A Stochastic Assessment of Hydrogen's Potential in Decarbonizing Road Transport

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SHORT SUMMARY

The decarbonisation of long-distance freight transport represents a considerable challenge, particularly in those transnational corridors characterised by high levels of road traffic. In this context, hydrogen-powered heavy-duty vehicles are increasingly regarded as a potential solution to this challenge. However, this is contingent upon the availability of hydrogen production pathways. This study uses a stochastic modelling approach to evaluate the deployment of hydrogen for freight corridors in uncertain conditions and its associated decarbonisation potential. The approach combines freight activity data at the corridor level with technology penetration and emission factor data in a Monte Carlo simulation model. The approach is employed to model the Brenner corridor, a significant freight corridor in Europe. The results indicate that emission reductions are contingent on hydrogen production pathways, varying from 13.5% to 20.5%, with the most likely value at 17%. The findings highlight the importance of explicitly accounting for uncertainty when evaluating hydrogen-based decarbonisation strategies.

Keywords: Freight transport; Hydrogen mobility; Monte Carlo simulation; Stochastic modelling; Transport decarbonization.

1. INTRODUCTION

The decarbonisation of freight transport has become a key component of European climate policy, with heavy-duty vehicles (HDVs) contributing substantially to greenhouse gas (GHG) emissions in the transport sector (IEA, 2023; ITF, 2021). Despite the advances in vehicle efficiency and electrification that have resulted in a reduction in GHG emissions, the long-distance freight transport sector is regarded as one of the most challenging to decarbonise (McKinnon, 2018).
Among the technological options being considered, hydrogen fuel cell mobility has been identified as a key solution to the problem of GHG emissions in the transport sector. Hydrogen fuel cell vehicles are considered suitable for long-distance freight transport due to their high energy density and short refuelling times (Staffell et al., 2019; IEA, 2022). The environmental impacts of hydrogen fuel cell vehicles are contingent on the production pathway. It has been posited that the production of fossil fuels exerts a substantial environmental impact, whilst the production of hydrogen from renewable sources has been demonstrated to engender a substantial reduction in environmental impacts (Bicer and Dincer, 2018).
The production of hydrogen can be undertaken in several different ways and consequently result in a range of differing environmental impacts. The key hydrogen production routes under consideration in this study are outlined in Table 1.

Table 1: Main hydrogen production pathways and environmental characteristics

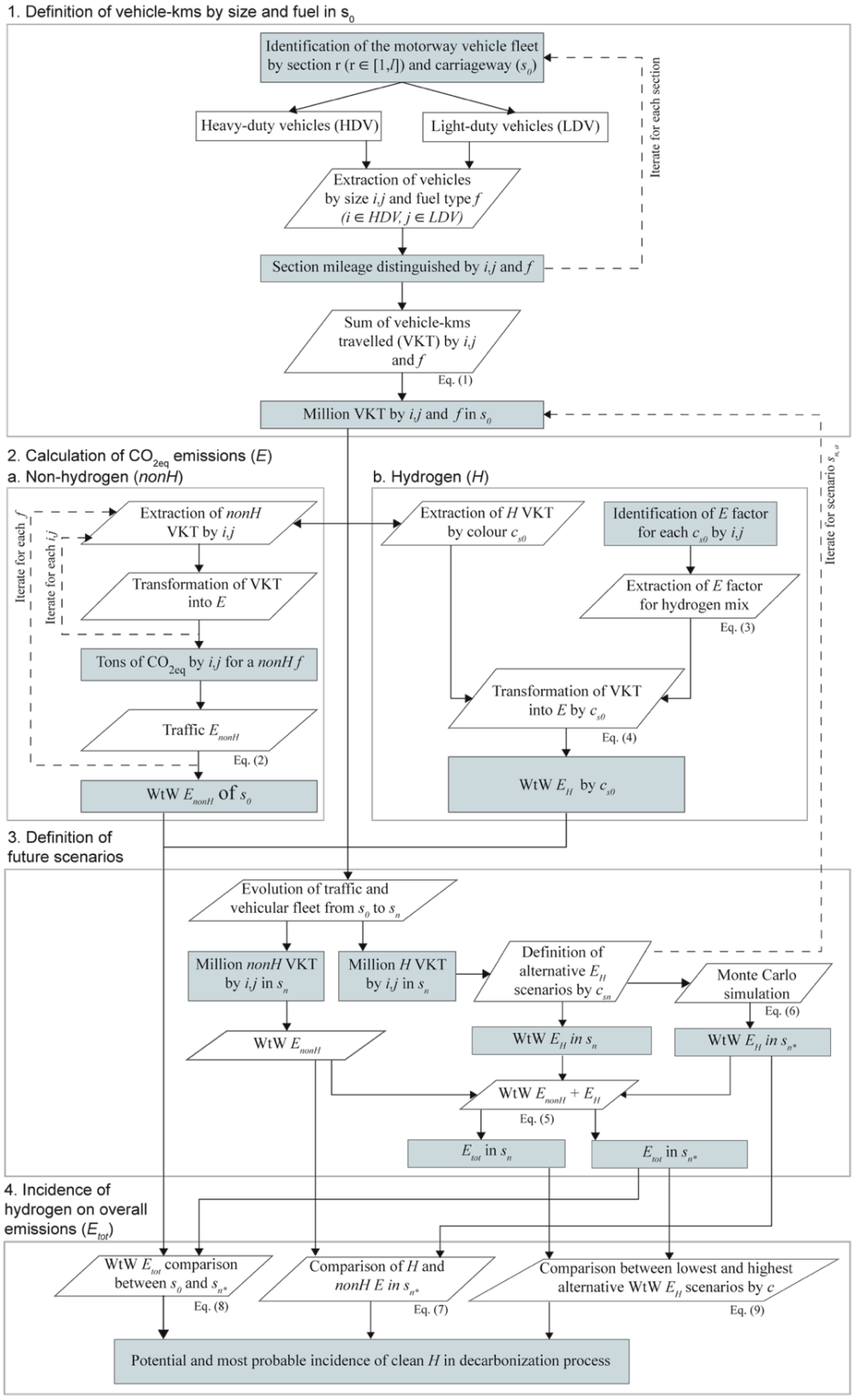
Hydrogen	Production process	Main energy source	Emission profile
Grey	Steam methane reforming (SMR)	Natural gas	High emissions
Blue	SMR with carbon capture and storage (CCS)	Natural gas + CCS	Medium emissions
Green	Electrolysis	Renewable electricity	Low emissions

The mobility of hydrogen has been extensively examined by lifecycle assessment methods, which have emphasised the role of upstream energy systems in determining overall emission results (Staffell et al., 2019). Concurrently, studies on transport modelling have increasingly focused on the transition towards alternative propulsion technologies by employing scenario-based methods and integrated modelling approaches (Creutzig et al., 2015).
However, extant studies have predominantly relied on deterministic assumptions regarding hydrogen production mixes and technology deployment rates. The deterministic methods may not fully capture the overall uncertainty surrounding future energy transitions. Indeed, the generation of hydrogen is subject to several uncertain factors, including fluctuations in energy prices, advancements in technology, support policies, and the availability of necessary infrastructures. Consequently, there is a necessity to employ modelling methodologies that can encapsulate the comprehensive uncertainty surrounding hydrogen-based transport strategies. The employment of stochastic modelling methods has been demonstrated as a valid option to address this issue. Stochastic models have the capacity to address a variety of scenarios by incorporating uncertain variables. Monte Carlo simulation methods are available to generate probability distributions of overall system results under uncertain conditions.
The contribution of the paper can be identified as follows: Firstly, it introduces a stochastic approach for evaluating hydrogen adoption in freight transport corridors under uncertainty. Secondly, it combines freight activity data at the corridor level with probabilistic hydrogen supply system representations. Thirdly, the programme provides a modelling tool that can be readily updated as new information becomes available. The proposed framework has been applied to the Brenner freight transport corridor, which connects Kufstein and Verona and is one of the most critical freight transport corridors in the Scandinavian-Mediterranean TEN-T.

2. METHODOLOGY

The proposed methodology aims to estimate the environmental impacts of hydrogen uptake in freight transport corridors, explicitly addressing the issue of uncertainty in the supply system of hydrogen. The model is designed to estimate emissions in corridors under various technology configurations, without addressing network or routing aspects. To be more precise, it calculates the effects of exchanging a specific percentage of diesel-powered HDVs with hydrogen-powered trucks on overall well-to-wheel (WtW) emissions, given that the carbon footprint of hydrogen is contingent on its production mix.
As illustrated in Figure 1, the methodological framework employed in this study is based on a WtW analysis, i.e., it will consider both upstream emissions related to the production and distribution of the energy carrier and downstream emissions related to the use of the energy carrier.
This analysis will be of particular interest with respect to hydrogen, since the overall environmental impact of this energy carrier is contingent on the production process as opposed to the utilisation of the energy carrier itself.

Figure 1: Overall methodological framework adopted for the assessment of hydrogen-related emissions along the Brenner corridor.



Three distinct hydrogen production processes are considered in this study: grey hydrogen, blue hydrogen and green hydrogen, which represent the hydrogen pathways most discussed in the scientific literature (Ajanovic and Haas, 2022).
At the corridor level, total emissions are modelled as the sum of freight activity by vehicle type and the corresponding technology-specific emission factors. Freight activity is treated as exogenous and expressed in aggregate annual form for the specified corridor. The total annual emissions are defined as:

$$E = \sum_{v} A_v \cdot EF_v \tag{1}$$

where the total annual emissions are denoted by E, the freight activity related to vehicle type v is denoted by A_v, and the related WtW emission factor for v is denoted by EF_v.
In the model outlined above, the fleet comprises two propulsion technologies: diesel and hydrogen. Accordingly, the set of vehicle types is restricted to $v \in \{diesel, H_2\}$.
Under this assumption, the general term EF_v can take only two values, namely EF_{diesel} and EF_{H_2}, and the corresponding aggregate emission factor of the fleet, here denoted by EF_{tot}, is obtained as the weighted average of these two technology-specific emission factors.
The transition from diesel to hydrogen is represented through a penetration parameter α, expressed as the percentage of freight activity carried out using hydrogen-fuelled vehicles. The residual percentage is constituted by diesel vehicles. The average emission factor of the fleet is expressed as:

$$EF_{tot} = (1 - \alpha) \cdot EF_{diesel} + \alpha \cdot EF_{H2} \tag{2}$$

EF_{diesel} denotes the emission factor of conventional diesel vehicles, whilst EF_{H2} signifies the aggregated emission factor of hydrogen-powered vehicles. The penetration rate α is scenario-dependent and fixed within each scenario.
The same total emissions can therefore also be expressed in aggregate form as:

$$E = A \cdot EF_{tot} \tag{3}$$

where A denotes total annual freight activity along the specified corridor.
The emission factor of hydrogen is defined as a weighted average of the emission factors associated with the different production pathways:

$$EF_{H2} = \sum_{k=1}^{K} p_k \cdot EF_k \tag{4}$$

where EF_k represents the emission factor of hydrogen pathway k, and p_k is its share in the hydrogen supply mix. The pathway shares satisfy the constraint:

$$\sum_{k=1}^{K} p_k = 1 \tag{5}$$

This enables the modelling of hydrogen as a heterogeneous energy carrier, with a carbon intensity determined by the share of grey, blue, and green hydrogen.
The pivotal methodological characteristic of the model pertains to the utilisation of stochastic modelling techniques in the representation of the hydrogen supply mix. The shares p_k are

modelled as random variables rather than parameters. In each Monte Carlo iteration, indexed by *s*, the shares of the pathways are sampled from bounded probability distributions:

$$p_k^{(s)} \sim f_k(p) \tag{6}$$

subject to the normalization constraint:

$$\sum_{k=1}^{K} p_k^{(s)} = 1 \tag{7}$$

The probability distributions have been specified to represent reasonable ranges for hydrogen production shares for a 2040 timeframe, based on extant literature. This method enables the model to address the inherent uncertainty of future hydrogen supply systems without specifying a single deterministic case.

The calculation of total emissions for each iteration of the simulation is achieved by utilising the shares of the hydrogen production pathway to determine the hydrogen emission factor, $EF_{H2}^{(s)}$. This factor is then multiplied by the penetration parameter to ascertain total emissions. In summary, the following equation can be used to express the emissions for iteration *s*:

$$E^{(s)} = A \cdot \left[(1-\alpha) \cdot EF_{diesel} + \alpha \cdot EF_{H2}^{(s)}\right] \tag{8}$$

where *A* is used to denote the total annual freight activity that occurs along the specified corridor. The simulation is run iteratively 10,000 times to guarantee the statistical stability of the results obtained. The model makes a clear distinction between fixed and stochastic parameters. In each of the scenarios under consideration, the parameters of freight activity *A*, the diesel emission factor EF_{diesel}, and the hydrogen penetration rate α are constant. Conversely, the hydrogen supply mix, denoted by pathway shares $p_k^{(s)}$, is subject to variation within the simulation. This enables the model to isolate the impact of the uncertainty in hydrogen production systems on total emissions.

The simulation's outcome is a probability distribution of emission outcomes. It is possible to derive a series of summary statistics from the probability distribution, including the expected value and the standard deviation:

$$\mu_E = \frac{1}{S}\sum_{s=1}^{S} E^{(s)} \tag{9}$$

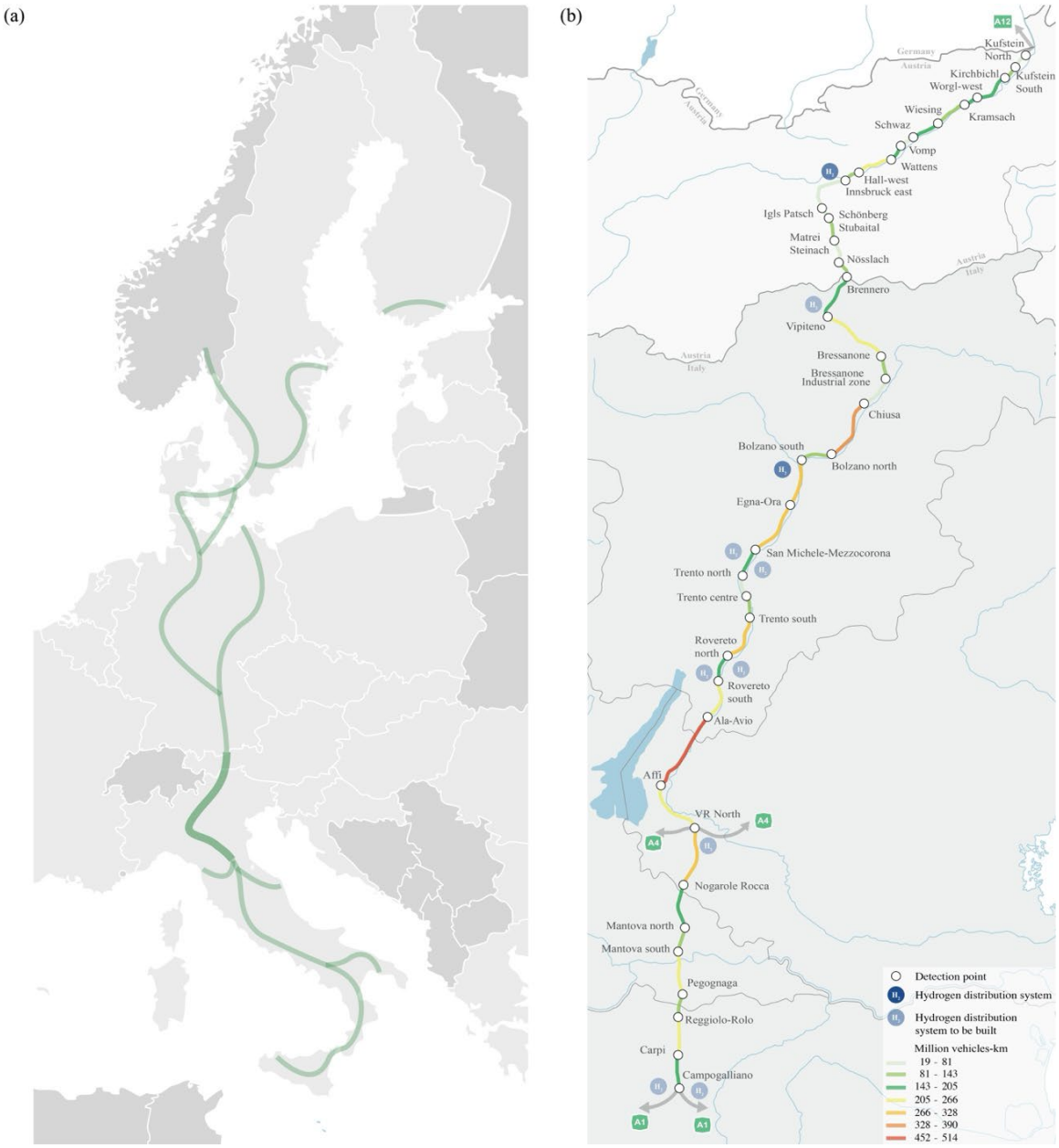
$$\sigma_E = \sqrt{\frac{1}{S-1}\sum_{s=1}^{S}\left(E^{(s)} - \mu_E\right)^2} \tag{10}$$

Where *S* denotes the total number of simulation iterations. Furthermore, percentile values are utilised to represent the distribution of results, thereby enabling the determination of best-case and worst-case scenarios. The methodology's greatest strength may be that it offers considerable flexibility. This is attributable to the fact that the configuration of the model can be adapted to incorporate updated freight traffic data, updated emission factors, and alternative assumptions regarding hydrogen production pathways. This renders the methodology ideal for iterative updates as more data becomes available.

3. CASE STUDY: BRENNER CORRIDOR

The proposed modelling framework is applied to the Brenner corridor, which connects Kufstein in Austria to Verona in Italy (Figure 2b). The subject corridor is included in the Scandinavian-Mediterranean TEN-T corridor network (Figure 2a).

Figure 2: (a) Map of the Brenner section; (b) Map of the Italian and Austrian Brenner corridor's sections and their relative traffic flows.



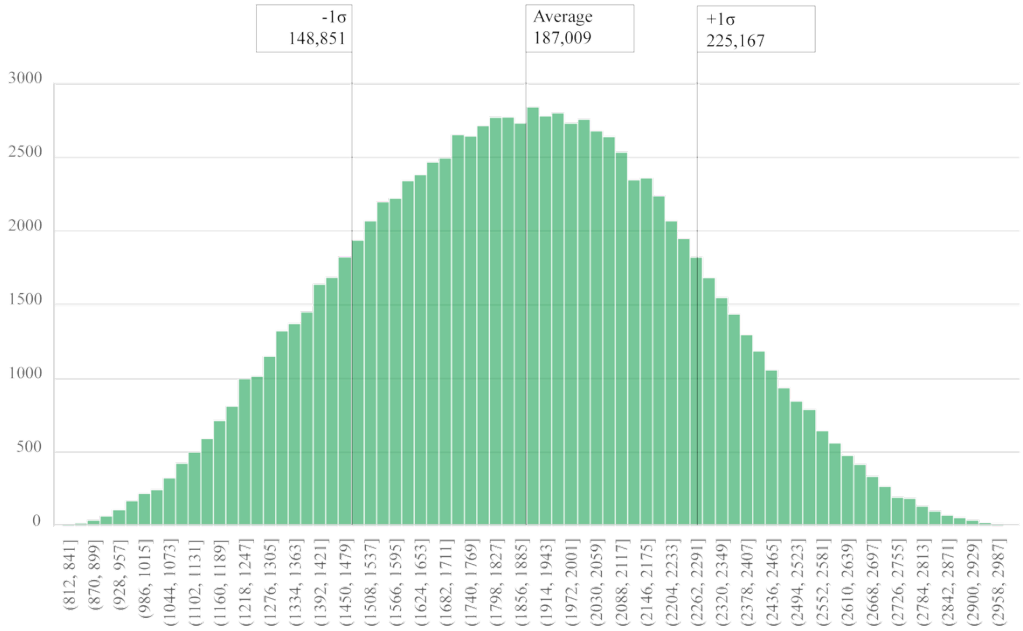
The freight transport on the Brenner axis is characterised by high traffic volumes and a strong dominance of road freight transport. Recent monitoring results indicate that road freight transport continues to account for a significant proportion of the total trans-Alpine freight traffic. This has

been identified as a significant contributing factor to the environmental pressures experienced in the Alpine regions (iMONITRAF!, 2024).
In the present application, the freight transport activity on the corridor is assumed to be exogenous and is given in aggregate annual form. The baseline data set reflects the most recent statistics on freight transport volumes and vehicle composition along the specified corridor.
The transition to hydrogen-fueled freight transportation is represented through alternative penetration rates for hydrogen vehicles by 2040, consistent with European decarbonization objectives.
In the Brenner application, uncertainty does not concern freight demand, which is treated as exogenous, but the future composition of the hydrogen supply mix, whose carbon intensity may vary depending on the relative shares of grey, blue, and green hydrogen.

4. RESULTS AND DISCUSSION

The Monte Carlo simulation generates a probability distribution of emission outcomes associated with hydrogen adoption in the corridor. As opposed to yielding a solitary point estimate, the model engenders a spectrum of emissions values, a consequence of the indeterminacies inherent in the hydrogen production pathways. The central tendency of the results is represented by the expected value of the emissions, as indicated by Equation (9).

Figure 3: Histogram of Monte Carlo simulation outcomes in tons of CO_{2eq}.



The variability in the results is represented by the standard deviation and percentiles. In absolute terms, the Monte Carlo simulation yields an average total emissions figure of approximately 1,714,075 tCO_{2eq} for the hydrogen adoption scenario, compared to around 2,060,000 tCO_{2eq} for the baseline scenario. This implies an expected reduction in WtW emissions of around 17%. As can be seen in Figure 3, most of the results are centred around this point. Extreme values are uncommon.
The results also indicate variability in the hydrogen-related emissions component. The average WtW emissions for hydrogen are around 187,009 tCO_{2eq}. The results suggest that the composition of the hydrogen mix will vary. Scenarios with a higher proportion of green hydrogen have lower

emissions and therefore greater potential for reduction. Conversely, those with a higher proportion of grey hydrogen have higher emissions and therefore lower reduction potential.
The results of the study highlight the necessity of explicitly considering the issue of uncertainty when evaluating hydrogen-based decarbonization strategies. Despite the considerable potential of hydrogen technologies in reducing GHG emissions, their environmental performance is influenced by a multitude of factors external to the freight transport system, particularly those associated with hydrogen production pathways. The analysis has demonstrated that hydrogen adoption itself does not guarantee emission reduction. Conversely, the environmental performance of hydrogen freight transportation is found to be closely associated with upstream energy conditions.
The stochastic modelling approach that has been proposed in this study allows for a more complete representation of these issues compared to a deterministic approach. From a methodological perspective, the findings of this study demonstrate that uncertainty surrounding hydrogen supply systems is directly correlated with variability in emissions. This finding is significant, as it demonstrates that a deterministic approach may be misleading.
In terms of policy implications, the study's findings indicate that the introduction of hydrogen vehicles should be complemented by policies that promote low-carbon hydrogen production. The findings of this study demonstrate the necessity of incorporating both freight transport systems and energy systems in the evaluation of decarbonization strategies.

6. CONCLUSIONS: LIMITATIONS AND FUTURE RESEARCH

In this paper, a stochastic modelling framework is presented for the evaluation of the environmental impacts of hydrogen adoption in freight transport corridors under uncertainty.
The findings of the paper indicate that hydrogen can play a role in reducing emissions; however, the degree of these reductions is heavily dependent upon the hydrogen production pathways, varying from 13.5% to 20.5%, with the most likely value at 17%. The proposed framework is more robust for evaluating alternative fuels to hydrogen through the explicit modelling of uncertainties. The methodology is characterised by its adaptability, allowing for the incorporation of additional information as it becomes available. This quality is particularly advantageous in the dynamic and constantly evolving domain of transport technologies. Furthermore, while the Brenner corridor has served as the empirical case study in this research, the proposed methodology may be extended to other freight transport corridors.
Notwithstanding the methodological advancements introduced by the model, the proposed framework also has some limitations that should be considered. Firstly, the model exclusively considers environmental performance, neglecting to incorporate economic factors such as investment costs, fuel prices, and infrastructure. Consequently, subsequent research endeavours should incorporate cost modelling within the stochastic framework. Secondly, the model's representation of hydrogen production is overly simplistic. Despite the model's capacity to differentiate between grey, blue, and green hydrogen, it remains incapable of accounting for the influence of regional disparities in the energy system, variations in the electricity mix across different regions, and the prospect of future enhancements. Thirdly, the model employs exogenous inputs to represent the penetration rate of different technologies. Consequently, future research should extend the framework to represent endogenous adoption modelling. Finally, the analysis considers only one corridor. However, the structure of the framework could be readily updated by considering updated traffic data, emission factors and hydrogen scenarios. Consequently, it can be posited that future research endeavours should concentrate on formulating an integrated stochastic analysis of transport modelling, energy system analysis, and economic evaluation.

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