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## Model of International Green Hydrogen Trade

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# About the Authors

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# Abstract

The Model of International Green Hydrogen Trade (MIGHTY) is an optimization model to investigate renewable hydrogen production, consumption, and trade between countries. MIGHTY supports strategic analysis by policymakers and investors about the potential roles that countries and regions will play in future renewable hydrogen markets. For this purpose, MIGHTY uses mixed-integer linear programming optimization to find the combination of domestic renewable hydrogen production and international imports that minimizes annual supply costs —which include production and transportation costs—while meeting the hydrogen demand of one country or a group of countries. This paper introduces the model and describes the model formulation, including a brief explanation of how MIGHTY accounts for pipeline diameters and renewable hydrogen cost curves. Finally, limitations and options for future development are discussed.

Version 0.1.0, 2022

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# 1. Introduction

Hydrogen is a versatile and sustainable energy carrier with many potential uses in mobility and stationary applications. Most importantly, hydrogen has the potential to tackle hard-to-abate emissions in sectors that account for over one-fourth of global $CO_2$ emissions, such as iron and steel production, high-temperature industrial heat, aviation, shipping, long-distance road transportation, and heat for buildings (Davis et al., 2018).

In recent years, hydrogen has gained unprecedented momentum. As governments worldwide have strengthened their commitment to decarbonization, their search for solutions to achieve net-zero emissions has renewed interest in clean hydrogen. As a result, policymakers and businesses are mobilizing a fast-increasing number of resources to bring about the hydrogen economy. In July 2021, McKinsey & Co. estimated that at least 359 large-scale hydrogen projects had been announced globally, amounting to 500 billion USD of associated investments through 2030 (McKinsey & Co., 2021). In addition, in 2021 alone, more electrolysis capacity for hydrogen production was installed around the world than during the previous decade (IEA, 2021).

While renewable hydrogen production is still costlier than production from fossil fuels, companies and governments are pursuing multiple strategies to improve its competitiveness, such as technology innovation, cost reductions along value chains, and carbon pricing (IRENA, 2020a). However, other key obstacles such as the lack of enabling infrastructure, established markets, and uniform regulations and policies may prove harder to address.

Research on renewable hydrogen's global geopolitical and market implications has shown that countries will assume specific roles in global renewable hydrogen markets based on their renewable energy and water endowments as well as their infrastructure potential (Pflugmann and De Blasio, 2020). One key insight is that while resource-rich countries will be able to develop their renewable hydrogen potential to meet their domestic demand and even become regional exporters, most countries will not. Instead, water-, renewable- or infrastructure-constrained countries will have to rely on imports from neighboring, regional or long-distance partners with the potential to become export champions.

A rapidly growing body of literature explores the technological and economic aspects of large-scale clean hydrogen production (El-Emam and Özcan, 2019) as well as its geopolitical and market implications (Pflugmann and De Blasio, 2020; Van der Graaf, 2020). However, little effort has been devoted to developing tools for enabling systematic scenario analyses of competitive, secure, and diversified supply options for bridging production gaps in one country or region with international green hydrogen trade.

Several reasons explain this gap in the academic literature. On the one hand, the economics of renewable hydrogen production (Glenk and Reichelstein, 2019) and their long-term evolution (Brändle et al., 2021) have often been addressed independently of global production potentials. In addition, the literature has focused on technological aspects, such as the design of national hydrogen networks (Baufumé et al., 2013; Welder et al., 2018). On the other hand, when renewable hydrogen potentials and costs have been jointly assessed, the analyses have disregarded geographical differences (Lux and Pfluger, 2020), have limited (Blanco et al., 2018) or excluded trade (Kakoulaki et al., 2021), or considered only a short-term horizon (Andreola et al., 2021). In addition, key variables such as freshwater availability and different infrastructure potentials are often overlooked.

This paper presents a new optimization model that contributes to bridging this knowledge gap by simultaneously considering renewable hydrogen production potentials, production and transportation costs, and projected hydrogen demand. Analyses based on this model could thus inform qualitative studies of geopolitical and market implications and complement scattered quantitative analyses of production potential and cost in the literature.

# 2. **Model Introduction**

The Model for International Green Hydrogen Trade (MIGHTY) was developed to investigate international hydrogen trade. MIGHTY is a mixed-integer linear programming (MILP) optimization model that finds the combination of domestic renewable hydrogen production and international imports that minimizes annual supply costs—which include production and transportation costs—while meeting the hydrogen demand of one country or a group of countries (e.g., the European Union).

The purpose of MIGHTY is to provide strategic guidance for policymakers and investors about the potential roles that countries and regions will play in future renewable hydrogen markets. MIGHTY simultaneously considers hydrogen demand projections, renewable hydrogen production potentials, production cost curves, geographical distances, and transportation costs.

MIGHTY was designed to investigate green hydrogen trade between countries. However, the geographical scope of the optimization depends on the inputs by the user. Therefore, the analysis area could be broadened to encompass groups of countries (e.g., the European Union) or economic regions. It could also be narrowed to the level of provinces or states within a single country. For simplicity, we refer to countries as the default unit of analysis. The temporal scope of MIGHTY's current version is based on annual variables.

To run MIGHTY, the user must define several sets, such as which countries are considered potential renewable hydrogen producers and which are considered hydrogen consumers, and provide input parameters, such as renewable hydrogen production potentials and technology costs.

MIGHTY applies a set of constraints to ensure that the solution it finds is viable:
- A demand constraint that ensures hydrogen production meets hydrogen demand;
- A supply constraint that guarantees that producer countries' supplies do not exceed their renewable hydrogen potentials;
- A hydrogen transport constraint that prevents duplicated pipelines and shipping routes; and
- A trade volume constraint that avoids unrealistically small hydrogen trades.

MIGHTY finds a solution that minimizes its objective function—total cost of hydrogen supply—within the constraints listed above. To do this, MIGHTY decides on renewable hydrogen production in each country, trading routes between producer and consumer countries, the diameter of the pipelines, and the number of ships connecting them.

The main outputs from MIGHTY are:

- Renewable hydrogen supply costs;
- Renewable hydrogen production in each country; and
- Hydrogen transportation infrastructure.

Thanks to MIGHTY's granularity, further analysis of the main outputs can reveal important insights about the solution found by MIGHTY. For instance, each producer and consumer country's investment requirements in renewable electricity generation, electrolysis, and transportation infrastructure can be estimated based on MIGHTY's results.

Overall, MIGHTY provides a realistic estimation of future international green hydrogen trade that considers different pipeline sizes and shipping fleets while remaining a tool for supporting strategic decision making rather than detailed technical planning. For this purpose, MIGHTY uses a set of discrete pipeline diameter sizes based on industry standards and a discrete number of vessels serving each shipping route. For each trade route, pipeline and shipping fleet sizes depend on how much hydrogen flows from the producer to the consumer country and how far apart they are.

Currently, there exists no large-scale infrastructure for transporting hydrogen between countries. In addition, hydrogen's low volumetric energy density as a gas and its liquefaction at a temperature below -253°C (-423°F) make its delivery particularly challenging. For these reasons, it remains uncertain how hydrogen will be transported between countries and whether it will be delivered as free hydrogen molecules or stored in some other chemical form, for example, in a hydrogen carrier like ammonia.

Therefore, MIGHTY can consider different hydrogen transportation technologies. MIGHTY Version 0.1.0 has been used with the following three options:

- *Hydrogen gas pipelines,* in which hydrogen is transported as a compressed gas through newly built pipelines;
- *Liquefied hydrogen shipping*, in which hydrogen is liquefied at an export terminal, shipped as a liquid, and regasified on arrival; and
- *Ammonia shipping*, in which hydrogen is used to produce ammonia, shipped to the importer country, and converted back to hydrogen on arrival.

In this version of MIGHTY, countries included as renewable hydrogen producers and consumers need to be assigned a primary mode of hydrogen transportation based on their geographies. For example, in an application of MIGHTY to the future of renewable hydrogen in the European Union (Nuñez-Jimenez and De Blasio, 2022), all continental European countries were assumed to use hydrogen pipelines for large-scale hydrogen transportation whenever possible because transportation costs are lower compared to shipping over distances less than 2,000 km. Meanwhile, countries in northern Africa, island states, and long-distance partners were assumed to ship their hydrogen.

The remainder of this document describes MIGHTY Version 0.1.0 formulated in Python using Pyomo (Hart et al., 2017). As a mixed-integer linear problem model, MIGHTY can be efficiently solved with commonly used solvers like Gurobi (Gurobi Optimization, 2020).

## 2.1 **Uses**

MIGHTY was initially developed to investigate the role different countries will play in future renewable hydrogen markets from a strategic perspective and elucidate the market and geopolitical consequences of large-scale trade of renewable hydrogen. Applied to the future of renewable hydrogen in the European Union, MIGHTY has already proved helpful for long-term strategic analysis (Nuñez-Jimenez and De Blasio, 2022). But MIGHTY can also be applied to other cases. For example, large countries like India, China, or the United States have states and provinces with different renewable energy resources and hydrogen demand outlooks. MIGHTY could be used to analyze future strategies for developing national renewable hydrogen industries. Another potential use of MIGHTY is to investigate import and export options for a single country. For - example, nations with high energy demands and moderate or low renewable hydrogen potentials, like Japan, will have to develop import strategies to meet their hydrogen needs. Similarly, aspiring export champions like Chile can explore different approaches to grow their renewable hydrogen trades by analyzing multiple scenarios with MIGHTY.

# 3. Model Formulation

This section describes the key elements of the mathematical formulation of MIGHTY, including model sets (Section 3.1), decision variables (Section 3.2), and parameters (Section 3.3).

## 3.1 Model Sets

Countries considered as hydrogen consumers (i.e., buyers) are members of the set $B$, while countries considered as hydrogen producers are members of the set $P$. The set of producer countries $P$ can contain members of the buyer countries set $B$. If this is the case, MIGHTY will consider the possibility of domestic self-consumption (i.e., production of renewable hydrogen for meeting demand within the country) during the optimization process.

The potential production of renewable hydrogen in each producer country $p$ is represented by a set of resources $R$, and each resource is characterized by a potential production and levelized cost of hydrogen production. This representation allows MIGHTY to incorporate renewable hydrogen cost curves for each producer country and use them to estimate production costs as a function of hydrogen production. In this way, a producer country $p$ with two resources $r1$ and $r2$ could produce $q_{r1}$ million tons of hydrogen per year (Mt/yr) at a levelized cost of production of $c_{r1}$ USD/kg and $q_{r2}$ Mt/yr at a different cost $c_{r2}$ USD/kg. The total production potential of country $p$ is thus the sum of $q_{r1}$ and $q_{r2}$ (see further details in Section 5).

MIGHTY considers a discrete number of hydrogen gas pipeline sizes represented in the model by the set $S$ (see further details in Section 4).

This version of MIGHTY requires the definition of two additional sets with the list of countries with pipeline $TMP$ and shipping $TMS$ as default hydrogen transportation modes, respectively.

All model sets and indices in MIGHTY are summarized in Table 1.

**Table 1. MIGHTY model sets and indices**

| Set | Index | Description |
|---|---|---|
| **B** | *b* | Buyer countries considered in the model scenario |
| **P** | *p* | Producer countries considered in the model scenario |
| **R** | *r* | Resources for renewable hydrogen production in each producer country |
| **S** | *s* | Sizes of hydrogen gas pipelines considered in the model |
| **TMP** | - | Countries with pipelines as the default hydrogen transportation mode |
| **TMS** | - | Countries with shipping as the default hydrogen transportation mode |

## 3.2 **Model Decision Variables**

MIGHTY has four decision variables. During the optimization process, the values of these variables are changed systematically to find what renewable hydrogen supply and trades minimize production and transportation costs while meeting the hydrogen demand of all consumer countries.

### 3.2.1. Renewable hydrogen production

MIGHTY decides how much renewable hydrogen each country produces by determining what share of their renewable hydrogen potential is developed.

In MIGHTY, a country's renewable hydrogen potential is represented as a list of resources $r$, each characterized by a production potential and levelized production cost (e.g., 1 Mt $H_2$ at 1.0 USD/kg). MIGHTY uses the float decision variable $x_{p,r,b}$ to determine the fraction of renewable hydrogen production from resource $r$, which is located in producer country $p$, that is developed for use in consumer country $b$. Following the previous example, a value of $x_{p,r,b}$ of 0.1 indicates that production of 0.1 Mt $H_2$ is developed in country $p$ to be consumed in country $b$. By adding up the fractions of a production potential $r$ destined for all consumer countries $\sum_{b \in B} x_{p,r,b}$, MIGHTY can estimate the total production developed from that resource. Continuing with the same example, a sum value of 0.8 indicates 0.8 Mt $H_2$ production at 1.0 USD/kg.

### 3.2.2. Renewable hydrogen trade route

MIGHTY decides whether producer country $p$ and consumer country $b$ establish a renewable hydrogen trade route with the Boolean decision variable $\alpha_{p,b}$.

### 3.2.3. Hydrogen gas pipeline size in a trade route

If two countries establish a renewable hydrogen trade route and both countries have pipelines as their default transportation mode, then MIGHTY decides on the size of the pipeline connecting the two countries with the Boolean variable $\beta_{p,b,s}$. The pipeline diameter determines pipeline size. To choose a pipeline diameter, MIGHTY sets the Boolean variable $\beta_{p,b,s}$ to one for the selected size $s$ and zero for all other sizes. The discrete set of pipeline diameters used in the current version of MIGHTY is described in Section 4.

### 3.2.4. Number of ships on a trade route

If two countries establish a renewable hydrogen trade route and at least one of them has shipping as their default transportation mode, then MIGHTY decides the number of ships covering the trade route with the integer variable $\gamma_{p,b}$. Besides cost minimization, the number of ships is also chosen based on ship capacity, speed, load and unload times, availability, and fuel efficiency—all of which are input data provided by the user.

MIGHTY systematically varies the values of these four variables to find the combination of domestic renewable hydrogen production and international trade that minimizes the total cost of renewable hydrogen supply while meeting the demand of consumer countries (see Table 2).

**Table 2.  Decision variables of MIGHTY**

| Decision variable | Type | Value range | Description |
|---|---|---|---|
| $x_{p,r,b}$ | Float | (0,1) | Fraction of renewable hydrogen resource $r$ in country $p$ that is developed to export hydrogen to country $b$ |
| $\alpha_{p,b}$ | Boolean | {0,1} | Hydrogen trade route between producer country $p$ and consumer country $b$ |
| $\beta_{p,b,s}$ | Boolean | {0,1} | Pipeline of size s between producer country $p$ and consumer country $b$ |
| $\gamma_{p,b}$ | Integer | $Z^+$ | Number of ships transporting hydrogen from producer country $p$ to consumer country $b$ |

## 3.3  Model Parameters

MIGHTY requires the user to specify the value of several parameters (See Table 3). These parameters mainly represent inputs relating to the cost of the different components of the renewable hydrogen supply chains. In addition, parameters not listed below (e.g., return trips per year a ship can complete for a specific trade route) are calculated by MIGHTY during the optimization process based on input data.

**Table 3.  MIGHTY parameters**

| Parameter | Unit | Description |
|---|---|---|
| $C_b$ | [Mt H$_2$/yr] | Annual hydrogen demand in consumer country $b$ |
| $OM^z$ | [%] | Annual operation and maintenance cost of component $z$, which is expressed as a percentage of investment costs |
| $av^z$ | [%] | Availability of component $z$ expressed as a percentage of hours in the year |
| $p_z^{el}$ | [USD/kWh] | The average cost of renewable electricity in the country $z$ |
| $p_p^{H2}$ | [USD/kg H$_2$] | The average cost of renewable hydrogen in producer country $p$ |
| $v_{ship}$ | [km/h] | The average velocity of the ship |
| $BOR^z$ | [%/day] | The boiloff rate of component $z$, which is expressed as the percentage of capacity per day |
| $p^h$ | [USD/kWh] | The average cost of heating |
| $i$ | [%] | Discount rate |
| $d_{p,b}$ | [km] | Distance between producer country $p$ and consumer country $b$ |
| $e^z$ | [kWh/kg HC] | Electricity use per unit of hydrogen carrier to operate component $z$ |
| $f^z$ | [kg HC/km] | The fuel efficiency of a ship carrying hydrogen carrier $z$ |

| | | |
|---|---|---|
| $h^z$ | [kWh/kg HC] | Heat use per unit of hydrogen carrier to operate component $z$ |
| $I^z$ | [bn USD/Mt HC or bn USD/Mt HC/yr or bn USD per unit] | The investment cost for component $z$ |
| $I_s^p$ | [bn USD/km] | Investment cost per unit of distance for a hydrogen pipeline of diameter $s$ |
| $c_{p,r}$ | [USD/kg H₂] | Levelized cost of renewable hydrogen production with resource $r$ in producer country $p$ |

When necessary, MIGHTY applies unit conversion factors to ensure all calculations are dimensionally correct.

## 3.4 **Objective Function**

MIGHTY's optimization goal is to minimize the total cost of renewable hydrogen supply, including production and transportation costs (see Equation 1).

**Equation 1. Objective function**

$$Min\left(PC + TC^{pipe} + TC^{ship}\right)$$

$PC$ is the annual renewable hydrogen production costs, $TC^{pipe}$ is the annual hydrogen transportation costs through the network of pipelines, and $TC^{ship}$ is the annual hydrogen shipping costs.

### 3.4.1. Hydrogen production costs

Hydrogen production costs $PC$ depend on two factors: one, the total fraction $\sum_{b \in B} x_{p,r,b}$ of hydrogen production potential $q_{p,r}$ developed from each resource $r$ in each producer country $p$, and two, the production cost $c_{p,r}$ of the renewable hydrogen produced from each resource $r$ in each producer country $p$.

The production costs $c_{p,r}$ represent the levelized cost of hydrogen production via water electrolysis powered with renewable electricity generated from the resource $r$ in the producer country $p$. Capacity factors of different renewable energy resources in a producer country $p$ range from below 10% to as high as 40% (e.g., in excellent offshore wind locations). Therefore, within each producer country $p$, there may be resources with different renewable hydrogen production costs.

MIGHTY takes production cost curves into account by computing annual production cost following Equation 2.

**Equation 2. Hydrogen production costs**

$$PC = \sum_{p \in P} \sum_{r \in R_p} q_{p,r} \cdot c_{p,r} \cdot \sum_{b \in B} x_{p,r,b}$$

## 3.4.2. Transportation costs: Hydrogen pipeline network

The transportation costs of sending hydrogen as a compressed gas through pipelines from producer to consumer countries $TC^{pipe}$ account for the cost of building and operating and maintaining a hydrogen pipeline network comprised of pipelines and storage facilities (see Equation 3).

**Equation 3. Hydrogen pipeline transportation costs**

$$TC^{pipe} = \sum_{p \in P} \sum_{b \in B} \sum_{s \in S} \gamma_{p,b,s} \cdot \left( d_{p,b} \cdot I_s^p \cdot (a^p + OM^p) + \frac{t^{scs}}{365} \cdot q_s^{max} \cdot I^{scs} \cdot (a^{scs} + OM^{scs}) \right)$$

Because of its focus on international hydrogen trade and strategic analysis, MIGHTY only considers transmission pipelines. However, networks formed by smaller hydrogen pipelines will be required for collecting hydrogen from dispersed producer plants to the main transmission pipelines and distributing hydrogen from the transmission pipeline to the end users. Similarly, the need for networks of smaller hydrogen pipelines will arise when hydrogen is shipped. In previous MIGHTY applications, the cost of these networks was approximated by considering the distance between the countries' centers instead of their hydrogen production and demand centers or their coasts (i.e., for shipping), thus making transmission pipelines and shipping routes slightly longer than they would be otherwise.

Taking a conservative approach, MIGHTY assumes all hydrogen pipelines are newly built. Various sources estimate that retrofitting existing natural gas pipelines to transport hydrogen as a compressed gas could significantly reduce investment costs. Estimates vary widely, with cost reductions ranging between 20% to over 70% (e.g., see Cerniauskas et al., 2020; Wang et al., 2020; Tezel and Hensgens, 2021). However, routes connecting renewable hydrogen supply and demand may differ from those covered by existing natural gas pipelines. Therefore, future hydrogen pipelines will be unable to rely entirely on retrofitting existing natural gas infrastructure. Given the difficulty of assessing what share of the existing infrastructure could be retrofitted, input parameters are based on new pipeline construction.

With the considerations mentioned above, MIGHTY uses the decision variable $\gamma_{p,b,s}$ to minimize transportation costs through pipelines. This variable determines whether a pipeline from producer country $p$ to consumer country $b$ is built and of which size. MIGHTY makes the variable $\gamma_{p,b,s}$ equal to one for the pipelines that need to be built while keeping it at zero for all others.

For the pipelines that are built, MIGHTY considers the annualized cost of building the pipeline and operating and maintaining it. Annualized investment costs depend on the distance between producer and consumer countries $d_{p,b}$, the investment cost $I_s^p$ of a pipeline with the selected diameter $s$, and the annuity factor $a^p$. Operation and maintenance costs are estimated as a percentage of investment costs with $OM^p$. The annuity factor $a^p$ is calculated with the general discount rate $i$ and the lifetime of the pipeline $l^p$ and a general formula for annuity factors (see Equation 4).

**Equation 4. Annuity factor**

$$a = \frac{i}{1 - (1 + i)^{-l}}$$

Regarding hydrogen storage, MIGHTY assumes that storage facilities are built along the pipelines to meet storage requirements for operating the hydrogen gas grid throughout the year. To approximate hydrogen storage costs, this version of MIGHTY builds a storage capacity capable of supplying the maximum flow through the pipeline $q_s^{MAX}$ over several days $t^{SCS}$. Building costs $I^{SCS}$ are annualized with $a^{SCS}$ while operation and maintenance costs are estimated as a percentage of investment costs with $OM^{SCS}$. For simplicity, this version of MIGHTY assumes no hydrogen losses in storage facilities.

### 3.4.3. Transportation costs: Liquefied hydrogen shipping

Hydrogen shipping costs $TC^{ship}$ account for the investment, operation, and maintenance costs of all steps in the hydrogen (or ammonia) shipping supply chain from producer to consumer countries. The costs taken into account depend on whether the hydrogen carrier for shipping is liquefied hydrogen or ammonia.

Trading renewable hydrogen between countries using liquefied hydrogen shipping involves five steps: hydrogen liquefaction, storage in the export terminal, transportation aboard a liquefied hydrogen vessel, storage in an import terminal, and, finally, evaporation (see Figure 1).

**Figure 1. Schematic representation of liquefied hydrogen shipping**
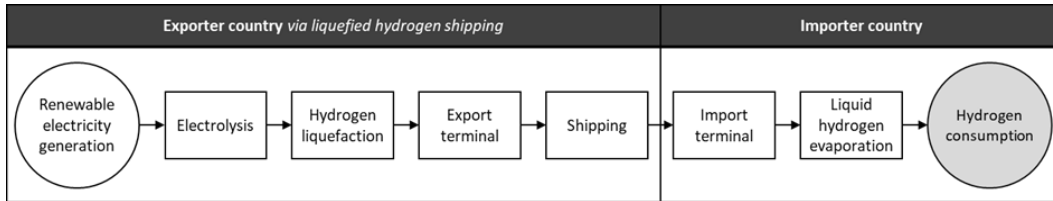


MIGHTY considers the cost of each of these five steps to compute the transportation costs of liquefied hydrogen shipping (see Equation 5).

**Equation 5. Transportation costs for liquefied hydrogen shipping**

$$TC^{ship} = LC + ET^{LH2} + SF^{LH2} + IT^{LH2} + EC$$

Liquefaction costs include the cost of building the liquefaction facility, operation and maintenance, and electricity use (see Equation 6). Construction costs $I^{LC}$ are adjusted for plant availability $av^{LC}$ to ensure that all hydrogen exported overseas by producer country $p$ can be liquefied. Construction costs are annualized with $a^{LC}$ and operation and maintenance costs are estimated as a percentage of construction costs with $OM^{LC}$. Costs from the electricity use required to run the liquefaction process $e^{LC}$ are computed based on the average cost of renewable electricity in the country $p_p^{el}$. The liquefaction capacity needed in the producer country is determined based on the total hydrogen exported via liquefied hydrogen shipping.

**Equation 6. Hydrogen liquefaction costs**

$$LC = \sum_{p \in P} \left( \left( \frac{I^{LC}}{av^{LC}} \cdot (a^{LC} + OM^{LC}) + e^{LC} \cdot p_p^{el} \right) \cdot \sum_{r \in R_p} \sum_{b \in B} x_{p,r,b} \cdot q_{p,r} \right) \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

Next, MIGHTY considers the cost of the export terminal. For each producer country sending hydrogen overseas, MIGHTY estimates the storage capacity required for the continuous operation of the export terminal throughout the year. Then, MIGHTY computes building, operation and maintenance, electricity use, and vented boiloff hydrogen costs (see Equation 7).

The export terminal capacity is estimated based on the capacity needed to hold in the terminal enough hydrogen to operate for a few days $t^{ET}$ at maximum export capacity, considering vessel capacity $q_{ship}^{LH2}$, number $\gamma_{p,b}$, and round trips per year $rty_{p,b}$. The decision variable $\gamma_{p,b}$ ensures only shipping routes that minimize supply costs are considered.

Construction costs $I^{ET-LH2}$ are adjusted for the terminal's availability throughout the year $av^{ET-LH2}$ and annualized with $a^{ET-LH2}$. Operation and maintenance costs are calculated as a percentage of construction costs with $OM^{ET-LH2}$. MIGHTY accounts for electricity use $e^{ET-LH2}$ based on average renewable electricity costs in the country $p_p^{el}$. Electricity use is computed based on storage capacity and accounts for the use of pumps and other equipment. In addition, MIGHTY also considers the cost of hydrogen lost while stored in the terminal based on boiloff rate $BOR^{ET-LH2}$, stored time $t^{ET}$, and average renewable hydrogen cost in the country $p_p^{H2}$.

**Equation 7. Export terminal costs for liquefied hydrogen shipping**

$$ET^{LH2} = \sum_{p \in P} \left( \left( \frac{I^{ET-LH2}}{av^{ET-LH2}} \cdot (a^{ET-LH2} + OM^{ET-LH2}) + e^{ET-LH2} \cdot p_p^{el} + BOR^{ET-LH2} \cdot t^{ET} \cdot p_p^{H2} \right) \right.$$

$$\left. \cdot \sum_{b \in B} \left( rty_{p,b} \cdot q_{ship}^{LH2} \cdot \gamma_{p,b} \cdot \frac{t^{ET}}{365} \right) \right) \forall p, b \in P, B \ if \ p \ or \ b \in TMS$$

MIGHTY estimates the round trips per year that a ship can complete between producer country $p$ and consumer country $b$ based on the ship availability $av_{ship}$, distance between the countries $d_{p,b}$, average ship velocity $v_{ship}$, and load and unload times (see Equation 8.)

**Equation 8. Ship round trips per year**

$$rty_{p,b} = \frac{av^{ship} \cdot 8760}{\left( 2 \cdot \frac{d_{p,b}}{v_{ship}} + t_{ship}^{load} + t_{ship}^{unload} \right)}$$

After export terminal costs are estimated, MIGHTY evaluates the cost of shipping fleets based on ship unit cost $I^{ship-LH2}$ that is annualized with $a^{ship-LH2}$, operation and maintenance costs $OM^{ship-LH2}$, and the cost of hydrogen for powering the ships.

MIGHTY assumes liquefied hydrogen ships use hydrogen as fuel. For the outbound leg of the trip, the vessel uses the hydrogen that boils off the vessel's storage, while, for the return leg, the ship retains part of the cargo hydrogen for fuel. The cost of this hydrogen is estimated considering round trips per year $rty_{p,b}$, route length $d_{p,b}$, and ship's fuel efficiency $f^{LH2}$. Boiloff hydrogen is estimated based on the ship's capacity $q_{ship}^{LH2}$, boiloff rate $BOR^{ship-LH2}$, and velocity $v_{ship}^{LH2}$, which determines how long hydrogen stays stored in the vessel.

**Equation 9. Shipping fleet costs for liquefied hydrogen shipping**

$$SF^{LH2} = \sum_{p \in P} \sum_{b \in B} \gamma_{p,b} \cdot \left( I^{ship-LH2} \cdot (a^{ship-LH2} + OM^{ship-LH2}) + rty_{p,b} \cdot d_{p,b} \cdot p_p^{H2} \cdot \left( \frac{q_{ship}^{LH2} \cdot BOR^{ship-LH2}}{v_{ship}} + f^{LH2} \right) \right)$$

The fourth step in the liquefied hydrogen shipping supply chain is the import terminal. Analogously to export terminals, but in consumer countries importing hydrogen by sea, MIGHTY estimates the storage capacity required to operate the import terminals throughout the year and then computes building, operation and maintenance, electricity use, and boiloff hydrogen costs (see Equation 10).

Import terminal construction costs $I^{IT-LH2}$ are adjusted for availability $av^{IT-LH2}$ and annualized using $a^{IT-LH2}$. Operation and maintenance costs are computed as a percentage of investment costs with $OM^{IT-LH2}$. Electricity costs are approximated based on the electricity used for operating the import terminal $e^{IT-LH2}$ and the average renewable electricity cost in the country $p_b^{el}$. Boiloff hydrogen costs are computed separately to account for the different costs of hydrogen $p_p^{H2}$ depending on the producer country $p$ where the imported hydrogen originated.

**Equation 10. Import terminal costs for liquefied hydrogen shipping**

$$IT^{LH2} = \sum_{b \in B} \left( \left( \frac{I^{IT-LH2}}{av^{IT-LH2}} \cdot (a^{IT-LH2} + OM^{IT-LH2}) + e^{IT-LH2} \cdot p_b^{el} \right) \cdot \sum_{p \in P} \left( rty_{p,b} \cdot q_{ship}^{LH2} \cdot \gamma_{p,b} \cdot \frac{t^{IT}}{365} \right) \right.$$

$$\left. + \sum_{p \in P} \left( rty_{p,b} \cdot q_{ship}^{LH2} \cdot \gamma_{p,b} \cdot \frac{t^{IT}}{365} \cdot BOR^{IT-LH2} \cdot t^{IT} \cdot p_p^{H2} \right) \right) \forall p, b \in P, B \text{ if } p \text{ or } b \in TMS$$

MIGHTY also considers evaporation (or regasification) costs for all liquefied hydrogen imports. Evaporation costs are estimated based on the cost of construction, operation and maintenance, and electricity use (see Equation 11). MIGHTY determines the size of the regasification facility based on annual liquefied hydrogen imported from overseas. Construction costs $I^{EC}$ are adjusted for availability $av^{EC}$ and annualized with $a^{EC}$. Operation and maintenance costs are estimated as a percentage of investment costs with $OM^{EC}$. Electricity costs are computed based on electricity use $e^{EC}$ and the average renewable electricity cost in the country $p_b^{el}$. For simplicity, the current version of MIGHTY assumes no losses in the process.

**Equation 11. Hydrogen evaporation costs**

$$EC = \sum_{b \in B} \left( \left( \frac{I^{EC}}{av^{EC}} \cdot (a^{EC} + OM^{EC}) + e^{EC} \cdot p_b^{el} \right) \cdot \sum_{r \in R_p} \sum_{p \in P} x_{p,r,b} \cdot q_{p,r} \right) \; \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

## 3.4.4. Transportation costs: Ammonia shipping

A different supply chain, adapted to ammonia's chemical and physical properties, is required for producing ammonia from renewable hydrogen, shipping it between countries, and converting it back to hydrogen on arrival. MIGHTY represents the ammonia shipping supply chain with five steps: ammonia production, export and import terminals, shipping, and ammonia reconversion (see Figure 2).

**Figure 2. Schematic representation of ammonia shipping**
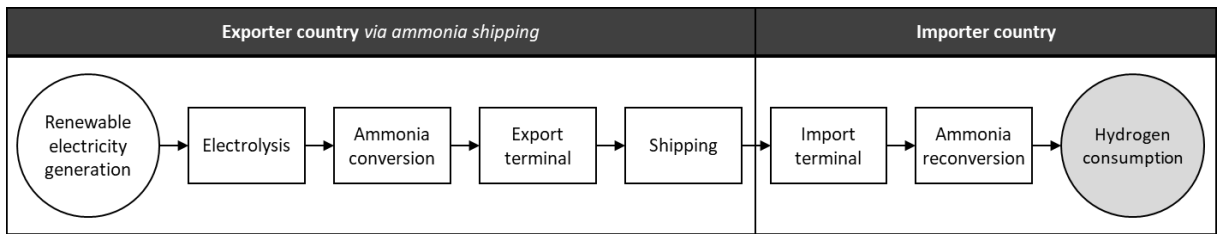


In scenarios with ammonia shipping, MIGHTY considers all five steps to estimate the total cost of ammonia shipping (see Equation 12).

**Equation 12. Transportation costs of ammonia shipping**

$$TC^{ship} = APC + ET^{NH3} + SF^{NH3} + IT^{NH3} + ARC$$

MIGHTY computes ammonia production costs by considering the construction cost of ammonia production $I^{AP}$, adjusted for the plant's availability $av^{AP}$ and annualized with $a^{AP}$. Operation and maintenance costs are estimated as a percentage of construction costs $OM^{AP}$. Electricity costs are based on electricity use $e^{AP}$ and the average renewable electricity cost in the country $p_p^{el}$ (see Equation 13). Production capacity is determined based on the total hydrogen exported via ammonia shipping. For simplicity, this version of MIGHTY assumes that there are no hydrogen losses during the production of ammonia.

**Equation 13. Ammonia production cost**

$$APC = \sum_{p \in P} \left( \left( \frac{I^{AP}}{av^{AP}} \cdot (a^{AP} + OM^{AP}) + e^{AP} \cdot p_p^{el} \right) \cdot \sum_{r \in R_p} \sum_{b \in B} x_{p,r,b} \cdot q_{p,r} \right) \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

The costs of ammonia export and import terminals are computed analogously to the costs of liquefied hydrogen export and terminals by applying conversion factors where necessary (see Equation 14 and 15).

**Equation 14. Export terminal costs for ammonia shipping**

$$ET^{NH3} = \sum_{p \in P} \left( \left( \frac{I^{ET-NH3}}{av^{ET-NH3}} \cdot (a^{ET-NH3} + OM^{ET-NH3}) + e^{ET-NH3} \cdot p_p^{el} + BOR^{ET-NH3} \cdot t^{ET} \cdot p_p^{H2} \right) \right.$$

$$\left. \cdot \sum_{b \in B} \left( rty_{p,b} \cdot q_{ship}^{NH3} \cdot \gamma_{p,b} \cdot \frac{t^{ET}}{365} \right) \right) \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

**Equation 15. Import terminal costs for ammonia shipping**

$$IT^{NH3} = \sum_{b \in B} \left( \left( \frac{I^{IT-NH3}}{av^{IT-NH3}} \cdot (a^{IT-NH3} + OM^{IT-NH3}) + e^{IT-NH3} \cdot p_b^{el} \right) \cdot \sum_{p \in P} \left( rty_{p,b} \cdot q_{ship}^{NH3} \cdot \gamma_{p,b} \cdot \frac{t^{IT}}{365} \right) \right.$$

$$\left. + \sum_{p \in P} \left( rty_{p,b} \cdot q_{ship}^{NH3} \cdot \gamma_{p,b} \cdot \frac{t^{IT}}{365} \cdot BOR^{IT-NH3} \cdot t^{IT} \cdot p_p^{H2} \right) \right) \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

MIGHTY assumes that ships transporting ammonia use ammonia as fuel. However, unlike in the case of liquefied hydrogen, boiloff rates are much lower for ammonia, and thus, MIGHTY must assess whether boiloff ammonia is enough to power the ship. If it is not, MIGHTY assumes that ships use as much boiloff ammonia as possible and take the rest from the cargo (see Equation 16).

**Equation 16. Shipping fleet costs for ammonia shipping**

$$SF^{NH3} = \sum_{p \in P} \sum_{b \in B} \gamma_{p,b} \cdot \left( I^{ship-NH3} \cdot (a^{ship-NH3} + OM^{ship-NH3}) + rty_{p,b} \cdot p_p^{H2} \cdot d_{p,b} \cdot \left( 2 \cdot f^{NH3} - BOR^{ship-NH3} \cdot \frac{q_{ship}^{NH3}}{v_{ship}} \right) \right)$$

Finally, MIGHTY assumes that ammonia is converted back to hydrogen on arrival. Ammonia reconversion costs include the cost of construction, operation and maintenance, electricity use, and heat use (see Equation 17). Construction costs $I^{AR}$ are adjusted for availability $av^{AR}$ and annualized with $a^{AR}$. Operation and maintenance costs are estimated as a percentage of investment costs $OM^{AR}$. Electricity costs are estimated based on electricity use $e^{AC}$ and the average renewable electricity cost in the country $p_b^{el}$, while heat costs are computed based on heat use $h^{AR}$ and an assumed cost of heating $p^h$, which is the same in all countries. For simplicity, this version of MIGHTY assumes that all hydrogen is recovered.

**Equation 17. Ammonia reconversion costs**

$$ARC = \sum_{b \in B} \left( \left( \frac{I^{AR}}{av^{AR}} \cdot (a^{AR} + OM^{AR}) + e^{AR} \cdot p_b^{el} + h^{AR} \cdot p^h \right) \cdot \sum_{r \in R_p} \sum_{p \in P} x_{p,r,b} \cdot q_{p,r} \right) \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

## 3.5 **Constraints**

MIGHTY has six constraints that ensure the search for an optimal solution that minimizes the objective function is mathematically correct and represents a realistic future scenario for international trades of green hydrogen.

### 3.5.1. Maximum renewable hydrogen production constraint

MIGHTY ensures that countries cannot produce more renewable hydrogen than their production potentials by limiting the fraction they can develop of each renewable hydrogen resource $r$ in each producer country $p$ to one (see Equation 18).

**Equation 18. Maximum renewable hydrogen production constraint**

$$\sum_{r \in R_p} x_{p,r,b} \leq 1; \; \forall p \in P$$

### 3.5.2. Supply and demand balance constraint

MIGHTY ensures that renewable hydrogen production meets consumer countries' demands by requiring that the sum of hydrogen flows into each consumer country $b$ adds up to the country's annual demand (see Equation 19).

**Equation 19. Supply and demand balance constraint**

$$\sum_{p \in P} \sum_{r \in R_p} x_{p,r,b} \cdot q_{p,r} = D_b; \ \forall b \in B$$

For simplicity and transparency of calculations, in this version of MIGHTY, the economic impact of hydrogen losses during transportation and storage is considered in the estimation of transportation costs. This is sufficiently detailed for the purpose of MIGHTY: long-term strategic decision making. In future versions of MIGHTY, the supply and demand balance constraint may include the overproduction requirements to account for hydrogen losses.

### 3.5.3. Maximum hydrogen transportation capacity constraint

MIGHTY ensures that a pipeline or a fleet of ships connecting two countries only carries as much hydrogen over the year as the pipeline diameter or the number of vessels allows.

If hydrogen is transported through a pipeline, the maximum hydrogen transportation capacity constraint depends on the maximum annual flow for each pipeline's diameter $q_s^{max}$ (see Equation 20).

**Equation 20. Maximum hydrogen transportation capacity constraint for pipelines**

$$\sum_{r \in R_p} x_{p,r,b} \cdot q_{p,r} \leq \sum_{s \in S} q_s^{max} \cdot \beta_{p,b,s} \ \forall p, b \in P, B \ if \ p \ and \ b \in TMP$$

If hydrogen is shipped, first, the ship's effective cargo is estimated (see Equation 21). The effective cargo is calculated based on three assumptions: (1) ships use the hydrogen carrier they transport as fuel (e.g., either hydrogen or ammonia); (2) fuel requirements are subtracted from the ship's cargo; and (3) in the outbound leg of the trip, ships use as much boiloff hydrogen or ammonia as possible, while using part of the cargo as fuel in the return leg.

**Equation 21. Effective cargo capacity for hydrogen-carrying vessels**

$$q_{eff}^{HC} = min\left(q^{HC} - q^{HC} \cdot BOR^{ship-HC} \cdot \frac{d_{p,b}}{v_{ship}} - f^{HC} \cdot d_{p,b}, q^{HC} - 2 \cdot f^{HC} \cdot d_{p,b}\right)$$

If the effective cargo of the ship is zero or negative, the route cannot be serviced based on the input data for the vessel design—vessels with more cargo space and higher fuel efficiencies would be required for that route. In this case, the number of ships covering the route is zero.

If there is a remaining capacity in the ship, then MIGHTY applies the constraint, based on the number of ships $\gamma_{p,b}$ covering the route, their effective cargo $q_{eff}^{HC}$ and round trips per year $rty_{p,b}$ (see Equation 22).

**Equation 22. Maximum hydrogen transportation capacity constraint for shipping**

$$\sum_{r \in R_p} x_{p,r,b} \cdot q_{p,r} \leq \sum_{s \in S} q_{eff}^{HC} \cdot rty_{p,b} \cdot \gamma_{p,b}; \; \forall p, b \in P, B \; if \; p \; or \; b \in TMS$$

## 3.5.4. Minimum hydrogen trade constraint

To avoid mathematically correct but unrealistically small international hydrogen trades, MIGHTY requires a minimum hydrogen trade $q_p^{min}$ to establish a trade route (see Equation 23).[1] In the application of MIGHTY to the European Union (Nuñez-Jimenez and De Blasio, 2022), minimum hydrogen trade constraints of $10^6$, $10^7$, and $10^8$ kg per year were required for establishing trade routes between European Union member states and neighboring, regional, and long-distance producers, respectively.

**Equation 23. Minimum hydrogen trade constraint**

$$\sum_{r \in R_p} x_{p,r,b} \cdot q_{p,r} \geq q_p^{min}; \; \forall p \in P$$

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[1] A maximum hydrogen trade constraint is required so that the model's mathematical formulation is complete. However, this constraint is assigned such a large value that it does not influence the optimization process.

### 3.5.5. Single pipeline constraint

MIGHTY ensures that only one hydrogen pipeline is built for transporting hydrogen between a producer and a consumer country. If trade between the producer and consumer countries requires hydrogen to be shipped, MIGHTY keeps the number of pipelines connecting the countries at zero (see Equation 24).

**Equation 24. Single pipeline constraint**

$$\sum_{s \in S} \beta_{p,b,s} \leq 1 \; \forall s \in S \; and \; \forall p, b \in P, B \; if \; p \; and \; b \in TMP$$

$$\sum_{s \in S} \beta_{p,b,s} = 0 \; \forall s \in S \; otherwise$$

### 3.5.6. Pipeline preference constraint

This version of MIGHTY includes this constraint to simplify the study of the future of renewable hydrogen in the European Union (Nuñez-Jimenez and De Blasio, 2022). Continental European nations were assumed to transport hydrogen between them using hydrogen pipelines. Distances between European Union countries are relatively short and guarantee that pipelines are less costly than shipping for transporting hydrogen on a large scale. To represent this, MIGHTY forces the number of ships between producers and consumers that can connect via pipelines to zero (see Equation 25).

**Equation 25. Pipelines preference constraint**

$$\gamma_{p,b} = 0 \;\; \forall p, b \in P, B \; if \; p \; and \; b \in TMP$$

$$\gamma_{p,b} \geq 0 \; otherwise$$

# 4. Accounting for Pipeline Diameters

Pipeline costs vary depending on the pipeline's size. Therefore, MIGHTY determines the diameter of each pipeline in order to minimize hydrogen transportation costs. While, in theory, pipelines of any size could be manufactured, there are standard pipeline sizes that manufacturers widely use. Therefore, MIGHTY incorporates standard hydrogen gas pipeline sizes as a discrete variable to bring calculations closer to reality.

MIGHTY considers transmission pipelines with diameters between 400 and 1,200 mm (around 16 and 48 inches) to transport compressed pure hydrogen gas between countries. This version of MIGHTY uses the standardized pipeline diameter sizes reported by Reuss et al. (2019) as input data, as shown in Table 4.

**Table 4. Hydrogen pipeline diameters**

Source: Reuss et al. (2019).

| Diameter nominal name | Approx. nominal pipe size equivalent [inches] | Diameter [mm] | Diameter nominal name | Approx. nominal pipe size equivalent [inches] | Diameter [mm] |
|---|---|---|---|---|---|
| DN100 | 4 | 106 | DN750 | 30 | 769 |
| DN125 | 5 | 131 | DN800 | 32 | 814 |
| DN150 | 6 | 159 | DN850 | 34 | 864 |
| DN200 | 8 | 207 | DN900 | 36 | 915 |
| DN250 | 10 | 259 | DN950 | 38 | 960 |
| DN300 | 12 | 306 | DN1000 | 40 | 1,011 |
| DN325 | 14 | 336 | DN1050 | 42 | 1,058 |
| DN350 | 16 | 384 | DN1100 | 44 | 1,104 |
| DN400 | - | 432 | DN1150 | 46 | 1,155 |
| DN450 | 18 | 480 | DN1200 | 48 | 1,249 |
| DN500 | 20 | 527 | DN1300 | 52 | 1,342 |
| DN550 | 22 | 578 | DN1400 | 56 | 1,444 |
| DN600 | 24 | 625 | 2xDN1200 | 2x48 | 1,648 |
| DN650 | 26 | 671 | 2xDN1300 | 2x52 | 1,771 |
| DN700 | 28 | 722 | 2xDN1400 | 2x56 | 1,905 |

As explained by Reuss and colleagues, pipeline diameters above 1,400 mm (around 56 inches) are unusual. So instead, two adjacent pipelines with smaller diameters are used. Reuss and colleagues calculated the equivalent diameters of looped pipelines in Table 4 following the method of Lenz and Schwarz (2016) with Equation 26.

**Equation 26. Equivalent pipeline diameter of looped pipes**

$$D = \left( D_1^{\frac{5}{2}} + D_2^{\frac{5}{2}} \right)^{\frac{2}{5}}$$

In Nuñez-Jimenez and De Blasio (2022), this set of discrete pipeline diameters was combined with the estimated investment cost as a function of diameter used by the International Energy Agency (IEA) (2019)—based on Baufumé et al. (2013)—and assuming a 20% cost reduction by 2050 (see Equation 27).

**Equation 27. Hydrogen gas pipeline investment cost**

$$I_s^p = 3{,}200 \cdot D^2 + 478.9 \cdot D + 253.2, with\ D\,[m]\ and\ I_s^p \left[ \frac{USD}{m} \right]$$

Figure 3 shows that the cost of transporting compressed gas hydrogen through pipelines is strongly influenced by pipeline diameter and distance. To illustrate this, the input data mentioned above were used, and the hydrogen storage required to operate each pipeline continuously was considered, as discussed in Section 3.4.

**Figure 3. Hydrogen transportation costs by pipeline**
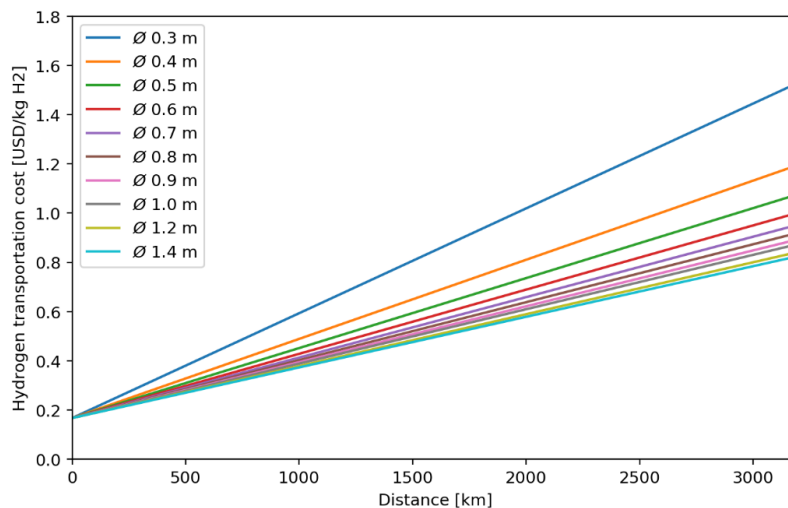
# 5. Renewable Hydrogen Cost Curves as Inputs

In its current version, MIGHTY requires the user to input producer countries' renewable hydrogen cost curves. Cost curves correlate production costs and the quantity of renewable hydrogen produced and thus combine estimates of production potential and cost. This section explains how cost curves were developed in Nuñez-Jimenez and De Blasio (2022) by combining the methodology developed by Pflugmann and De Blasio (2020) with estimates of the levelized cost of hydrogen production for renewable resources in each producer country.

Each country's available renewable energy resources were calculated based on peer-reviewed databases of renewable electricity potentials (Eurek et al., 2017; Pietzcker et al., 2014). The overall land availability for renewables in each country was derived by subtracting protected natural areas and built urban environments. Remote and uneconomic resources were also excluded (see Table 5), aligning with recent literature (Kakoulaki et al., 2021). In addition, the equivalent of each country's current primary energy consumption was assumed to be used in other sectors or remain undeveloped to account for competing demand for renewable electricity (BP, 2020). Renewable energy potentials were then used to calculate renewable hydrogen production potentials—assuming an electrolysis efficiency of 74%, as projected by the IEA (2019).

**Table 5. Assumptions for economic renewable electricity generation potentials**

| Variable | Economic viability assumptions | Data source |
|---|---|---|
| Solar energy | Economically viable resources have a capacity factor higher than 11% (equivalent to 1,000 full-load hours) and are less than 100 km away from an urban area. | Pietzcker et al. (2014) |
| Onshore wind energy | Economically viable resources have a capacity factor higher than 26% (equivalent to 2,278 full-load hours) and are less than 160 km away from an urban area. | Eurek et al. (2017) |
| Offshore wind energy | Economically viable resources have a capacity factor higher than 26% (equivalent to 2,278 full-load hours), are less than 20 nautical miles (approx. 37 km) away from the coast, and at sea depths below 30 meters. | Eurek et al. (2017) |

The availability of freshwater resources can further reduce a country's renewable hydrogen potential. Considering that 9 kg of water is needed per kg of hydrogen produced, based on stoichiometric relations, water availability was limited to 5% of each country's internal renewable freshwater resources, a fraction of the average water withdrawal for industrial use worldwide of 13% (UN FAO, 2020).

In a second step, renewable hydrogen production costs in each country were calculated. Economic and financial parameters, including a discount rate of 8%, were based on long-term technology cost projections by the IEA and the International Renewable Energy Agency (IRENA) (see Table 6). The IEA's World Energy Outlook 2020 includes projections of renewable energy technology costs up to 2040. Therefore, the IEA's outlook was combined with cumulated installed capacity scenarios from IRENA (2020b) to project costs until 2050 using experience curves.

**Table 6. Renewable energy technology economic inputs**

|  | PV | Onshore wind | Offshore wind |
|---|---|---|---|
| **Global cumulated installed capacity**[1] | 2040: 5,982 GW<br>2050: 10,651 GW | 2040: 4,195 GW<br>2050: 6,693 GW | 2040: 552 GW<br>2050: 1,143 GW |
| **Learning rate**[2] | 20% | 15% | 15% |
| **Investment cost**[3] | 2040: 490 USD/kW<br>2050: 407 USD/kW | 2040: 1,420 USD/kW<br>2050: 1,273 USD/kW | 2040: 2,040 USD/kW<br>2050: 1,720 USD/kW |
| **Operation and maintenance costs**[4] | 2.5% CAPEX | 2.9% CAPEX | 2.5% CAPEX |
| **Lifetime**[5] | 25 years | 25 years | 25 years |

[1] Data from cumulative capacity additions in IRENA (2020b). [2] Based on learning rates review in Brändle et al. (2021). [3] Investment cost in 2040 based on Stated Policy Scenario for Europe in IEA (2020). Investment in 2050 was estimated using each technology's experience curve. [4] Estimated from capital costs, operation and maintenance costs and capacity factors for Europe 2040 in the Stated Policies Scenario in IEA (2020). [5] Based on IEA (2019).

The input data for water electrolysis were based on the IEA's long-term projections for polymer electrolyte membrane (PEM) electrolyzers (see Table 7). While PEM electrolyzers are costlier than alkaline and less efficient than solid oxide electrolyzers, their greater flexibility to operate efficiently with variable power sources and more robust learning effects could make them the most competitive electrolyzer technology in the short-to-medium term (Böhm et al., 2020).

**Table 7. Electrolysis input parameters**

Source: IEA (2019)

| Electrolyzer | |
|---|---|
| **Investment cost** | 450 USD/kW |
| **Operation and maintenance costs** | 1.5% CAPEX |
| **Efficiency** | 74% LHV |
| **Lifetime** | 20 years |
| **Water consumption** | 9 kg water/kg $H_2$ |

Renewable hydrogen production costs were estimated using a levelized hydrogen (LCOH) cost, considering all costs and expected hydrogen production over the electrolysis plant's lifetime. Then, based on the granularity of the databases (Eurek et al., 2017, Pietzcker et al., 2014), renewable hydrogen potential and production costs in each country were estimated as a list of resources, each characterized by a renewable electricity production potential (i.e., in TWh per year) and a resource quality (i.e., in terms of full-load hours per year). Finally, the process described below was repeated for every renewable energy resource in each producer country and used as input for MIGHTY.

First, the levelization factor for hydrogen production $L_{H2}$ was computed. This factor represents the equivalent full-load hours that the electrolysis plant operates during its lifetime $T_H$ and discounted over time with a rate $i$. The quality of the renewable energy resources co-located with the water electrolysis plant determines the full-load hours $FLH_{RE}$ that the plant operates. In this case, wind and solar power generation were considered with the same power rating as the electrolysis plant (see Equation 28).

**Equation 28. Levelization factor for hydrogen production**

$$L_H = \sum_{y \in T_H} \frac{FLH_{RE}}{(1+i)^y}$$

Second, capital expenditures $CAPEX_H$ were estimated by calculating the investment cost of the electrolysis plant $I_H$ for each kilogram of hydrogen produced during the plant's lifetime based on the levelization factor $L_H$, electrolyzer efficiency $\mu_H$, and hydrogen's lower heating value $LHV$ (see Equation 29).

**Equation 29. Capital expenditures for an electrolysis plant**

$$CAPEX_H = \frac{LHV}{\mu_H \cdot L_H} \cdot I_H$$

Third, operational expenditures $OPEX_H$ per kilogram of hydrogen produced were computed by estimating operation and maintenance cost $O\&M_H$ as a percentage of the investment cost $I_H$ and considering the discount rate $i$, the levelization factor $L_H$, electrolyzer efficiency $\mu_H$, and hydrogen's lower heating value $LHV$ (see Equation 30).

**Equation 30. Operational expenditures of an electrolysis plant**

$$OPEX_H = \frac{LHV}{\mu_H \cdot L_H} \cdot \sum_{y \in T_H} \frac{O\&M_H \cdot I_H}{(1 + i)^y}$$

Finally, renewable electricity costs were estimated using the levelized cost of electricity $LCOE_{RE}$ of the wind or solar energy resource co-located with the electrolysis plant, which depends on the investment cost of the renewable electricity plant $I_{RE}$, operation and maintenance $O\&M_{RE}$ as a fraction of the investment cost, the plant's operational lifetime $T_{RE}$, full-load hours per year $FLH_{RE}$, and discount rate $i$ (see Equation 31).

**Equation 31. Levelized cost of renewable electricity**

$$LCOE_{RE} = \frac{I_{RE} + \sum_{y \in T_{RE}} \frac{O\&M_{RE} \cdot I_{RE}}{(1 + i)^y}}{\sum_{y \in T_{RE}} \frac{FLH_{RE}}{(1 + i)^y}}$$

Subsequently, the production costs of renewable hydrogen for the resources available in each country were estimated using Equation 32, where the electrolyzer efficiency $\mu_H$ and hydrogen's lower heating value $LHV$ are used to estimate renewable electricity costs per kilogram of hydrogen produced.

**Equation 32. Levelized cost of hydrogen production**

$$LCOH = CAPEX_H + OPEX_H + LCOE_{RE} \cdot \frac{LHV_H}{\mu_H}$$

Renewable hydrogen cost curves for all the producer countries considered were then grouped into sets and used as inputs to MIGHTY. The cost curves of selected European Union countries and potential trade partners are shown in Figure 4 and Figure 5, respectively. The significant differences in production potentials and costs between countries highlight the relevance of investigating international green hydrogen trade using strategic analysis tools like MIGHTY.

**Figure 4. Renewable hydrogen cost curves in selected European Union countries**
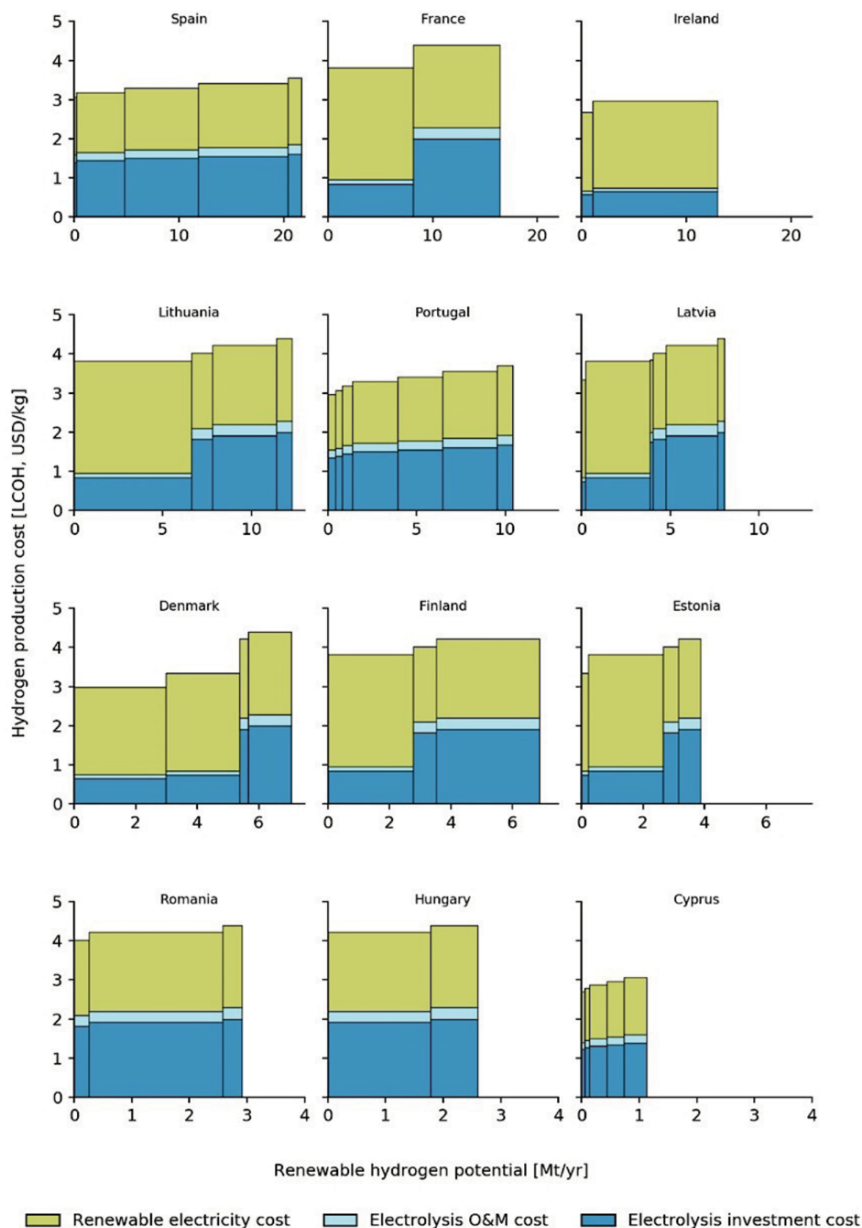
**Figure 5. Renewable hydrogen cost curves in European Union regional and long-distance partners**
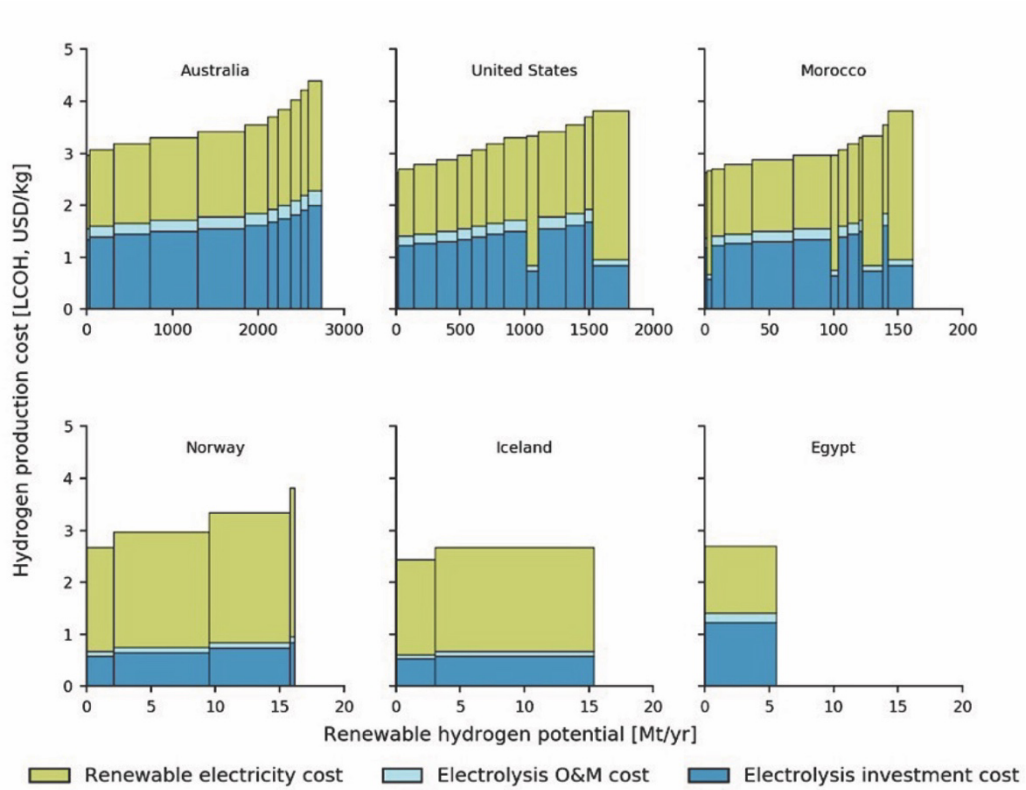
# 6. Limitations and Options for Future Development

MIGHTY is a simple and transparent model. Its purpose is to identify which countries might benefit most from future renewable hydrogen markets and prompt more detailed investigations of their potential roles. MIGHTY's purpose is not to capture the complexity of real-world energy markets or the engineering details of large-scale energy supply chains. Instead, MIGHTY focuses on the fundamental relation between renewable hydrogen potentials, future hydrogen demand outlooks, and technology costs to offer a transparent way to inform strategic discussions.

MIGHTY's current version has limitations that provide avenues for further development. First, MIGHTY requires the user to specify primary transportation modes of hydrogen for all countries in the analysis. Future versions will let the model decide which transportation mode between two countries trading green hydrogen minimizes supply costs (i.e., choosing between hydrogen gas pipelines, liquefied hydrogen shipping, and ammonia shipping). Second, MIGHTY estimates the cost of transporting hydrogen via pipelines by considering pipelines that run from the producer to the consumer country. However, in the real world, gas pipelines connect several countries, and gas flows from one or more producers to several consumer countries using the same infrastructure. Future versions will let the model decide which hydrogen pipeline network minimizes supply costs instead of considering pipeline routes independently. Third, MIGHTY only incorporates the economies of scale of building larger pipelines and shipping fleets. Future versions will also consider the economies of scale of constructing larger liquefaction and ammonia production plants, export and import terminals, regasification facilities, hydrogen storage, and ammonia reconversion plants.

Considering detailed engineering aspects of renewable hydrogen production and transportation falls beyond the scope of MIGHTY. Thus, their representation is simplified compared to models focused on the technical aspects of future hydrogen systems. However, if some of those aspects are considered strategic, they could be added to future versions of MIGHTY. Further developments are also possible, for example, integrating geospatial information on the location of renewable energy resources, existing natural gas pipelines, and demand hubs, which would enable MIGHTY to consider hydrogen gas distribution networks.

Finally, beyond the current scope of the model, we have identified several adjacent research topics in need of further academic analysis where MIGHTY could be applied to gain significant insights specifically other hydrogen production technologies and/or renewable energy sources.

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