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A Novel Framework for Simulating Market Equilibrium in International Hydrogen Trade

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ABSTRACT

Hydrogen has gained significant attention as a possibly important energy vector in the pursuit of climate change mitigation objectives. Global demand for renewable hydrogen is anticipated to increase across many decarbonization scenarios. To meet this demand, many countries have unveiled strategies aimed at bolstering domestic low-carbon hydrogen production or facilitating imports. Within this context, international trade has emerged as a means of importing hydrogen from regions with low-cost production capabilities. However, investment decisions in the development of international hydrogen markets are moving slowly due to large uncertainties regarding the magnitude of future demand and willingness to pay for hydrogen in key end-use applications.

In this study, we develop a novel modelling framework capable of simulating global hydrogen market equilibrium and international trade scenarios in the long-term future. Our methodology includes the development of supply and demand curves, as well as a global hydrogen trade model that takes into account various supply chain options. Using this framework, we are able to derive quantitative insights into equilibrium supply and demand, pricing dynamics, trade flows, costs, and many more. We apply this framework to investigate the optimal development of hydrogen markets in 2050 under a 1.5°C climate change mitigations scenario. Our findings indicate that new hydrogen sectors could see a global demand surge to 195.2 Mt, with international trade constituting a quarter of this demand.

Keywords: hydrogen trade, hydrogen markets, energy systems modelling, supply-demand equilibrium

1. INTRODUCTION

Hydrogen has emerged as a critical energy vector for achieving climate change mitigation objectives [1]. Global demand for renewable hydrogen is expected to rapidly increase across many decarbonization scenarios [2]. International trade may play a critical role in meeting this demand at a low cost [3]. However, the development of international hydrogen supply chains is moving slowly, largely due to the absence of established hydrogen markets and the lack of historical price data to inform the decision-making process. Additionally, due to high uncertainty in electrolysis technology growth rates, low-carbon hydrogen may remain scarce in the long-term [4]. Therefore, it is important that sensible climate policies prioritize its use in hard-to-abate sectors for an efficient use of the hydrogen resource in the future [5]. Against this background, the key research questions addressed in this work are related to optimal hydrogen markets development in the long-term future at a global scale.

A critical literature review is conducted on this topic, revealing several studies that have modeled the production cost of hydrogen or its derivatives based on individual countries' renewable energy resources. Some studies have taken this a step further by determining bilateral trade flows between potential supply and demand countries, considering production and transport costs and assuming a constant demand for hydrogen. Another less commonly applied approach is an agent-based game-theoretic approach, which considers the strategic behavior of market agents throughout the supply chain. However, it is important to note that these studies do not provide insights into the development of international hydrogen markets, as they primarily focus on production and transport costs and employ a simplified assumption of constant demand that does not

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reflect the fact that hydrogen is a commodity where demand will be influenced by its future price.

In light of this, the aim of this research is to develop a methodological framework which simulates a hydrogen market equilibrium and international trade scenarios in the long-term future, i.e. 2050. This framework will improve existing approaches for hydrogen market modelling by incorporating a price-demand function within a hydrogen trade model, moving beyond the simple assumption of inelastic constant demand.

2. METHODOLOGY

This research introduces a novel framework that aims to simulate hydrogen market equilibrium and international trade flows in the long-term future. The framework consists of three fundamental stages (see Figure 1). First, renewable hydrogen supply curves are computed for every country, taking into account their respective renewable energy resources. Second, the integrated assessment model (IAM), TIAM-Grantham, is used to construct regional hydrogen demand curves (i.e. relationships between demand and price) in 1.5 °C climate scenario. Third, a global hydrogen trade model is developed to optimize hydrogen supply and demand, aiming to maximize the overall system surplus.

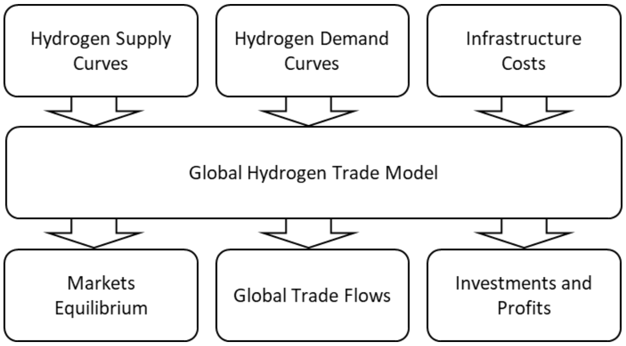

Fig. 1 Proposed hydrogen trade modelling framework

Hydrogen supply curves: The first step in studying hydrogen markets development involves assessing global renewable energy potential available for hydrogen production. In this study, we focus on countries that have active policies on hydrogen deployment plans. Approximately 60 countries are included in the hydrogen supply module based on their pursuit of hydrogen strategies. Renewable energy resources are calculated using established databases for solar PV, onshore, and offshore wind technologies [6]. The consideration of those technologies is based on several factors including their global availability, scalability and minimal environmental impact. The levelized cost of electricity (LCOE) is computed for each country, technology, and resource class, forming individual renewable electricity supply curves. Subsequently, hydrogen production costs are calculated using the levelized cost of hydrogen (LCOH) over electrolysis plant lifetimes, incorporating techno-economic data from International Energy Agency (IEA) and International Renewable Energy Agency (IRENA). The cost of water sourcing for electrolysis is factored into the LCOH. This accounts for IRENA's worst-case scenario estimate of $0.05 per kilogram of hydrogen produced [7]. Additionally, the electricity consumption for water desalination is assumed to constitute 1% of the total electricity usage of the electrolyzer. Finally, the total supply costs for each renewable energy resource class, coupled with their respective energy potentials, are utilized to construct step-wise renewable hydrogen supply curves for each country.

Hydrogen demand curves: One of the main goals of this research is to establish a methodology for deriving long-term regional hydrogen demand curves, which will subsequently be integrated into a global framework to simulate future market dynamics using a market equilibrium model. To achieve this, a detailed assessment of demand outlook is conducted, focusing on specific applications and their willingness to pay for hydrogen under climate neutrality targets. The study focuses on eight key hydrogen end-use applications, which are:

- Steel & iron production
- High temperature heat for industry
- Power generation
- Medium- and heavy-duty FCEVs
- Shipping
- Aviation

Using the TIAM-Grantham integrated assessment model, which includes 15 regions and various scenario-based analyses, this study examines the price-demand relationship for these sectors. Key input parameters include future price assumptions, ranging from 1 – 4 USD/kg, and technoeconomic considerations, enabling the determination of hydrogen demand across key end-use applications and the creation of an aggregate price-demand function.

Infrastructure costs: This step focuses on estimating hydrogen transportation costs, a significant component alongside production costs, to determine the overall cost of delivering hydrogen to specific countries. The primary goal is to calculate unit transportation costs in USD/kg of hydrogen for international supply chains, considering multiple stages such as conversion, transportation, storage, and re-conversion. Currently, the model incorporates three hydrogen supply chains: pipelines, liquid hydrogen, and ammonia. Pipeline costs encompass investment, operation, compressor stations, and storage, while other carriers involve three steps: conversion, shipping, and reconversion. Capital and operating costs are calculated for each supply chain step, relying on long-term technology cost projections from the IEA and other relevant sources.

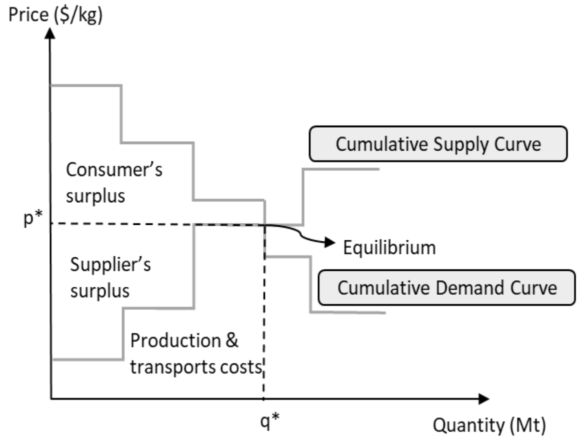

Fig. 2 Supply-demand curves endogenously generated by the trade model

Global hydrogen trade model: The final step in the proposed framework is the development of a global hydrogen trade model that simulates market equilibrium in demand regions. The model matches supply and demand taking into account viable supply chains options and transport cost parameters. In this approach, hydrogen trade model is formulated as a mixed-integer linear programming (MILP) that aims to maximize the sum of producer and consumer surplus, which is effectively the area circumscribed by the supply and demand curves shown in Figure 2.

The objective function maximizes the total surplus which is defined as the sum of revenues from hydrogen sales minus the sum of production and transportation costs.

$$\text{Max total surplus} = \sum_{\text{imp} \in \text{IMP}} \text{Revenue}_{\text{imp}} - \sum_{\text{exp} \in \text{EXP}} \text{ProdCost}_{\text{exp}} - \sum_{\substack{\text{exp} \in \text{EXP} \\ \text{imp} \in \text{IMP}}} \text{TranCost}_{\text{exp, imp}}$$

The trade model formulation assumes a benevolent social planner that seeks optimal hydrogen resource allocation under perfect competition assumption. The model considers producers supply curves and consumers demand curves as discretized production and consumption levels. Supply and demand nodes are mapped through possible supply chain options. Taking into account potential production and consumption levels, the model simulates the optimal market equilibrium with supply and demand curves calculated endogenously.

3. RESULTS AND DISCUSSION

This section presents the results of the applied modelling framework. In subsequent sections, we present our findings for the supply and demand curves as well as trade optimization results. It is important to note that although we present our findings of supply and demand curves that are used in the trade model, those data are only input to the trade model, and the model is generic can be fed any other supply and demand curves.

3.1 Renewable hydrogen cost-potential curves

Figure 3 displays the renewable hydrogen cost-potential curves for selected countries in the year 2050. The combined production potential for renewable hydrogen across these countries significantly exceeds the highest demand projections found in the literature, which is about 706 Mt [8]. Investigating the results in greater detail reveals distinct variations in hydrogen potential among the countries, highlighting the uneven global distribution of hydrogen resources.

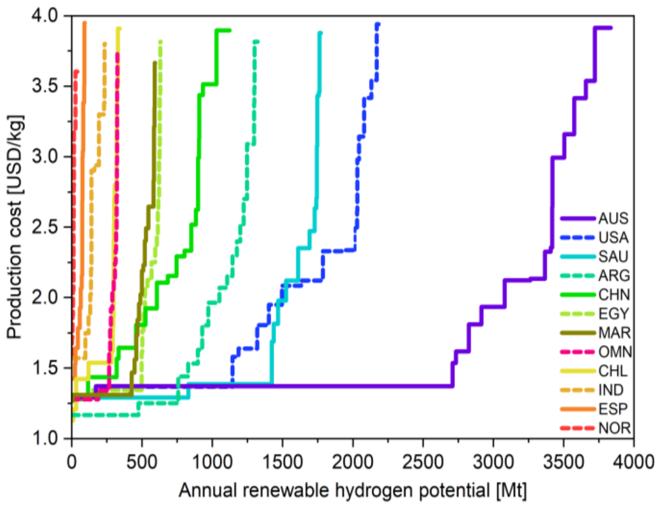

Fig. 3 Renewable hydrogen cost-potential curves for selected countries by 2050

Moreover, there are notable differences in hydrogen production costs among the nations. Countries with large desert areas, such as Argentina, Saudi Arabia, and Australia, exhibit high hydrogen production potential at reduced costs, primarily due to their strong solar energy potentials. Conversely, countries like Chile, while showcasing competitive production costs, demonstrate a mixed distribution of low to medium hydrogen potentials. European regions, represented by Spain and Norway, indicate limited production capabilities with their hydrogen production leaning towards the higher cost spectrum when compared with other regions.

3.2 Regional hydrogen demand-price curves

Figure 4 presents global hydrogen demand as a function of the assumed prices (willingness to pay) in 2050. Our results indicate that, under a 1.5 °C climate scenario with a lower price assumption of 1 USD/kg, the sectors examined in this study could collectively contribute to a potential annual demand of 380 Mt. When hydrogen price reaches the upper price assumption of 4 USD/kg, global demand is about 150 Mt. This demand predominantly originates from sectors with a limited alternatives to hydrogen, including steel production, heavy-duty transportation, maritime shipping, and aviation. Demand from these sectors consistently rises with lowering hydrogen prices. However, steel production exhibits an inelastic demand pattern, showing more resilience to price variation.

For lower hydrogen prices, specifically at 2 USD/kg and below, demand for high-temperature heat for industry starts to appear in various regions. This infers that, within this price bracket, hydrogen begins to be cost-competitive compared to other low-carbon alternative technologies. Finally, hydrogen demand for power generation starts to appear at a threshold price of 1.5 USD/kg. This trend is especially discernible in select regions such as India, the Middle East, and China.

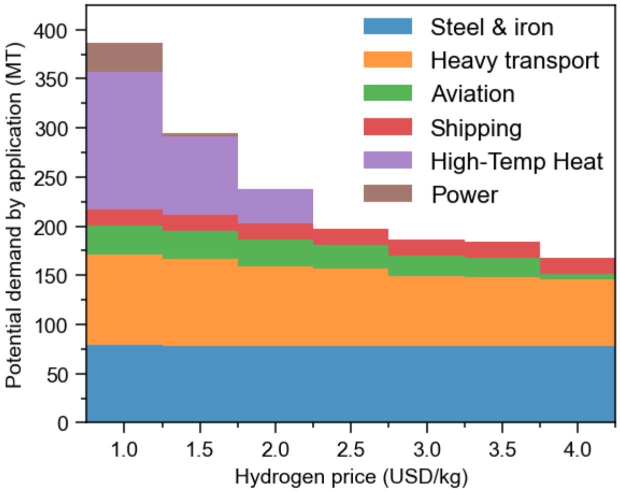

Fig. 4 Global demand for hydrogen as a function of willingness-to-pay price in 2050.

3.3 Hydrogen trade optimization

Using the aforementioned supply and demand curves as inputs to the global trade optimization model, the outcome results include market equilibrium curves, trade flows, required investments and expected producers' profits. This short paper presents the initial two findings, with the remainder of the results set for future publication.

3.3.1 Hydrogen trade flows by 2050

Figure 5 shows a detailed view of global hydrogen trade flows based on the investigated scenario of optimal allocation in 2050. Out of the 60 countries considered under the assumption of a highly competitive markets, about half show a cost-competitive advantage, positioning them as potential future producers and exporters of hydrogen.

The results indicate the global renewable hydrogen market is estimated to reach around 195.2 Mt by 2050 to meet the demand in key hydrogen applications identified in this study, except for its use in ammonia production which is outside the scope of this study. International trade accounts for about a quarter of the total demand.

Pipelines emerge as the primary choice for hydrogen trade within regions due to their cost advantage. Major producing countries like China, USA, and India utilize pipelines for hydrogen transportation. European countries, notably Spain and France, also rely on pipelines for intra-European hydrogen trade. Similarly, countries in the Middle East and Africa predominantly use pipelines for regional hydrogen trade.

For international hydrogen trade, ammonia stands out as the preferred hydrogen carrier due to its lower cost compared to liquid hydrogen option. Countries in South America, especially Argentina and Chile, are identified as leading hydrogen exporters, attributed to their vast solar energy resources and available land. Chile predominantly exports hydrogen to Japan, South Korea, and Western Europe, while Argentina exports mainly to other Asian countries.

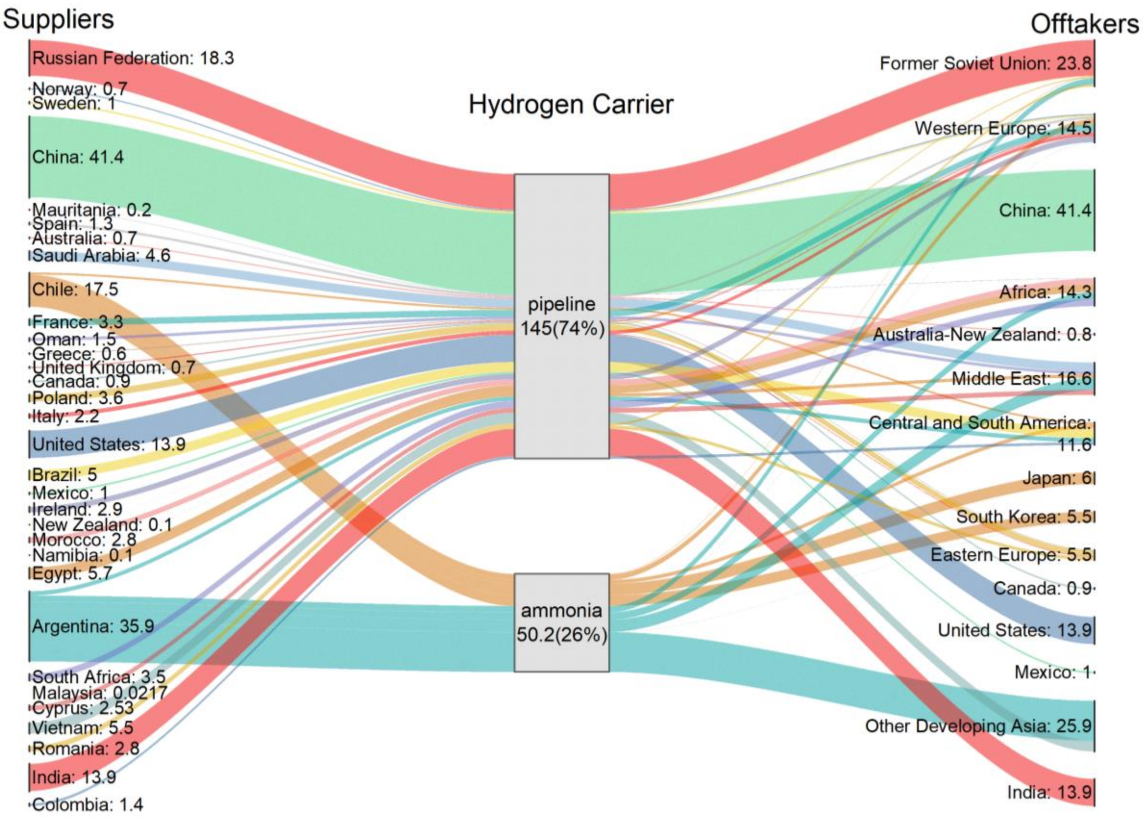

Fig. 5 Global hydrogen trade flows in 2050

3.3.2 Hydrogen supply-demand equilibrium curves

Figure 6 presents the hydrogen market equilibrium curves endogenously generated by the trade model. These curves depict price-demand equilibrium in corresponding demand regions in the investigated scenario of optimal allocation in 2050.

In most regions, the equilibrium prices for hydrogen in the range of 2 USD/kg. Countries like Japan and South Korea can fulfill their entire hydrogen demand around this price from a single supplier. Major economies, including China, USA, and India, maintain consistent prices at or below 2 USD/kg, primarily due to their competitive domestic production capabilities. For other regions, hydrogen supply is obtained from various suppliers at different prices, converging to a market clearing price around 2 USD/kg.

Equilibrium demand, however, showcases more diversity across regions. The primary factors affecting the equilibrium demand stem from potential demand levels provided to the trade model, notably the less price-influenced demand for end-use applications such as steel and iron production and heavy-duty transportation. The geographical proximity of a demand region to hydrogen suppliers also plays a significant role in shaping the equilibrium demand. China leads with the highest equilibrium demand, capturing 20% of the market share.

Following this are the Other Developing Asia and the Former Soviet Union regions, each with a 12% market share. The USA, Western Europe, Middle East, and Africa each hold nearly 7%. Meanwhile, Japan and South Korea each have market shares around 3%.

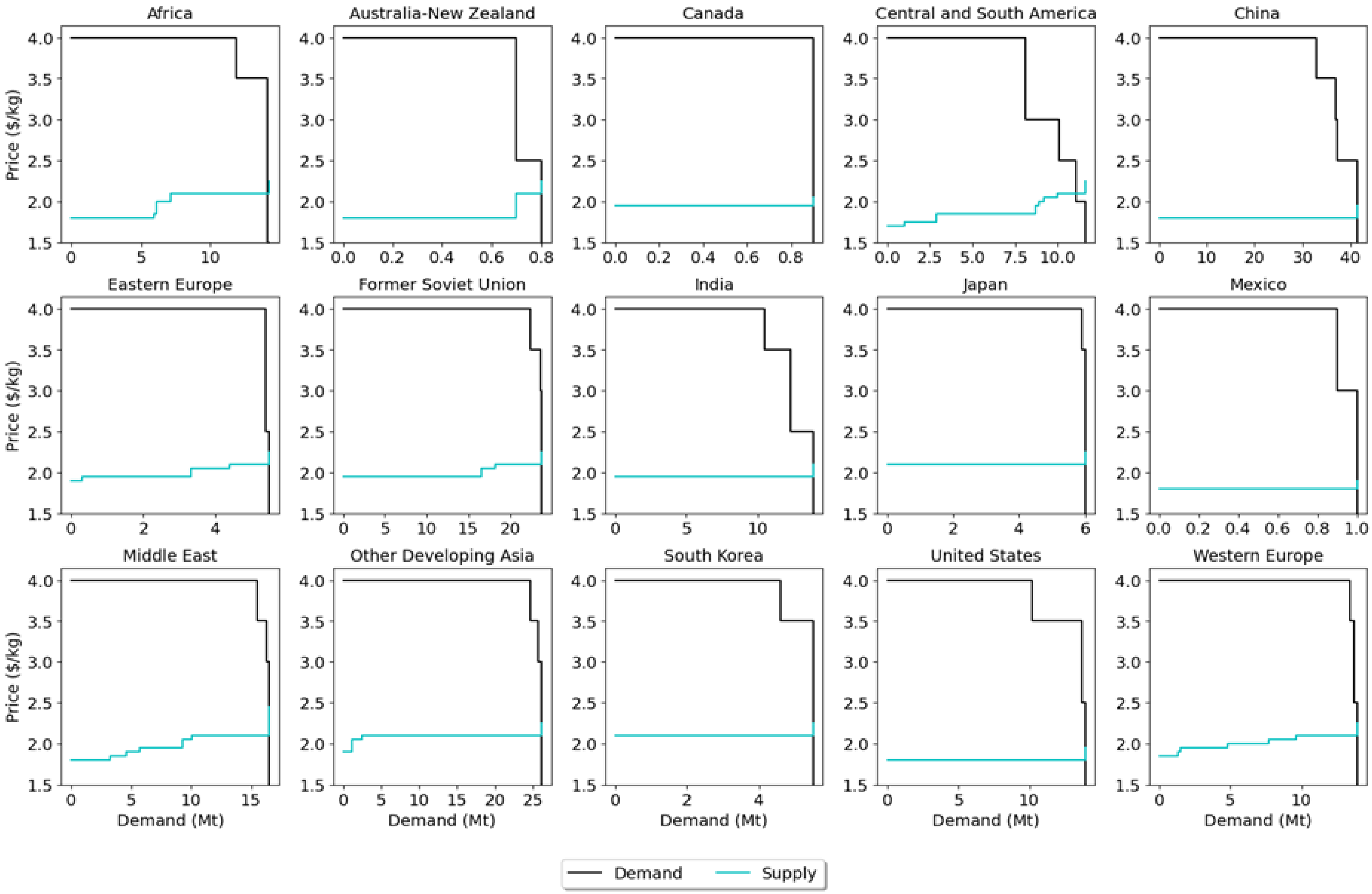

Fig. 6 Regional hydrogen market equilibrium curves by 2050

4. CONCLUSIONS

In this study, we introduce a novel modelling framework designed to simulate hydrogen market equilibrium and international trade scenarios in the long-term future. Our methodology includes the development of supply and demand curves, as well as a global hydrogen trade model that takes into account various supply chain options. Using this framework, we are able to derive quantitative insights into equilibrium supply and demand, pricing dynamics, trade flows, costs, and many more. When used in scenario-based analyses, our modelling framework emerges as a valuable tool for informing policy and decision-making processes regarding the future development of hydrogen markets. Finally, we apply this framework to study optimal global hydrogen markets development in the year 2050. The findings of this study contribute significantly to the efforts aimed at realizing an efficient allocation of global hydrogen resources.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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