure system functionality. For passenger vehicles, the number of required posts is a function of population density and average charging time, while for commercial vehicles, it depends on the energy throughput required for freight operations. The annual investment is given by:

$$I_{charge,t} = \Delta N_{posts,t} \cdot P_{post} \tag{A11}$$

where $\Delta N_{posts,t}$ is the annual increment of new charging stations and P_{post} represents the unit cost of installation, including hardware and grid connection. We distinguish between standard wallbox units for private use and high-power fast-chargers (e.g., 50–150 kW) for heavy-duty commercial logistics.

Charging infrastructure requirements are parametrized following a high-utilization shared model derived from Xylia et al. (2025) [37]. Private and depot-based settings—comprising residential, workplace, and commercial logistics hubs—are modeled with a ratio of 0.20 chargers per vehicle. Public infrastructure utilizes a lower ratio of 0.043, assuming a technological mix dominated by fast and super-fast charging units. This configuration prioritizes high unit occupancy and shared access, significantly reducing the total material and spatial footprint of the charging network compared to conventional slow-charging deployments.

The Rail Scenario necessitates a massive structural shift requiring the expansion and full electrification of the EU-27 rail network ($I_{rail,t}$). The investment covers the electrification of the remaining non-electrified lines (approximately 46% of the current network) and the construction of new high-speed and medium-speed tracks to absorb the transferred road activity:

$$I_{rail,t} = \sum_{type} \left(L_{new,type,t} \cdot C_{km,type} \right) \tag{A12}$$

where L_{new} is the length of tracks added or upgraded, and $C_{km,type}$ represents the specific cost per kilometer. Following [11], we calculate weighted mean infrastructure costs that incorporate platforms, rails, signalling, and electrification across the diverse European orography.

Table A3. Consolidated economic parameters for the transport transition model (Base Year 2025) in USD.

Category/Component	Unit	Avg. Value (USD)	Reference
Vehicle Purchase Price			
Passenger Car (BEV)	per unit	43,500	[43]
Light Commercial (LCV)	per unit	53,000	[68]
Heavy Goods (HGV)	per unit	470,000	[68]
Electric Bus	per unit	585,000	[69]
Electric Locomotive	per unit	4,900,000	[70]
Charging Infrastructure			
AC Wallbox (Private/Slow)	per post	1800	[71]
DC Fast Charger (Public/HGV)	per post	76,000	[71,72]
Rail Infrastructure			
Electrification of existing lines	per km	1,300,000	[70]
New High-Speed Rail (HSR)	per km	25,500,000	[11]
New Standard Track (Double)	per km	15,840,000	[11]
New Single-Track Line	per km	10,820,000	[11]

Appendix E. Additional Data Tables

Table A4. Assumed mean battery capacities (C_{avg}) by vehicle segment and technology used by pymedeas2 model.

Vehicle Segment	Technology	Capacity (kWh)	Reference
Passenger Car	BEV (Electric)	66	[36]
Passenger Car	PHEV (Hybrid)	12	[36]
Light Commercial (LCV)	BEV (Electric)	80	[43]
Heavy Goods (HGV)	BEV (Electric)	600	[73]
Buses	BEV (Electric)	450	[74]

Table A5. Historical Market Shares of Battery Chemistries in the EU-27 (1995–2023). Light and heavy commercial vehicle data reflect early fleet adoption trends [36,43].

Segment/Technology	1995	2015	2016	2017	2018	2019	2020	2021	2022	2023
Cars (Passenger)										
NCM 111	85%	85%	84%	80%	60%	40%	15%	5%	2%	0%
LFP	1%	1%	1%	1%	2%	3%	5%	15%	28%	32%
NCM 622	0%	0%	0%	5%	20%	40%	55%	40%	20%	15%
NCM 811	0%	0%	0%	0%	0%	2%	10%	25%	38%	43%
NCA	14%	14%	15%	14%	18%	15%	15%	15%	12%	10%
Buses										
NCM 111	95%	85%	80%	60%	40%	20%	5%	0%	0%	0%
LFP	5%	15%	20%	25%	30%	35%	40%	42%	45%	48%
NCM 622	0%	0%	0%	15%	30%	45%	50%	43%	35%	22%
NCM 811	0%	0%	0%	0%	0%	0%	5%	15%	20%	30%
Light Trucks (LCV)										
NCM 111	95%	85%	80%	60%	40%	20%	5%	0%	0%	0%
LFP	5%	5%	5%	5%	5%	5%	5%	15%	25%	35%
NCM 622	0%	10%	15%	35%	55%	70%	80%	60%	40%	25%
NCM 811	0%	0%	0%	0%	0%	5%	10%	25%	35%	40%
Heavy Trucks (HGV)										
NCM 111	95%	85%	80%	60%	40%	20%	5%	0%	0%	0%
LFP	5%	5%	5%	5%	5%	5%	10%	15%	20%	30%
NCM 622	0%	10%	15%	35%	55%	75%	80%	65%	40%	20%
NCM 811	0%	0%	0%	0%	0%	0%	5%	20%	40%	50%

Table A6. Projected market shares of battery chemistries by vehicle segment in the EU-27 (2025–2050). Passenger car projections follow the LFP scenario from Xu et al. [36], while commercial segments integrate demand forecasts from recent industry literature [43,75].

Segment/Technology	2025	2030	2035	2040	2045	2050
Cars (Passenger)						
LFP	45.0%	60.0%	60.0%	60.0%	60.0%	60.0%
NCM 811	45.0%	35.0%	35.0%	35.0%	35.0%	35.0%
NCM 622	5.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NCA	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Buses						
LFP	50.0%	60.0%	65.0%	75.0%	80.0%	85.0%
NCM 811	50.0%	40.0%	35.0%	25.0%	20.0%	15.0%
Light Trucks (LCV)						
LFP	40.0%	55.0%	60.0%	65.0%	70.0%	75.0%
NCM 811	55.0%	45.0%	40.0%	35.0%	30.0%	25.0%
NCM 622	5.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Heavy Trucks (HGV)						
LFP	40.0%	55.0%	65.0%	70.0%	75.0%	80.0%
NCM 811	60.0%	45.0%	35.0%	30.0%	25.0%	20.0%

Table A7. Adapted Transport Mode Share Projections for the EU-27 (2020–2050) based on the CETO Scenario.

Category	Mode	2020	2025	2030	2035	2040	2045	2050
Freight (tkm)	Road Heavy	71.96%	70.20%	67.40%	63.50%	59.80%	55.40%	51.50%
	Road Light	3.61%	3.75%	3.80%	3.80%	3.80%	3.80%	3.80%
	Rail	15.82%	17.40%	20.10%	24.10%	28.30%	32.50%	36.50%
	Maritime	8.61%	8.65%	8.70%	8.60%	8.10%	8.30%	8.20%
	Air (Domestic)	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Passenger (pkm)	Road Bus	6.87%	7.75%	8.32%	8.94%	9.60%	10.30%	11.06%
	Road Car	85.52%	81.30%	78.50%	74.20%	68.80%	63.10%	58.60%
	Rail	6.51%	9.10%	11.80%	15.60%	20.80%	26.10%	30.34%
	Maritime	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Air (Domestic)	1.10%	1.85%	1.38%	1.26%	0.80%	0.50%	0.00%

Table A8. Projected fuel shares by transport mode for the EU-27 Rail Scenario (2025–2050).

Mode	Fuel Type	2025	2030	2035	2040	2045	2050
Rail	Liquid	18.50%	14.80%	11.10%	7.40%	3.70%	0.00%
	Electricity	81.50%	85.20%	88.90%	92.60%	96.30%	100.00%
Road Heavy (HGV)	Liquid	94.50%	80.00%	65.00%	50.00%	35.00%	20.00%
	Gas	2.00%	5.00%	8.00%	10.00%	12.00%	15.00%
	Electricity	3.50%	15.00%	27.00%	40.00%	53.00%	65.00%
Road Light (LCV)	Liquid	92.00%	75.00%	55.00%	35.00%	15.00%	5.00%
	Gas	3.00%	5.00%	5.00%	5.00%	5.00%	5.00%
	Electricity	5.00%	20.00%	40.00%	60.00%	80.00%	90.00%
Maritime	Liquid	98.00%	93.00%	88.00%	83.00%	78.00%	73.00%
	Gas	2.00%	7.00%	12.00%	17.00%	22.00%	27.00%
Air (Domestic)	Liquid	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table A9. Projected installed capacity for renewable sources and storage (TW) in the EU27 (2020–2050).

Variable [TW]	2020	2025	2030	2035	2040	2045	2050
Hydro	0.1061	0.1072	0.1087	0.1087	0.1087	0.1087	0.1087
Geothermal elec.	0.0009	0.0010	0.0017	0.0043	0.0067	0.0075	0.0084
Solid Bioenergy	0.0207	0.0199	0.0192	0.0186	0.0158	0.0146	0.0117
Oceanic energy	0.0003	0.0003	0.0005	0.0005	0.0005	0.0006	0.0006
Onshore wind	0.1627	0.2173	0.3115	0.4059	0.4785	0.5299	0.5957
Offshore wind	0.0146	0.0240	0.0831	0.1497	0.1891	0.2129	0.2212
Solar PV	0.1273	0.3377	0.6179	0.8434	1.1718	1.4958	1.7393
CSP	0.0023	0.0023	0.0052	0.0054	0.0054	0.0064	0.0064
Pumped Hydro (PHS)	0.0452	0.0474	0.0535	0.0552	0.0552	0.0556	0.0556

Table A10. Material intensity factors for different battery architectures (kg/kWh). Calculated from [36].

Material	NCM 111	LFP	NMC Leg.	NMC 811	NCA
Copper (Cu)	0.7530	0.8535	0.7414	0.7361	0.7449
Nickel (Ni)	0.3512	0.0000	0.5275	0.6706	0.6706
Lithium (Li)	0.1428	0.1004	0.1269	0.1136	0.1037

Table A11. Economic sectors aggregation used in pymedeas2, with 49 industries, 4 final consumption and 2 value added categories. The corresponding sector number from the EXIOBASE classification is also added (c.f. Table A12).

No.	Sector Name	Exio.	No.	Sector Name	Exio.
Industries			30	Metallurgy	72–82
1	Accommodation, food and beverage services	117	31	Other business activities	133
2	Activities of membership organizations	157, 161	32	Other personal service activities	159
3	Agriculture, livestock and related services	1–17	33	Paper and paper products industry	52–54
4	Air transport	123	34	Postal and telecomunication activities	125
5	Chemical industry	58–63	35	Private households with employed pers.	160
6	Coke and petroleum refineries	56–57	36	Public admin, defense and social sec.	134
7	Computer activities and info services	131	37	Real estate activities	129
8	Construction	111–112	38	Rec., cultural and sporting activities	158
9	Education	135	39	Rental activities	130
10	Electricity, gas, steam and air-cond.	94–109	40	Research and development	132
11	Extractive industries, mining and quarrying	20–34	41	Retail trade, exc. motor vehicles	114, 116
12	Financial intermediation	126	42	Sale and repair of motor vehicles	113
13	Fishing and aquaculture	19	43	Sanitation, waste management and decont.	92–93, 137–156
14	Food, beverages and tobacco industries	35–46	44	Support activities for financial interm.	128
15	Forestry and logging	18	45	Textile, clothing, leather and footwear	47–49
16	Graphic arts and recorded media	55	46	Warehousing and support activities	124
17	Healthcare and social work activities	136	47	Water collection, treatment and supply	110
18	Insurance and pension funds	127	48	Wholesale trade and intermediation	115
19	Land transport; pipeline transport	118–120	49	Wood and cork industry	50–51
20	Manuf. computer, electronic and optical	85, 87–88			
21	Manuf. metal products, exc. machinery	83	**Value Added**		
22	Manuf. motor vehicles, trailers	89	1	Labor Compensation	–
23	Manuf. of machinery and equipment n.e.c.	84	2	Capital Compensation	–
24	Manuf. of other non-metallic mineral prod.	65–71			
25	Manufacture of electrical equipment	86	**Final Demand**		
26	Manufacture of furniture; manuf. n.e.c.	91	1	Household Consumption	–
27	Manufacture of other transport equipment	90	2	Government Expenditure	–
28	Manufacture of rubber and plastic products	64	3	Gross Fixed Capital Formation	–
29	Maritime and inland water transport	121–122	4	Changes in Inventories	–

Table A12. Complete list of the 163 EXIOBASE industries. For more detail, see [21].

#	Sector	#	Sector	#	Sector	#	Sector
1	Cultivation rice	42	Sugar refining	83	Reproc. other nonfer	124	Inland water trans.
2	Cultivation wheat	43	Proc. food prod nec	84	Casting of metals	125	Air transport
3	Cultiv. cereal nec	44	Manuf. beverages	85	Manuf. fabric. metal	126	Support/aux trans.
4	Cultiv. veg/fruit	45	Manuf. fish prod.	86	Manuf. machinery nec	127	Post and telecom
5	Cultiv. oil seeds	46	Manuf. tobacco prod	87	Manuf. office/comp.	128	Financial intermed.
6	Cultiv. sugar crops	47	Manuf. textiles	88	Manuf. elec. mach.	129	Insurance/pension
7	Cultiv. plant fiber	48	Manuf. apparel/fur	89	Manuf. communic. eq.	130	Aux. financial act.
8	Cultiv. crops nec	49	Manuf. leather prod	90	Manuf. med/opt inst	131	Real estate act.
9	Cattle farming	50	Manuf. wood prod.	91	Manuf. motor vehicle	132	Renting machinery
10	Pigs farming	51	Reproc. wood mat.	92	Manuf. other trans.	133	Computer activities
11	Poultry farming	52	Pulp	93	Manuf. furniture nec	134	RandD
12	Meat animals nec	53	Reproc. paper/pulp	94	Recycling waste	135	Other business act.
13	Animal products nec	54	Paper	95	Recycling bottles	136	Public admin/defense
14	Raw milk	55	Publishing and print.	96	Elec. prod: coal	137	Education
15	Wool and silk cocoons	56	Manuf. coke prod.	97	Elec. prod: gas	138	Health and social work
16	Manure trt. (conv.)	57	Petroleum Refinery	98	Elec. prod: nuclear	139	Incineration: Food
17	Manure trt (biogas)	58	Proc. nuclear fuel	99	Elec. prod: hydro	140	Incineration: Paper
18	Forestry and logging	59	Plastics, basic	100	Elec. prod: wind	141	Inciner. Plastic
19	Fishing and services	60	Reproc. plastic	101	Elec. prod: oil	142	Inciner. Metals
20	Mining coal and peat	61	N-fertiliser	102	Elec. prod: biomass	143	Inciner. Textiles
21	Extr. crude petrol.	62	P- and other fert.	103	Elec. prod: solar PV	144	Inciner. Wood
22	Extr. natural gas	63	Chemicals nec	104	Elec. prod: solar th	145	Inciner. Oil/Haz
23	Extr. petro/gas nec	64	Manuf. rubber/plast	105	Elec. prod: tide/wav	146	Biogas. food waste

Table A12. *Cont.*

#	Sector	#	Sector	#	Sector	#	Sector
24	Mining uranium/thor	65	Manuf. glass prod.	106	Elec. prod: geotherm	147	Biogas. paper
25	Mining iron ores	66	Reproc. glass	107	Elec. prod: nec	148	Biogas. sewage
26	Mining copper ores	67	Manuf. ceramic	108	Transmission of elec	149	Compost food waste
27	Mining nickel ores	68	Manuf. bricks/tiles	109	Dist/trade elec.	150	Compost paper/wood
28	Mining alum. ores	69	Manuf. cement/lime	110	Manuf/dist gas	151	Waste water, food
29	Mining precious met	70	Reproc. ash/clinker	111	Steam/hot water	152	Waste water, other
30	Mining Pb, Zn, Sn	71	Manuf. non-metal nec	112	Water supply/dist.	153	Landfill: Food
31	Mining other nonfer	72	Manuf. iron and steel	113	Construction	154	Landfill: Paper
32	Quarrying stone	73	Reproc. steel	114	Reproc. constr. mat.	155	Landfill: Plastic
33	Quarrying sand/clay	74	Prod. precious met.	115	Sale/rep motor veh.	156	Landfill: Inert/Met
34	Mining chem/fert nec	75	Reproc. precious met	116	Retail auto fuel	157	Landfill: Textiles
35	Proc. meat cattle	76	Aluminium product.	117	Wholesale trade	158	Landfill: Wood
36	Proc. meat pigs	77	Reproc. aluminium	118	Retail trade	159	Membership orgs nec
37	Proc. meat poultry	78	Prod. Pb, Zn, Sn	119	Hotels and restaurants	160	Rec/cult/sport act.
38	Meat products nec	79	Reproc. Pb, Zn, Sn	120	Rail transport	161	Other service act.
39	Proc. veg oils/fats	80	Copper production	121	Other land transport	162	Private households
40	Proc. dairy prod.	81	Reproc. copper	122	Pipeline transport	163	Extra-territor. orgs
41	Processed rice	82	Prod. other nonfer.	123	Sea/coast transport		

Table A13. Aggregation of the IEA fuels into the five fuel categories used in pymedeas2.

No.	Energy Carrier	No.	Energy Carrier
Electricity		23	Bio jet kerosene
1	Electricity	24	Other liquid biofuels
2	Hydro	25	Fuel oil
3	Wind	26	Refinery gas
4	Solar photovoltaics	27	Petroleum coke
5	Nuclear	**Gases**	
6	Electricity	1	Gas works gas
Heat		2	Coke oven gas
1	Heat	3	Blast furnace gas
2	Geothermal	4	Other recovered gases
3	Solar thermal	5	Natural gas
Liquids		6	Biogases
1	Crude oil	**Solids**	
2	Natural gas liquids	1	Gas coke
3	Refinery feedstocks	2	Municipal waste (non-renewable)
4	Additive/blending components	3	Hard coal (if no detail)
5	Other hydrocarbons	4	Brown coal (if no detail)
6	Crude/NGL/feedstocks (if no detail)	5	Anthracite
7	Ethane	6	Coking coal
8	Liquefied petroleum gases (LPG)	7	Other bituminous coal
9	Motor gasoline excl. biofuels	8	Sub-bituminous coal
10	Aviation gasoline	9	Lignite
11	Gasoline type jet fuel	10	Patent fuel
12	Kerosene type jet fuel excl. biofuels	11	Coke oven coke
13	Other kerosene	12	Coal tar
14	Gas/diesel oil excl. biofuels	13	BKB
15	Naphtha	14	Peat
16	White spirit and SBP	15	Peat products
17	Lubricants	16	Oil shale and oil sands
18	Bitumen	17	Industrial waste
19	Paraffin waxes	18	Municipal waste (renewable)
20	Other oil products	19	Primary solid biofuels
21	Biogasoline	20	Non-specified primary biofuels and waste
22	Biodiesels	21	Charcoal

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