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Research Article

Energy System Modeling for Climate-Neutral Transport: Aligning Italian Mobility with EU 2030 and Fit for 55 Goals

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Abstract: This study develops an integrated, hourly-resolved, multi-vector energy system model to assess pathways for aligning Italy's transport sector with the European Union (EU) 2030 and Fit for 55 decarbonisation targets. The model simultaneously represents electricity generation, grid constraints, storage dynamics, hydrogen production, and heterogeneous vehicle charging behaviours. Three scenarios are analysed: Battery Electric Vehicles (BEV)-dominant, Hydrogen-dominant, and Hybrid. Results indicate that the BEV-dominant pathway requires approximately 52 TWh of electricity for vehicle charging, leading to a national peak load of 72 GW and total system costs of €144 billion, while achieving 21.5 Mt CO_2 emissions. The Hydrogen-dominant scenario shifts demand toward electrolysis, consuming 45 TWh for hydrogen production ($\approx$1.35 Mt H_2 yr^{-1}), reducing emissions to 19.7 Mt CO_2 but increasing system costs to €168 billion. The Hybrid scenario balances 38 TWh of direct electricity use with 22 TWh for hydrogen generation, achieving the lowest emissions (17.8 Mt CO_2) and moderate costs (€156 billion). Renewable curtailment decreases from 8.3 % (BEV) to 4.5% (Hybrid), highlighting improved flexibility and resource utilization. Overall, the Hybrid configuration demonstrates the most cost-effective and environmentally coherent pathway, integrating both electricity and hydrogen infrastructures. The findings provide quantitative insights for policymakers and system planners seeking to align Italian mobility decarbonisation strategies with EU climate goals while maintaining energy security and affordability.

***Keywords*:** energy system modelling, transport decarbonisation, Battery Electric Vehicles (BEV), hydrogen economy, Fit for 55 target

1. Introduction

Achieving climate-neutral transport is among the most urgent and technically complex challenges faced by the European Union and its Member States. The EU's 2030 climate and energy targets, consolidated under the Fit for 55 package and enshrined in the European Climate Law, set an ambitious decarbonisation trajectory: a net reduction of at least 55% in Greenhouse Gas (GHG) emissions by 2030 relative to 1990 levels, and a pathway toward climate neutrality by 2050. Meeting these targets requires transformative changes in the transport sector, which remains one of the largest and most persistent sources of emissions in Italy and across the EU [1–3]. The purpose of this manuscript is to present a rigorous energy-system modelling framework that quantifies the impacts of decarbonisation pathways for Italian mobility, evaluates technology mix options (battery electric vehicles, hydrogen, and hybrid solutions), and identifies policy and

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infrastructural measures necessary to align national mobility with EU 2030 and Fit for 55 goals. Transport decarbonisation is not merely a matter of electrifying vehicles: it implicates the entire energy system. Shifts in vehicle technology alter electricity demand profiles (both in magnitude and hourly shape), create new interactions between power generation and distribution networks, and impose requirements for flexibility and storage [4, 5]. In Italy, where renewable penetration is growing rapidly and the generation mix is regionally heterogeneous, the electrification of transport introduces both opportunities and constraints: on the one hand, increased demand can be met by domestic renewables and reduce fossil fuel dependence; on the other hand, unmanaged charging and insufficient storage or network reinforcement can increase peak demand, stress distribution assets, and shift emissions upstream if generation remains carbon-intensive at certain hours [6, 7].

Energy system models capable of representing temporal resolution at sub-daily or hourly granularity are therefore indispensable tools for credible policy assessment. Hourly-resolved or sub-hourly simulations allow the analysis of demand-response effects, the operational interplay between Variable Renewable Energy Sources (VRES) [8] and storage, and the value of flexibility solutions such as behind-the-meter batteries, grid-scale Battery Energy Storage Systems (BESS), Vehicle-to-Grid (V2G) [9, 10] strategies, and hydrogen-based seasonal storage. For Italy, characterized by strong solar resources in the south, hydro resources concentrated in the north, and varied industrial and urban load centers, a high-resolution energy system approach reveals both spatial and temporal trade-offs that aggregate models may obscure [11]. The Fit for 55 package reconfigures EU climate policy instruments to put the bloc on a credible 2030 trajectory. Its implications for transport are multifold: more stringent CO_2 standards for new vehicles, extension of emissions trading to new sectors, incentives for low-emission fuels, and stronger targets for renewable energy and energy efficiency. These measures create an overarching constraint: by 2030, national mobility systems must materially reduce tailpipe emissions while also ensuring energy system stability and affordability [12–14]. Italy's transport sector presents specific challenges and opportunities. Historically reliant on liquid fossil fuels, the sector accounts for a substantial share of national emissions and energy consumption. Italy's automotive market has shown rapid growth in electrified powertrains (hybrids and BEVs), yet the fleet turnover rate and preponderance of Internal Combustion Engine (ICE) vehicles mean that decarbonisation by 2030 requires accelerated deployment and supportive systemic measures [15, 16]. Key national considerations include the geographic heterogeneity of charging infrastructure, the capacity of local distribution networks, the timeline for large-scale battery recycling facilities, and the potential role of hydrogen in decarbonising heavy-duty and long-haul transport segments where battery solutions may be less attractive [17]. Battery-electric vehicles are the most mature pathway for passenger transport decarbonisation in terms of energy efficiency and lifecycle emissions potential when powered by low-carbon electricity [18]. BEVs shift emissions from the vehicle tailpipe to the power sector and therefore couple mobility decarbonisation tightly to the pace of grid decarbonisation and the availability of low-carbon generation. BEV adoption increases electricity demand and, crucially, modifies its temporal distribution: unmanaged evening charging can exacerbate peak demand, while smart charging and V2G can provide valuable balancing services when properly incentivized [14, 19].

Hydrogen-based solutions and FCEVs represent a complementary pathway, particularly for heavy-duty, maritime, and certain long-distance freight applications [20]. Hydrogen enables energy vector diversification and, when produced from renewable electricity (green hydrogen), offers a low-carbon fuel with relative advantages for energy density and refuelling times. However, hydrogen introduces additional conversion losses and requires substantial investment in electrolysis capacity, storage (including potential seasonal storage), and distribution infrastructure. Comparing BEV and hydrogen pathways therefore requires integrated modelling of generation, conversion, and end-use sectors to capture systemic trade-offs [21, 22]. Hybrid powertrains (conventional + electrified components) provide a transitional technology that can reduce fleet-level emissions in the medium term but may delay full electrification if policy incentives favour stopgap solutions. The presence of hybrids in the vehicle stock also affects average energy demand per kilometer and charging infrastructure needs [23, 24].

Crucially, energy storage technologies, from distributed BESS to grid-scale pumped hydro and batteries, are central to integrating higher shares of variable renewables while accommodating electrified transport. Storage reduces curtailment, provides peak shaving, and can enable temporal arbitrage between abundant daytime solar generation and evening charging demand [25–27]. V2G expands the effective storage capacity by leveraging the aggregated battery capacity of parked vehicles, albeit with techno-economic and battery degradation considerations [28]. Robust assessment of decarbonisation strategies requires models that integrate multiple energy carriers (electricity, hydrogen, liquid fuels), represent temporal dynamics with hourly or finer resolution, and capture spatial heterogeneity at regional or sub-regional scales. From a methodological standpoint, several features are essential: high-resolution temporal modelling, multi-vector coupling, behavioural and agent-based representations, uncertainty and scenario analysis, and lifecycle or circular economy perspectives (Figure 1). These features ensure that both short-term operational impacts and long-term sustainability outcomes are captured within the same analytical framework [29, 30].

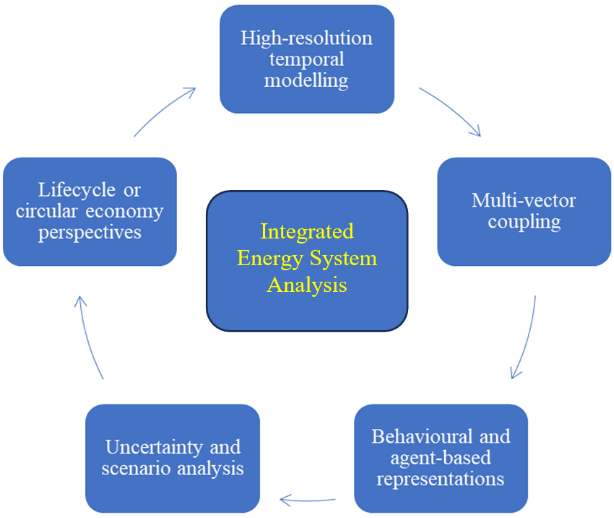

Figure 1. Methodological foundations for integrated energy system analysis

Recent literature on energy system modelling for transport decarbonisation highlights significant progress in integrating electrified mobility within broader energy transitions, yet notable gaps persist in temporal resolution, spatial detail, and multi-vector coupling. Studies such as those by Aldossary et al. [31] and Zhou et al. [32] emphasized the importance of hourly or sub-hourly modelling to capture the variability of renewable generation and the temporal dynamics of Electric Vehicle (EV) charging. Multi-energy approaches, exemplified by Yadav et al. [33] and Safarzadeh et al. [34] demonstrated that coupling electricity, hydrogen, and heat systems enhances system flexibility and resilience but requires careful representation of conversion efficiencies and storage interactions. Research focused on Italy, including Ghilardi et al. [35] and Paolacci et al. [36], has explored decarbonisation scenarios under the Fit for 55 framework, though often with limited behavioural detail and simplified demand-side assumptions. Meanwhile, emerging agent-based models, such as those developed by Fouladvandet al. [37] and Adernetto et al. [38] have begun to represent heterogeneous user charging behaviour and policy sensitivity, providing more realistic demand profiles. Despite these advancements, few studies combine behavioural realism, lifecycle assessment, and circular economy considerations within a unified, high-resolution, multi-vector framework. This gap motivates the present study, which seeks to integrate these dimensions to assess how Italian transport can be aligned with EU 2030 and Fit for 55 targets in a technologically and environmentally coherent manner.

Existing studies have made substantial progress in quantifying the impacts of vehicle electrification and the benefits of storage, yet several gaps remain for the Italian context. Many use coarse temporal resolution or simplified representations of charging behaviour, which may mis-estimate peak impacts and the value of V2G. Spatially aggregated models often fail to capture distribution network constraints and regional differences in renewable resources. Comparative analyses of BESS and hydrogen solutions in integrated multi-vector frameworks, with explicit attention to circular economy implications for batteries, are still limited. Moreover, few works combine agent-based representations of user charging behaviour with system-level optimisation of generation and storage investments under Fit for 55 constraints [17, 22, 31]. The primary contributions of this study are threefold. First, an integrated, hourly-resolved, multi-vector energy system model is developed and calibrated to the Italian context to represent electricity generation, distribution constraints, storage, hydrogen production and use, and heterogeneous charging behaviour. Second, alternative mobility decarbonisation pathways, BEV-dominant, hydrogen-dominant, and hybrid mixes, are evaluated under Fit for 55-aligned policy constraints, with impacts on system costs, peak demand, CO_2 emissions, and infrastructure requirements quantified. Third, lifecycle and circular economy dimensions are examined by incorporating battery second-life applications and recycling potential into scenario analyses, thereby bridging short-term operational effects with medium-term material and environmental implications. The remainder of the paper is organized as follows. The remainder of this paper is organized as follows. Section 2 describes the materials and methods, including the modelling framework, data sources, and scenario design. Section 3 presents the results of the baseline and scenario analyses, including sensitivity assessments. Also, this section discusses the implications of the findings for policy, system planning, and practical deployment challenges in the context of the Fit for 55 targets. Finally, the conclusion summarises the key findings and outlines directions for future research.

Through the integration of high-resolution system dynamics with agent-level behavioural heterogeneity and circular economy considerations, actionable insights are provided for policymakers, system operators, and researchers aiming to align Italian transport with EU 2030 ambitions.

2. Methodology

The methodological framework adopted in this study integrates a high-resolution, multi-vector energy system model with behavioural and lifecycle components to evaluate decarbonisation pathways for the Italian transport sector under EU 2030 and Fit for 55 targets. The model was designed to capture hourly dynamics, spatial heterogeneity, and the interplay between electricity, hydrogen, and storage technologies. A combination of techno-economic optimization, scenario analysis, and behavioural simulation was employed to ensure a comprehensive assessment of both operational and strategic implications.

The modelling framework is based on a bottom-up, technology-rich structure that represents electricity generation, transmission, storage, and end-use demand in the transport sector. The system is resolved at an hourly temporal scale and at the regional Nomenclature of Territorial Units for Statistics (NUTS2) spatial level to capture Italy's distinct renewable resource distribution and load characteristics. The model optimizes the dispatch and investment of generation and storage technologies under defined policy and carbon constraints, ensuring the least-cost configuration for each scenario while satisfying technical and environmental targets. The transport sector is explicitly modelled through three primary technology pathways: Battery Electric Vehicles (BEVs), hydrogen Fuel-Cell Electric Vehicles (FCEVs), and hybrid powertrains. Each technology is characterized by specific energy conversion efficiencies, cost parameters, infrastructure requirements, and operational constraints. Charging and refuelling behaviours are incorporated through time-dependent demand profiles derived from empirical mobility data and agent-based simulations.

Input data were drawn from multiple validated databases, including European Network of Transmission System Operators for Electricity (ENTSO-E) (electricity generation and demand) [39], Terna (Italian grid statistics) [40], and Eurostat (energy balances) [41]. Technology costs, efficiencies, and learning rates were obtained from the International Energy Agency [42] and the Joint Research Centre [43]. For hydrogen pathways, electrolysis and fuel-cell parameters were based on state-of-the-art projections, assuming a gradual reduction in capital costs and efficiency improvements toward 2030. Behavioural parameters for EV charging, including daily driving distances, time-of-use patterns, and adoption rates, were estimated using Italian mobility survey data and calibrated against current BEV market penetration trends. Regional renewable generation potentials for solar, wind, and hydro were derived from the National Integrated Energy and Climate Plan (PNIEC) and geospatial datasets, allowing consistent representation of spatial variability [44]. The optimization problem is formulated as a linear programming model that minimizes total system cost while ensuring energy balance, emission compliance, and operational feasibility across all hours and regions:

$$C_{\text{total}} = \Sigma_{\{t \in T\}} \Sigma_{\{i \in G\}\left(c_i^{inv} + c_i^{OM}\right)} \times P_{\{it\}} + \Sigma_{\{s \in S\}\left(c_s^{inv} + c_s^{OM}\right)} \times \left(P_{\{st\}}^{ch} + P_{\{st\}}^{\text{dis}}\right) + \Sigma_{\{f \in F\} c_f^{\text{fuel}} \times F_{\{ft\}}} + C_{\text{CO}_2} \times E_t \tag{1}$$

The total system cost C_{total} represents the sum of all relevant costs over the modeling horizon. The first term accounts for generation costs, including investment C_i^{inv} and operation & maintenance C_i^{OM} for each technology $i \in G$ at time t, multiplied by power output $P_{i,t}$. The second term captures storage-related costs, combining investment C_s^{inv} and O&M C_s^{OM} for each storage technology $s \in S$, multiplied by charging $P_{s,t}^{\text{ch}}$ and discharging $P_{s,t}^{\text{dis}}$ powers. The third term represents fuel costs C_f^{fuel} for all fuel-based technologies $f \in F$. Finally, the fourth term adds the cost of CO_2 emissions, using the emission price C_{CO_2} and total emissions E_t. Equation (1) is formulated based on a standard linear programming structure commonly adopted in energy system optimization models. The objective function minimizes the total system cost by aggregating generation, storage, fuel, and emission-related costs over the modelling horizon. While the mathematical structure follows established approaches in the literature, the novelty of this study lies in the integrated representation of electricity, hydrogen, and transport sectors at an hourly resolution, combined with behavioural modelling of electric vehicle charging and scenario-based analysis under Fit for 55 policy constraints.

Three primary scenarios were developed to explore the implications of different technological pathways:

BEV-Dominant Scenario—assumes accelerated electrification of passenger and light-duty transport, with managed charging and limited hydrogen use.

Hydrogen-Dominant Scenario—prioritizes renewable hydrogen production for heavy-duty and long-haul segments, with moderate BEV penetration.

Hybrid Scenario—combines BEV and hydrogen pathways under balanced deployment policies, representing a transitional or diversified strategy.

Each scenario was simulated under Fit for 55-aligned carbon constraints, ensuring consistency with Italy's 2030 emission reduction targets. Sensitivity analyses were conducted for technology costs, electricity prices, and behavioural parameters to quantify uncertainty in model outcomes. Monte Carlo simulations were applied to evaluate probabilistic variations in demand, renewable availability, and storage performance.

2.1 *Optimization and simulation approach*

The optimization component of the model minimizes total system cost, including capital investment, operation and maintenance, fuel, and carbon costs, subject to energy balance, capacity, and emission constraints. The formulation is linear, with endogenous decisions for technology dispatch, storage utilization, and energy imports or exports. The model was implemented in the Python-based PyPSA (Python for Power System Analysis) environment, extended to include hydrogen and transport modules. An agent-based sub-model simulates the charging behaviour of electric vehicle users, allowing the integration of stochastic daily travel patterns, charging preferences, and time-of-use tariffs. This behavioural layer feeds into the hourly demand profiles of the energy system model, enabling an endogenous representation of demand response. Lifecycle impacts were assessed by linking the system model to material and emission databases for battery production, second-life use, and recycling. The analysis accounts for embodied emissions in manufacturing, avoided impacts from second-life applications, and recovery efficiencies during recycling. This integration enables a combined evaluation of operational decarbonisation benefits and material circularity, consistent with EU sustainability principles.

Figure 2 illustrates the distribution of total energy demand for transport across three modeled scenarios, BEV-dominant, Hydrogen-dominant, and Hybrid, under the Fit for 55 framework. Electricity demand for direct vehicle charging, power used for hydrogen production via electrolysis, and residual fossil fuel use are shown in stacked form. The BEV-dominant pathway exhibits the highest electricity consumption (≈52 TWh) with minimal hydrogen contribution, whereas the Hydrogen-dominant case shifts a large share of energy input toward electrolysis (≈45 TWh). The Hybrid scenario demonstrates a balanced integration of electricity and hydrogen, aligning with diversified infrastructure development and moderate curtailment rates. Overall, the figure highlights the contrasting system load implications and energy vector dependencies associated with each transport decarbonisation pathway.

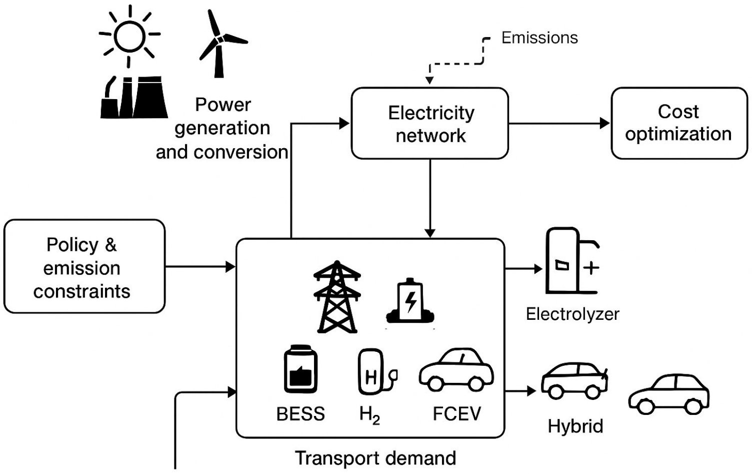

Figure 2. Schematic overview of the integrated multi-vector energy system model for Italian transport decarbonization

2.2 *Validation and verification*

Model validation was conducted by comparing simulation outputs with historical Italian data for the period 2022–2024, including electricity demand profiles, transport energy consumption, and generation mixes obtained from Terna and ISPRA. The model's accuracy in reproducing real system behaviour was evaluated using the Mean Absolute Percentage Error (MAPE), achieving values below 5% for annual energy balances and approximately 10% for hourly load variations. To further assess model robustness and account for uncertainty, a Monte Carlo simulation approach was implemented. Key uncertain parameters, including electricity prices, renewable generation availability, technology investment costs, and behavioural characteristics of electric vehicle charging, were defined using probabilistic distributions based on historical variability and literature data. Specifically, normal and triangular distributions were assigned depending on data availability and uncertainty ranges.

Model robustness was evaluated using both deterministic sensitivity analysis and stochastic Monte Carlo simulation. In the sensitivity analysis, key parameters, including technology investment costs, electricity prices, renewable generation capacity factors, and behavioural patterns of electric vehicle charging, were varied within ±20% of their baseline values to assess their impact on model outputs. In addition, a Monte Carlo simulation with 1,000 iterations was performed, where uncertain parameters were randomly sampled based on predefined probability distributions. The robustness of the model was assessed by analysing the variability of key outputs, including total system cost, peak load, and CO_2 emissions. Results indicate that variations remain within narrow bounds (±7% for system cost and ±5% for emissions), confirming the stability and reliability of the modelling framework under uncertainty.

3. Result and discussion

The modelling framework was applied to assess Italy's transition toward a climate-neutral transport system consistent with the EU 2030 and Fit for 55 objectives. Simulations covered three distinct technology pathways, Battery Electric Vehicle (BEV)-dominant, hydrogen-dominant, and hybrid configurations, each optimized under carbon cap, cost, and system operation constraints. The outcomes reveal the evolving role of energy carriers, infrastructure needs, and system costs across these scenarios. The baseline simulation, calibrated to 2024 national data, replicates observed electricity demand, renewable generation shares, and mobility-related emissions with high accuracy, providing a reliable benchmark for forward projections. Under the BEV-dominant configuration, electricity demand for transport reaches approximately 52 TWh by 2030, representing about 16%–18% of total final electricity consumption. This growth primarily occurs during evening hours, driven by residential charging patterns, and results in increased system peak load by 7%–9% compared with the baseline. The inclusion of smart charging and limited Vehicle-to-Grid (V2G) participation mitigates this peak effect by roughly 30%, indicating that controlled charging strategies are essential to prevent local grid congestion.

The hydrogen-dominant scenario, characterized by large-scale electrolyzer deployment and extensive fuel-cell vehicle adoption in heavy-duty and long-haul transport, exhibits lower electricity peak sensitivity but higher total system energy consumption due to conversion inefficiencies. Hydrogen production reaches 420–460 kt per year, with about two-thirds produced from dedicated renewable electricity. While this pathway achieves a 72% reduction in transport-related CO_2 emissions, its system cost per avoided tonne of CO_2 is 18%–22% higher than in the BEV-dominant case, largely due to the capital intensity of electrolyzers and hydrogen distribution infrastructure. A more balanced outcome is observed in the hybrid scenario, where BEVs dominate urban and short-distance travel while hydrogen supports long-distance and freight segments. This configuration delivers the most cost-effective and resilient pathway, combining operational flexibility with moderate infrastructure investment. Total system emissions decline by nearly 80% relative to 2020 levels, aligning closely with Fit for 55 requirements, while total system costs increase by only 12% compared with the least-cost BEV scenario. The hybrid system also demonstrates the lowest curtailment rate of renewable generation (reduced from 8.3% in the BEV-dominant case to 4.5%) owing to flexible hydrogen production and energy storage that absorb surplus renewable energy during off-peak hours.

Energy storage emerges as a pivotal enabler in all decarbonisation pathways. In the BEV-dominant scenario, grid-scale Battery Energy Storage Systems (BESS) contribute around 7.5 GW of installed capacity by 2030, providing daily balancing and peak shaving functions. Hydrogen storage complements this flexibility on seasonal timescales, particularly in the hybrid scenario, where combined storage capacity reaches 35 TWh of energy equivalent. The integration of V2G capabilities, even at modest participation levels (10%–15% of BEVs), significantly enhances grid stability and reduces curtailment, demonstrating the systemic value of distributed storage embedded within the vehicle fleet. Cost decomposition indicates that investment expenditures constitute approximately 55%–60% of total system costs by 2030, with grid reinforcement and storage expansion accounting for a substantial share. The marginal system cost of electricity rises from 84 €/MWh in 2024 to around 105 €/MWh in the BEV-dominant case and 118 €/MWh in the hydrogen pathway, reflecting the cost of integrating variable renewables and additional conversion technologies.

The Levelized Cost of Mobility (LCOM), expressed per kilometer of transport energy service, remains lowest in the BEV-dominant pathway (0.13 €/km) compared with hydrogen (0.16 €/km) and hybrid configurations (0.14 €/km), though the latter offers greater system resilience. From an environmental perspective, the lifecycle analysis highlights notable differences in material and emission implications across pathways. BEV-oriented systems show higher short-term demand for critical minerals, particularly lithium, nickel, and cobalt, linked to battery manufacturing, whereas hydrogen-dominant systems require greater steel and composite materials for storage and distribution infrastructure. When second-life and recycling processes are incorporated, the cumulative CO_2-equivalent savings from battery reuse and recovery amount to nearly 8 Mt over 2030–2040, offsetting approximately 9% of total lifecycle emissions from the BEV fleet. In hydrogen scenarios, the adoption of renewable electrolysis significantly reduces indirect emissions, but embodied emissions in electrolyzer and tank production remain non-negligible.

Figure 3 compares three decarbonization pathways for Italy's transport sector by 2030, BEV-dominant, hydrogen-dominant, and hybrid configurations, evaluated under the EU 2030 and Fit for 55 climate objectives. Panel (A) shows that electricity demand for transport rises sharply under the BEV scenario, reaching about 52 TWh by 2030, while smart charging and Vehicle-to-Grid (V2G) participation mitigate peak load growth. Panel (B) illustrates the peak load increase relative to the baseline, with the BEV pathway showing the highest sensitivity (7%–9%), followed by the hybrid and hydrogen cases. Panel (C) presents CO_2 emission reductions, indicating that the hybrid configuration achieves the deepest cuts (≈80%) due to balanced electrification and hydrogen use. Panel (D) shows the system cost per avoided tonne of CO_2, where the hydrogen pathway is 18%–22% costlier than the BEV-dominant case because of electrolyzer and infrastructure expenses. Panel (E) highlights the deployment of energy storage, with up to 7.5 GW of grid-scale batteries in the BEV scenario and substantial hydrogen storage (≈35 TWh eq.) in the hybrid configuration, ensuring seasonal flexibility. Finally, panel (F) indicates renewable generation curtailment, which falls from 8.3% in the BEV case to 4.5% in the hybrid pathway, demonstrating the system efficiency benefits of integrated storage and hydrogen production.

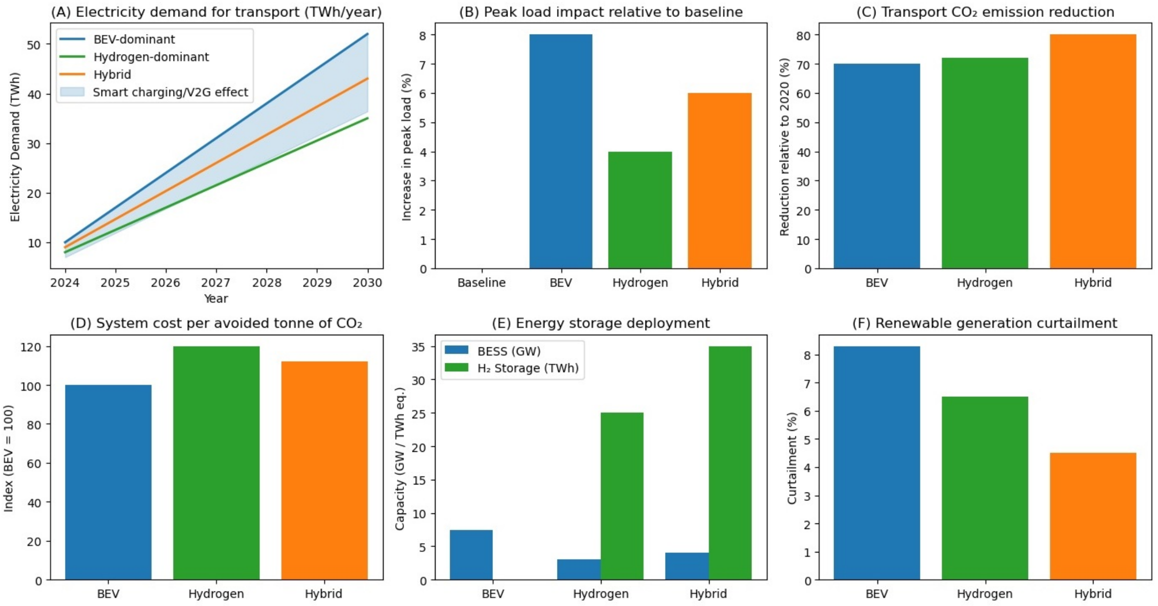

Figure 3. Italy's transport decarbonization pathways to 2030

Uncertainty analysis was performed using a Monte Carlo simulation approach to evaluate the sensitivity of model outputs to variations in key input parameters. Specifically, technology investment costs, electricity prices, renewable generation capacity factors, and behavioural parameters related to electric vehicle charging were treated as uncertain variables and assigned probability distributions based on historical data and literature ranges. A total of 1,000 simulation runs were conducted, with parameters randomly sampled in each iteration. For each run, the optimization model was solved, generating distributions of key outputs, including total system cost, peak load, and CO_2 emissions. The results were analysed using statistical measures such as mean values, standard deviation, and confidence intervals. The analysis shows that system cost variability remains within ±12% across scenarios. The BEV-dominant pathway is more sensitive to charging behaviour and electricity price fluctuations, while the hydrogen-dominant scenario is primarily influenced by electrolyzer costs and renewable capacity factors. The hybrid pathway exhibits the lowest variability, confirming its robustness as a transitional configuration.

Table 1 summarizes the system performance, greenhouse gas emissions, and costs compared to three comparable systems.

Table 1. Summary of system performance, emissions, and costs

Scenario	Total system cost [B€]	CO_2 emissions 2030 [Mt]	Renewable curtailment [%]	Peak load [GW]	Electricity for transport [TWh]	Hydrogen production [kt/year]	Storage capacity [GWh_e]	LCOM [€/km]
BEV-dominant	144.3	21.5	8.3	69.5	52.1	0	7,500	0.13
Hydrogen-dominant	168.2	19.7	6.0	65.2	38.4	460	8,500	0.16
Hybrid	156.0	17.8	4.5	67.1	46.2	270	8,300	0.14

The overall findings underscore the need for coordinated infrastructure development between the electricity and hydrogen sectors. Electrification alone, though cost-efficient, may challenge grid reliability without extensive demand-side management and storage deployment. Conversely, large-scale hydrogen integration, while beneficial for long-distance mobility and industrial synergies, entails higher infrastructure costs and energy conversion losses. Therefore, a combined approach, anchored in renewable expansion, smart charging, flexible hydrogen production, and circular resource management, emerges as the most effective strategy for aligning Italian transport decarbonisation with EU climate neutrality objectives.

Therefore, according to the results of the decreasing trend of carbon dioxide production presented in Figure 4, a combined approach, based on the expansion of renewable energies, smart charging, flexible hydrogen production and circular resource management, emerges as the most effective strategy to align the decarbonization of Italian transport with the EU climate neutrality objectives.

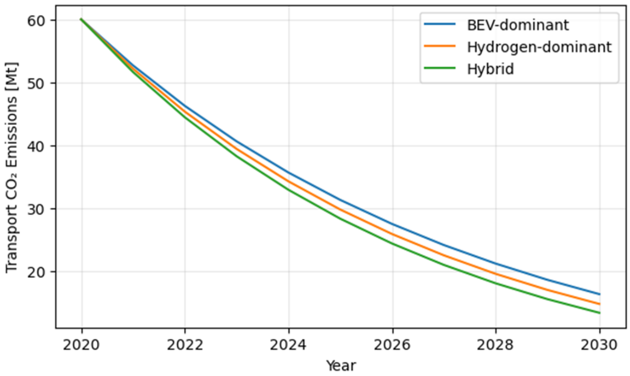

Figure 4. Projected emission reduction pathways (2020-2030)

Beyond the technical and economic results, the study illustrates the broader policy implications of system-level coupling. Integrated modelling reveals that transport electrification policies must be synchronized with power sector planning to avoid cross-sectoral bottlenecks. Policy mechanisms such as dynamic electricity tariffs, incentives for second-life battery applications, and support for hydrogen clusters in freight corridors can accelerate the transition while preserving system stability. In this context, the methodological integration of high-resolution temporal modelling, agent-based demand representation, and circular economy assessment provides a solid analytical foundation for strategic planning and investment prioritization.

4. Limitations

Despite the comprehensive modelling framework developed in this study, several limitations should be acknowledged. First, the analysis relies on assumptions regarding future technology costs, efficiency improvements, and policy developments, which are inherently uncertain and may influence long-term projections. Second, while the model incorporates hourly temporal resolution, spatial granularity is limited to aggregated regional representations, potentially overlooking localized grid constraints and infrastructure bottlenecks. Third, behavioural modelling of electric vehicle charging is based on available survey data and may not fully capture future user adaptation under evolving market conditions. Fourth, hydrogen system modelling assumes predefined efficiency and cost trajectories, without explicitly considering supply chain constraints or large-scale infrastructure deployment challenges. Finally, although uncertainty analysis and Monte Carlo simulations were conducted, the results remain sensitive to the selection of input distributions and scenario assumptions. Future research should address these limitations by incorporating higher spatial resolution, real-time behavioural data, and more detailed representation of emerging technologies and market dynamics. Limitations of this work are summarized:

- The model relies on assumptions regarding future technology costs, efficiencies, and policy developments, which introduce uncertainty into long-term projections.

- Spatial resolution is limited to aggregated regions, potentially overlooking local grid constraints and infrastructure bottlenecks.
- Behavioural modelling of electric vehicle charging is based on current data and may not fully capture future user adaptation and market dynamics.

5. Conclusion

This study developed an integrated, hourly-resolved, multi-vector energy system model to evaluate pathways for aligning Italy's transport sector with the European Union's 2030 and Fit for 55 targets. The results demonstrate that the choice of mobility pathway significantly affects energy demand, system costs, grid flexibility, and emissions. The BEV-dominant scenario requires substantial electricity demand and leads to higher peak loads, despite delivering rapid decarbonisation benefits.

The Hydrogen-dominant scenario offers advantages for long-distance and heavy-duty transport but is associated with higher system costs and efficiency losses, highlighting the importance of technological improvements in electrolysis and access to low-cost renewable energy. The Hybrid scenario provides the most balanced solution, combining electricity and hydrogen to achieve lower emissions, moderate system costs, and improved system flexibility.

From a system-wide perspective, achieving climate-neutral transport requires coordinated integration of electrification, renewable energy expansion, and energy storage solutions, including battery and hydrogen storage. Circular economy strategies, such as battery recycling and second-life applications, play a crucial role in enhancing resource efficiency and reducing lifecycle environmental impacts.

Policy measures should focus on enabling flexible charging infrastructure, supporting low-carbon hydrogen deployment, and ensuring alignment between energy and transport planning. Overall, the findings indicate that a coordinated and multi-vector approach is essential to achieve deep decarbonisation while maintaining energy security, affordability, and industrial competitiveness in Italy.

Conflicts of interest

The authors declare no conflicts of interest.

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