Hydrogen Market Module of the National Energy Modeling System: Model Documentation 2025

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1. Introduction

The Hydrogen Market Module (HMM) is the component of the National Energy Modeling System (NEMS) that represents hydrogen market production, prices, inter-regional transmission, and storage in the United States. We developed the NEMS, an energy-economic modeling system, as the third in a series of computer-based energy-economy modeling systems. EIA and its predecessor, the Federal Energy Administration, have used NEMS to analyze and project U.S. domestic markets to provide 25-to-30-year projections and to analyze a broad range of energy issues at both national and regional levels. Although the NEMS was first used in 1992, the model is updated each year; updates in individual modules range from simple historical data updates to completely replacing submodules. The HMM is an entirely new model that we incorporated in the NEMS for the *Annual Energy Outlook 2025* (AEO2025) to fully represent current laws and regulations. Prior to AEO2025, hydrogen representation in NEMS was spread out across multiple modules and only represented implicitly as an intermediate product.

Documentation purpose and scope

This report provides a reference document for model analysts, and the public that defines the objectives of HMM, in the NEMS. This report also fulfills EIA's legal obligation to provide adequate documentation in support of our models under Public Law 93-275, Federal Energy Administration Act of 1974, Section 57(B)(1) (as amended by Public Law 94-385, Energy Conservation and Production Act).

In this report, we:

- Describe HMM's design and model formulation
- Provide details on the methodology employed
- Detail the model inputs, outputs, and key assumptions

Model Summary

The HMM models the hydrogen market in the NEMS. The model code is written in Advanced Integrated Multidimensional Modeling Software (AIMMS) and is a linear program that minimizes the total cost of producing hydrogen to meet hydrogen demand minus costs of transportation. The HMM determines hydrogen production, flows, and storage decisions for each of the four seasons in a given model year. The HMM projects:

- Hydrogen production by technology pathway
- The price of hydrogen, including delivered prices to end users in the industrial, transportation, and electric power sectors
- Volume of CO_2 captured during hydrogen production associated with carbon capture technology
- The cost of capturing CO_2 during hydrogen production associated with carbon capture technology
- Consumption of electricity and natural gas for hydrogen production

Although most projections in the HMM are made seasonally, HMM results are generally passed to other NEMS modules as annual totals or quantity-weighted annual average prices because most other NEMS modules operate on an annual basis.

2. Model Purpose.

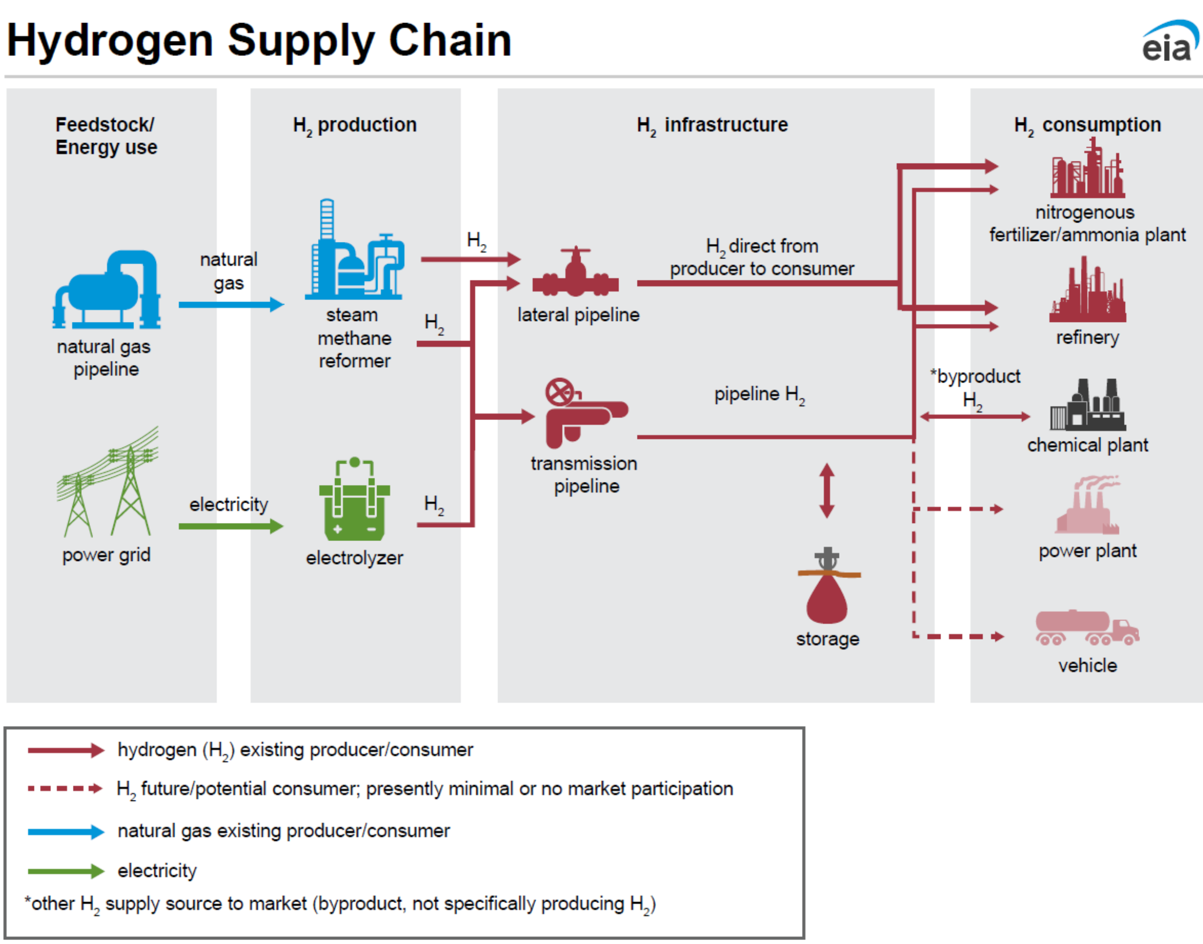
Model objectives

The Hydrogen Market Module (HMM) represents the hydrogen market in the National Energy Modeling System (NEMS), both as it operates today and how it may evolve in the future. The HMM balances supply and demand of hydrogen, projecting, among other things, long-term production and price trends. The HMM also reflects the effect of current laws and regulations that affect the economics of the hydrogen market from the perspective of producers.

Hydrogen market overview

Historically, most hydrogen in the United States is consumed by the chemicals and petroleum refining industries. In the chemicals industry, hydrogen is commonly used as a feedstock to produce nitrogenous fertilizers (ammonia and derivatives). In the petroleum refining industry, refiners use hydrogen to lower the sulfur content of diesel fuel in a process known as hydrotreating (Figure 1).

Figure 1. Illustration of the hydrogen market supply chain



Source: U.S. Energy Information Administration

To date, hydrogen production is generally produced via a process known as steam methane reforming (SMR), which converts natural gas feedstock into hydrogen. However, chemical plants and refineries can also produce hydrogen as a byproduct during other chemical processes for which hydrogen is not the main product. For example, hydrogen is a byproduct of chlorine production in the chlor-alkali industry and petrochemical plants release hydrogen as a byproduct of olefin production during alkane dehydrogenation. Refineries also produce hydrogen from their catalytic reformers, which is later used by the refinery.[1]

Hydrogen production is often classified as either “merchant” hydrogen production or “captive” hydrogen production. During captive production, hydrogen production is intentionally produced and consumed on site, contrasting with merchant production where hydrogen is produced and then shipped or sold to some other consumer of the hydrogen.[2]

While SMR currently produces nearly all hydrogen in the United States, some recent policies have been enacted to encourage alternative hydrogen production pathways:

- The 45Q production tax credit encouraging SMR with carbon capture and sequestration (CCS), which lowers the carbon intensity of steam methane reforming by capturing most of the CO_2 emissions preventing them from being released in the atmosphere
- The 45V production tax credit encouraging clean hydrogen production, namely electrolysis, which is a process that uses electricity to split water molecules (H_2O) into hydrogen and oxygen. If the electricity consumed by the electrolyzer comes from renewable sources (i.e., the associated carbon intensity of the electricity produced is below a defined threshold), the produced hydrogen is considered “clean”.

The electric power and transportation sectors are potential future large-scale consumers of hydrogen. In the transportation sector, hydrogen may be used as a vehicle fuel, particularly for heavy duty vehicles where hydrogen fuel cells are viable when policy requires the phase-out of fossil fuels. Hydrogen may also be used in the electric power sector by burning hydrogen in hydrogen turbines to generate electricity for the grid.

Hydrogen production

The HMM represents three hydrogen production technology options:

- steam methane reforming (SMR)
- steam methane reforming with carbon capture and sequestration (SMR + CCS)
- electrolysis

Other hydrogen production pathways exist that are not represented by the HMM, however the three production technologies represented by the HMM are well understood commercially and allow the HMM to represent policies that affect emerging technology options, such as SMR + CCS and electrolysis.

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[1] https://www.eia.gov/todayinenergy/detail.php?id=61983

[2] https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/16015_current_us_h2_production.pdf?Status=Master

It should be noted that the HMM's scope with respect to projecting hydrogen produced from SMR + CCS is that the HMM projects the capacity expansion of only new SMR + CCS facilities. Retrofitting existing SMR + CCS facilities is currently not represented by the HMM.

Alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis are all potential technology options to produce hydrogen via electrolysis. Of these options, the HMM assumes the electrolyzers the model builds operate as a PEM electrolyzer.[3]

The HMM's scope represents both merchant and captive hydrogen production. The HMM does not model hydrogen produced as a byproduct. Instead, byproduct hydrogen production is received from the Industrial Demand Module (IDM) and is added to supply for total hydrogen market balancing.

Hydrogen inter-regional transportation

The HMM has a limited representation of hydrogen transportation, explicitly representing only inter-regional transportation via dedicated hydrogen pipelines. Intra-regional hydrogen transportation is not explicitly represented; it is implicitly represented through end-use markup costs. The definition of inter-regional transportation used by HMM is a pipeline between different census divisions—the regional demand representation in the model. The HMM has the option to build new inter-regional hydrogen pipelines at an assumed capital cost. Converting existing natural gas pipelines into a dedicated hydrogen pipeline or blending hydrogen into natural gas pipelines are not represented by the HMM.

The model then operates hydrogen pipelines by paying the cost to move hydrogen from one region to another (also known as an arc) region to another, where the cost is based on the electricity needed to compress the hydrogen necessary to transport it across the arc. Both assumed capital and operational costs are customized for each potential arc to represent shorter or longer pipeline distances between regions.[4] Currently there is no representation of hydrogen lost during inter-regional pipeline transmission; however, the electricity consumption of the infrastructure is modeled and reflected in HMM.

Hydrogen storage

Hydrogen storage is proposed as a way to provide seasonal flexibility to the hydrogen market, allowing the market to produce hydrogen and inject it into storage at times when production is cheap (e.g., during spring and fall when wind power is traditionally high and electricity demand is relatively low), and withdraw the hydrogen from storage at times when production costs are high or demand for hydrogen may peak (e.g., during peak hours in seasons of high electricity demand).

The HMM specifically represents long-duration, seasonal geologic storage of hydrogen using salt caverns. If economic, the HMM has the option of building additional salt cavern storage capacity for an assumed capital cost, and pay a cost based on energy intensity[5] to compress the hydrogen to inject it into storage.[6] Other geologic hydrogen storage options, such as aquifers and depleted oil and gas

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[3] For assumptions regarding production capital and operational costs, see the Assumptions to the Hydrogen Market Module

[4] For assumptions regarding pipeline capital and operational costs, see the Assumptions to the Hydrogen Market Module

[5] We assume it takes about 2.2kwh/kg H_2 to compress hydrogen for use in storage.

[6] For assumptions storage production capital and operational costs, see the Assumptions to the Hydrogen Market Module

reservoirs have been proposed, but the viability of non-salt cavern storage options has not been proven, so they are not represented in the HMM.

Because HMM models each year independently, the HMM does not have the ability to inject hydrogen into storage in a given season in one model year and later withdraw the hydrogen from storage in a season for some later model year. All hydrogen the model injects into storage must be eventually withdrawn from storage that same year.

Representation of the hydrogen market in NEMS

NEMS overview

The NEMS is a modular system, including the Integrating Module and a series of relatively independent modules that represent the domestic energy system, the international energy market, and the economy.

The domestic energy system includes fuel supply markets, conversion activities, and end-use consumption sectors.[7] The projections in the AEO assume that energy markets are in equilibrium[8], using a recursive price adjustment mechanism.[9] For each fuel and consuming sector, the NEMS balances energy supply and demand, accounting for the economic competition between the various fuels and sources. The system includes a routine that can simulate a carbon emissions cap-and-trade system with annual fees to limit carbon emissions from energy-related fuel combustion. The primary flows of information between each of these modules are the delivered prices of energy to the end user and the quantities consumed by product, census division, and end-use sector. Other data in the module includes economic activity, domestic production activity, and international petroleum supply availability (Figure 2).

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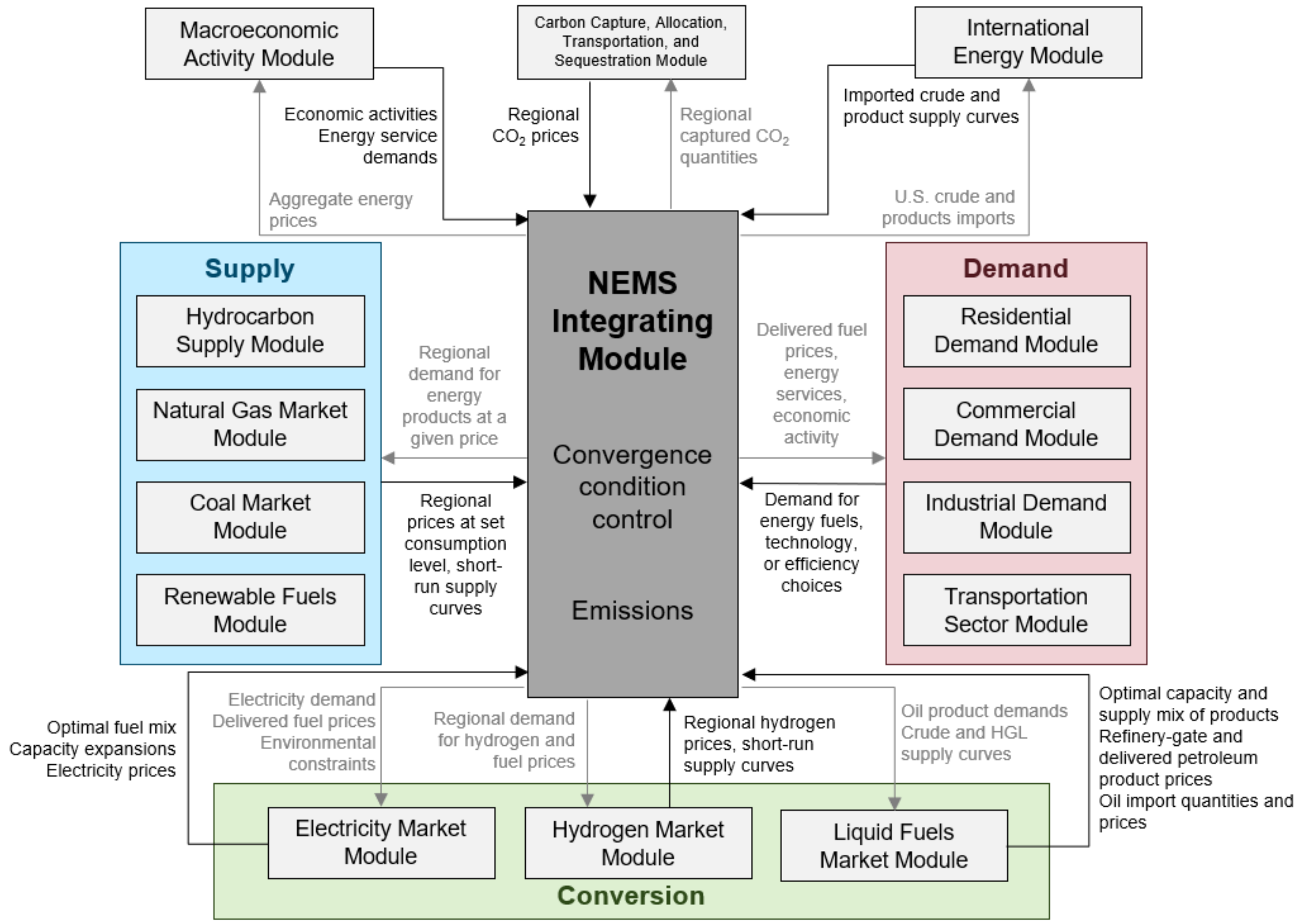
[7] U.S. Energy Information Administration, Documentation of the National Energy Modeling System (NEMS) modules (see latest documentation for the Integrating Module)

[8] Markets are said to be in equilibrium when the quantities demanded equal the quantities supplied at the same price; that is, at a price that sellers are willing to provide the commodity and consumers are willing to purchase the commodity.

[9] The central theme of the approach used is that supply and demand imbalances will eventually be rectified through a price adjustment that eliminates excess supply or demand.

Figure 2. Schematic of the NEMS and flow of information between modules

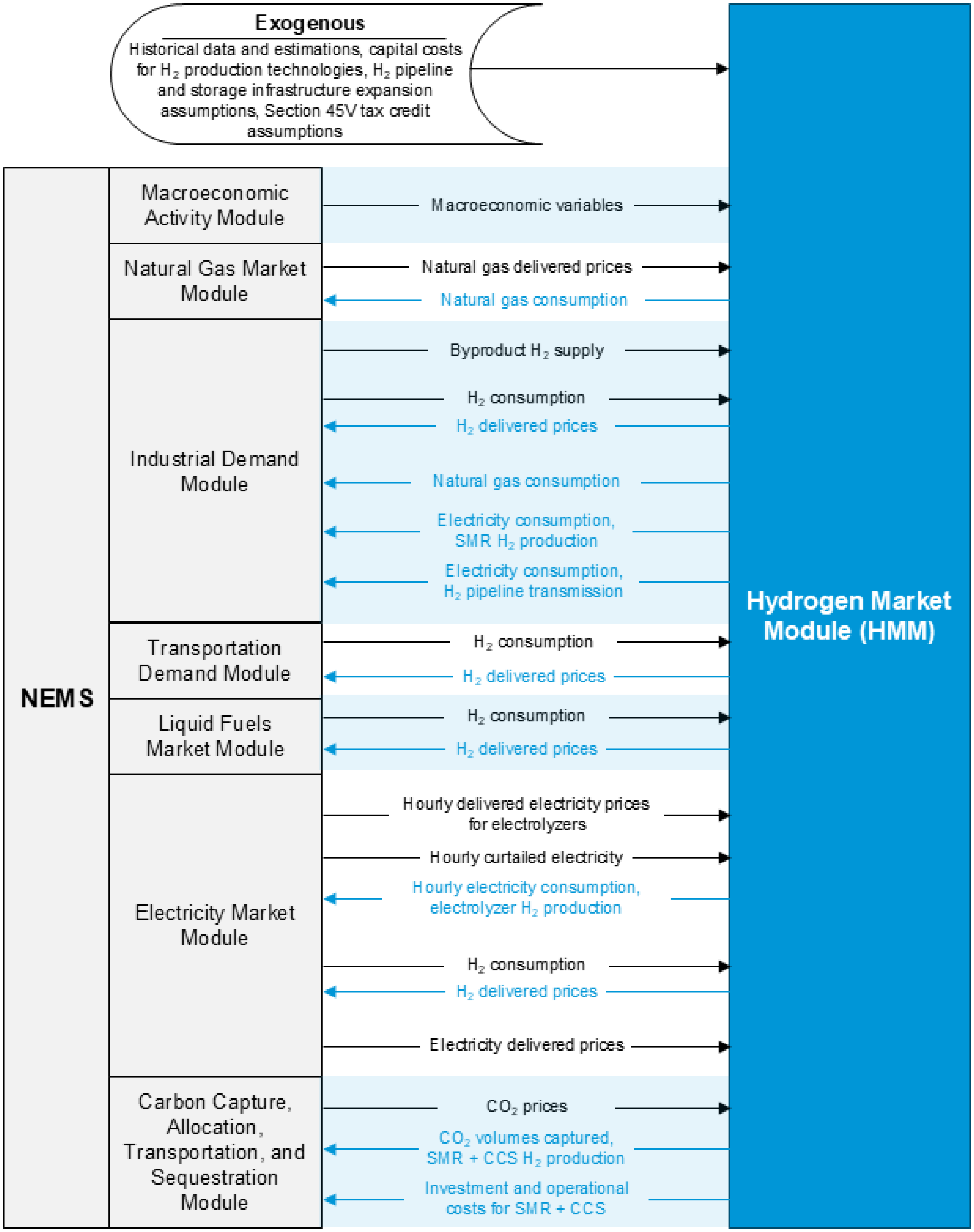


Source: U.S. Energy Information Administration

For each projection year, the NEMS solves by iteratively calling each module in sequence (once in each NEMS iteration for most modules) until the delivered prices and quantities of each fuel in each region have converged within tolerance between the various modules, achieving an economic equilibrium of supply and demand in the consuming sectors. For some applications, the model is also run in several cycles, generally to converge on a solution that involves foresight using prior cycles' projected values for future years when solving the current projection year. Module solutions are reported for each projection year through the midterm horizon. Although each module can operate at the level of detail—both regionally and temporally—most appropriate for its particular sector, they all aggregate (or disaggregate) their solutions to the census-division structure on an annual basis to transfer information within the NEMS.

Relation to other modules

Figure 3. Inputs and outputs of the HMM, including relationships between other NEMS modules



Source: U.S. Energy Information Administration

Note: H_2 = hydrogen

The HMM requires and provides input to other NEMS modules, which can be visualized in Figure 3. Data in the global data structure that are required by the HMM to project the hydrogen market include:

<u>Macroeconomic Activity Module (MAM)</u>

- Rate on industrial BAA bonds
- S&P 500 common stock index
- Real yield on U.S. treasury long-term bonds
- Gross domestic product (GDP) inflation adjustment factors

<u>Natural Gas Market Module (NGMM)</u>

- Seasonal industrial natural gas prices by census division

<u>Electricity Market Module (EMM)</u>

- Hourly electricity prices delivered to electrolyzers by EMM region[10]
- Competitive reliability component of the industrial electricity price, by EMM region
- Competitive transmission and distribution component of industrial electricity price, by EMM region
- Price of electricity to industrial consumers by census division
- Quantity of hydrogen consumed in the electric power sector by census division
- Hourly constraints on the hourly electricity load that electrolyzers can place on the grid
- Hourly renewable generation by technology and EMM region
- Vintage ratios of renewable generation by production technology by EMM region
- Hourly curtailment by EMM region

<u>Carbon Capture, Allocation, Transportation, and Sequestration Module (CCATS)</u>

- CO_2 price without 45Q tax credit by census division
- CO_2 price with 45Q tax credit by census division

<u>Industrial Demand Module (IDM)</u>

- Quantity of hydrogen consumed by the industrial sector by census division
- Industrial sector byproduct hydrogen supply by census division

<u>Transportation Demand Module (TDM)</u>

- Quantity of hydrogen consumed by the transportation sector by census division

<u>Liquid Fuel Market Module</u>

- Quantity of hydrogen consumed in the refinery sector by census division

[10] See Figure 6.

The HMM also sends data to the NEMS global data structure for other modules to use, including data used by the integration module to calculate total hydrogen supply-demand balance and data published in the *Annual Energy Outlook*. HMM outputs, and the modules that use them include:

- Delivered hydrogen price in the industrial, electric power, and transportation sectors by census division to the IDM, LFMM, EMM, and TDM
- Volume of CO_2 captured from hydrogen production, without and without the 45Q tax credit by census division to CCATS
- Operations and maintenance costs for carbon capture from hydrogen production by census division to CCATS
- Investment cost for carbon capture from hydrogen production by census division to the CCATS
- Quantity of natural gas consumed from hydrogen production (as feedstock and for heat and power) by census division to IDM
- Amount of electricity consumed for hydrogen production by census division to EMM
- Hourly electrical load from electrolyzers by EMM region to EMM

3. Hydrogen Market Module Design and Structure

Model design

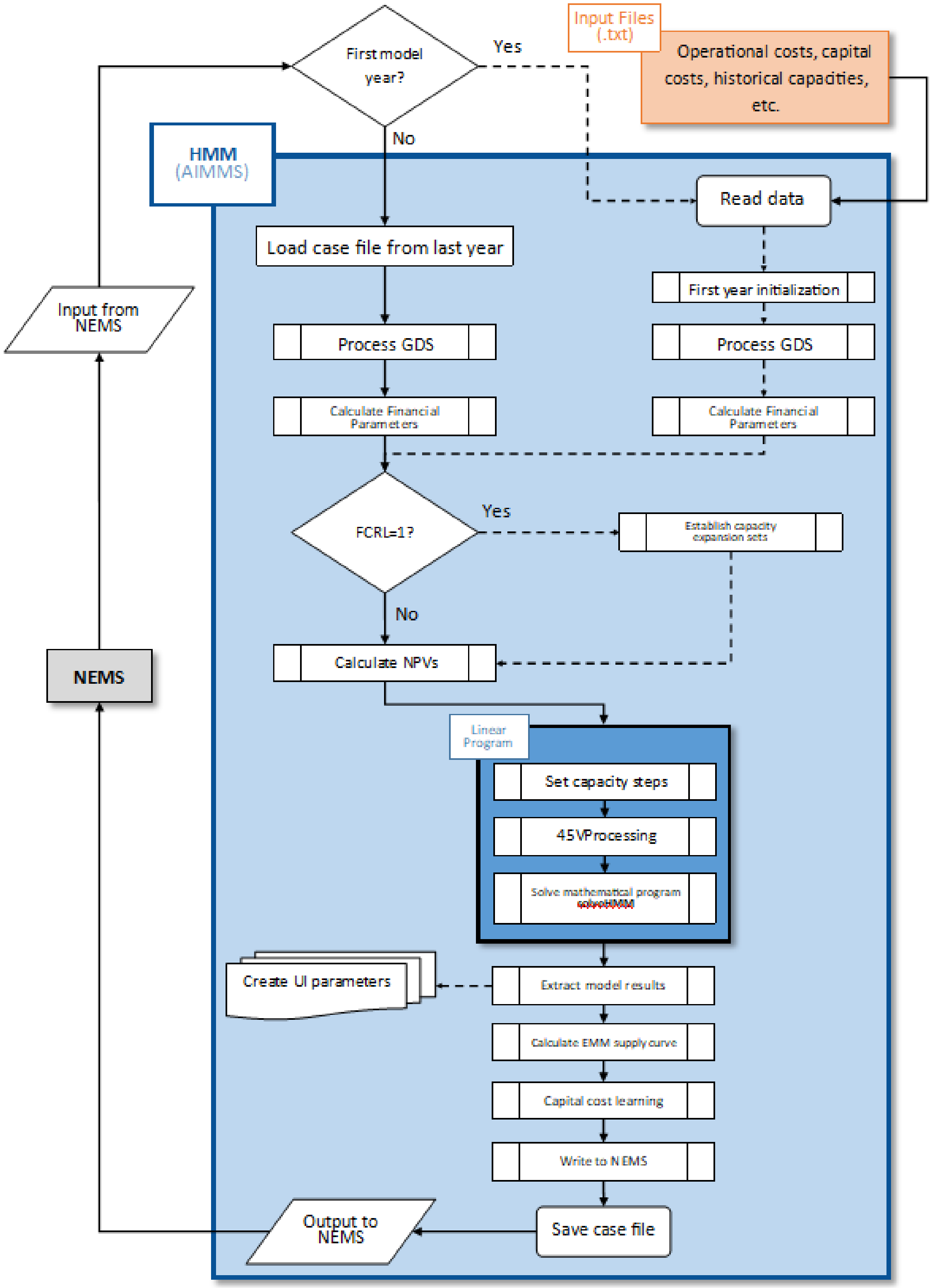
The Hydrogen Market Module (HMM) is a linear optimization model that balances hydrogen market supply with demand minus transportation, minimizing total costs.

After reading in global data from NEMS modules, which is transferred from NEMS via text files, a binary case file is loaded into AIMMS, a sparse-execution programming language. The case file contains the data saved from the prior HMM solve, except in the first model year where initial data and configuration input are from text files to initialize the model. Annual data received from NEMS is generally disaggregated to seasonal data for use in HMM. After the HMM solves its main LP, it will also solve several other times at different assumed demand levels to calculate to help determine a supply curve to send to EMM. After all data from the LP solves are extracted, the HMM processes technological learning, and converts data into report variables to return back to the NEMS.

The general flow of an HMM iteration can broadly be described using several key procedures (Figure 4):

- **First year initialization:** The first model year that HMM is called, the HMM will first read all of the HMM's local input data and configuration declarations needed to initialize the model. This includes loading all historical capacities, operational and capital costs, set declarations, and run time configuration settings.
- **Pre-processing routines:** HMM's pre-processing routines are a collection of procedures that extract, transform, and prepare model inputs. (Further details on the mechanics of these pre-processing procedures can be found in Section 4. Pre-Processing Routines) The pre-processing routines can generally be categorized into three procedures:
  - <u>Process Global Data Structure (GDS</u>) – Processes data from the NEMS restart file into AIMMS model parameters
  - <u>Calculate financial parameters –</u> Calculates the weighted average cost of capital (WACC) based on GDS data using the Capital Asset Pricing Model (CAPM) framework
  - <u>Calculating net present values of model inputs</u> – Aggregates data into the HMM planning periods
- **Running the linear program:** Immediately prior to running the LP, the HMM establishes its capacity expansion steps and process data relating to model inputs for 45V representation. The solver is then loaded and solves the mathematical program known in AIMMS as "solveHMM".

Figure 4. Process flow diagram representing the HMM and its operation within NEMS in a given year



Source: U.S. Energy Information Administration

Note: GDS = Global Data Structure, FCRL = Final Convergence and Reporting Loop, NPV = Net Present Value, UI = User Interface

- **Post-processing routines:** After the LP solves, the HMM runs as series of post-processing procedures that extracts solution results and prepares data to be sent to NEMS (for more details, see Section 5. Post-Processing Routines). These are the primary post-processing procedures.
  - Extract model results – After the LP has solved, the HMM extracts the model solution, including the model's shadow prices and capacity expansions
  - Calculate EMM supply curve – To calculate the EMM supply curve, the HMM re-runs the model's LP additional times at higher assumed demand levels, representing potential incremental demand for the EMM. The resulting demand and price combination from the LP solutions form the supply curve that is sent to EMM.
  - Capital cost learning – HMM uses the extracted capacity builds from the LP solution to inform its capital cost learning algorithm. This algorithm incorporates endogenous learning via learning-by-doing and exogenous, minimum learning. The new capital costs calculated in this procedure are used as capital costs for future model years.
  - Write to NEMS – HMM populates the arrays with the extracted model solution results and writes them to a text file to be read in by the NEMS integration module.

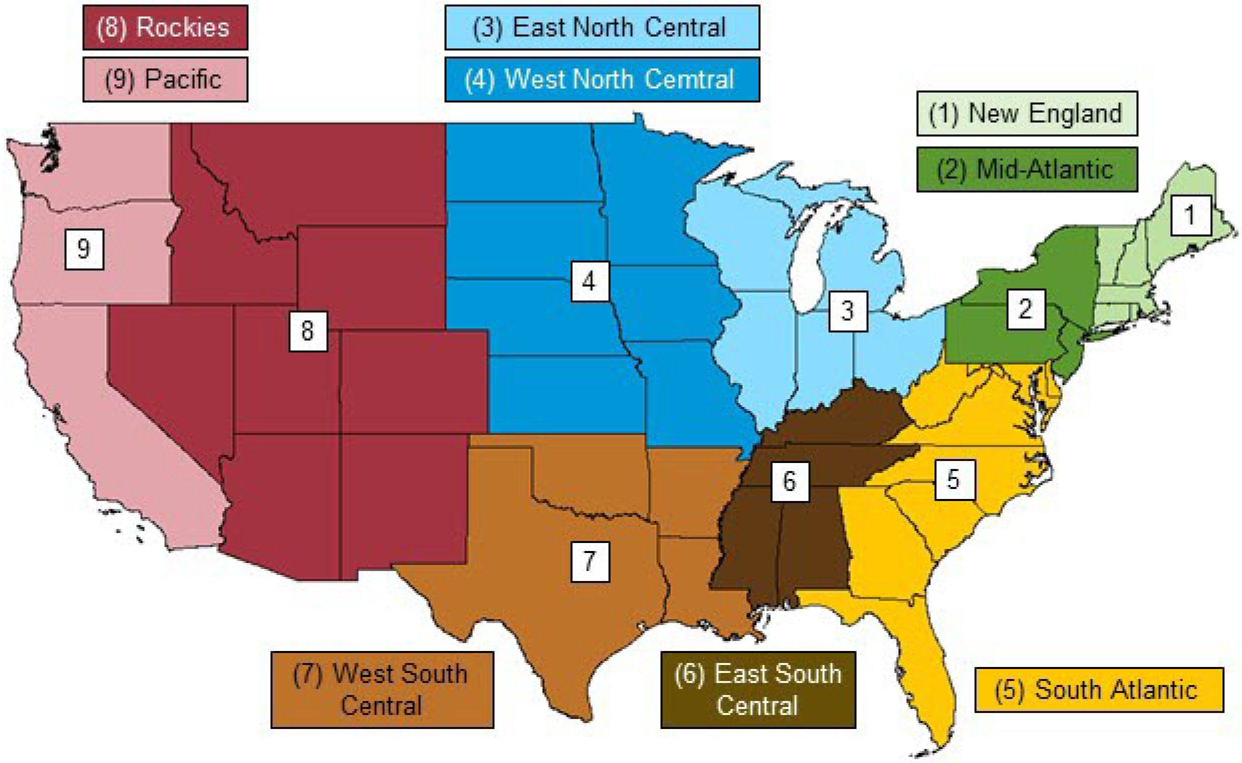
Regionality

The HMM uses two different levels of regionality to represent the hydrogen market. Most modeling decisions in HMM, including non-electrolytic hydrogen production, seasonal storage, interregional transportation, hydrogen demand, and total market balancing are made at the U.S. census division level (Figure 5). These nine census divisions serve as supply, demand, and storage nodes within the market, as well as market balancing hubs.[11]

Hydrogen production from electrolyzers occur at the Electricity Market Module (EMM) supply region level (Figure 6). Using these regions allows electrolyzer decisions to be more closely aligned with input data from the EMM. Electrolyzer production decisions the model determines at the EMM regions ultimately get aggregated to HMM supply nodes at the census division level (Table 1).

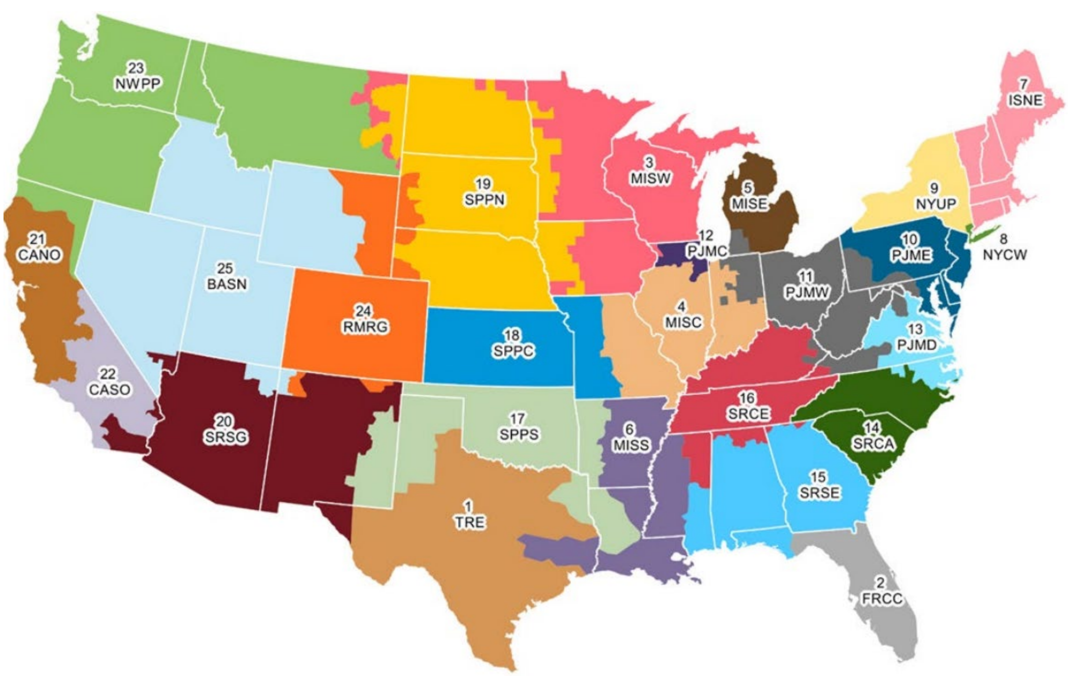
[11] Note, these "hubs" have no relation to the DOE Regional Hydrogen Hubs

Figure 5. Census divisions used in the HMM



Source: U.S. Energy Information Administration

Figure 6. Electricity Market Module (EMM) supply regions



Source: U.S. Energy Information Administration

Table 1. EMM supply region names and corresponding census division mapping in HMM

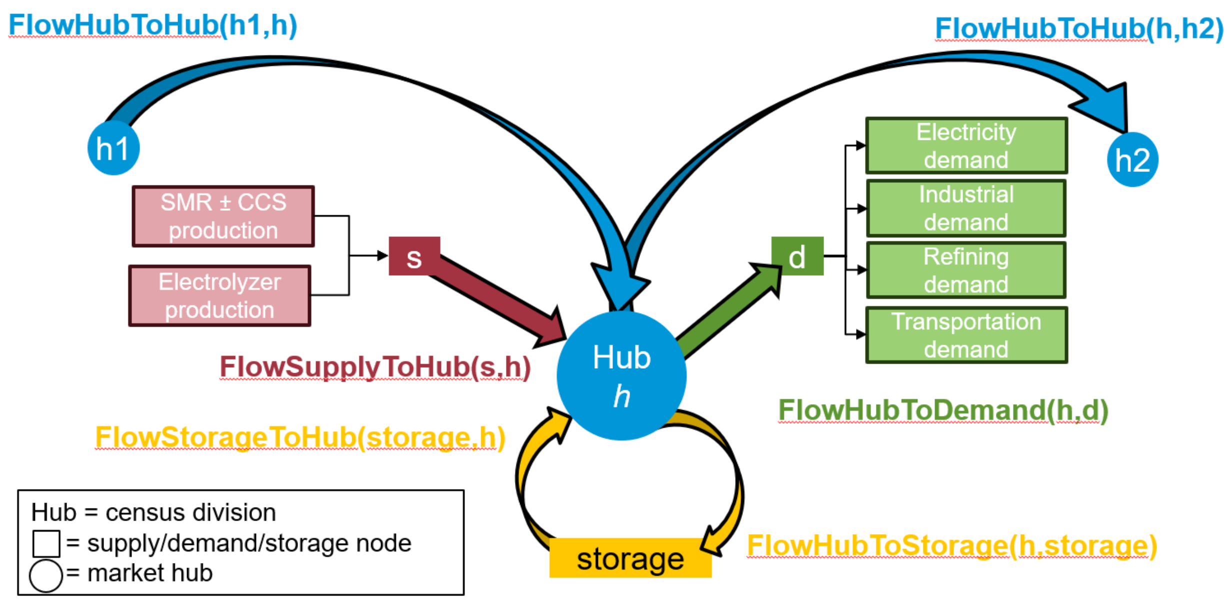
EMM supply region		
Number-code	**Name**	**Census division mapping**
1 – TRE	Texas Reliability Entity	West South Central
2 – FRCC	Florida Reliability Coordinating Council	South Atlantic
3 – MISW	Midcontinent ISO/West	West North Central
4 – MISC	Midcontinent ISO/Central	East North Central
5 – MISE	Midcontinent ISO/East	East North Central
6 – MISS	Midcontinent ISO/South	East South Central
7 – ISNE	Northeast Power Coordinating Council/New England	New England
8 – NYCW	Northeast Power Coordinating Council/New York City and Long Island	Mid-Atlantic
9 – NYUP	Northeast Power Coordinating Council/Upstate New York	Mid-Atlantic
10 – PJME	PJM/East	Mid-Atlantic
11 – PJMW	PJM/West	East North Central
12 – PJMC	PJM/Commonwealth Edison	East North Central
13 – PJMD	PJM/Dominion	South Atlantic
14 – SRCA	SERC/East	South Atlantic
15 – SRSE	SERC/Southeast	East South Central
16 – SRCE	SERC/Central	East South Central
17 – SPSS	Southwest Power Pool/South	West South Central
18 – SPPC	Southwest Power Pool/Central	West North Central
19 – SPPN	Southwest Power Pool/North	West North Central
20 – SRSG	Western Electricity Coordinating Council/Southwest	Mountain
21 – CANO	Western Electricity Coordinating Council/California North	Pacific
22 – CASO	Western Electricity Coordinating Council/California South	Pacific
23 – NWPP	Western Electricity Coordinating Council/Northwest Power Pool	Pacific
24 – RMRG	Western Electricity Coordinating Council/Rockies	Mountain
25 – BASN	Western Electricity Coordinating Council/Basin	Mountain

Source: U.S. Energy Information Administration

The HMM uses the concept of market-clearing hubs and nodes in its linear program (Figure 7). In this concept, HMM balances supply and demand at the U.S. census division level, where each census division is considered by the model to be a market clearing hub. Every market clearing hub is an associated demand node, whose demands must be satisfied by flows from the hub to the demand node. The market-clearing hubs are supplied with hydrogen produced from either SMRs, SMRs + CCS, or electrolyzers via the hub's supply node.

In addition to supply nodes delivering hydrogen to market-clearing hubs, the hubs can also receive hydrogen from neighboring hubs in the form of inter-regional hydrogen pipeline transmission or withdraw hydrogen that it previously injected from the hub's storage node.

Figure 7. Illustration of hub and node concept in HMM



Source: U.S. Energy Information Administration

Temporal resolution

Every year In the HMM is separated into four seasons (Table 2). Hydrogen demand from the industrial, refining, and transportation sectors is assumed to be constant across all four seasons. Hydrogen demand from the electricity sector is not assumed to be the same each season of the year as the EMM calculates its own seasonal demand for hydrogen and sends that information to the HMM to satisfy at the seasonal level.

SMR and SMR+CCS production are projected for each season. HMM projects hourly hydrogen production from electrolyzers using 24 representative hours for each season (Figure 8). Hourly representation for electrolyzers is needed to consider hourly electricity prices and integrate with the hourly renewable generation data from the EMM.

Figure 8. Seasonal and hourly representation in HMM

Source: U.S. Energy Information Administration

Table 2. Seasonal definitions within the HMM

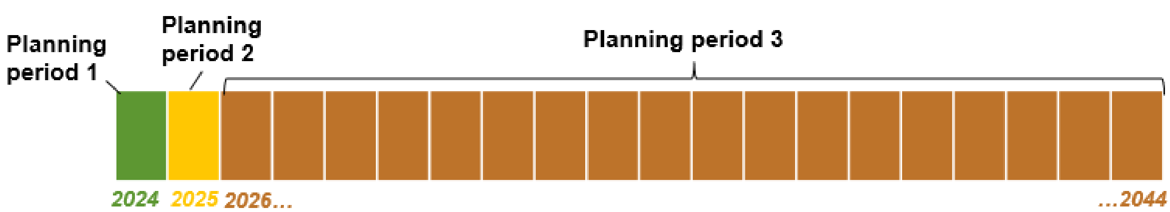
Season	Months
Spring	April – May
Summer	June – September
Fall	October – November
Winter	December – March

Source: U.S. Energy Information Administration

Foresight

HMM utilizes perfect foresight to aid in its capacity expansion decisions. The HMM is configured so that it solves for 3 distinct planning periods each time it solves a model year (Figure 9). Planning period 1 represents the current model year that HMM is optimizing for. Planning period 2 is the year after the current model year, and planning period 3 is an aggregation of the years that span from two years after the current model year to 18 years after the current model year.

Figure 9. Planning periods in the HMM



Source: U.S. Energy Information Administration

For example, if the current model year is 2024, then planning period 1 would represent 2024, planning period 2 would represent 2025, and planning period 3 would represent an aggregate of 2026-2044. HMM's objective function minimizes the sum of total costs to meet hydrogen demand, summing across *all three* planning periods, using discounted cash flows.

Within the HMM, each of the three planning periods serves a distinct role:

- Planning period 1 – Determines the current model year output that is delivered to the other modules within NEMS. Capacity expansion is now allowed in this planning period as it represents operations based on existing capacity.
- Planning period 2 – Primarily serves to build capacity so that it is available for future model years. Capacity expansion decisions from planning period 2 are extracted will become available as existing capacity for the model to use during planning period 1 when HMM runs its next model year.
- Planning period 3 – Informs capacity expansion decisions in planning period 2 by providing foresight, allowing the model to assess how capacity will be utilized in the future if built. Capacity expansions are also allowed in planning period 3, however those capacity expansion results are discarded.

The HMM is configured to be able to run only considering planning period 1 (where no capacity expansion decisions take place) or considering all three planning periods (thus, enabling capacity expansion decisions). In both cases, the HMM output from its planning period 1 is identical, meaning HMM sends the same data to other NEMS modules regardless of if the model is running in its capacity expansion configuration or not.

To reduce model runtime, the HMM only considers planning period 1 for most NEMS iterations. However, when HMM runs for the Final Control and Report Loop (FCRL) iteration,[12] the HMM will run its model using the configuration that considers all three planning periods, enabling capacity expansions.

Policy

The HMM represents key policies that seek to drive the future of the hydrogen market. The two federal policies that are considered in the HMM are the 45V and the 45Q production tax credit (PTC). By law, hydrogen projects cannot take both the 45V and the 45Q PTCs. The HMM assumes that hydrogen facilities with carbon capture will opt to claim the 45Q PTC while electrolyzers will opt to claim the 45V PTC.

45Q tax credit

The 45Q is a PTC that allows projects to claim a credit of $60/ton captured CO_2 if the CO_2 is re-used for enhanced oil recovery (EOR) or a credit of $80/ton captured CO_2 if the captured CO_2 is stored in a geologic storage facility dedicated to storing CO_2. Eligible capture projects must begin construction by the end of 2032 and can claim the credit for up to 12 years.

The HMM objective function considers the revenue generated via 45Q for hydrogen production facilities with carbon capture technology. The CCATS module calculates the CO_2 prices and the value of the 45Q PTC and sends to the HMM two prices for CO_2, a price that includes the 45Q PTC and another price that excludes the 45Q PTC. HMM takes the difference between these two prices to calculate the implied 45Q PTC value. The HMM then uses the implied 45Q PTC in its objective function for minimizing total costs. It

[12] In the FCRL iteration?, all models are run one more time to ensure that the solution remains converged and to allow the models to generate summary results and reports. See Integrating Module of the National Energy Modeling System: Model Documentation 2022 for more information.

should be noted that only capacity vintages eligible for the 45Q PTC receive the subsidy in the HMM's LP.

45V tax credit

The 45V PTC allows clean hydrogen projects (represented in the HMM as electrolyzers) to claim a PTC based on the emissions generated by the hydrogen facility (Table 3). Eligible facilities must begin construction before the end of 2032 and can claim the 45V PTC for up to 10 years.

Table 3. 45V credit values by emission intensity

Emission intensity (kg of CO_2e per kg H_2)	Credit value ($/kg H_2)
0 – 0.45	$3.00
0.45 – 1.5	$1.00
1.5 – 2.5	$0.75
2.5 – 4	$0.60

Note: credit value assumes prevailing wage and apprenticeship requirements are met.
Source: U.S. Energy Information Administration

The HMM models electrolyzers that produce hydrogen using electricity consumed from the grid. For modeling purposes, the HMM assumes that electrolyzers can purchase clean electricity by contracting with grid-connected clean energy generators (such as wind or solar plants). Electrolyzers purchasing electricity from clean power generators can generate Energy Attribute Certificates (EACs). These EACs document the generation and purchase of electricity, verifying that the electrolyzer has contracted electricity purchases with a clean energy source, despite the electrolyzer consuming electricity from the grid.

By law, in order to qualify for the 45V PTC, the EAC must meet three criteria:

- Deliverability - The EAC must be generated and consumed in the same region where the electrolyzer is operating.
- Incrementality—The generator that produces the EAC must be built within three years of an in-service date of an electrolyzer that retires the EAC.
- Hourly time matching—The electrolyzer must retire the EAC in the same hour that the EAC is generated.

In order for the HMM to consider these three criteria in the model, the EMM sends data for hourly solar and wind generation in the year the power plant began operating. The HMM's LP then uses that information in a constraint to ensure that any electricity electrolyzers consume to claim the 45V PTC is truly clean and available. Electrolyzers may consume electricity outside of this constraint, however, the electrolyzer would receive no 45V PTC for the hydrogen produced with that electricity.

By law, electrolyzers are also able to claim the 45V PTC if the electricity consumed to generate hydrogen is otherwise curtailed electricity and does not need to be from a new renewable generation source. The EMM sends hourly curtailed electricity data to the HMM to be used as another constraint in the model. The HMM LP then solves for the optimal amount of electrolytic hydrogen produced without the 45V PTC, with the 45V PTC via incrementality, and with the 45V PTC via otherwise curtailed electricity.

Solver

The HMM uses the CPLEX solver to optimize the linear objective function. Either the barrier (dual crossover) or dual simplex methods may be used to solve the linear program. By default, HMM will use the barrier method to solve the main LP, and the dual simplex method to solve for EMM's supply curve. Our testing that the barrier method solves the HMM's LP the fastest in a cold start (where the solver cannot use information from a previous solution to inform the starting point for the solve), while the dual simplex method solves the HMM's LP fastest in a warm start (where the solver can use information from a previous solution to inform the starting point for the solve.) Regardless of which solve method is used, our testing has shown little to no differences in output results for this model.

Mathematical formulation

LP identifiers

The HMM model formulation uses several sets, parameters, and variables in its objective functions and constraints to model the hydrogen market. Table 4 describes the sets the HMM uses to index its parameters and variables. Table 5 and Table 6 describe the parameters and variables (respectively) HMM uses for its objective function and constraints.

Table 4. Description of HMM model sets

Set	Index	Content
Hub, node, and regional sets		
EMM Region	ER	EMM regions {1…25}
Census division	CD	U.S. census divisions {1…9}
Hub	h	U.S. census divisions {1…9}
Storage Node	n^{st}	U.S. census divisions {1…9}
Demand Node	n^{d}	U.S. census divisions {1…9}
Supply Node	n^{s}	U.S. census divisions {1…9}
Time sets		
Season	s	{1…4}
Hour	h	{1…24}
Planning period	pp	{1,2,3}
Capacity Expansion Planning Period	Cepp	{2,3}
Other sets		
Fuel	f	{natural gas, electricity}
Electricity fuel	f^{e}	
Credit Step	cs	{45V, 45VCurtail,No45V,No45VCurtail}
Credit Step utilizing 45V Incrementality	cs^{45V}	{45V}
Credit Step utilizing curtailed electricity	cs^{c}	{45VCurtail,No45VCurtail}
Production Technology	pt	{Electrolyzer,SMR, SMR CCS}
Capacity Vintage Year	cy	{1990...2050}
Production Step	ps	{1,2,3}
Storage Step	ss	{1,2,3}
Storage Technology	st	{Salt Cavern}
Transportation Step	ts	{1,2,3}
Electricity Vintage Year	ey	{1990…2050}

Source: U.S. Energy Information Administration

Table 5. Description of HMM model parameters

Parameter name	Description	Indexes	Unit
HourlyFuelCostCredit	Hourly electricity prices for electrolyzers	ER,s,h,f,cs,pp	$/MMBtu
ElectrolyzerFuelConsumption	Electrolyzer fuel consumption	pt, f	MMBtu/MMmt H_2
FixedOMCostElectrolyzer	Electrolyzer fixed operation and maintenance costs	s,ER,pt,pp	$/MMmt H_2
VarOMCostElectrolyzer	Variable operation and maintenance costs	s,ER,pt,pp	$/MMmt H_2
TaxCredit45V	Value of 45V production tax credit	pp,cy,cs	$/MMBtu
FuelCost	Fuel costs for non-electrolyzers	S,CD,f,pp	$/MMBtu
FeedstockConsumption	Non-electrolyzer feedstock consumption	pt,f	MMBtu/MMmt H_2
HPConsumption	Non-electrolyzer heat and power consumption	pt,f	MMBtu/MMmt H_2
FixedOMCostNonElectrolyzer	Non-electrolyzer fixed operation and maintenance costs	s,CD,pt,pp	$/MMmt H_2
VarOMCostNonElectrolyzer	Non-electrolyzer variable operation and maintenance costs	s,CD,pt,pp	$/MMmt H_2
CO2CaptureRate	Amount of CO_2 captured during hydrogen production	pt	ton CO_2/MMmt H_2
CO2Price	Price of CO_2	CD,pp	$/ton CO_2
TaxCredit45Q	Value of 45Q tax credit to hydrogen producer	CD,pt,pp,cy	$/ton CO_2
PUCCostElectrolyzer	Cost of electrolyzer capacity expansion	ER,pt,cepp	$/MMmt H_2
ProductionStepCostMultiplier	Production step cost multiplier	ps	N/A
PUCCostNonElectrolyzer	Cost of non-electrolyzer capacity expansion	CD,pt,cepp	$/MMmt H_2
StorageElecConsRate	Amount of electricity to need to inject hydrogen into storage	N/A	MMBtu/MMmt H_2
StorageWthCost	Storage withdrawal cost	n^{st},st,pp	$/MMmt H_2
SUCCost	Storage capacity expansion cost	n^{st},st,cepp	$/MMmt H_2
StorageStepCostMultiplier	Storage step cost multiplier	ss	N/A
PipeEnergyIntensity	Electricity consumed to move hydrogen from one region to another	h,h_j	MMBtu/MMmt H_2
TUCCost	Cost of inter-regional pipeline transportation capacity expansion	h,h_j,cepp	$/MMmt H_2
TransportationStepCostMultiplier	Transportation step cost multiplier	ts	N/A
EligibleGeneration45V	Hourly electricity generation electrolyzer can consume while being eligible for the 45V credit	ER,cy,ey,h,s,pp	MMBtu
ElecCurtailed	Amount of electricity being curtailed for each hour	ER,s,hr,pp	MMBtu
H2Demand	Hydrogen demand	s,n^d,pp	MMmt
ByproductSupply	Byproduct hydrogen supply	n^d,s,pp	MMmt
ExistingTransportationCapacity	Existing inter-regional pipeline transportation capacity that exists prior to first model year	h,h_j,pp	MMmt

Parameter name	Description	Indexes	Unit
SeasonalFraction	Fraction that divides annual values into seasonal values	s	N/A
ExistingStorageCapacity	Existing storage capacity that exists prior to first model year	n^{st},st,pp	MMmt
ExistingCapacityNonElectrolyzer	Existing non-electrolyzer production capacity that exists prior to first model year	CR,pt,pp,cy	MMmt
ExistingCapacityElectrolyzer	Existing electrolyzer production capacity that exists prior to first model year	ER,pt,pp,cy	MMmt
MaxElectrolyzerLoad	Maximum amount of hourly load electrolyzers can draw from the grid	ER,h,s,pp	MMBtu

Source: U.S. Energy Information Administration

Table 6. Description of HMM model variables

Variable name	Description	Indexes	Unit
H2ProdElectrolyzer	Electrolyzer production	ER,s,h,pt,pp,cy,cs	MMmt H_2
H2ProdNonElectrolyzer	Non-electrolyzer production	CD,s,pt,pp,cy	MMmt H_2
PUCByStepElectrolyzer	Amount of electrolyzer capacity expansion to build	ps,ER,pt,cepp	MMmt H_2
PUCByStepNonElectrolyzer	Amount of non-electrolyzer capacity expansion to build	ps,CD,pt,cepp	MMmt H_2
FlowHubToStorage	Hydrogen storage injections	s,n^{st},h,pp,st	MMmt H_2
FlowStorageToHub	Hydrogen storage withdrawals	s,n^{st},h,pp,st	MMmt H_2
SUCByStep	Amount of storage capacity expansion to build	ss,n^{st},st,cepp	MMmt H_2
FlowHubToHub	Amount of hydrogen transported between regions	s,h,h_j,pp	MMmt H_2
TUCByStep	Amount of inter-regional pipeline transportation capacity expansion to build	ts,h,h_j,cepp	MMmt H_2
ElectricityConsumedIncrementality	Amount of electricity consumed for each electricity vintage by each electrolyzer capacity vintage	ER,cy,ey,h,s,pp	MMBtu
FlowHubToDemand	Amount of hydrogen flowing from hub to demand node	s,n^d,h,pp	MMmt H_2
FlowSupplyToHub	Amount of hydrogen flowing from supply nodes to hub	s,n^s,h,pp	MMmt H_2
NetStorageToHub	Net hydrogen withdrawls	s,n^{st},h,st,pp	MMmt H_2

Source: U.S. Energy Information Administration

Objective function

The individual component pieces to the HMM objective function are detailed below. These components are summed together, resulting in HMM's combined objective function that it seeks to minimize given the model's constraints. Note that model decision variables are in bold font.

Electrolyzer production costs

Electrolyzer production costs are a function of hourly electricity prices, the amount of electricity consumed by electrolyzers, fixed operations and maintenance costs, variable operations and maintenance costs, and the value of the 45V tax credit.

$$\sum_{ER,s,h,pt,pp,cy,cs}\left(\left(\left(\left(\sum_{f} HourlyFuelCostCredit_{ER,s,h,f,cs,pp} * \ ElectrolyzerFuelConsumption_{pt,f}\right) + FixedOMCostElectrolyzer_{s,ER,pt,pp} + VarOMCostElectrolyzer_{s,ER,pt,pp} - TaxCredit45V_{pp,cy,cs}\right) * \boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,pp,cy,cs}}\right)\right) \quad (1)$$

Non-electrolyzer costs

Non-electrolyzer production costs are a function of fuel costs, natural gas and electricity consumed by electrolyzers, fixed and variable operations and maintenance costs, the rate at which CO_2 is captured, CO_2 prices, and the value of the 45Q tax credit

$$\sum_{\boldsymbol{CD,s,pt,pp,cy}}\left(\left(\left(\left(\sum_{f}\left(FuelCost_{s,CD,f,pp} * \ \left(FeedstockConsumption_{pt,f} + HPConsumption_{pt,f}\right)\right)\right) + FixedOMCostNonElectrolzer_{s,CD,pt,pp} + VarOMCostNonElectrolyzer_{s,CD,pt,pp} + \left(CO2CaptureRate_{pt} * \ \left(CO2Price_{CD,pp} + TaxCredit45Q_{CD,pt,pp,cy}\right)\right)\right) * \boldsymbol{H2ProdNonElectrolyzer_{CD,s,pt,pp,cy}}\right)\right) \quad (2)$$

Electrolyzer capacity expansion costs

Electrolyzer capacity expansion costs are a function of electrolyzer capital costs and a short-term elasticity multiplier, where steps are set individually for electrolyzers and non-electrolyzers.

$$\sum_{ps,ER,pt,cepp} \left(\boldsymbol{PUCByStepElectrolyzer_{ps,ER,pt,cepp}} * PUCCostElectrolyzer_{ER,pt,cepp}\right) * ProductionStepCostMultiplier_{ps} \tag{3}$$

Non-electrolyzer capacity expansion costs

Non-electrolyzer capacity expansion costs are a function of non-electrolyzer capital costs and a short-term elasticity multiplier, where steps are set individually for electrolyzers and non-electrolyzers.

$$\sum_{ps,CD,pt,cepp} \left(\boldsymbol{PUCByStepNonElectrolyzer_{ps,CD,pt,cepp}} * PUCCostNonElectrolyzer_{CD,pt,cepp}\right) * ProductionStepCostMultiplier_{ps} \tag{4}$$

Storage injection costs

The cost to compress and inject hydrogen into storage is a function of the price of electricity and an assumed amount of electricity to compress the hydrogen for storage.

$$\sum_{s,n^{st},h,pp,st} \boldsymbol{FlowHubToStorage_{seas,h,stn,st,pp}} * \left(FuelCost_{s,n^{st},elec,pp} * StorageElecConsRate\right) \tag{5}$$

Storage withdrawal costs

The cost to withdraw hydrogen from storage is a function of some assumed withdrawal cost.

$$\sum_{s,n^{st},h,pp,st} \boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} * StorageWthCost_{n^{st},st,pp} \tag{6}$$

Storage capacity expansion costs

Storage capacity expansion costs are a function of the capital cost to build a new hydrogen storage facility and a short-term elasticity multiplier.

$$\sum_{ss,n^{st},st,cepp} \left(\boldsymbol{SUCByStep_{ss,\,n^{st},st,cepp}} * SUCCost_{n^{st},st,cepp}\right) * StorageStepCostMultiplier_{ss} \tag{7}$$

Inter-regional pipeline transportation costs

Inter-regional pipeline transportation costs are a function of how much electricity is consumed to move hydrogen from one arc to another and the price of electricity.

$$\sum_{s,h,h_j,pp} \boldsymbol{FlowHubToHub_{s,h,h_j pp}} * \left(PipeEnergyIntensity_{h,h_j} * FuelCost_{s,h,elec,pp}\right) \tag{8}$$

Inter-regional pipeline capacity expansion costs

Inter-regional pipeline capacity expansion costs are a function of the capital cost to build a new inter-regional hydrogen pipeline across a given arc and a short-term elasticity multiplier.

$$\sum_{ts,h,h_j,cepp}\left(\boldsymbol{TUCByStep_{ts,h,h_j,cepp}} * TUCCost_{h,h_j,cepp}\right) + TransportationStepCostMultiplier_{ts}$$
(9)

Combined objective function

Below is HMM's complete objective function after summing the component pieces from above. This combined objective function represents the total costs of producing, storing, and transporting hydrogen in the network.

$$
\begin{aligned}
min. \sum_{ER,s,h,pt,pp,cy,cs} & \Bigg(\bigg(\Big(\Big(\sum_{f} HourlyFuelCostCredit_{ER,s,h,f,cs,pp} * \ ElectrolyzerFuelConsumption_{pt,f}\Big) \\
& + FixedOMCostElectrolyzer_{s,RE,pt,pp} + VarOMCostElectrolyzer_{s,RE,pt,pp} - TaxCredit45V_{pp,CY,cs}\Big) \\
& * \boldsymbol{H2ProdElectrolyzer_{RE,s,h,pt,pp,cy,cs}}\bigg) \\
& + \sum_{CD,s,pt,pp,cy}\Bigg(\bigg(\Big(\Big(\sum_{f}\Big(FuelCost_{s,CD,f,pp} * \Big(FeedstockConsumption_{pt,f} + HPConsumption_{pt,f}\Big)\Big)\Big) \\
& + FixedOMCostNonElectrolzer_{s,CD,pt,pp} + VarOMCostNonElectrolyzer_{s,CD,pt,pp} \\
& + \Big(CO2CaptureRate_{pt} * \Big(CO2Price_{CD,pp} + TaxCredit45Q_{CF,pt,pp,cy}\Big)\Big)\bigg) * \boldsymbol{H2ProdNonElectrolyzer_{CD,s,pt,pp,cy}}\Bigg) \\
& + \sum_{ps,ER,pt,cepp}\left(\boldsymbol{PUCByStepElectrolyzer_{ps,ER,pt,cepp}} \ * PUCCostElectrolyzer_{ER,pt,cepp}\right) \\
& * ProductionStepCostMultiplier_{ps} \\
& + \sum_{ps,CD,pt,cepp}\left(\boldsymbol{PUCByStepNonElectrolyzer_{ps,CD,pt,cepp}} \ * PUCCostNonElectrolyzer_{CD,pt,cepp}\right) \\
& * ProductionStepCostMultiplier_{ps} \\
& + \sum_{s,n^{st},h,pp,st} \boldsymbol{FlowHubToStorage_{seas,h,stn,st,pp}} \ * \left(FuelCost_{s,n^{st},elec,pp} * StorageElecConsRate\right) \\
& + \sum_{s,n^{st},h,pp,st} \boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} * StorageWthCost_{n^{st},st,pp} \\
& + \sum_{ss,n^{st},st,cepp}\left(\boldsymbol{SUCByStep_{ss,\,n^{st},st,cepp}} \ * SUCCost_{n^{st},st,cepp}\right) * StorageStepCostMultiplier_{ss} \\
& + \sum_{s,h,h_j,pp} \boldsymbol{FlowHubToHub_{s,h,h_j,pp}} * \left(PipeEnergyIntensity_{h,h_j} * FuelCost_{s,h,elec,pp}\right) \\
& + \sum_{ts,h,h_j,cepp}\left(\boldsymbol{TUCByStep_{ts,h,h_j,cepp}} * TUCCost_{h,h_j,cepp}\right) + TransportationStepCostMultiplier_{ts}
\end{aligned}
$$
(10)

Constraints

The constraints for the LP are listed below. Model decision variables are in bold font.

45V Constraints

Total Incrementality Sum Constraint - For each capacity vintage, the sum of the electricity used by the electrolyzer capacity vintage must be less than or equal to the total electricity the capacity vintage is eligible for.

$$\sum_{ey} \boldsymbol{ElectricityConsumedIncrementality_{ER,cy,ey,h,s,pp}} \leq \sum_{ey} EligibleGeneration45V_{ER,cy,ey,h,s,pp} \quad \forall\, ER.cy,s,h,pp \tag{11}$$

Incrementality Capacity Year Sum Constraint - For each electricity vintage, the sum of the electricity used by all of the electrolyzer capacity vintages must be less than the eligible generation for that electricity vintage.

$$\sum_{cy} \boldsymbol{ElectricityConsumedIncrementality_{ER,cy,ey,h,s,pp}} \leq \sum_{cy} EligibleGeneration45V_{ER,cy,ey,h,s,pp} \quad \forall\, ER,ey,s,h,pp \tag{12}$$

Electricity Consumption Constraint - Amount of electricity consumed for the incrementality portion of the 45V credit is equal to electrolyzer hydrogen production using the 45V credit step multiplied by electrolyzer fuel consumption for electricity.

$$\sum_{ey} \boldsymbol{ElectricityConsumedIncrementality_{ER,cy,ey,h,s,pp}} = \sum_{pt} \boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,cy,cs^{45V}}} * ElectrolyzerFuelConsumption_{pt,elec} \quad \forall\, ER,cy,h,s,pp \tag{13}$$

45V Curtailment Constraint - Amount of electricity consumed to produce hydrogen via curtailed electricity must be less than the available curtailed electricity.

$$\sum_{pt,cy,cs^{c}} \boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,pp,cy,cs^{c}}} * ElectrolyzerFuelConsumption_{pt,f^{e}} \leq ElecCurtailed_{ER,s,h,pp} \quad \forall\, ER,s,h,pp \tag{14}$$

Node Constraints

Supply Mass Balance Constraint - Total amount of supply going to hub must be equal to the sum of volume produced by electrolyzers, non-electrolyzers, and from storage.

$$\sum_{h} \boldsymbol{FlowSupplyToHub_{s,n^{s},h,pp}} = \sum_{h,cy,cs,pt} \boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,pp,cy,cs}} + \sum_{cy,pt} \boldsymbol{H2ProdNonElectrolyzer_{CD,s,pt,pp,cy}} \quad \forall\; s,n^{s},pp \tag{15}$$

Demand Mass Balance Constraint - For all demand nodes, the flow from the hub to the demand region must equal demand for that region.

$$H2Demand_{s,n^d,pp} - ByproductSupply_{s,n^d,pp} = \sum_{h} \boldsymbol{FlowHubToDemand_{s,n^d,h,pp}} \quad \forall\ s, n^d, pp \tag{16}$$

Hub Balance Constraint - Quantity of flows into a hub must equal all flows out of a hub.

$$\sum_{st,n^{st}} \boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} + \sum_{n^s} \boldsymbol{FlowSupplyToHub_{s,n^s,h,pp}} + \sum_{h} \boldsymbol{FlowHubToHub_{s,h,h_j,pp}} = \sum_{n^d} \boldsymbol{FlowHubToDemand_{s,n^d,h,pp}} + \sum_{st,n^{st}} \boldsymbol{FlowHubToStorage_{s,n^{st},h,st,pp}} + \sum_{h_j} \boldsymbol{FlowHubToHub_{s,h,h_j,pp}} \quad \forall\ s, h, pp \tag{17}$$

Transportation and storage constraints

Maximum Transportation Constraint - Maximum transportation flows must be less than or equal to the transportation capacity between those regions.

$$\boldsymbol{FlowHubToHub_{s,h,h_j,pp}} \le \left(ExistingTransportationCapacity_{h,h_j,pp} + \sum_{pp_j \mid pp_j \le pp} \sum_{ts} \boldsymbol{TUCByStep_{ts,h,h_j,pp_j}} \right) * SeasonalFraction_s \quad \forall\ s, h, h_j, pp \tag{18}$$

Maximum Storage Injection Constraint – The maximum amount that can be injected into storage must be less than storage capacity.

$$\sum_{h} \boldsymbol{FlowHubToStorage_{s,n^{st},h}} \le ExistingStorageCapacity_{n^{st},st,pp} + \sum_{pp_j \mid pp_j \le pp} \sum_{ss} \boldsymbol{SUCByStep_{ss,n^{st},st,pp_j}} \quad \forall\ s, n^{st}, st, pp \tag{19}$$

Maximum Storage Withdrawal Constraint – The maximum amount that can be withdrawn from storage must be less than storage capacity.

$$\sum_{h} \boldsymbol{FlowStorageToHub_{s,n^{st},h}} \le ExistingStorageCapacity_{n^{st},st,pp} + \sum_{pp_j \mid pp_j \le pp} \sum_{ss} \boldsymbol{SUCByStep_{ss,n^{st},st,pp_j}} \quad \forall\ s, n^{st}, st, pp \tag{20}$$

Storage Mass Balance Constraint – Total amount of storage flowing to Census Region hub is the difference between the amount of hydrogen withdrawn from storage and the amount of hydrogen injected. When NetStorageToHub is positive, there is net storage withdrawal, and if NetStorageToHub is negative, there is a net storage injection.

$$\sum_{h}\left(\boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} - \boldsymbol{FlowHubToStorage_{s,n^{st},h,st,pp}}\right) = \sum_{h}\boldsymbol{NetStorageToHub_{s,n^{st},h,st,pp}} \quad \forall\ s, n^{st}, st, pp$$

(21)

Seasonal Storage Balance Constraint - The total quantity of hydrogen that gets injected to storage must be withdrawn from storage in that planning period.

$$\sum_{s,h}\boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} = \sum_{s,h}\boldsymbol{FlowHubToStorage_{s,n^{st},h,st,pp}} \ \forall\ n^{st}, st, pp$$

(22)

Cumulative Storage Injection Constraint - The cumulative net injections into storage through a given season must be less than or equal to planned plus existing storage capacity. This constraint ensures that consecutive storage injections do not result in total hydrogen in storage exceeding capacity.

$$\sum_{h,s_j \mid s_j<s} -\boldsymbol{NetStorageToHub} \leq ExistingStorageCapacity_{n^{st},st,pp} + \sum_{pp_j \mid pp_j \leq pp}\sum_{ss}\boldsymbol{SUCByStep_{ss,n^{st},st,pp_j}} \ \ \forall\ s, n^{st}, st, pp$$

(23)

Storage Withdrawal Availability Constraint - The quantity of hydrogen withdrawn from storage in a season (s) must be available in that season from prior seasonal (s_j) injections.

$$\sum_{h}\boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} \leq \sum_{h,s_j \mid s_j<s}\left(\boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} - \boldsymbol{FlowHubToStorage_{s,n^{st},h,st,pp}}\right) \ \forall\ s, n^{st}, st, pp$$

(24)

Production constraints

Maximum Non-electrolyzer Production Constraint - Maximum amount of hydrogen production from non-electrolyzers must be less than existing plus planned non-electrolyzer capacity for a given season.

$$\boldsymbol{H2ProdNonElectrolyzer_{CD,s,pt,pp,cy}} \leq \left(ExistingCapacityNonElectrolyzer_{CD,pt,pp,cy} + \sum_{pp_j \mid pp_j, \leq pp, ps}\boldsymbol{PUCByStepNonElectrolyzer_{ps,CD,pt,pp_j,cy}}\right) * \ SeasonalFraction_s \ \ \forall\ CD, s, pt, pp, cy$$

(25)

Maximum Electrolyzer Production Constraint - Maximum amount of hydrogen production from electrolysis must be less than existing plus planned electrolyzer capacity for a given hour.

$$\sum_{cs} \boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,pp,cy,cs}} \le \left(ExistingCapacityElectrolyzer_{ER,pt,pp,cy} + \sum_{pp_j \mid pp_j \le pp, ps} \boldsymbol{PUCByStepElectrolyzer_{ps,ER,pt,pp_j,cy}} \right) * SeasonalFraction_s * HourlyFraction_h \ \forall ER,s,h,pt,pp,cy \quad (26)$$

<u>Electrolyzer Load Limit</u> – The amount of electricity electrolyzers can draw from the grid must be less than or equal to the electricity load limit set by the EMM.

$$\sum_{pt,cy,cs} \left(\boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,pp,cy,cs}} * ElectrolyzerFuelConsumption_{pt,f^e} \right) \le MaxElectrolyzerLoad_{ER,h,s,pp} \ \forall \ ER,h,s,pp \quad (27)$$

Non-negativity constraints

Almost all model decision variables are restricted from taking a negative value.

$$\boldsymbol{H2ProdElectrolyzer_{ER,s,h,pt,pp,cy,cs}} \ge 0 \ \forall ER,s,h,pt,pp,cy,cs$$

$$\boldsymbol{H2ProdNonElectrolyzer_{CD,s,pt,pp,cy}} \ge 0 \ \forall CD,s,pt,pp,cy$$

$$\boldsymbol{PUCByStepElectrolyzer_{ps,ER,pt,cepp}} \ge 0 \ \forall ps,ER,pt,cepp$$

$$\boldsymbol{PUCByStepNonElectrolyzer_{ps,CD,pt,cepp}} \ge 0 \ \forall ps,CD,pt,cepp$$

$$\boldsymbol{FlowHubToStorage_{s,h,stn,st,pp}} \ge 0 \ \forall s,h,n^{st},st,pp$$

$$\boldsymbol{FlowStorageToHub_{s,n^{st},h,st,pp}} \ge 0 \ \forall s,n^{st},h,st,pp$$

$$\boldsymbol{SUCByStep_{ss,n^{st},st,cepp}} \ge 0 \ \forall ss,n^{st},st,cepp$$

$$\boldsymbol{FlowHubToHub_{s,h,h_j pp}} \ge 0 \ \forall s,h,h_j,pp$$

$$\boldsymbol{TUCByStep_{ts,h,h_j,pp}} \ge 0 \ \forall ts,h,h_j,pp$$

$$\boldsymbol{ElectricityConsumedIncrementality_{ER,cy,ey,h,s,pp}} \ge 0 \ \forall ER,cy,ey,h,s,pp$$

$$\boldsymbol{FlowHubToDemand_{s,n^d,h,pp}} \ge 0 \ \forall s,n^{st},h,pp$$

$$\boldsymbol{FlowSupplyToHub_{s,n^s,h,pp}} \ge 0 \ \forall s,n^s,h,pp \quad (28)$$

4. Pre-Processing Routines

Offline pre-processing

To generate the HMM primary input files, a python program is run outside of the NEMS. This python program injects hydrogen historical data, under construction projects, operational parameters, and capital costs stored as .csv files and writes them to text fills as AIMMS composite tables. These files are then copied over to *hmm/input* folder so they are available to the HMM during a model run inside of the NEMS.

A configuration file (*input/h2config.txt*) is also configured prior to an HMM model run where various model runtime parameters and assumptions are established.

First year initialization

The first year that the HMM is called by NEMS, the HMM runs a series of pre-processing routines that establishes some key model parameters for the first of the run. During this initialization procedure, the HMM reads in all input data via a collection of text files detailing operational costs, capital costs, historical capacities, planned capacity expansions, and other exogenous parameters needed to run the model.

After reading the data, the HMM then processes the data by converting parameters to consistent units, generally million metric tons (MMmt H_2) for quantities involving hydrogen, million British thermal units (MMBtu) for other energy quantities, and 1987$ for prices and costs. The HMM uses this data to fill its initial historical capacity arrays and capital cost arrays.

Also in the first year initialization procedure, HMM establishes its matrix defining 45Q eligibility by capacity vintage year and, if needed for a side case, read in the capital costs from a previous Reference case run.

Global Data Structure processing

NEMS sends its data (known as the Global Data Structure, or GDS) to the HMM via text files that are formatted as AIMMS composite tables. While processing this data, HMM uses a collection of binary mapping parameters to map any NEMS-specific indexes to HMM index nomenclature for use within HMM.

Data from NEMS is generally converted to consistent units, where hydrogen quantities demanded by NEMS are converted to MMmt H_2, prices are converted to $/MMBtu, and other energy quantities, such as electricity-related data, are converted to MMBtu. Since data from NEMS is generally annual data, the HMM disaggregates much of the annual data so that the parameters are expressed as seasonal values for each year.

HMM's three planning period framework requires the model to have foresight 18 years following the last model year in planning period 3. However, data from NEMS is typically only available in 2050. To provide the module with data to use as foresight, the HMM extends the data read in by NEMS an additional 30 years based on the value of the data in its final model year.

Financial parameter calculations

In the HMM, future values are discounted to a net present value (NPV) using the weighted average cost of capital (WACC). In this approach, the cost of debt and the cost of equity are calculated, and the weighted average of the cost of debt and the cost of equity are calculated at an assumed 40% equity share (60% debt share). The cost of debt is determined by using the interest rate on industrial bonds from NEMS, while the cost of equity can be determined by using the Capital Asset Pricing Model (CAPM) framework.

Weighted average cost of capital

The equation for the WACC is described below.

$$WACC = ShareDebt * CostOfDebt * (1 - CorporateTaxRate) + ShareEquity * CostOfEquity \tag{29}$$

where:

$ShareDebt$ = The fraction of financing raised through debt,

$CostOfDebt$ = The interest rate on debt, based on industrial bonds,

$CorporateTaxRate$ = The corporate tax rate,

$ShareEquity$ = The fraction of financing raised equity,

$CostOfEquity$ = The cost of equity

To determine the cost of equity, HMM uses the CAPM framework. This framework determines the implied opportunity cost for an investor, or the required rate of return for an investment, and is shown below.

Cost of equity

$$CostOfEquity = RiskFreeRate + \beta(ExpMarketRate - \ RiskFreeRate) \tag{30}$$

$RiskFreeRate$ = The risk-free rate, based on 10-year treasury notes,

β = The volatility beta, where a value of less than 1 implies that the asset is less volatile than the S&P500, while a greater than 1 implies that the asset is more volatile than the S&P500,

$ExpMarketRate$ = The expected market rate based on the S&P500 index,

NEMS provides HMM with projections for the 10-year treasury notes and the S&P 500 index.

Capital recovery factor

With a WACC and cost of equity calculated, HMM can also determine a capital recovery factor, which represents the ratio of a constant annuity to the present value of receiving that annuity for a given length of time[13]. The capital recovery factor is eventually multiplied by HMM's capital cost inputs to calculate an annualized capital cost for the HMM to use in the LP.

The equation for the capital recovery factor (CRF) can be expressed as:

$$CRF = WACC * \left[\frac{1}{1 - \frac{1}{(1 + WACC)^t}} \right] \tag{31}$$

where:

$WACC$ = the weighted average cost of capital,

t = the number of years over which to recover the investment

Process model parameters into net present values

Each year the model runs, the HMM calculates the net present value (NPV) for all three planning periods for most parameters of the model.

For all parameters, the NPV in the first planning period will equal the annual value for the current model year. So if the model is running model year 2030, then the parameter's value in the year 2030 will fill the parameter's "planning period one" array.

To calculate the NPVs for the second and third planning periods, three additional equations are used depending on the model parameter.

Prices, costs, and tax credit values

For model prices, production costs (excluding capacity expansion costs), and tax credit values, the model calculates the NPV for the second planning period by dividing the annual value corresponding to the second planning period year by one plus the discount rate, or:

$$NPV_{pp=2} = \frac{NextModelYearValue}{1 + WACC} \tag{32}$$

where:

$NPV_{pp=2}$ = the net present value in planning period two,

$NextModelYearValue$ = the value of the parameter of which the NPV is being calculated for one year following the HMM's current model year,

$WACC$ = the weighted average cost of capital

[13] https://atb.nrel.gov/electricity/2022/equations_&_variables

To calculate the NPVs in the third planning period, the HMM determines the sum of the NPVs for the 3rd planning period, divided by one plus the discount rate, raised to the power of two, in order to account for the values as starting two periods into the future. The equation is shown below:

$$NPV_{pp=3} = \frac{\sum_{i=1} \frac{V_i}{(1+WACC)^i}}{(1+WACC)^2} \tag{33}$$

Where:

$NPV_{pp=3}$ = the net present value in planning period three,

i = index of the set of years in the planning period three

V_i = the value of the parameter in year i

$WACC$ = the weighted average cost of capital

Quantities and historical capacities

NPV calculations for quantities and historical capacities for the second planning period follow the same methodology laid out for prices, costs, and tax credit values. In the third planning period, however, rather than summing up the NPVs of all the years in the third planning period set, an NPV-weighted average is taken using the following equation:

$$NPV_{pp=3} = \frac{\sum_{i=1} \frac{V_i}{(1+WACC)^i}}{\sum_{i=1} \frac{1}{(1+WACC)^i}} \tag{34}$$

where:

$NPV_{pp=3}$ = the net present value in planning period three,

i = index of the set of years in planning period three

V_i = the value of the parameter in year i

$WACC$ = the weighted average cost of capital

Capacity expansion costs

NPVs for capacity expansion costs in the third planning period are identical to how NPVs are calculated in the third planning period for prices, production costs, and tax credit values where the sum of the NPVs for each year in the third planning period is taken. In the second planning period, however, the model adds the annual NPVs for HMM's next model year with the summed annual NPVs for the years in the third planning period. The intuition behind this is that the summed annual costs of capacity expansion in the second planning period consider the full cost of capacity expansion in the second planning period, instead of just one year's portion of capacity expansion. The equation to calculate the NPV for capacity expansion in the second planning period is below:

$$NPV_{pp=2} = \frac{V_k}{1 + WACC} + \frac{\sum_{i=1} \frac{V_i}{(1 + WACC)^i}}{(1 + WACC)^2} \tag{35}$$

where

$NPV_{pp=2}$ = the net present value in planning period three,

i = index of the set of years in the third planning period

k = index of the year in the second planning period (the next model year)

V_i = the value of the parameter in year i

$WACC$ = the weighted average cost of capital

5. Post-Processing Routines

After the linear program (LP) solves, the solution values can be pulled directly to set output variables for the HMM to pass to other modules, or to the report writer in the NEMS. Several HMM output variables require further calculations.

Prices

The HMM derives the hydrogen spot price for each census division by extracting the shadow price from the LP's "Hub Balance Constraint". This shadow price represents the marginal cost to the objective function if the Hub Balance Constraint was relaxed by one MMmt of hydrogen. Since the shadow price only represents the marginal price of hydrogen, an additional capital cost adder is added to the shadow price to arrive at the final hydrogen spot price for each region. This capital cost adder is determined by taking a capacity-weighted average cost of capital for each of the census divisions.

To calculate the end-use prices in the industrial, electric power, and transportation sectors, exogenous markups are applied to the spot price. For the industrial and electric power sector, these markups represent short pipelines needed to deliver hydrogen to end-use facilities. The transportation sector markup is significantly higher than the markups in the industrial and electric power sector, since it reflects the cost of compressors, pumps, storage, dispensers, refrigerators, heat exchange units, and other equipment required to build a refill station for hydrogen fueled vehicles with onsite hydrogen production.[14]

Process capacity expansion results

If the NEMS is running in the Final Convergence and Reporting Loop (FCRL) iteration[15], which is the final iteration that the HMM runs in, the LP calculates any capacity expansion for production, storage, and transportation. After the LP runs, in post-processing, any solved capacity expansions for production, storage, and transportation from planning period two (which represents the next model year) of the LP are used to fill their respective "existing capacity" arrays for the following model year, allowing the capacity to be available in planning period one the next time the HMM runs.

EMM Supply Curve

Each time the HMM is called by NEMS, the module generates and sends a hydrogen supply curve to the Electricity Market Module (EMM). This hydrogen supply curve represents the change in regional and seasonal hydrogen prices to the electric power that would result from various amounts of increased demand from the EMM.

The supply curve is generated by running the HMM's LP assuming levels of increasingly higher demand from the electric power sector at different demand steps and then extracting the shadow price in the resulting solution at the higher demand level. The resulting demand quantity and price pairs form the hydrogen supply curve sent to HMM.

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[14] For additional details on end-use markups, see the Assumptions to the Hydrogen Market Module

[15] In the FCRL loop, all models are run one more time to ensure solution remains converged and to allow the models to generate summary results and reports. See Integrating Module of the National Energy Modeling System: Model Documentation 2022 for more information.

The demand quantities used in the supply curve are calculated by applying demand factor multipliers to the total hydrogen demand the HMM receives from NEMS. The supply curve features six demand steps that each have an associated demand factor. The first step of the supply curve uses the same demand used by HMM in its main LP, so the supply curve quantity is set to be the same as the demand received from NEMS (Table 7).

Table 7. Hydrogen demand factors for EMM's hydrogen supply curve

Demand step	Demand factor
1	1.0
2	1.02
3	1.04
4	1.06
5	1.08
6	1.095

Source: U.S. Energy Information Administration

Steps two through six increase the demand factor to a maximum of 1.095, representing a 9.5% increase in demand. The HMM builds capacity to meet the hydrogen demand the HMM receives from NEMS, plus an additional 10% for total capacity utilization to average 90%. This means that the highest demand factor for the final supply curve step must be 1.10 or below, otherwise, the LP would likely not have enough built capacity to solve if the demand factor was higher than 1.10. This, combined with the supply curve structure, also has the additional implication of limiting the rate at which electricity demand for hydrogen can increase in a single NEMS cycle to 9.5% of hydrogen of total hydrogen demand in each model year. Total electric power demand for hydrogen is still allowed to far exceed 9.5% of total hydrogen demand, but it would take multiple NEMS cycles to do so.

It should be noted that a seventh and final step of the supply curve is also sent to the EMM but is exogenously declared instead of calculated by re-running the LP. This final step sets an arbitrarily large (999,999) price/quantity pair in the supply curve that the EMM uses as an escape vector.

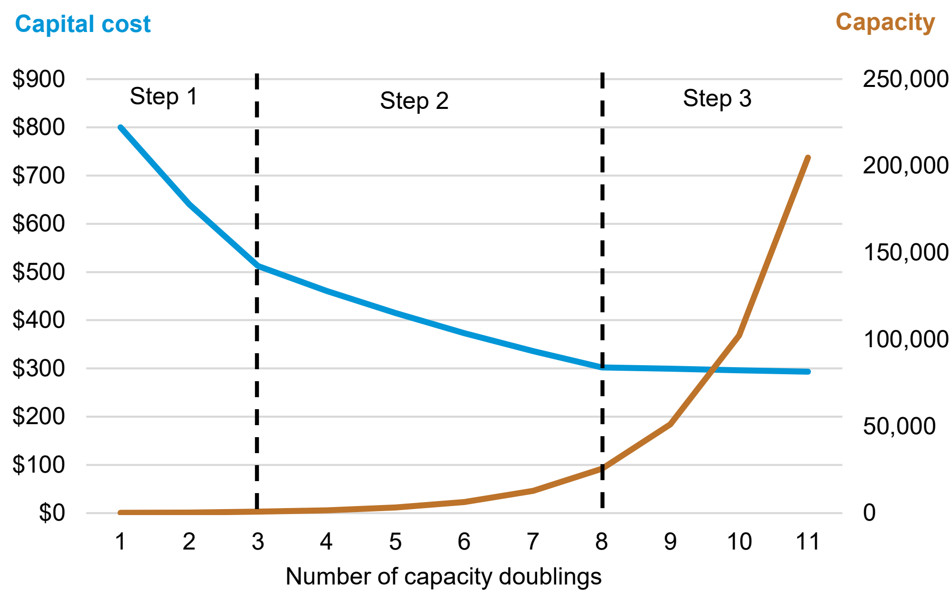
Capital Cost Learning

Endogenous learning

The HMM uses learning curves to represent declines in capital cost that result from increased experience in building a production technology due to wider adoption (Figure 10). This process is also known as a "learning-by-doing". In this learning-by-doing method, an assumed rate of cost reduction[16] is applied to each doubling of capacity.

[16] For learning rate assumptions, see the Assumptions to the Hydrogen Market Module.

Figure 10. Illustrative example of capital cost decline as a function of capacity doublings via three-step learning curve



Source: U.S. Energy Information Administration

The learning curve has three steps which vary cost declines as a function of installed capacity. The first step of the learning curve has the highest learning rate, meaning that a doubling of capacity results in a large reduction in capital costs. The final step of the learning curve has the lowest learning rate, where a doubling of capacity results in very little change in capital costs.

Each step persists for a specified number of capacity doublings. Each step's length and learning rate are specified individually for each production technology. Some technologies may not use all three steps. Technologies that are more mature may only have a single learning rate defined in the third step, limiting cost reductions from learning-by-doing. However, more nascent technologies would have learning rates defined for all three steps, with those learning rates declining in each step.

Describing the above mathematically, the capital costs at installed capacity level N are expressed as follows:

$$C_N = C_I * \left(\frac{N}{I}\right)^{b_s} \tag{36}$$

Where:

C_N = The capital cost at current capacity level

C_I = Initial capital cost

N = Current capacity level

I = Initial capacity level

The exponent for each step (b_s) is defined as a function of a doubling of capacity and a specified learning rate, so:

$$b_s = \frac{\ln(1 - LCR_s)}{\ln 2} \tag{37}$$

Where:

LCR_s = Learning cost reduction for each doubling of capacity in step s, expressed as a fraction

The equation above results in a negative b_s so that as the ratio of current capacity to existing capacity (N/I) increases, the capital costs decrease.

Exogenous learning

In addition to cost reductions via learning-by-doing, the HMM also represents capital cost reductions through exogenous, minimum learning rates applied to some technologies. This minimum learning rate represents technological learning that occurs regardless of domestic capacity installments of a particular technology, such as from research and development or potential capacity builds.

The minimum learning rate specifies the percent reduction in capital cost that must occur by a specified minimum learning year. The minimum learning amount is spread out linearly between the HMM's first model year and the minimum learning year.

If endogenous learning also occurs during the minimum learning period, then only the learning that yields the greatest reduction to capital costs applies, the endogenous learning is not applied in addition to the minimum learning.

Reporting to the NEMS

The final step in the HMM is filling in the NEMS global data arrays. Within the HMM, all NEMS variables are renamed and mapped to HMM indexes to adhere to the model code's naming conventions and units. In the HMM procedure *Write_To_NEMS,* parameters are assigned to the corresponding NEMS global variables. In addition, any aggregations unique to NEMS variables, such as assigning a total U.S. value to the final position of an array, are calculated here. The HMM writes out this data in text files as AIMMS composite tables that NEMS reads and uses to update the global data structure.