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Global hydrogen trade pathways: A review of modelling advances and challenges

Jana Fakhreddine [a,*], Paul E. Dodds [a,b], Isabela Butnar [a]

[a] Institute for Sustainable Resources, University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK
[b] Energy Institute, University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK

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ABSTRACT

Trade of hydrogen, as an energy commodity, would enable its widespread use in global energy systems. Hydrogen, unlike electricity, could be traded globally in its pure form or as a derivative compound (e.g. ammonia).

The development and potential size of global hydrogen trade remains uncertain due to technological, economic, infrastructural, and political complexities. We critically review how hydrogen trade models represent: (i) hydrogen supply and demand; (ii) derivatives supply and demand; (iii) hydrogen and derivative trade; and (iv) policy aspects affecting hydrogen scale-up.

While energy system models have the most detailed representation of hydrogen production and end-use demands, supply chain and techno-economic models have more detailed representations of trade supply chains of hydrogen and hydrogen derivatives. The implications of hydrogen policies have received limited consideration across all three model paradigms. Consequently, none of these approaches is yet to successfully and comprehensively represent the complexity of hydrogen and derivative trade systems.

1. Introduction

1.1. Background

As the world faces the pressing decarbonisation challenge and the cost of renewable energy generation continues to decline, the energy supply landscape is set to transform. Renewable energy sources such as solar, wind, and marine energy are poised to become the dominant energy sources of the future. Renewable energy generation capacity is expected to grow by 2.7 times between 2022 and 2030, while prices have been dropping sharply over the past years [1]. However, renewable energy production is intermittent and variable in nature and expensive to move over long distances due to high infrastructure costs and transmission losses [2,3]. Consequently, flexible and robust energy storage techniques will be crucial to ensure global energy supply resilience, security and accessibility.

Chemical energy storage through compounds such as hydrogen and its derivatives offer an attractive solution that provides both temporal and spatial flexibility to the energy system. They can be produced cheaply in regions with high solar and wind potential and traded to other regions where renewable energy sources are limited or less cost-efficient. The ability to store them for longer periods of time also provides a form of seasonal energy storage that can be used in seasons when renewable energy resources are diminished [4].

Long-distance trade of renewable energy carriers is expected to grow with the projected decrease in the global trade of fossil-fuel based energy vectors. This is enabled by four main drivers: (i) the emergence of new technologies for the production and transport of renewable energy, (ii) the regional difference in technical viability and social acceptance of energy production, (iii) the decreasing costs of renewable energy generation, and (iv) the opportunity of reusing fossil fuel infrastructure for renewable energy trade and reducing the risk of stranded assets [5,6]. However, the probability and form of development of a global hydrogen trade market is still uncertain [7].

Hydrogen is produced as a gas and can be transported in liquid or gas form using a range of methods (ships, trucks, rail, and pipelines) at both local and global scales. It can also be converted into other compounds such as ammonia, methanol, and liquid organic hydrogen carriers (LOHCs) which can be used to move the hydrogen between supply and demand centres. The advantage of such derivative hydrogen compounds is that their transport is generally easier, less energy intensive, and safer due to their higher densities and boiling points compared to hydrogen [8–11]. Some of those compounds also have their own independent end

* Corresponding author.
E-mail address: jana.fakhreddine.22@ucl.ac.uk (J. Fakhreddine).

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Abbreviations

BOG	Boil-off Gas
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
DACC	Direct Air Carbon Capture
DBT/PDBT	Dibenzyltoluene/Perhydro-dibenzyltoluene
DME	Dimethyl Ether
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOH	Levelised Cost of Hydrogen
LOHC	Liquid Organic Hydrogen Carrier
LNG	Liquified Natural Gas
MCH/TOL	Methylcyclohexane/Toluene
PV	Photovoltaic

use applications that can both complement and compete with hydrogen uses, adding to the complexity of hydrogen trade markets.

1.2. Current developments

Hydrogen trade prospects are currently witnessing increased national and regional interest. A growing number of governments – 58 as of May 2024 – have adopted national hydrogen strategies or roadmaps for hydrogen deployment [12]. Such plans focus on outlining low-carbon hydrogen production and end-use targets, and positioning the countries in terms of future trade status (importer vs. exporter) [12,13]. An increasing number of low-carbon hydrogen trade agreements has been announced starting in 2018 outlining pilot projects or studies for hydrogen trade between countries [7,14].

Based on announced export-oriented projects, 16 Mt of low-emission hydrogen could be exported around the world by 2030 and 25 Mt by 2040, with around 80 % of those projects planning to export the hydrogen in ammonia form [15]. Announced projects indicate that potential hydrogen exporters could be in areas such as Australia, the Middle East, the United States, and Southern America, while importers are likely to be concentrated in Europe and Asia. It is important to note that the majority of these projects are still at early stages of development, and only around 30 % have already identified potential off-takers [15].

The potential geopolitical implications of a new hydrogen energy commodity market have also fuelled interest in this topic. Some sources argue that hydrogen can help democratise the energy system because unlike fossil fuels, it can theoretically be produced anywhere with access to water and an electricity source [14,16]. Others argue that global variations in hydrogen production costs and constraints around water, land, and infrastructure availability will incentivise hydrogen trade over expensive domestic supply [17]. National and regional decisions and policy developments around hydrogen trade ambitions are in turn expected to impact the scale and shape of the future hydrogen trade market and alter the global geopolitical energy landscape as countries develop into exporting, importing, or self-sufficient users of hydrogen [14,18].

With the emerging interest and activity around hydrogen trade and the uncertainty surrounding its development [7], modelling can be a useful tool to help understand and unravel such complexities. Several modelling tools are already being developed to explore hydrogen trade development prospects. Such tools help identify and evaluate the potential medium- and long-term energy system implications of an emerging global hydrogen trade market.

1.3. Contribution and organisation of this paper

Hydrogen systems have recently been the subject of extensive reviews looking at various aspects of hydrogen technologies and economics. Some studies have focused on reviewing hydrogen production technology options [19–22]. Others have reviewed the possible end use applications of hydrogen [21,23–26]. Several modelling-focused review studies have also been published. For instance, Blanco et al. [27] proposed a taxonomy of models that investigate hydrogen energy systems, Zhang et al. [28] focused on the integration of hydrogen into energy systems, Hanley et al. [24] reviewed the role of hydrogen as projected by integrated energy system modelling scenarios, while Agnolucci and McDowall [29], and Riera et al. [30] reviewed available hydrogen supply chain modelling and optimisation studies. A few studies have also focused on ammonia, reviewing its potential role as an energy vector [31] and particularly as a shipping fuel [32,33] and for energy storage [34].

A few other studies have also explored challenges and opportunities of hydrogen port infrastructure development and how that might impact trade prospects [35–37]. For instance, Chen et al. [37] examined global port readiness for hydrogen trade from infrastructural, regulatory, financial, and public perspectives and identified 12 ports across Australia, East Asia, Europe and Africa that could be first movers. Hydrogen integration in ports can also help decarbonise port operations and help repurpose fossil-fuel ports for hydrogen trade to evade the risks of stranded assets [35,36].

However, no review study has specifically focused on hydrogen trade and the modelling tools that are being developed to investigate its development. Given the aforementioned interest in hydrogen trade, there is a need for a trade-focused review paper that identifies the current modelling landscape and outlines possible future pathways for development.

This paper presents a review of the modelling methods that have been used to explore hydrogen trade market developments. The main contributions of this paper are (1) identifying the key modelling tools that have been used to model hydrogen trade, (2) summarising key modelling outputs and insights from existing modelling studies, and (3) discussing the strengths, challenges and suggested future developments for trade modelling practices.

The remainder of this paper is organised as follows: Section 2 identifies and summarises the key literature available on modelling global hydrogen trade market development. Section 3 focuses on the representation of hydrogen and derivatives in those models in terms of trade, supply, and demand modelling assumptions. Section 4 summarises the key results and insights that can be derived from such models. Section 5 then discusses key strengths, challenges and limitations of current hydrogen trade models and provides recommendations for future research directions. Finally, Section 6 summarises the key takeaways from this paper.

2. Methods

2.1. Literature identification and screening

A Web of Science search was performed to identify papers that have looked at global modelling of hydrogen trade. Details of the performed search are listed in Table 1.

The search yielded 576 results, dating back to the publication year of 2005. The title and abstract of these studies were then screened individually based of the following criteria: the study should (1) look at hydrogen and/or derivative transport or trade between locations, (2) have a global or regional scope (i.e. national and sub-national models were excluded), and (3) discuss technical and/or economic aspects of trade. This screening process resulted in 78 papers. After reviewing those papers, a further 16 papers and reports from major global institutions (e.g. IEA, IRENA, and the Hydrogen Council) that were

Table 1
Details of the Web of Science advanced literature search.

Search Criteria	Advanced search details
Search method	Topic: Searches title, abstract, keyword plus, and author keywords.
Search terms	hydrogen and (trade or export or import) and (economic or cost or techno-economic) and (global or regional or international or intercontinental or (Asia or Europe or Africa or America or Middle East or Australia or Oceania))
Publication date	2005-01-01 to 2025-03-19
Number of results	576

repeatedly mentioned in the original papers were also added to the search results list. The entire process resulted in a total of 94 papers which are summarised in Table 2 by model type.

2.2. Overview of modelling approaches in the literature

The growing number of recent studies on hydrogen trade modelling highlights the increasing interest in this topic (Fig. 1a). A review of the types of models used in the screened papers also reveals a predominance of three main types: energy system models, supply chain models, and techno-economic models (Fig. 1b). These three model paradigms are part of the classifications of modelling approaches for hydrogen energy systems proposed by Zhang et al. [28] and Blanco et al. [27].

2.2.1. Techno-economic models

Techno-economic models have most commonly been used to compare the competitiveness of hydrogen trade routes. The techno-economic studies listed in Table 2 have developed techno-economic models that calculate the cost, energy efficiency, and emissions associated with the transport of hydrogen and/or derivatives (e.g. ammonia, methanol, and LOHCs) along specific trade routes. Pre-selected trade routes are usually studied, with Australia most often considered as the export location due to the low cost of hydrogen production, while Europe (particularly Germany) and Eastern Asian (particularly Japan and South Korea) countries are most frequently featured as importers. Such models usually have high temporal resolutions that can capture variations in renewable energy supply for electrolytic production of hydrogen over relatively short periods of time, e.g. hourly and daily [38–41].

2.2.2. Supply chain models

Supply chain models have been commonly used to model various aspects of hydrogen supply networks and infrastructure, as discussed by Riera et al. [30]. More recently, several studies such as those listed in Table 2 have developed supply chain models that focus on the development of hydrogen trade networks from local city-level to global-level spatial scopes [30]. Such studies often focus on specific end use applications for hydrogen and optimise aspects related to network costs, emissions, and carbon reduction costs. Common solution algorithms used have included linear optimisation [7,42–44], mixed integer linear optimisation [45,46], and Monte Carlo simulation approaches [47].

Supply chain models usually have high spatial and temporal resolutions that can capture variations in renewable energy supply and represent supply chain infrastructure in detail [42,48,49]. Some models have focused on specific trade links between pre-selected countries, e.g. between Argentina and Japan [48] and between Australia/New Zealand and Southeast Asian countries [49]. Others have modelled hydrogen and derivative trade supply chains at global scale [7,42–45,50–52].

2.2.3. Energy system models

Energy system models are mathematical tools that model energy system interactions and development to inform policy and support decision-making in the energy sector. Energy system models have been used to explore various aspects of hydrogen's role in the energy system [24,53–59], and more recently incorporated the trade of hydrogen or its derivatives in their energy system model definitions (Table 2) [60–63]. Some older studies have also incorporated basic hydrogen trade representation, but hydrogen trade was not used by those models mainly due to high costs and minimal hydrogen demand representation [54,59]. Some studies have also soft-linked energy system models to other models to study hydrogen trade aspects. For instance, Seck et al. [64] linked an energy system model to a supply chain optimisation model to examine the role of hydrogen in decarbonising the European energy system and the need for hydrogen imports.

The main advantage of these models is their whole-systems scope that enables a full representation of system-wide interactions. They also have long-term time horizons and can usually explore future scenarios of energy system development up to 2050 and beyond. However, they generally have lower temporal resolutions, i.e. yearly or 5-yearly time slices, lower spatial resolutions with regional aggregation of countries, and less technical detail especially on supply chain infrastructure.

2.2.4. Other models

A few other modelling techniques have also been used to explore hydrogen trade aspects. Some studies have used life cycle assessment methods to evaluate the environmental impacts of hydrogen import and export supply chains [65–69]. For instance, Kolb et al. [66], Kudoh and Ozawa [69] compared the life-cycle impacts of renewable various hydrogen trade options (hydrogen, ammonia, LOHC) for imports into Germany and Japan. Shiraishi et al. [70] used a power system model to examine the role of hydrogen imports as a low-carbon fuel source for power generation. Other economic modelling approaches used have also included sequential trade modelling based on long-term contracts [71], multi-criteria decision analysis (MCDA) [72], and a partial equilibrium model focused on imperfect competition [73].

These three broad modelling approaches have very different characteristics and capabilities, particularly due to their varied solution algorithms and differences in spatial and temporal resolutions and scopes. The studies in Table 2 use these models to address a wide range of questions concerning hydrogen trade, each adopting unique methods to represent hydrogen trade and systems. These differing approaches yield a diversity of observations and insights, highlighting how each modelling approach brings specific strengths and weaknesses to examining the potential development of a global hydrogen market.

The remainder of this review will therefore delve into those differences in model inputs and outputs to pinpoint key trends and research gaps.

3. Representation of hydrogen and derivatives in models

The representation of hydrogen trade varies significantly across the identified modelling studies. The principal differences are evident in the supply chain components included within the scope of the studies, the methods of hydrogen transport that are represented, and the methodologies used to calculate trade costs.

3.1. Trade supply chain components

Modelling studies have represented hydrogen trade supply chains at different levels of resolution and detail. As seen in Fig. 2, each modelling approach typically considers certain steps of the supply chain that are modelled at varying level of detail.

Supply chain and techno-economic models usually represent the most detail around trade infrastructure aided by their higher spatial and temporal resolutions. Additionally, techno-economic models that focus on specific trade routes usually represent the greatest detail around export and import port operations, such as the loading and unloading of cargoes, on-land storage, and compression and pumping facilities [8,

Table 2
Overview of models used to investigate hydrogen trade in the selected studies (*Note: For techno-economic models, the solution algorithm column includes the techno-economic parameters considered by the study).

Model Type	Solution Algorithm*	Geographic Scope	Traded Commodity	Trade mode	Source
Energy system models	System dynamics, Linear/Non-linear optimisation (MESSAGE-MACRO)	Global	H_2 liq.	Ships	Barreto et al. [54]
	Partial equilibrium, linear optimisation (TIAM-ECN)	Europe and MENA	H_2 gas, H_2 liq., ammonia	Pipeline, ships	Fattahi et al. [60]
	Partial equilibrium, linear optimisation (TIAM-ECN)	Europe and North Africa	H_2 gas, H_2 liq., ammonia	Pipeline, ships	Dalla Longa and van der Zwaan [74]
	Linear optimisation (LUT-ESTM)	Global	Ammonia, methanol	Ships	Galimova et al. [61]
	Partial equilibrium, linear optimisation (eTIMES-EUNA)	Europe and North Africa	H_2 gas, H_2 liq.	Pipeline, ships	Guillot and Assoumou [75]
	Partial equilibrium, linear optimisation (ETSAP-TIAM)	Global	H_2 liq., synthetic fuels	Ships	Lippkau et al. [76]
	Partial equilibrium, dynamic simulation (AIM/Technology)	Global	Ammonia, synthetic fuels	NA	Oshiro and Fujimori [62]
	Partial equilibrium, linear optimisation (JRC-EU-TIMES)	Europe	H_2 gas, H_2 liq.	Pipeline, ships	Pinto et al. [77]
	Partial equilibrium, linear optimisation linked to supply chain model (MIRET-EU)	Europe and North Africa	H_2 gas, H_2 liq., synthetic fuels	Pipeline, ships	Seck et al. [64]
	Linear optimisation (EnergyModelsX)	Exports from Norway	H_2 gas, H_2 liq., ammonia	Pipeline, ships	Svendsmark et al. [63]
	Partial equilibrium, linear optimisation (TIAM-ECN)	Europe and	H_2 gas	Pipeline	van der Zwaan et al. [78]
	System dynamics, simulation (TIMER 2.0)	Global	H_2 liq.	NA	van Ruijven et al. [59]
	Linear optimisation (REMix)	Europe	H_2 gas	Pipeline	Wetzel et al. [79]
	Dynamic recursive, simulation (GCAM-TU)	Global	H_2 gas, H_2 liq., ammonia	Pipeline, ships	Zhang et al. [80]
Supply chain models	Mixed integer linear programming	Global	H_2 gas, liq. H_2, ammonia	Pipeline, ships	Alanazi et al. [81]
	Optimisation	Norway to Germany	H_2 gas, ammonia, steel	Pipeline, ships	Cloete et al. [82]
	Monte Carlo simulation	Global	H_2 gas, liq. H_2	Pipeline, ships	Collis and Schomäcker [47]
	Linear optimisation	Australia to Germany	H_2 liq., ammonia	Ships	Egerer et al. [83]
	Optimisation	Exports from Saudi Arabia	H_2 liq., ammonia	Ships	Florez et al. [84]
	Optimisation	Imports into Germany	H_2 gas, H_2 liq., ammonia, methanol, LOHC (DBT)	Pipeline, ships	Hampp et al. [85]
	Stochastic mixed integer linear optimisation	Regional trade - South Korea	H_2 gas	Pipeline	Hwangbo et al. [46]
	Optimisation	Global - Argentina to Japan	H_2 liq.	Ships	Heuser et al. [48]
	Optimisation	Global	H_2 gas, H_2 liq., ammonia, methanol, e-kerosene, green steel	Pipeline, ships	Hydrogen Council [43]
	Optimisation	Global	H_2 gas, H_2 liq., ammonia	Pipeline, ships	IRENA [7]
	Mixed integer linear programming	Imports into Germany, Japan, and South Korea	H_2 liq., ammonia, MCH/TOL	Ships	Kim et al. [86]
	Mixed integer linear programming	Saudi Arabia, Chile, and Australia to East Asia, Europe, and USA	H_2 liq.	Ships	Kim et al. [87]
	Stochastic optimisation	Saudi Arabia to East Asia	H_2 liq., ammonia	Ships	Kim et al. [88]
	Linear optimisation	Global	H_2 gas, H_2 liq., ammonia, methanol, LOHC	Pipeline, ships, truck, train	Makepeace et al. [50]
	Mixed integer linear programming	Global	H_2 liq.	Ships	Nuñez-Jimenez and de Blasio [89]
	Optimisation	Global	H_2 liq., ammonia, methanol, e-diesel, DBT	Ships	Runge et al. [51]
	Mixed integer linear programming	Global	Ammonia	Ships	Salmon et al. [42]
	Linear optimisation	Global	H_2 liq., ammonia, methanol, e-kerosene	Ships	Shirizadeh et al. [44]
	Optimisation	Global	Ammonia	Ships	Wang et al. [90]
	Optimisation	Regional trade – Australia/New Zealand to ASEAN	Liq. H_2	Ships	Zhuang et al. [49]
*Techno-economic models**	Boil-off gas losses	NA	H_2 liq., ammonia, DME, LNG, methanol	Ships	Al-Breiki and Bicer [91]
	Cost	Australia to Japan, Germany, and Singapore	H_2 gas, H_2 liq., ammonia, methanol	Ships	Aadil Rasool et al. [38]
	Cost	Global	Green steel	Ships	Bilici et al. [92]
	Cost	NA	H_2 liq., H_2 gas	Road transport (pipeline, trucks, rail)	Borsboom-Hanson et al. [93]
	Cost	Imports into Germany and Japan	H_2 liq., H_2 gas	Ships, pipeline	Brändle et al. [94]
	Cost	Colombia to Asia and Europe	H_2 liq.	Ships	Burdack et al. [95]
	Energy efficiency, cost, carbon footprint	NA	Synthetic methane	Ships	Carels et al. [96]
	Energy efficiency, cost, carbon footprint	Australia, Brazil, Morocco, and Norway to Italy	H_2 liq., ammonia, LNG	Ships	Cava et al. [97]

(continued on next page)

Table 2 (*continued*)

Model Type	Solution Algorithm*	Geographic Scope	Traded Commodity	Trade mode	Source
	Cost	Australia to Japan	H_2 liq.	Ships	Chapman et al. [98]
	Cost	Australia to South Korea	H_2 liq.	Ships	Choi et al. [99]
	Cost	Global	E-diesel	Ships	Fasihi et al. [100]
	Cost	Morocco/Chile to Europe	Methanol	Ships	Galimova et al. [101]
	Cost	Morocco and Chile to Germany and Finland	H_2 liq., H_2 gas	Pipeline, ships	Galimova et al. [102]
	Cost	Morocco and Chile to Germany, Spain and Finland	Ammonia	Pipeline, ships	Galimova et al. [103]
	Energy efficiency, cost, carbon footprint	Europe	LOHC (TOL/MCH and DBT/PDBT)	Ships, rail, trucks	Godinho et al. [104]
	Cost	North Africa to central Europe	H_2 gas	Pipeline	Hampp [105]
	Energy efficiency, cost	Morocco to Northwestern Europe	H_2 liq., ammonia, methane, methanol, LOHC	Ships	Hank et al. [106]
	Energy efficiency	New Zealand to Japan	H_2 liq., ammonia, MCH/TOL	Ships	Hinkley [107]
	Energy efficiency, cost, carbon avoidance	Imports into Singapore	H_2 liq., gas H_2, MCH, ammonia	Ships	Hong et al. [108]
	Cost	NA	Compressed gas H_2, LOHC (DBT)	Road transport (trucks)	Hurskainen and Ihonen [109]
	Energy efficiency, cost, carbon footprint	Norway to Europe and Japan	H_2 liq., ammonia	Ships	Ishimoto et al. [39]
	Cost	Exports from Australia	H_2 liq., ammonia, methanol, LOHC (TOL/MCH), LNG	Ships	Johnston et al. [110]
	Energy efficiency, costs	Imports into Germany	H_2 liq., ammonia	Ships	Kenny et al. [111]
	Cost, carbon footprint	GCC to South Korea	H_2 liq., ammonia	Ships	Lee et al. [112]
	Energy efficiency, cost, carbon footprint	Imports into China	H_2 liq., ammonia	Ships	Li et al. [113]
	Cost	Brazil to Spain/Netherlands and Australia to Japan	H_2 liq., methanol	Ships	Meca et al. [114]
	Energy efficiency, cost, carbon footprint	Imports into Germany and Japan	H_2 liq., steel	Ships	Neumann et al. [115]
	Energy efficiency, cost	Algeria to Germany	H_2 liq., H_2 gas, LOHCs	Pipeline, ships	Niermann et al. [116]
	Cost	Canada to USA, Europe, and Asia-Pacific	H_2 liq., gas H_2, ammonia	Pipeline, ships	Okunlola et al. [117]
	Energy efficiency, cost, carbon footprint	NA	H_2 liq., methanol	Ships	Ong et al. [118]
	Cost	Canada/Australia to Japan	Ammonia	Ships	Palandri et al. [119]
	Cost	Within USA	H_2 gas, methanol, ammonia, TOL/MCH	Pipeline, rail	Papadias et al. [120]
	Cost	Australia to South Korea	H_2 liq., ammonia	Ships	Park et al. [121]
	Cost	Imports into Northwest Europe	H_2 liq., H_2 gas	Ships, pipeline	Perey and Mulder [122]
	Energy efficiency, cost	Australia to Japan	H_2 liq., TOL/MCH	Ships	Raab et al. [123]
	Cost	Australia to Japan	H_2 liq., ammonia, methanol, TOL/MCH	Ships	Rezaei et al. [124]
	Cost	South Africa to Japan and Europe	H_2 liq., ammonia, LOHC	Ships	Roos [125]
	Cost, GHG emissions	North Africa to Europe	H_2 liq., H_2 gas	Ships, pipeline	Sayer et al. [126]
	Cost	Australia/ME to Japan, Chile to USA, ME to Germany	H_2 liq., methanol	Ships	Schorn et al. [127]
	Cost, GHG emissions	Australia/Tunisia to Germany	H_2 liq., ammonia, LOHC, e-methanol, e-methane	Ships	Scheffler et al. [128]
	Cost	Middle East to Asia Pacific/Europe	H_2 liq., ammonia	Ships	Sleiti et al. [41]
	Energy efficiency, boil-off gas losses	NA	H_2 liq., ammonia, methanol, LNG	Ships	Song et al. [8]
	Cost	Vietnam to Japan and South Korea	H_2 liq., ammonia, LOHC	Ships	Ta et al. [129]
	Cost	North Africa to Europe	H_2 liq., H_2 gas, LOHC	Ships, pipeline, truck	Teichmann et al. [130]
	Cost	North Africa to central Europe	H_2 gas	Pipeline	Timmerberg and Kaltschmitt [131]
	Cost	Australia to Japan and Germany	H_2 liq., ammonia, methanol, bio-methane	Ships	Wang et al. [52]
	Cost	Imports into Germany	H_2 liq., H_2 gas, DBT/PDBT	Ships, pipeline	Wolf et al. [132]
	Energy efficiency, cost	Australia to Japan	H_2 liq., ammonia, MCH	Ships	Wijayanta et al. [133]
	Cost	Saudi Arabia to China	H_2 liq., MCH	Ships	Zhang et al. [134]
Other models	Life cycle assessment	Australia to South Korea	H_2 liq., ammonia, LOHC	Ships	Lee et al. [67]
	Life cycle assessment	Africa to Germany	H_2 gas	Pipeline	Kanz et al. [65]
	Life cycle assessment	Imports into Japan	H_2 liq., MCH	Ships	Ozawa et al. [68]
	Life cycle assessment	Imports into Germany	H_2 liq., LNG	Ships	Kolb et al. [66]
	Life cycle assessment	Imports into Japan	H_2 liq., ammonia, MCH	Ships	Kudoh and Ozawa [69]
	Well-to-wheel analysis	Norway to Germany	H_2 liq., gas H_2	Pipeline, ships	Stiller et al. [135]
	MCDA, analytic hierarchy process	Imports into South Korea	H_2 liq., ammonia, methanol, LNG	Ships	Kim et al. [72]
	Power system model	Imports into Japan	H_2 liq.	Ships	Shiraishi et al. [70]
	MCDA, supply chain optimisation	Imports into Europe	H_2 liq., gas H_2, ammonia	Ships, pipeline	Brauer et al. [136]
	Techno-economic model of oligopolistic hydrogen trade	Global	H_2 liq., ammonia	Ships	Barner [73]
	Dynamic sequential trade based on long-term contracts	Global	H_2 liq.	Ships	Antweiler and Schlund [71]

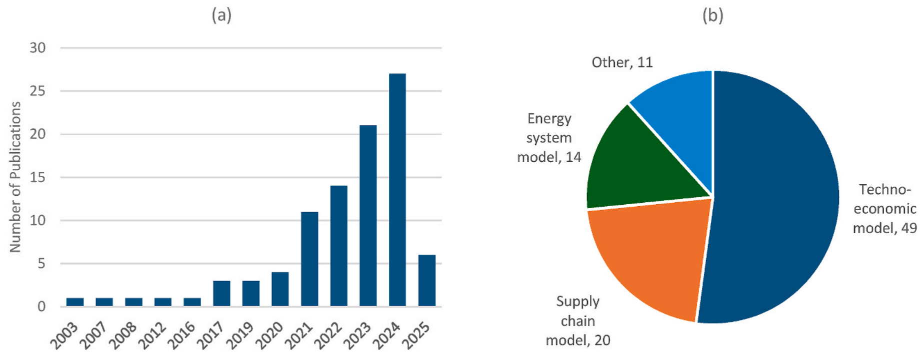

Fig. 1. Overview of literature review results: (a) number of publications per year; (b) breakdown of publications by model type.

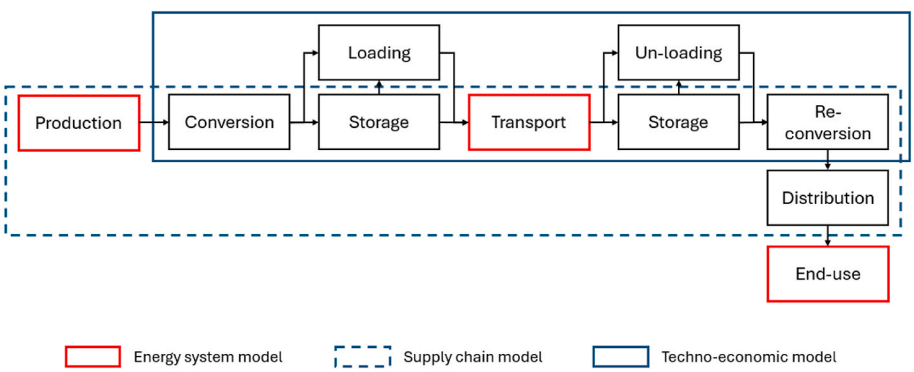

Fig. 2. Schematic of the hydrogen trade supply chain highlighting the steps typically covered by each of the modelling approaches.

120,123].

Energy system models usually only represent the major steps of the hydrogen trade system, namely hydrogen production, transport, and end-use, with other steps modelled at a basic level if included [54,61,62,76]. However, some energy system models have represent aspects of hydrogen storage and distribution, such as the MIRET-EU model which has been soft-linked to a supply chain model for hydrogen trade [64].

3.2. Hydrogen transport options

3.2.1. Transport of pure hydrogen

Across all the three main modelling approaches, the transport of liquid hydrogen in ships has most frequently been modelled as it is usually considered the most efficient option for long-distance transport of pure hydrogen [137]. However, there does not seem to be a consensus around the definition of "long distance"; the IEA [137] has reported costs for transport distances (for both land and sea transport) of up to 5000 km, while IRENA [138] has looked at distances of up to 25,000 km.

Around a third of the identified studies have looked at the potential for international trade of gaseous hydrogen using pipelines. These studies are generally limited to those that focus on specific trade routes, and particularly those looking at hydrogen imports into Europe from North Africa [60,61,63,64,78,102,122,132]. The majority of studies that have modelled pipeline trade also use techno-economic [61,93,94,116,117,120,122,132] and supply chain [7,43,46,47,50] modelling techniques that have high spatial resolutions and infrastructure representation. Energy system models have more recently started modelling hydrogen trade in pipelines, particularly in studies looking at hydrogen trade between North Africa and Europe [74,75,77].

The land transport of hydrogen using trucks and trailers has only been studied using a few techno-economic models [50,93,109,120]. This transport method is generally only considered for short-distance transport requirements due to volume and cost limitations [137].

3.2.2. Transport of hydrogen derivatives

The challenging physical and thermochemical properties of hydrogen has created an interest in using hydrogen derivatives as an alternative option for hydrogen transport [138]. In such cases, hydrogen would be converted to a derivative compound at the export location, traded as a carrier of hydrogen, before being converted back into hydrogen at the import or demand location (Fig. 2) [8,110,132]. As seen in Table 2, an increasing number of models have incorporated such compounds into their trade models to examine their competitiveness with pure hydrogen trade.

Ammonia is the most studied hydrogen derivative across all identified studies [e.g. 8, 41, 43, 44, 61, 133, 138], with some studies even focusing exclusively on the development of global ammonia trade independently from hydrogen [42,62,119]. Ammonia is generally regarded as the most promising hydrogen carrier due to its high volumetric energy density and hydrogen content, as well as the ease of its transport and storage and its already established trade and transport infrastructure for fertiliser commodity trade [9,10].

The inclusion of other hydrogen derivatives varies across the various studies. Techno-economic modelling studies have generally represented the widest range of derivatives, including methanol [42,91,101,106,110,114,118,128] and various LOHCs. They also usually represent the most detail around derivative storage, handling, transport, and re-conversion to hydrogen (Fig. 2) due to their higher resolutions [39,41,108,114,120]. They have thus provided valuable insights around costs and energy performance of derivatives across the studied transport routes (see Section 4.1 for more details).

LOHC transport has predominantly been modelled using techno-economic models. The transport of such compounds usually involves a carrier pair: the first compound is hydrogenated in a chemical reaction to form the second compound, which is then transported to the demand location. There, it undergoes dehydrogenation, releasing hydrogen and converting it back to the first compound, which is then transported back to the hydrogen production site. The most commonly modelled LOHC pairs include carbon dioxide and methanol (CO_2/CH_3OH) [116]; toluene and methylcyclohexane (TOL/MCH) [104,110,120,123,134]; and dibenzyltoluene and perhydro-dibenzyltoluene (DBT/PDBT) pairs [104,109,132].

Supply chain and energy system models have predominantly focused on modelling ammonia as the hydrogen derivative for trade, although more recent studies have also expanded to include methanol and some synthetic fuels such as e-kerosene [43,44,62,64,76,81].

The trade of green steel has also recently been explored as an alternative for hydrogen trade to help decarbonise the iron and steel sector [43,92].

3.3. Supply and demand representation

3.3.1. Hydrogen supply and demand

Another key distinction between the trade models developed in the identified studies is their approach to modelling hydrogen supply. Modelling the hydrogen supply step is important to understand trade development since most studies have argued that the variation in global hydrogen production costs will be the key driver for the development of a trade market [94,139–141].

The majority of supply chain and techno-economic trade modelling studies listed in Table 2 have only modelled electrolytic hydrogen production powered by solar PV and onshore wind energy sources [47,48,61,83]. Some studies have also considered offshore wind, natural gas, nuclear, geothermal, and hydro-powered options [41,83]. In contrast, energy system models usually include a range of hydrogen production processes including fossil fuel plants (natural gas and coal) and low-carbon options such as electrolysers, biomass gasification and carbon capture -enabled technologies [54,59,62,64].

The reviewed studies also model hydrogen demand differently. In addition to its existing uses in the chemicals and refining sectors [15], hydrogen can also be used for industry, heating, transport, synthetic fuels, and power applications [25]. Energy system modelling studies are distinct from other modelling approaches in that they endogenously model sector-specific hydrogen demand, though at various level of detail. Some energy system models have only represented hydrogen's use in fuel cells for power and transport applications [54,59,64], while others have expanded to multiple hydrogen end use technologies in the transport, power, heat, and industry sectors [61,62,76]. Supply chain modelling studies often use exogenous demand assumptions that are not always sector-specific [43,44,46,49,81], while techno-economic models usually ignore all aspects around the demand of the traded hydrogen commodity. Existing uses of hydrogen are not usually considered in any of the mentioned model types.

3.3.2. Derivatives supply and demand

Similar to hydrogen, the representation of derivatives supply and demand also varies significantly between studies. Studies that have modelled hydrogen production have also usually modelled derivative production processes, though at varying levels of detail. For instance, some techno-economic models have included detailed process modelling of derivative production such as ammonia, methanol and synthetic fuels [41,83,106,120]. Energy system and supply chain modelling studies on the other hand have adopted a simplified approach to modelling derivative production using assumptions on overall process energy consumption and costs [44,50,51,61,62].

Ammonia production has usually been modelled through the Haber-Bosch process [41,42,44,83,106,120]. Both methanol and synthetic fuel production have usually been modelled through the Fischer-Tropsch process [51,61,120], with some studies specifying direct air carbon capture (DACC) as the source of carbon needed to produce them [44,51,61,106].

The main limitation in LOHC modelling is that their production processes are usually not modelled in any of the reviewed studies. The LOHC compound that is hydrogenated is usually assumed to be sourced as a readily available commodity, with no discussion of the source of carbon used to synthesise it [51,106,116].

Modelling demand options for hydrogen derivatives also varies between studies. Demand for derivatives such as ammonia and methanol already exists in the chemical and fertiliser sectors, but could also expand to other sectors where they could compete with or complement hydrogen use [9,142–144]. For instance, ammonia can be used as low-carbon fuel for shipping [144–147], power [148], and industry applications [9]. Similarly, methanol can be used as a fuel in internal combustion engines or marine transport, and as a precursor for the production of sustainable fuels such as gasoline, kerosene, dimethyl ether and jet fuels [127,143].

Ammonia is the main derivative whose demand has been modelled using supply chain and energy system models, although more recent studies have also expanded to include methanol and some synthetic fuels such as e-kerosene [43,44,62,76]. The advantage of these modelling approaches is that they can represent an independent demand for hydrogen derivatives beyond a sole role as hydrogen carriers. For instance, Oshiro and Fujimori [62] have incorporated the use of ammonia as a maritime transport fuel and for industry and power applications, while others have also enabled the use of synthetic fuels for transport applications in their energy system definitions [43,62,64,76]. Techno-economic models have not usually modelled demand aspects for hydrogen derivatives.

3.4. Hydrogen transport cost methodologies

The differences in the representation of hydrogen trade supply chains across the studies translates into varying hydrogen trade costing methodologies. These usually differ on which trade supply chain components are included, their assumptions on trade distance, and their modelling of transport efficiency aspects.

The costs of the individual process steps modelled in trade supply chains (Fig. 2) are usually incorporated into overall cost calculations. Techno-economic modelling studies, which focus on selected trade routes and model port-level operations, usually include the most detail on transport costs, such as port and canal charges [39,108,110]. On the other hand, energy system [61,62,76,80] and supply chain [7,42–44,47,50,89] modelling studies with global scopes usually simplify their trade supply chain representations and include less detail on cost.

Another important methodological difference is the assumptions made around transport distance and duration. For trade in ships, techno-economic modelling studies usually calculate costs for specific trade route distances, considering loading, unloading and shipping times [39,91,110]. Similarly, supply chain models studying specific trade routes usually consider the shipping distance between representative ports which are often assumed to be LNG ports located in the regions under study [48,49].

In contrast, global-scale supply chain and energy system models often resort to simplifying assumptions for calculating maritime transport distances. For instance.

- Collis and Schomäcker [47] and Alanazi et al. [81] calculated least distance between ports using a high-resolution network of shipping routes.

- Nuñez-Jimenez and De Blasio [89] assumed the transport distance to be that between the geometric centres (centroids) of exporting and importing countries.
- Shirizadeh et al. [44] and Lippkau et al. [76] modelled generic representative ports from each country or region under study.
- Oshiro and Fujimori [62] and Galimova et al. [61] used fixed transport costs.

For hydrogen transport in pipelines, a generic assumption of a 20 % increase in straight line distance between export and import locations is often assumed to account for possible pipeline deviations [47,48,137]. Alanazi et al. [81], on the other hand, used a 40 % increase in centroid-to-centroid distance to model pipeline length between two countries. Pipeline distances and costs are highly location- and project-specific and difficult to approximate, and are consequently only modelled in route-specific trade studies as discussed in Section 3.2.1 [137,138].

Other technical parameters associated with the transport of pure hydrogen have also been modelled by some techno-economic modelling studies and incorporated into cost calculations. These include the overall energy efficiency of the transport method, accounting for energy consumption and losses along the transport route [106,109,123,133], and calculating the resulting CO_2 emissions [39,108]. For instance, Song et al. [8] and Al-Breiki and Bicer [91] incorporated the additional costs and efficiencies of the equipment needed to recycle and recover boil-off gas (BOG) losses from hydrogen transport. A few supply chain hydrogen trade models, such as the MIGHTY model, have also been developed to consider the impact of BOG losses on overall transport performance [45].

3.5. Data assumptions

The previous sections have demonstrated the variations in the breadth and the detail of the supply chain that are represented in different modelling approaches and even within modelling approaches. These will affect the insights from models. In addition to these structural variations, technoeconomic data assumptions such as capital and operating costs, energy conversion efficiencies and lifetimes of technologies also vary between studies, even for those using the same modelling approach [149].

Studies tend to use a huge amount of technoeconomic data. Their assumptions are often not transparent, and even where they are, the use of different spatial or temporal scales mean that the assumptions are difficult to compare across an entire supply chain. For this reason, detailed studies comparing parametric data assumptions tend to focus on one part of the supply chain (e.g. Kim et al. [149]). There is a need for a similar set of studies across the hydrogen supply chain. These could help us to understand the extent to which the insights from the various studies are affected by structural or parametric uncertainty, which is an important research question for the future. As an example, model archaeology has been developed as a method that separately assesses structural modelling choices and data assumptions [150].

3.6. Policy considerations

Policy modelling has been limited in the context of hydrogen trade models, with a focus on climate policy when modelled. Techno-economic modelling studies have usually not included any policy considerations in their models, while energy system and supply chain modelling studies are increasingly incorporating policy aspects in their models and scenario design.

Energy system modelling approaches are unique in their ability to model short- and long-term policy interventions and targets in their scenario-based approaches. Most studies have evaluated the development of the hydrogen economy under climate policy scenarios such as net-zero emission targets and various carbon budgets [59,60,62,64,78,80]. Others have also looked at energy security policy with scenarios looking at import diversification requirements [76] and the costs penalties of restricting trade [74].

Some supply chain modelling studies have also incorporated net-zero emission constraints in their supply chain optimisation models [7,43,44]. Others have also modelled the impacts of geopolitical constraints on hydrogen trade in Europe [89], and the impacts of land constraints on supply and trade volumes [42,48].

3.7. Summary

After reviewing hydrogen and derivative systems in the identified hydrogen trade modelling approaches, their representation can be summarised across four lenses.

1. Hydrogen and derivatives trade (i.e. which transport options are considered for trade and how trade costs are calculated).
2. Hydrogen supply and demand.
3. Derivatives supply and demand.
4. Policy considerations.

Table 3 summarises how each of the three main trade modelling approaches have represented hydrogen trade across these four categories.

4. Hydrogen trade modelling insights

Techno-economic studies have compared the cost and technical performance of trading hydrogen in different forms between selected locations, primarily using ships or pipelines. Studies using supply chain or energy system models have explored how global hydrogen trade might develop in the future.

4.1. Cost competitiveness

Hydrogen production costs have been studied extensively over the past few years, with several studies estimating high-resolution hydrogen production costs at several global locations [94,151–154].

Hydrogen trade studies that have calculated levelised costs of hydrogen (LCOH) across production (mainly using electrolysis) and trade agree that electricity generation is typically the main cost component of LCOH, followed by electrolyser capital costs [48,50,89,94,114,116,132,139]. Since hydrogen production costs are a common cost component of trade supply chains for both hydrogen and its derivatives, their trade cost competitiveness boils down to the other supply chain cost components. These include costs of hydrogen liquefaction or conversion to other derivatives, transport, handling, and regasification or re-conversion (Fig. 2).

4.1.1. Transport in ships

The studies that have compared the costs of transporting liquid hydrogen and derivatives in ships identified that the main contributor to shipping costs was the capital expenditure (CAPEX) costs associated with the ship and storage facilities, followed by the cost of the fuel needed to run the ships [110,114,123,137]. The geographical proximity between the exporter and the importer also has an important impact on shipping costs. BOG losses are also seen to have an impact on shipping costs for liquid hydrogen in particular [99,110].

Table 3
Hydrogen and derivative system representation detail in the three studied modelling approaches.

Category	Energy system models	Supply chain model	Techno-economic models
Hydrogen and derivative trade	Limited options for trade with focus on liquid hydrogen and ammonia; several simplifying assumptions to model trade	Focus on liquid hydrogen, ammonia, and a few other derivatives for trade; include some trade infrastructure and cost detail	Multiple derivative options modelled for trade; use the most detailed trade cost methodologies
Hydrogen supply and demand	Usually have the most detail on hydrogen production technologies; model endogenous hydrogen demand in one or more sectors	Usually limited to electrolytic hydrogen production technologies; model exogenous demand assumptions limited to specific sectors	Usually limited to electrolytic hydrogen when production is modelled; don't usually model demand
Derivative supply and demand	Basic representation of derivative supply; some modelling of derivative demand in specific sectors; mainly ammonia and synthetic fuels	Basic representation of derivative supply and demand; mainly ammonia, methanol, and synthetic fuels	Limited representation of derivative supply; don't usually model demand
Policy considerations	Usually include policy considerations around hydrogen and the wider energy system (e.g. energy security, national hydrogen targets, etc.)	Some include policy considerations which are usually limited to specific sectors or commodities	Minimal

The results of these studies indicate that liquid hydrogen is most expensive option to transport in ships, while ammonia is the cheapest [106,110]. Liquid hydrogen has a lower energy density than all its derivatives and must be stored at very low temperatures in very large storage containers, all of which translates into higher costs. On the other hand, multiple sources have agreed that ammonia is the cheapest transport option when shipped, especially if the required end-use demand is ammonia itself with no need to crack it back to hydrogen [31,39,106,110,111,124,133].

As for LOHCs, and despite their low transport costs, their high production and reconversion costs decrease their overall competitiveness, especially when the cost of carbon used to produce them is taken into account [106]. The use of external heat sources to power their production and reconversion has the potential to improve their economic attractiveness, especially for long-distance applications and compared to liquid hydrogen transport [106,109,116,123].

The use of a methanol as a hydrogen carrier was identified as the cheapest option among studied carrier pairs due to its low dehydrogenation heat requirement, followed by DBT/PDBT and TOL/MCH [40,116]. The cost of methanol trade was determined largely by the costs of producing its constituent hydrogen and carbon, indicating that a global methanol trade market could be largely driven by a global variation in the costs of producing those elements [124,127].

Long-distance transport of gaseous hydrogen by ship is not considered in the reviewed studies as the low energy density of hydrogen gas leads to a very high transportation cost.

4.1.2. Transport in pipelines

Transporting gaseous hydrogen in pipelines is also expected to be an option for both national and international trade. Multiple studies have agreed that pipelines could be the cheapest option for transporting large quantities of pure hydrogen for distances up to around 3000 km [40,132,155].

Other derivatives and carriers of hydrogen were not seen as competitive when transported in pipelines. Among the studied derivatives, methanol was identified as the cheapest transmission option, followed by ammonia [120]. Long-distance pipeline transport routes are generally considered unsuitable for LOHC options due to their low hydrogen content and the need to construct a parallel pipeline to transport the carrier back to the hydrogen production site for re-hydrogenation [116,120].

However, the data published around hydrogen pipeline costs is generally location-specific, non-generalisable, and inconsistent in terms of ideal transport distance or volume ranges. This is mainly due to the high impact of location-specific labour costs and right-of-way fees on overall pipeline construction costs [156].

4.1.3. Transport in trucks and rail

A few studies have examined transporting hydrogen and its derivatives using trucks or rail [50,93,104,109,120,157,158]. Cost analyses have indicated that such modes of transport are usually only cost effective when transporting small-to-medium quantities (up to 50 tonnes per day) over short distances (below 100 km) [50,93,158]. For such applications, transporting liquid or compressed gaseous hydrogen in trucks or tube trailers was found to be most cost effective, while production and transport of hydrogen derivatives were cheaper for delivery over longer distances [109,120,157,158]. Consequently, such modes of transport are not expected to contribute to global-scale hydrogen transport, with their applications limited to localised distribution on national and sub-national levels [109,120,158].

4.2. Technical performance of hydrogen trade options

Several techno-economic modelling studies have focused on modelling and comparing technical aspects in the trade of hydrogen and its derivatives. This includes supply chain energy requirements, energy efficiency, and BOG losses [8,106,116,133]. While some supply chain and energy system modelling studies have included technical trade parameters in their hydrogen trade representation and cost methodologies [45,64], technical performance evaluations have not generally been a focus of such modelling approaches.

4.2.1. Energy consumption and efficiency

Techno-economic studies agree that hydrogen production (which is usually assumed to be electrolysis) is the most energy-intensive step of the trade supply chain for both hydrogen and derivatives. This is followed by the conditioning step used to prepare the commodity for transport, whether it is liquefaction of hydrogen or production of derivatives and carriers [106,116].

The reviewed studies have reported various energy efficiency results which outline how much of the traded energy is consumed or lost during the trade process. Some studies have calculated efficiency values of the individual process steps outlined in Fig. 3. Others have also reported overall round-trip efficiencies of the entire trade supply chain. However, efficiency values are not always comparable between studies due to their varying scopes and assumptions on supply chain components.

For short transport distances, gaseous hydrogen transport in trucks or pipelines had the lowest overall energy consumption and highest efficiency [116]. For long-distance transport, overall energy efficiency calculations showed contradicting results: liquid hydrogen was reported as the most efficient option in some studies (52–58 % overall efficiency reported by Hank et al. [106]), but the least efficient in others [116,133]. Overall efficiency was also shown to decrease with the increasing transport distance for all the hydrogen transport options, with the decrease more rapid for liquid and gaseous hydrogen than for other

Table 4
Average daily boil-off gas rates associated with the transport of hydrogen, ammonia, methanol, and LNG in ships [8,91].

BOG (%/day)	Liquid H_2	Ammonia	Methanol	LNG
Land storage	0.3–0.7	0.02	0.0003	0.08–0.12
Loading	0.5–0.9	0.02–0.04	0.02	0.09–0.1
Ship transport	0.3–1.1	0.02–0.03	0.0005	0.1
Unloading	0.5–0.9	0.01–0.04	0.02	0.09–0.1
Total	**2.4–3.4**	**0.05–0.1**	**0.05**	**0.4–0.5**

LOHCs [116].

The performance of hydrogen transport options has also varied across the different steps of the supply chain outlined in Fig. 3. For instance, LOHCs were identified as the most energy efficient in the transport and storage steps with efficiencies exceeding 90 %, while liquid hydrogen efficiencies averaged 60–70 % [116,133]. However, the main disadvantage of LOHCs is the high energy and heat required to de-hydrogenate them. Consequently, some studies have highlighted that the overall efficiency of LOHCs can be increased by either using heat integration and recovery or external heat sources instead of the internal use of the hydrogen commodity itself, or using of CO_2 from concentrated streams (such as those from carbon capture and storage (CCS) and DACC) to produce the LOHC pairs [106,116].

4.2.2. Boil-off gas losses

BOG losses associated with the various supply chain steps of the hydrogen transport modes were also shown to have a major impact on overall energy efficiency. Ambient temperatures, transport distance, storage time, and loading and unloading times all have a significant impact on BOG losses [8,91].

Liquid hydrogen has significantly higher BOG loss rates than other energy carriers across the entire trade supply chain (Table 4) and particularly during shipping, while methanol has the lowest [8,91]. Both ammonia and methanol have lower BOG rates than liquefied natural gas (LNG), which increases their attractiveness for use in international trade.

The impact of gas losses on overall energy efficiency can be minimised by deploying BOG treatment or recovery processes. Such systems were shown to improve the efficiency of liquid hydrogen systems by 5 %, LNG by 2 % and ammonia by 0.3 % [8].

In summary, techno-economic modelling studies have provided detailed comparisons of the technical and economic performance of various hydrogen trade options. Key performance indicators explored have included: costs, energy consumption, energy efficiency, and BOG losses across the hydrogen trade supply chains. Reported results have indicated that there is not one “optimal” or universal option for trading hydrogen. Overall costs and technical performance are case-specific and highly dependent on several variables, such as the transport volume, transport distance and duration, and supply chain energy and heat requirements. However, ammonia seems to be a promising option for hydrogen transport, particularly if the end use demand required is ammonia itself. This highlights the importance of understanding demand considerations in hydrogen trade development, an aspect which is generally not well represented in models (Section 3.3).

4.3. Global hydrogen trade futures

Aside from techno-economic modelling studies that have provided route-specific insights on the cost and technical competitiveness of the different hydrogen transport options, supply chain modelling and energy system modelling studies have provided important insights into the possible shape, size, and form of a future global hydrogen trade market.

The types of insights provided by each modelling type range from qualitative aspects around potential trade routes and market structures to quantitative projections of future trade volumes. Note that results vary significantly between studies as they are highly influenced by underlying assumptions made around representing hydrogen supply chains and spatial and temporal resolutions, as discussed in Section 3.

4.3.1. Trade market structure

Global-scale trade studies all indicate that a global trade market is likely to develop for hydrogen and/or its derivatives. Oshiro and Fujimori [62] projected that the trade of ammonia and synthetic fuels could represent 5–15 % of global energy trade by 2050. Galimova et al. [61] estimated that the demand for e-fuels and e-chemicals will grow substantially (by more than 10-fold) by 2050 and estimated that around 20–35 % of this demand is expected to be traded at a global scale. They also argued that trading those chemicals would reduce their average levelised costs by 4–7 % because trade enables producing them in regions with cheap renewable energy resources. Seck et al. [64] estimated that 10–15 % of Europe’s hydrogen demand in 2050 would need to be imported using pipelines. Several other studies have also indicated that hydrogen pipelines linking North Africa to Europe will be key to help decarbonise the European energy system [74,75,77]. Moreover, in scenario analyses from both Lippkau et al. [76] and Oshiro and Fujimori [62], hydrogen and derivative trade markets were seen to expand with more stringent greenhouse gas mitigation targets.

4.3.2. Trade projections

A few studies have provided quantitative projections on hydrogen and derivatives trade [7,43,44,50,80]. IRENA [7] developed a global supply chain optimisation model that covers both power and gas systems and considers hydrogen production from renewable power sources only (solar, onshore and offshore wind, supported by battery storage), with hydrogen trade enabled either as a gas in pipelines, as liquid in ships, or converted into ammonia that can be shipped. The Hydrogen Council [43] and Shirizadeh et al. [44] consider more end uses for hydrogen (transport, industry, and buildings) and hydrogen transport options that included pure hydrogen, ammonia, methanol, synthetic fuels (kerosene) [43,44], and green steel [43]. Makepeace et al. [50] also included LOHC options for hydrogen trade but did not include any hydrogen demand aspects in their model, focusing solely on production and transport. Zhang et al. [80] developed a global integrated assessment model to include bi-lateral hydrogen trade in the form of liquid hydrogen in ships, gaseous hydrogen in pipelines, and ammonia. Alanazi et al. [81] developed a modelling framework that simulates long-term renewable hydrogen market equilibrium and trade flows.

Projected global hydrogen trade volumes in net-zero scenarios varied significantly between the studies (Fig. 3). Makepeace et al. [50] projected 290 Mt of hydrogen trade by 2050, which is 85 % of the total projected supply. In contrast, the other studies projected lower trade of 90–200 Mt with a much smaller proportion of hydrogen being traded (20–53 %) [7,43,44,80,81].

Similarly, expected transport methods have also varied between studies (Fig. 4). While the Hydrogen Council [43], IRENA [7], and

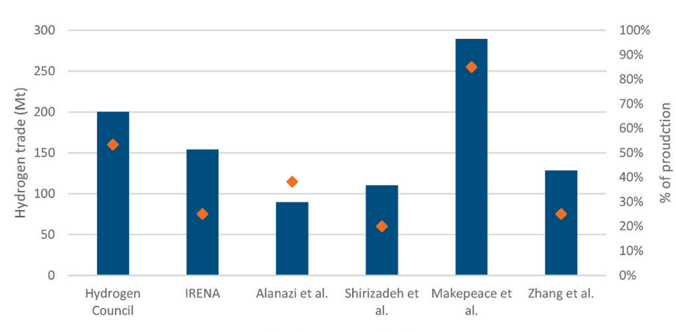

Fig. 3. Projected volumes of global hydrogen trade in 2050 in published net zero scenarios [7,43,44,50,80,81].

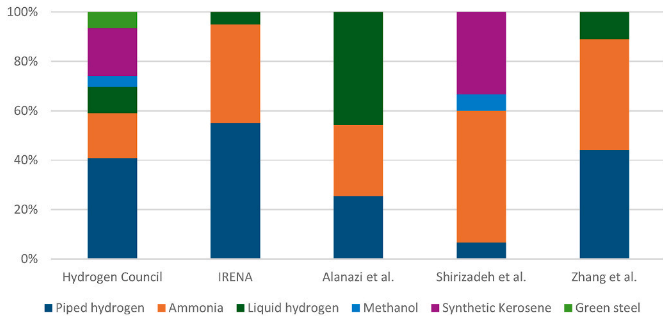

Fig. 4. Breakdown of hydrogen trade in 2050 by transport method in published studies [7,43,44,80,81].

Zhang et al. [80] expect 40–60 % of hydrogen to be traded in pipelines, Shirizadeh et al. [44] saw only a minor role for pipelines. IRENA [7] also indicated that most of these pipelines will be retrofitted from existing natural gas pipelines. The Hydrogen Council [43] projects that hydrogen trade will initially begin in the form of hydrogen derivatives (ammonia and methanol) as early as 2025 due to their established of trade infrastructure, while piped hydrogen will only begin towards the end of the decade. IRENA [7], Shirizadeh et al. [44], and Zhang et al. [80] also project a major role for ammonia as a hydrogen carrier, with IRENA [7] projecting ammonia shipping prices to drop ten-fold to around 0.8 USD/kgH_2 by 2050. All models forecast that liquid hydrogen shipping will have only a small market share, except Alanazi et al. [81] who project around 46 Mt of liquid hydrogen trade in ships.

Available hydrogen trade models also provide an indication of expected trade routes, and the locations of potential major importers or exporters of hydrogen and hydrogen-based compounds. Across most modelling studies, projected hydrogen export and import locations have generally been aligned with renewable energy resource potential. Hence, regions with abundant solar and/or wind energy resources (e.g. Australia, Middle East, South America, North Africa) are projected to be exporters, while regions with low renewable generation potential or high generation costs (Europe, Japan, South Korea, Asia) are expected to be importers of hydrogen energy [41,43,44,50,61,76,106,110,123]. This can be attributed to the fact that most of the mentioned models have only modelled electrolytic hydrogen produced by renewable electricity sources (Section 3.1), and electricity costs are the largest fraction of the levelised cost of hydrogen (Section 4.1).

Multiple studies have also indicated that regional-rather than global-scale trade is likely to develop for hydrogen and its derivatives. Pure hydrogen is projected to be predominantly produced and consumed locally, mainly transported in pipelines, and only traded in liquid form under stringent mitigation scenarios [7,43,76]. Similarly, Salmon et al. [42] concluded that ammonia trade and distribution is likely to happen at regional scales (for distances of around 5000 km) with land availability presenting the main constraint to ammonia production in resource-rich areas. Other studies have also indicated that synthetic fuels are expected to be traded at a wider scale compared to pure hydrogen [44,62,76].

5. Discussion

5.1. Strengths and weaknesses of existing modelling practices

Based on an in-depth review of hydrogen trade modelling through 4 lenses, i.e. representation of hydrogen, its derivatives, their trade, and polices (Table 3), this study has identified the strengths and limitations of the commonly used model types (Fig. 6). In the following we analyse how fit for purpose the current modelling approaches are for modelling global hydrogen trade.

The main strengths of energy system modelling approaches are: their ability to model multiple hydrogen supply options, their endogenous and cross-sectoral hydrogen demand modelling, and their ability to model wider energy system aspects (e.g. policy, climate, economy). However, such modelling tools still need to be expanded further to capture the full spectrum of possible hydrogen production routes and demand applications, particularly for existing and new industry uses (e.g. refining, chemicals, and heating). Hydrogen derivatives have been increasingly integrated into energy system models over the past few years, but their representation can be further expanded to include more derivative options and to model their independent end-uses aside from being hydrogen carriers. Moreover, their low temporal and spatial resolution limits the detail at which they can model hydrogen trade supply chain infrastructure and costs. It also limits their suitability for modelling the role of hydrogen in power sector development, as high resolutions would be required to accurately capture variable renewable energy generation and evaluate short- and long-term energy storage needs [27,159]. Finally, their representations and analysis around trade-related hydrogen policies could also be expanded.

Supply chain modelling studies have been unique in their sector-specific focus that usually models trade infrastructure at a high level of detail. Supply chain models have also increasingly represented derivative supply chains and their role as hydrogen carriers for trade. Such studies have also provided long-term projections and insights on the possible development of global hydrogen trade markets, while also touching on some policy aspects (see Section 3.5). However, supply chain models are usually limited in their exogenous, sector-specific demand assumptions that have not usually included demand for derivatives.

Techno-economic modelling studies have been unique in their detailed representation of hydrogen and derivative trade, developing the most detailed cost methodologies that take several technical and economic factors into account when estimating trade performance. They have also been the most diverse in the number of hydrogen derivatives that they have explored, expanding beyond ammonia to look at LOHCs and other possible hydrogen derivatives. However, techno-economic modelling studies have fallen short on representing hydrogen supply, demand, and policy aspects.

Across all three modelling approaches, model structure and scope limits or dictates the types of analyses and insights that can be performed. For instance, energy system models seem to be best fit for providing long-term, whole-system insights on global hydrogen trade market development under different policy scenarios. Techno-economic models are better suited to provide detailed comparisons of technical and cost performance of various hydrogen trade options along selected trade routes. Meanwhile, supply chain models are most effective in providing high spatial resolution insights on required trade infrastructure in different locations and sectors. This points to an opportunity to soft-link different model types to make use of their respective strengths, as has been demonstrated by Seck et al. [64] and Alanazi et al. [81].

In Fig. 5 we summarise the identified and discussed limitations and gaps of each of the three modelling approaches, both in terms of their representation of hydrogen and derivative systems and their modelling capabilities.

Fig. 6 presents a visual summary that combines the strengths and weaknesses discussed in this section with the insights derived from the review of hydrogen system representations presented in Section 3 and Table 3. The aim of Fig. 6 is to enable a visual comparison of the performance of each modelling approach in tackling the identified four lenses relative to the other modelling approaches. It also sets a theoretical "target" which represents a level of model coverage that addresses the gaps that have been identified across the four lenses. For instance, target (1) hydrogen and (2) derivative supply and demand representation would cover the full spectrum of production technologies and possible end use applications across multiple sectors, both for existing and new uses; (3) target hydrogen and derivative trade representation would entail detailed trade infrastructure representation and

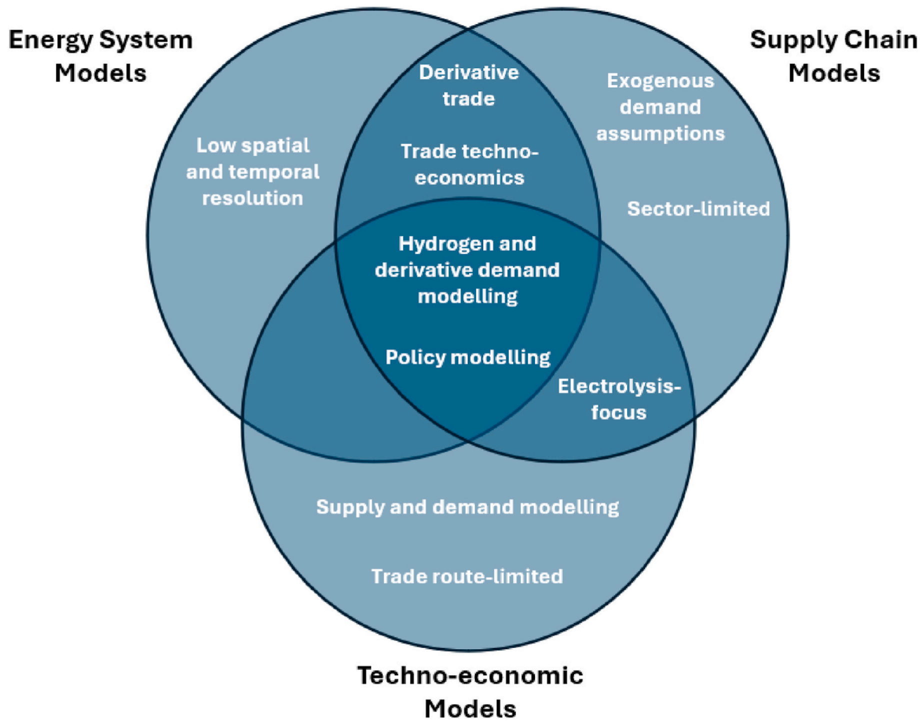

Fig. 5. Overview of modelling weaknesses and gaps in the reviewed modelling approaches
Note central overlap of all approaches on hydrogen and derivative modelling and policy representation, albeit at different temporal, spatial and technical resolution.

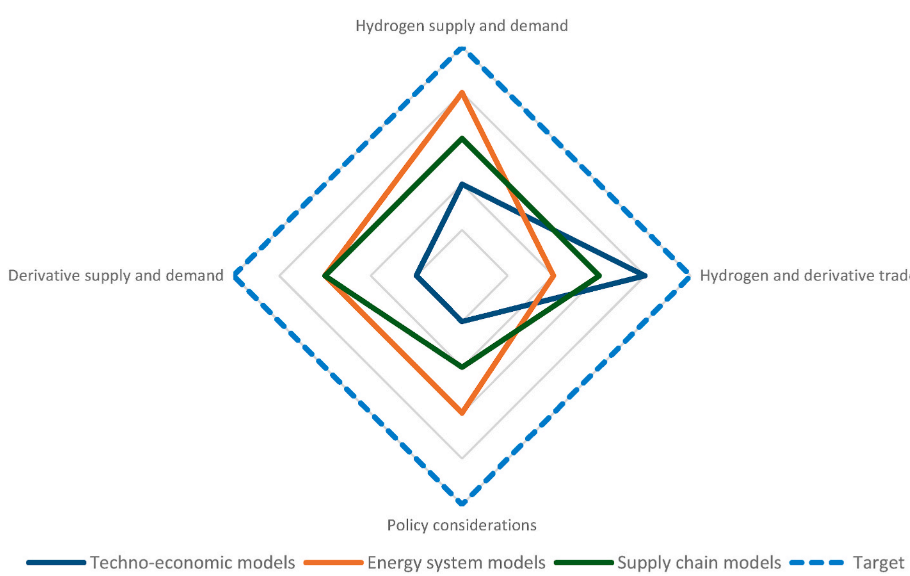

Fig. 6. Hydrogen system detail in hydrogen trade modelling studies
The solid lines illustrate the performance of each key model type against the four lenses. The target interrupted line illustrates the ideal representation models should have for each of the four lenses we utilise here.

trade cost calculation methodologies that take several technical and economic parameters into consideration when modelling trade; while (4) target policy representation would incorporate policy into modelling analysis to explore the impacts and efficacy of policies on trade market development.

In summary, we argue that individual model types should be continuously improved and used complementarily to achieve "target" hydrogen and derivatives system representation when modelling trade, as opposed to aiming for an overall hydrogen modelling framework. Given the discussed limitations around model scope and capabilities, such targets might not be realistically achieved using a single modelling approach.

5.2. Challenges for model development

Improving and expanding hydrogen trade modelling to adequately cover the four categories outlined in Fig. 5 still faces several challenges that are mainly linked to (1) the complexity and uncertainty around hydrogen trade and hydrogen systems in general, and (2) limitations on data availability.

The development of a possible global hydrogen trade market will be influenced by a complex range of factors ranging from supply and demand to infrastructure, policy, geopolitics, and environment. Existing trade modelling practices will thus need to be further developed to be able to capture those complex system interactions and their influence on the trade market. This complexity is also compounded by the huge technical and cost uncertainties of hydrogen systems. Such uncertainties cascade across the entirety of the hydrogen supply chain from supply (e.g. electrolyser and carbon capture technology development), through to infrastructure (hydrogen storage, transport, and distribution infrastructure), demand, social acceptance, and policy [159,160].

Issues of data availability also impede model advancement. Successfully modelling the complexity of hydrogen energy system and technologies is expected to be data intensive. Such data points are usually limited for emerging technologies that are yet to be commercially available (e.g. CCS-enabled production technologies, hydrogen fuel cells, hydrogen heating technologies). Techno-economic data availability on a global, regional, and national levels also varies significantly. Despite some progress on publishing techno-economic databases on hydrogen technologies, e.g.Plazas-Niño et al. [161], more efforts are needed on that front.

5.3. Recommendations for future research

After reviewing the current state of the art of hydrogen trade modelling and identifying some of the challenges facing its development, three recommendations can be outlined for improving the robustness and usefulness of future trade modelling practices.

5.3.1. Expanding the modelling of the techno-economics of hydrogen trade

Given the current varying structure and level of detail used in modelling trade techno-economics, there is a need for more robust trade costing and performance evaluation when modelling hydrogen trade. This could include incorporating regional transport cost variations, as well as enabling a more detailed representation of trade supply chains and infrastructure requirements for both hydrogen and its derivatives.

Even though IRENA [7] and Hydrogen Council [43] expect a significant role for pipelines in regional and global hydrogen trade (Fig. 4), only a few studies have explored the potential of this transport option. There is thus a need to further explore the potential and challenges of pipeline hydrogen transport by improving and expanding region- and country-specific modelling of pipeline trade.

Finally, the role of existing natural gas and oil infrastructure in a future hydrogen trade market also needs to be better understood. In addition to the potential retrofitting of natural gas pipelines for hydrogen transport, other infrastructure such as liquefied natural gas liquefaction and regasification facilities, bunker ships, ports, and storage facilities could also potentially be used for hydrogen and derivative trade [162].

5.3.2. Improving modelling of potential future demands for hydrogen and derivatives

There are still a lot of uncertainties around the possible development of demand for hydrogen [25,159] and the impact that this would have on the size and shape of a hydrogen trade market, especially since most existing trade projections are supply-cost driven (see Section 4). For instance, out of the announced export projects reported by the IEA [155], less than one-third of the volume that could be traded by 2030 has already identified a potential off-taker.

This uncertainty is also reflected in hydrogen trade models that have either ignored demand aspects (techno-economic models), used exogenous demand assumptions (supply chain models), or focused on modelling limited demand sectors for hydrogen (energy system models with their focus on hydrogen use in the transport sector). Consequently, studies need to expand their modelling of hydrogen demand, both for existing (refining and chemicals) and new (industry, power, shipping, aviation, heating, new chemicals) hydrogen applications.

Studies also need to expand the modelling of hydrogen derivative demand beyond their role as hydrogen carriers to explore their possible use across multiple sectors. An increasing role for such derivatives might impact hydrogen trade market development on two fronts. First, it will lead to an increased demand for the hydrogen used to produce them. Second, some of these derivatives (e.g. ammonia and methanol) already have their established supply and trade infrastructure which might enable a faster scale up of their trade and use compared to pure hydrogen.

5.3.3. Expanding policy modelling in hydrogen trade models

Most studies to date have examined the techno-economics of hydrogen trade to understand possible market development. Across the reviewed studies, only a few have incorporated policy analysis into their modelling, and these have mainly focused on geopolitical aspects of hydrogen trade (Section 3.5).

On the other hand, there is a growing international interest in hydrogen trade that has led to a burgeoning number of national and international initiatives and policies to remove barriers and encourage the development of trade links. These include policies such as national and regional import and export targets [155,163], hydrogen low-carbon standard and certification schemes [164,165] and energy diversification and security policies [14,18,166,167]. Other policies target the use of hydrogen in specific sectors (e.g. Japan's ambitions of using ammonia in the power sector [168]) and social, environmental, and safety aspects of hydrogen systems [169,170].

Given this increased activity on the policymaking front, hydrogen trade modelling approaches can play an active role in policy development and innovation. For example, models could examine the implications of not removing barriers to trade, developing infrastructure at different rates, and providing subsidies to encourage market development. They can also help identify critical innovation areas that can help unlock trade potential when developed.

Technological and regulatory innovation across the entire hydrogen supply chain can support the development of hydrogen trade markets [7,71,171]. For instance, technological improvements and cost reductions for renewable energy and for hydrogen production technologies such as electrolysis – whose costs are main contributors to overall LCOH (Section 4.1) – can help unlock hydrogen export potential in several global locations [71]. Innovation that supports infrastructure (e.g. storage, liquefaction, cracking) and end-use technology (e.g. fuel cells, furnaces, combustion engines) development for both hydrogen and its derivatives could also significantly impact the shape of the hydrogen trade market [7,172]. For instance, the development of ammonia demand technologies for power, transport and heat applications [9] could significantly boost its trade market potential compared to hydrogen since it has been demonstrated as the cheapest transport option if it does not need to be cracked back into hydrogen (see Section 4.1).

6. Conclusion

This paper has reviewed current trends in global hydrogen trade modelling to understand the current state-of-the-art and identify pathways for future model development. Three main modelling approaches have been used to investigate global hydrogen trade: energy system models, supply chain models, and techno-economic models.

The representation of hydrogen and derivatives in the identified modelling studies has been reviewed and summarised across four categories: (1) the representation of trade supply chains and costs, (2) the supply and demand modelling of hydrogen and (3) hydrogen derivatives, and (4) policy considerations.

While energy system models have the most detailed representation of hydrogen production and end-use demands, supply chain and techno-economic models have demonstrated more detailed representations of trade supply chains of hydrogen and hydrogen derivatives. Policy modelling has been limited across all three types of modelling. Consequently, none of these approaches is yet to successfully and comprehensively represent the complexity of hydrogen and derivative trade systems.

This review identifies some key challenges and opportunities for future hydrogen trade model development. Modelling challenges can mainly be attributed to the complex nature of hydrogen systems with its cross-sectoral decarbonisation potential, various uncertainties across the entire hydrogen and derivative supply chains, and limited data availability for emerging technologies and developing countries.

To improve trade model robustness and usefulness, future modelling research can focus on three suggested aspects. First, the modelling of the techno-economics of hydrogen and derivative trade can be expanded to improve cost assumptions and to include a wider array derivative and transport options. Second, future work can focus on exploring the possible impacts of hydrogen and derivative demand development on trade dynamics. Finally, hydrogen trade models can be developed to model policy developments and analyse the implications of national and international initiatives and policies.

CRediT authorship contribution statement

Jana Fakhreddine: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul E. Dodds:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Isabela Butnar:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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