Requirements for the Hydrogen Market Module in the National Energy Modeling System

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Abbreviations

Abbreviation	Description
AEO	*Annual Energy Outlook*
AIMMS	Advanced Interactive Multidimensional Modeling Software
CCS	Carbon Capture and Sequestration
CCATS	Carbon Capture, Allocation, Transportation, and Sequestration Module
CMM	Coal Market Module
ECRM	Electricity, Coal & Renewables Modeling Team
EIA	U.S. Energy Information Administration
EMM	Electricity Market Module
EPM	Emissions Policy Module
FECM	Office of Fossil Energy and Carbon Management
HMM	Hydrogen Market Module
HSM	Hydrocarbon Supply Module
IDM	Industrial Demand Module
IRA	Inflation Reduction Act
LFMM	Liquid Fuels Market Module
MET	Macroeconomics & Emissions Team
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NGMM	Natural Gas Market Module
PNGM	Petroleum & Natural Gas Modeling Team
RFM	Renewable Fuels Module
SMR	Steam methane reformer
TDM	Transportation Demand Module

Introduction

The National Energy Modeling System (NEMS) is an integrated energy-economy modeling system of U.S. energy markets that projects annual production, imports, exports, conversion, consumption, and prices of energy. Its projections are subject to certain assumptions, through 2050, which we publish in our *Annual Energy Outlook* (AEO).

NEMS has a modular structure where distinct modules represent energy demand, conversion, and supply activities. These modules iteratively exchange data through a central database until the system reaches an equilibrium between supply and demand. This modular structure of NEMS allows us to introduce additional modules to NEMS that limit impacts to existing modules in the system.

Due to the potential growth in use of hydrogen as a clean energy carrier, we are prioritizing the implementation of an integrated domestic hydrogen market in NEMS. A new Hydrogen Market Module (HMM) will connect different sources of hydrogen supply and production technologies to existing and future hydrogen consumers. As a conversion module, HMM will demand energy provided by other modules, such as electricity and natural gas, use technology to transform those inputs into hydrogen, and deliver that hydrogen to either end users or large-volume seasonal storage. HMM will allow us to evaluate the long-term impacts of policies, laws, and regulations governing hydrogen markets, the impacts of a growing hydrogen market on domestic energy markets, and deep decarbonization scenarios.

Purpose

The purpose of this document is to explicitly define and describe the requirements HMM must meet to be deemed successfully implemented in NEMS for AEO2025. During HMM model development, these requirements will facilitate project planning and communication among EIA modelers by explicitly stating what they can expect when interacting with HMM. Clearly stated requirements describe the scope of the project, decreasing the likelihood of scope creep and increasing the likelihood of introducing the new HMM successfully and on schedule.

For external stakeholders, this document serves to communicate our plans for modeling hydrogen markets in NEMS and our expectations for HMM in AEO2025.

Scope

Hydrogen market representation in scope of HMM

HMM will:

- Meet U.S. hydrogen demand with hydrogen supply
- Represent competition between various hydrogen production pathways, including grid electrolysis, steam methane reformers (SMRs) without carbon capture and sequestration (CCS), and SMRs (or autothermal reformers) with CCS
- Project energy use and emissions associated with the production of hydrogen

- Represent policies that affect hydrogen production and prices: Section 45V and Section 45Q credits
- Deliver regional end-use hydrogen prices to NEMS, including hydrogen supply-price curve assumptions to the Electricity Market Module (EMM)
- Represent limited expansion of interregional pipeline infrastructure
- Represent large volume seasonal hydrogen storage
- Align baseline estimates to historical data where appropriate and include known planned capacity and production from new facilities where appropriate
- Ensure that facility capital costs, operation and maintenance (O&M) costs, carbon intensity, and efficiency assumptions used by the model align with the available hydrogen market data
- Supply of CO_2 captured for a given price of CO_2 while distinguishing between CO_2 that is eligible for 45Q tax credits and CO_2 that is not eligible for 45Q tax credits

Because hydrogen is traditionally a chemical input for various industrial activities and petroleum refining, small representations currently exist throughout multiple NEMS modules. To properly model emerging hydrogen markets and maintain assumption consistency across NEMS, nearly all hydrogen production modeling will be taking place within HMM. Hydrogen demand modeling will be determined by the NEMS demand modules. This scope covers both on-site, or *captive*, hydrogen to be used as an input into further industrial processes and hydrogen produced directly for market.

Hydrogen market representation beyond scope of HMM

There is significant uncertainty related to what a future hydrogen market may look like, as well as a wide range of proposed production technologies, end uses, and infrastructure needs in a future market where hydrogen use grows. For the initial implementation of HMM, we have limited our scope to the features listed above to ensure the module can explore key questions related to future energy markets. This means that there are several potential sources of hydrogen supply, hydrogen end users, and transportation network features excluded from HMM's scope, including:

- Production technologies with feedstocks other than natural gas or grid electricity (that is, we will not represent coal or biomass gasification or nuclear-specific technologies)
- Production technologies with a low technology readiness
- Storage using uncertain or unproven geological options such as aquifers and depleted oil or natural gas wells
- Alternative storage such as conversion to ammonia and methanol
- Hydrogen and natural gas blending within HMM by a supplier or transporter of hydrogen
- International hydrogen exports and imports
- Current production retirements
- Hydrogen produced as a byproduct and consumed internally (that is, refinery catalytic reforming)
- Off-grid electrolysis (see discussion below)

We note here that although we are currently not planning to include off-grid electrolysis in HMM for AEO2025, this production technology is being evaluated and will be prioritized for model improvements after AEO2025. Implementing this form of production would require HMM to build its own renewable capacity, requiring coordination among HMM, RFM, and EMM. To maintain consistency between modules, we would need to build connections to share parameters such as renewable resource availability, capacity factors, and capacity expansion costs (including technology learning and technology-specific, short-term elasticity factors). Even with the assumption that renewable capacity built by HMM is unable to sell power to the grid, also known as *islanded hydrogen production,* modeling off-grid electrolysis requires additional coordination and consideration before implementation. It will be a high-priority model improvement for future AEO publications.

Although this document focuses on AEO2025, HMM scope may increase for future AEOs, when new data are acquired or with the advancement of published research. HMM's optimization will be designed to allow for easy expansion of new technologies based on the data provided. Where feasible, equations with empty parameters will be built in to be expansion ready for future AEOs. Features such as off-grid electrolysis will require advanced coordination with other NEMS modules.

Document organization

This document is organized into the following sections:

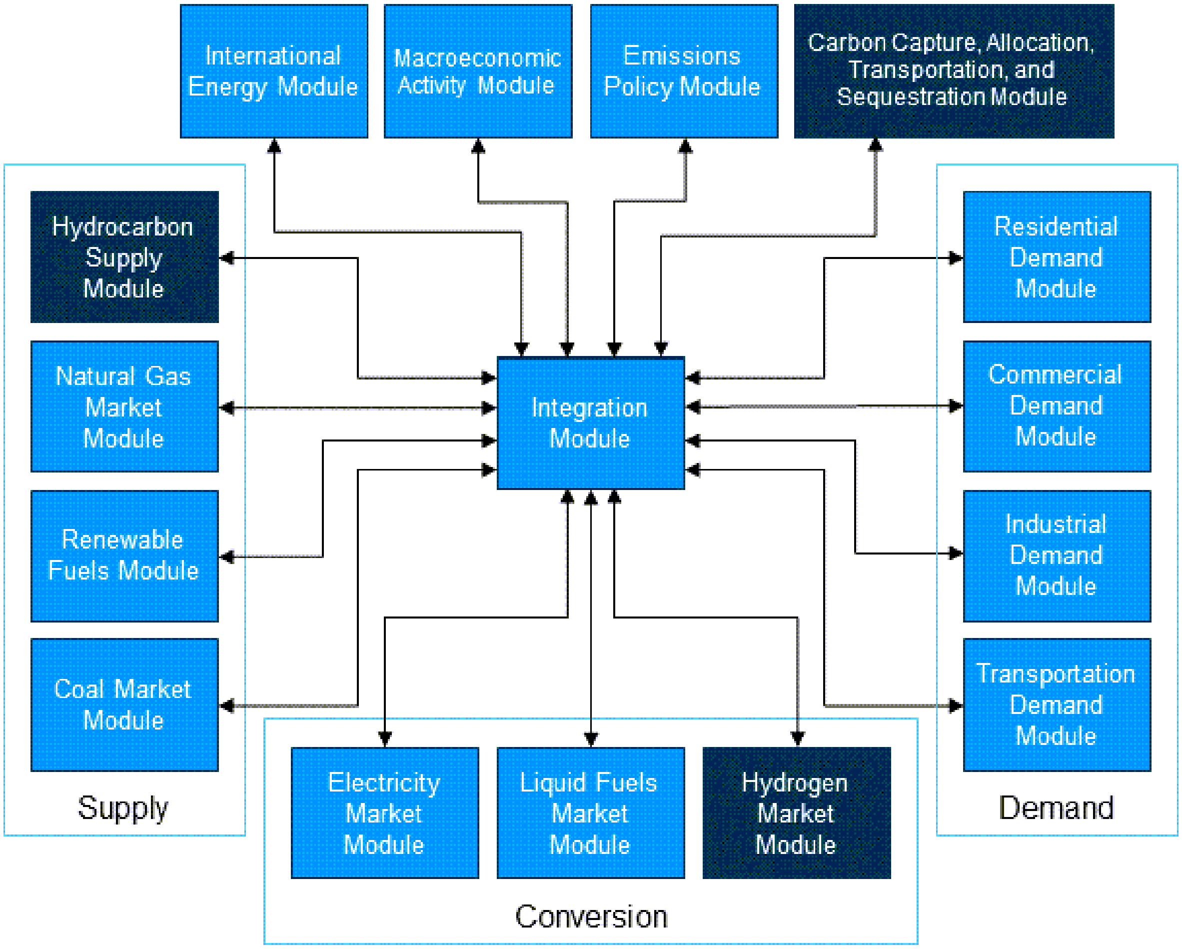
- **Model overview**, which describes how HMM fits into the larger NEMS framework and interacts with specific NEMS modules, as well as software decisions, constraints that must be considered in HMM model development, and important key model assumptions and dependencies
- **Model requirements**, which are broken out and organized by four key categories:
    - ***Integration requirements***, which address requirements directly related to how HMM is implemented, operated, and interacts with the larger NEMS system, specifically the Integration Module and Global Data Structure (GDS)
    - ***Functional requirements***, which outline the specific model outputs and market representations that must be a part of HMM as well as specific processes or model operations that must be performed as part of HMM
    - ***Data requirements***, which name requirements related to the input and output data associated with HMM, including data expected to be published as part of the AEO
    - ***Other requirements***, which cover miscellaneous requirements related to HMM performance, maintainability, usability, etc.
- **Appendix A**, which contains a table that presents the organized, enumerated list of all requirements and any hierarchical structure, including a description or definition of each

Model Overview

Model perspective

The proposed HMM will be one of three new modules introduced into NEMS for AEO2025 (the others being the Carbon Capture, Allocation, Transportation, and Sequestration Module [CCATS] and Hydrocarbon Supply Module [HSM]). Figure 1 illustrates NEMS and the different modules it consists of, with the three new modules highlighted in dark blue. HMM will be the third energy conversion sector module in NEMS. It will determine hydrogen sector demand for natural gas and electric power energy feedstocks (the Industrial Demand Module [IDM] will determine heat and power needs for SMRs), project an annual price and quantity of hydrogen, and deliver those values to the NEMS restart file for use by other modules.

Figure 1. NEMS overview, including modules (dark blue) for AEO2025

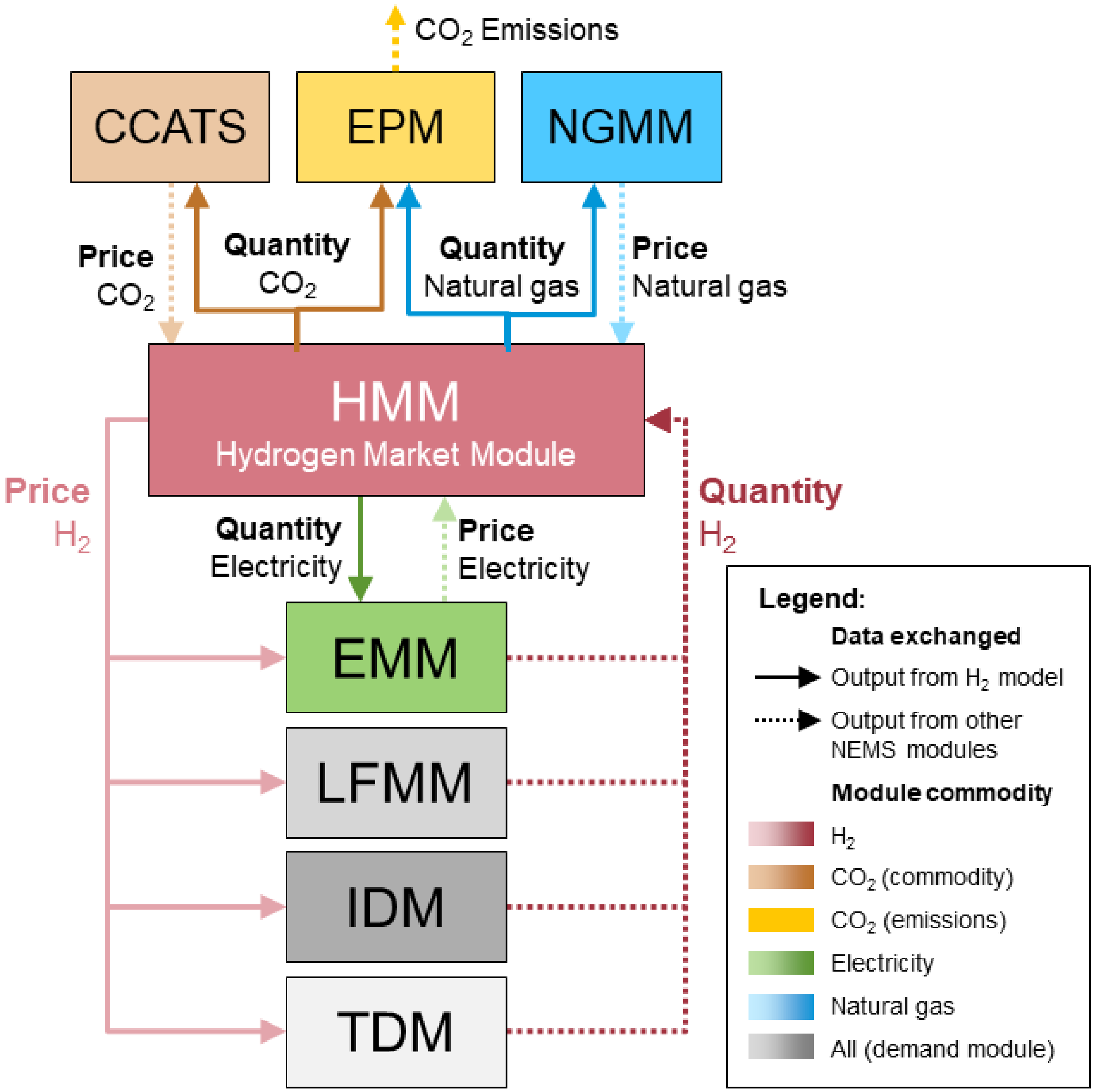


Source: U.S. Energy Information Administration

Note: NEMS=National Energy Modeling System

The relationships between HMM and other NEMS modules can be visualized in Figure 2.

Figure 2. Overview of Hydrogen Market Module (HMM) in relation to other NEMS modules



Source: U.S. Energy Information Administration

Note: CCATS = Carbon Capture, Allocation, Transportation, and Sequestration module, EPM = Emission Policy Module, NGMM = Natural Gas Market Module, EMM = Electricity Market Module, LFMM = Liquid Fuels Market Module, IDM = Industrial Demand Module, TDM = Transportation Demand Module

The following are the key projections through 2050 that HMM will *receive* from NEMS:

- The price of natural gas from the Natural Gas Market Module (NGMM)
- The hourly price of electricity from the Electricity Market Module (EMM)
- The value of CO_2 from CCATS, inclusive of 45Q tax credits (reflected as the price of CO_2 to other modules)
- Consumption of hydrogen from other NEMS modules, such as the IDM, Liquid Fuels Market Module (LFMM), Transportation Demand Module (TDM), and EMM

The following are the key projections through 2050 that HMM will *send* to NEMS, both for reporting purposes and as inputs to other modules:

- Price of hydrogen, including delivered prices to end users (IDM, LFMM, EMM, TDM)
- Volume of CO_2 captured (CCATS, EPM), distinguishing between CO_2 that is eligible for 45Q tax credits and CO_2 that is not
- The cost of capturing CO_2 split between capital and O&M costs
- Consumption of electricity and natural gas for hydrogen production (NGMM, IDM, EMM, EPM)

Software

We are developing the HMM optimization model using AIMMS. Any data preparation, cleaning, and processing required to create static model input files will be coded and designed to run outside of the optimization runtime environment and written in Python.

Even though HMM will run exclusively in AIMMS, we will need to interface with the NEMS Integration Module. The Integration Module will write relevant restart file values to HMM in an AIMMS readable format and call the execution of the AIMMS code. After HMM solves and writes model output and debug information, the Integration Module will write the output back to the restart file.

Figure 3 illustrates the software design choices for HMM and its related code as well as its interface with NEMS. HMM will use the data interfacing method implemented by NGMM and the Coal Market Module (CMM), which are also written in AIMMS. Restart file variables will be exchanged via the NEMS Integration Module using text files that are read or written using a Fortran subroutine. These input text files have standard names that include the current model year “yyyy” and current iteration “ii.”

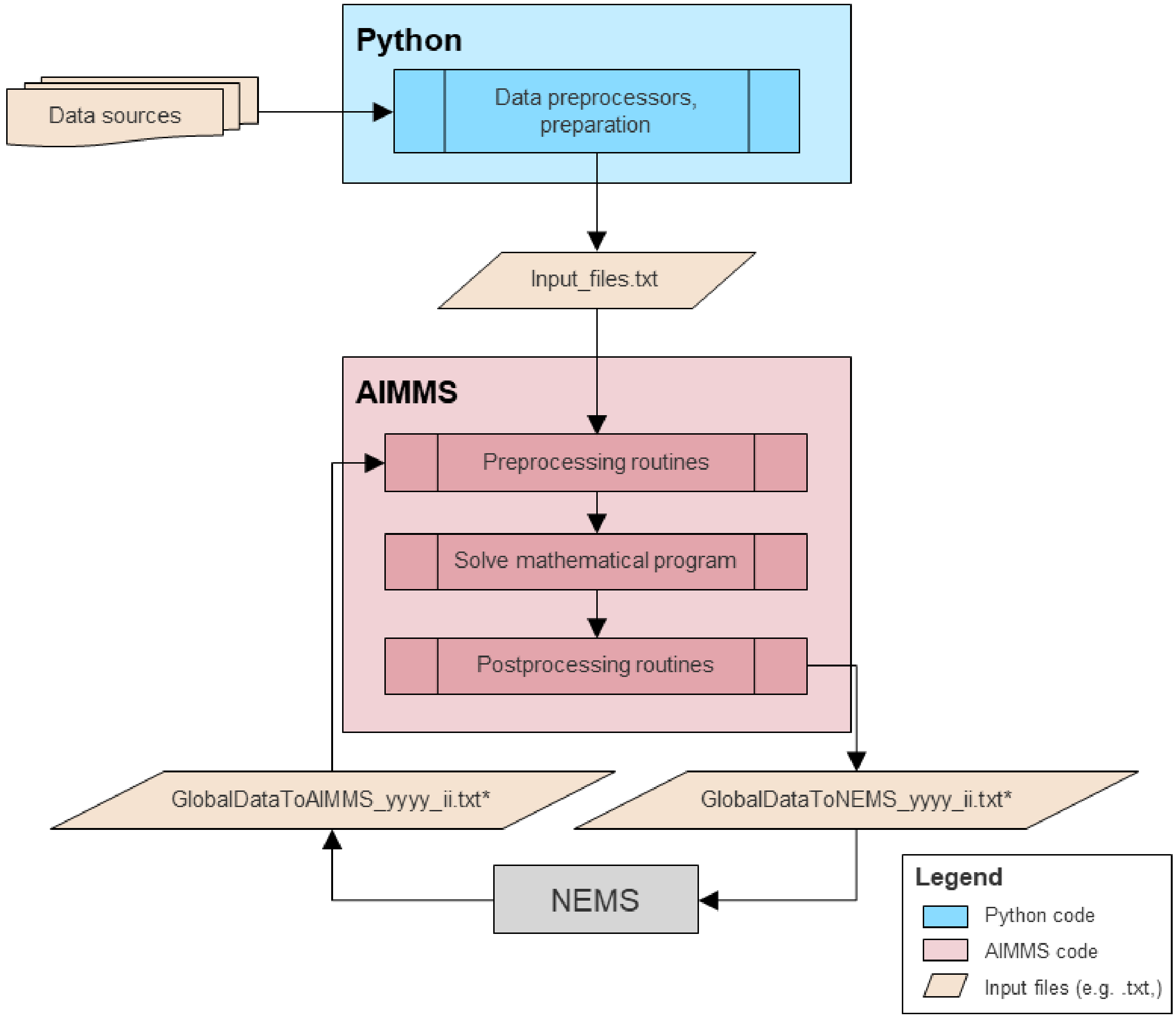
Data management philosophy

NEMS modules have an indefinite lifespan, potentially requiring maintenance from a changing team of modelers over many years. Managing model data carefully to improve model sustainability is therefore important. To do this, data will only interact with HMM from three sources.

- Directly from the Integration Module
- A single configuration text file in the HMM model folder
- Static data copied directly from preprocessor output

Limiting data pathways reduces the chance of undocumented zombie files that are missed during annual data updates. Running most data through a preprocessor achieves multiple goals: consistent data formatting, documentation through code, and ease of version control.

Figure 3. HMM software design decisions and data flows



Source: U.S. Energy Information Administration

Design and implementation constraints

Software and programming language

Model implementation in AIMMS causes additional constraints to the system due to the incompatibility of AIMMS to natively read or write to the NEMS restart file. We plan to use the existing code and model infrastructure to adhere to these constraints and ensure successful implementation and operation in the NEMS environment.

We do not expect any Python code within HMM during NEMS runtime; however, this decision may be revised as the Integration Module replaces main.f with main.py, converting its code and functionality from Fortran to Python. This implementation is currently scheduled to occur in late spring 2024. AIMMS models in the World Energy Projection System (WEPS) interface with the main Python integration code and restart files via wrappers in Python, which are written and maintained by the individual modules. Therefore, if future NEMS system changes require modifications, any preprocessing or postprocessing outside of AIMMS will be programmed in Python as well.

NEMS system

In NEMS, demand modules (for example, TDM and IDM) operate at the census-division level, which constrains regional representation within HMM. Hydrogen prices and volumes must be passed to NEMS at the census division level for most end-use sectors and for reporting purposes of all sectors. The electric power sector representation of electricity supply and hydrogen demand will interface with HMM at the EMM region level (based on regions delineated by the North American Electric Reliability Corporation [NERC]) to maintain consistency with EMM (note that EMM and NERC region may be used interchangeably).

Assumptions and dependencies

Production cost estimates

Since HMM will represent competing hydrogen production technologies, production cost estimates by production technology will be a key assumption in the module. Given the nascent nature of certain hydrogen production technologies, estimating capital and O&M costs will be difficult for less developed production technologies. We will ensure that default production cost assumptions are based on the best available data or estimates and use consistent methodologies across the different production technologies to ensure suitable comparisons. The module will be designed so that production cost estimates can be varied easily.

Carbon intensities and emissions

To calculate hydrogen production credits that are based on carbon intensities per the Inflation Reduction Act (IRA), we will assume the carbon intensity of each hydrogen production technology. Default assumptions for carbon intensities across production technologies will be made using the best available data and estimates with consistent methodologies for arriving at the carbon intensities to allow for suitable comparisons of carbon intensities between technologies.

However, HMM will be constrained in its handling and representation of carbon intensities by emissions accounting in NEMS, which is handled by EPM. This method will restrict our modeling in several ways:

- The only greenhouse gas (GHG) represented in EPM (and NEMS in general) is CO_2; however, carbon intensity as defined in the IRA must also include emissions related to methane and

natural gas, specifically all methane emissions from exploration- and production-related natural gas and methane losses across the entire supply chain from the well to the end user.
  - Methane is a GHG (with a higher warming potential than CO_2).
  - Methane eventually reacts to form CO_2 in the atmosphere.
  - We do not currently plan to expand emissions accounting to include methane in AEO2025.
- Specifically with respect to CO_2, we generally limit scope to *energy-related CO_2 emissions* in accounting and reporting; however, hydrogen production technologies (for example, SMRs) also release process emissions in addition to CO_2 emissions from the combustion of fossil fuels.
  - Combustion and process CO_2 emissions are released at different points of the production process and at different CO_2 concentrations (a key factor in the ease and cost to capture CO_2).
  - Any ability to correctly ascertain the carbon intensity of hydrogen production and any associated CCS technology, and the resulting impact on emissions, requires a complete accounting and handling of process emissions; we haven't decided whether this task will be done for AEO2025. It would require an expanded scope for our emissions accounting and data programs.
  - Given this issue, as well as the absence of methane in NEMS in its GHG accounting, Section 45V eligibility, which is determined using the carbon intensity of a hydrogen production pathway, will not be considered for technologies using CCS to mitigate emissions. We assume those producers will receive the Section 45Q credit.

Model Requirements

This section summarizes the specific model requirements for HMM and is organized into four sections: integration requirements, functional requirements, data requirements, and other requirements. Appendix A contains the table of every HMM requirement enumerated hierarchically, and it is organized to aid the team throughout the model development process and manage the requirements as they are met.

1. Integration requirements

Three broad categories of integration requirements must be met to successfully integrate HMM into the established NEMS structure:

- Requirements related to the NEMS interface with HMM, encompassing how HMM will be called during NEMS runtime, how data flows between NEMS and HMM must be implemented, and HMM runtime diagnostics that must be reported to NEMS per guidance by the Long-Term Integrated Products Team to more easily evaluate and debug NEMS behavior and outputs
- Requirements related to software versioning
- Requirements related to offline HMM data management, processing, and version control

These requirements are summarized below, with specific requirements and their definitions outlined in Appendix A.

1.1. NEMS interface

HMM development will proceed under the assumption that the existing NEMS integration code and infrastructure will be used in AEO2025. Therefore, calling AIMMS and writing runtime parameters from the scedes file with the existing process flow is required. We assume HMM will be called every year starting in an assumed *first model year* and run every iteration.

Similarly, HMM will interact with the NEMS restart file using existing methods employed by other AIMMS modules, such as NGMM and CMM. NEMS uses an unstructured raw binary file format (.unf) that modules read from and write to, which facilitates the exchange of data between various modules in NEMS. AIMMS cannot natively interact with this file format. Therefore, to read data from the restart file, a list of desired restart file variables will be passed to NEMS, and NEMS will write out restart file data in a text file that can be read by AIMMS. To write output data back to the restart file, AIMMS will write data destined for the restart file to a text file that is passed to NEMS, which then adds the data to the restart file.

The final subset of NEMS interface requirements pertains to runtime diagnostics and error handling. HMM must generate a clear log that documents model operations during runtime. This log must be understandable to non-HMM users and provide information about model performance. If HMM crashes or fails to solve during runtime, the result must be logged, and the NEMS run must be terminated, instead of allowing the system to bypass HMM and continue. Finally, HMM implementation also requires that we define a series of quality assurance tests that must be added to the NEMS validator tool. These validator tests will define the criteria HMM projections must meet to publish AEO data tables.

1.2. Software version

All code and software will adhere to the standard versions on the NEMS servers, including AIMMS 4.96.4.5 (x64) and Python pointing to the aeo2025_py311 environment. This practice will ensure syntax and capability consistency across modules. HMM will adhere to future version standards.

1.3. Hydrogen Market Module repository

Hydrogen data processing code will be performed in a separate git repository to be consistent with NEMS infrastructure best practices. Any input files read during NEMS runtime will be required to be tracked in the NEMS repository; furthermore, we require all input data files to be published annually with the NEMS code base (that is, any restricted or third-party data will not be present within input files).

2. Functional requirements

Section 2 in Appendix A lists the functional requirements for the new HMM in detail. In addition to the requirements listed in this table, key elements related to the module’s structure apply across the functional requirements.

The primary goal of HMM will be to produce reasonable hydrogen price and production projections given a certain set of assumptions, which will be passed to the rest of NEMS. HMM will solve for an optimal price that balances supply and demand while minimizing production costs of hydrogen. The following subsections describe the full set of functional requirements for the model.

2.1. Level of detail in market representation

2.1.1. Temporal detail

To properly represent grid-based electrolysis, decisions on when to run grid-connected electrolyzers must be made at an hourly time scale so that the model can evaluate hourly electricity prices, load constraints, and carbon emissions (necessary for 45V credit calculations). To represent seasonal storage of hydrogen, additional seasonal temporal dimensions will be required to account for injecting hydrogen into storage or withdrawing hydrogen from storage for summer, winter, and shoulder seasons.

2.1.2. Regional detail

Because the nine census divisions are the base regions used in NEMS for reporting purposes, the primary regionality requirement for HMM is the ability to read input data from NEMS dimensioned by census division and to write back data to NEMS dimensioned by census division. Within HMM’s optimization logic, grid-connected electrolysis decisions will be made at the EMM region level and will be aggregated to their corresponding census divisions to adhere to the requirement that data are written to NEMS by census division.

2.2. Production

At a minimum, HMM will model SMRs with or without CCS and on-grid electrolyzers as its hydrogen production technologies, which are either already established or are easier to incorporate in the current NEMS structure. Technology-specific capital and O&M costs will be used in capacity expansion to model the competitiveness of each technology. On-grid electrolyzer production will be modeled by hour, season, EMM region, and year. All other hydrogen production technologies will be modeled by year and census division. The price of fuels for feedstock and for heat and power will be obtained from the NEMS restart file.

Tax credits will be important sources of revenue for these production technologies and therefore must be incorporated into technology cost minimization. Also important to the sustainability of this production is the expectation of cost declines over time given technological breakthrough and market scaling. Therefore, learning rates will be applied to hydrogen production technology capital cost.

2.3. Consumption

HMM must represent, account for, and provide NEMS with the energy consumption associated with hydrogen production facilities. This consumption will be classified and accounted for under the larger industrial sector; however, the ability to specifically report volumes associated with hydrogen production manufacturing will exist. At a minimum, we will project natural gas and electricity consumption by production technology. Furthermore, IDM requires that HMM provide the consumption volume of natural gas used in hydrogen production separately from fuel used as petrochemical feedstock and fuel used for heat and power.

2.4. Policy

All core AEO cases project energy market trends that assume current laws and regulations, and HMM must also be able to reflect existing policies that may affect the development of a U.S. hydrogen market, including those related to decarbonization and lowering emissions. Therefore, HMM must reflect the two specific tax credits recently passed into law in its evaluation of hydrogen production technologies and their economic viability.

2.4.1. Section 45Q Tax Credit

Per the IRA, Section 45Q of the U.S. tax code provides a performance-based tax credit for carbon management projects, which capture carbon oxides (carbon dioxide and its precursor, carbon monoxide) from eligible industry and power facilities, as well as directly from the atmosphere. We will require that the impacts of this tax credit on CCS projects associated with hydrogen production facilities account for the impact of this tax credit on the economic competitiveness of qualifying hydrogen production facilities, specifically those facilities that combine SMR capacity with CCS. We must also ensure that the representation of the 45Q tax credit in HMM is coordinated with its implementation in CCATS, ensuring consistency across modules. Note that for initial implementation of HMM in NEMS, it is assumed that all CCS technologies choose to receive the 45Q credit in lieu of the 45V credit for hydrogen supplied.

2.4.2. Section 45V Production Tax Credit

Per the IRA, Section 45V of the U.S. tax code provides a hydrogen production tax credit (PTC) subsidy to suppliers based on the carbon intensity of hydrogen production: the life-cycle greenhouse gas emissions intensity (equivalent kilograms [kg] of CO_2) resulting from 1 kilogram of hydrogen produced (kg CO_2e/kg H_2). Treasury guidance outlines the requirements to earn a given level of the PTC, which may be as much as $3/kg for hydrogen produced with a carbon intensity of 0.45 kg CO_2e/kg H_2. Given the proposed guidance and in anticipation of the final rule, we will require the following criteria be used to determine the PTC earned per kg of hydrogen produced:

- **Regionality**. New renewable generation capacity sufficient to meet the electricity load for on-grid electrolyzers that produce hydrogen must be built in the same EMM region as the new electrolyzer capacity.
- **Hourly clean electricity matching**. The carbon intensity of hydrogen produced from grid-fueled electrolysis will be determined using the hourly CO_2 combustion emissions for utility power generation in the corresponding EMM region, month, and hour. This determination will depend on the fuel generation mix at the hourly level.

Note that for initial implementation of HMM in NEMS, we assume that only production of hydrogen via electrolysis can receive the 45V tax credit.

In addition to these two specific policies, HMM's formulation and model structure will be designed while considering the ability to also implement other potential policies in the future, which includes the ability to model the impact of carbon taxes (as opposed to subsidies) in NEMS runs.

2.5. Prices

HMM will use the dual price of its demand constraints to produce a supply price for every census division. These prices will represent the price basis for sector specific prices. EMM will receive a hydrogen supply curve representing price-quantity pairs over a set number of supply steps. The number of steps will be the same across all regions. All other modules will receive a single hydrogen price with sector-specific markups. Hydrogen prices will include the marginal price of production given life-cycle costs of capacity expansion, fuel prices, the cost of long-term seasonal storage, and transportation costs.

2.6. Transmission and distribution

HMM will include transmission modeling between census divisions. Although the significant growth of interregional hydrogen trade remains unlikely given the current regulatory challenges and additional costs related to safe transport of hydrogen, we will allow for the flexibility to model myriad assumptions. However, given the above challenges and hub-focused hydrogen market development plans, HMM will model low-cost intraregional trade and high-cost interregional trade for AEO2025. This strategy will reflect the difficulty in establishing mature transmission infrastructure that we see in other markets such as natural gas. The model structure will allow for easy expansion of transmission modeling as the market matures and new technology and data emerges.

Transmission often incurs losses from transformation and purification processes. If data are available, HMM will include these losses and ensure they are incorporated in total mass balancing.

2.7. Storage

We will require a minimum representation of hydrogen storage modeled in HMM, which is defined as storage technology available to build in the module that is applicable for seasonal storage. We will only be allowing salt cavern storage to be built in HMM. This representation will include capturing total capital costs (drilling, cushion gas, compressors, etc.) and variable operating costs (electricity, costs based on the quantity of withdrawal and injection). HMM will also model increasing costs of storage under the assumption that low-cost land is finite.

HMM will model seasonal injections and withdrawals within a given year but will not be required to model year-over-year hydrogen storage. Proper hydrogen storage balances will be maintained.

3. Data requirements

As a conversion model, inputs from other modules have a high impact on HMM's results, and HMM's output can have a high impact on other modules. Formalizing data requirements is imperative to ensure these connections are planned and executed correctly.

Beyond static inputs from the HMM preprocessor, the module will require fuel prices from several modules, fuel carbon intensity and CO_2 prices to implement tax credits, and aggregated demand from multiple modules. Output data include energy consumption for feedstock and for heat and power, sectoral prices of hydrogen, and quantity of CO_2 captured in the production process.

Strict adherence to data agreements must be met for the use of third-party input data. The HMM code and data must be able to be published under the NEMS open source license.

3.1. Input data

Table 1 summarizes key data inputs for HMM to produce quality results. The data are identified by function, dimensions, and source. New variables will be created in the restart file prior to testing to allow data connections with other modules. Non-EIA data will be sourced from third-party sources and preprocessed accordingly.

Table 1. Summary of primary input requirements

Requirement	Usage	Dimensions	Source
Annual price of natural gas	Calculate fuel costs for SMRs	year,region	NGMM
Hourly price of electricity	Calculate costs for grid electrolyzers	hour,year,region,season	EMM
Annual value of CO_2	Calculate economics of SMR CCS	year,region,45Q_eligibility	CCATS
Hourly electricity generation by generation source	Calculate carbon intensity of generation mix; constrain amount of electricity used by grid electrolysis for each hour	hour,year,region,season, gen_source	EMM
Annual hydrogen consumption in the industrial sector	Meet hydrogen demand from industrial facilities	year,region	IDM

Requirement	Usage	Dimensions	Source
Seasonal hydrogen consumption in the electric power sector	Meet hydrogen demand from hydrogen-fueled turbine generators	year,region,season	EMM
Annual hydrogen consumption in the refining sector	Meet hydrogen demand from refineries	year,region	LFMM
Annual hydrogen consumption in the transportation sector	Meet hydrogen demand from transportation vehicles	year,region	TDM
Hydrogen production capital and operations costs	Assumption used to calculate net present value of adding and maintaining additional hydrogen capacity	tech	Non-EIA
Hydrogen production fuel consumption efficiency	Assumption that specifies how much fuel is consumed to produce one kilogram of hydrogen	tech	Non-EIA
Capacity utilization limit	Assumption that constrains hydrogen production capacity utilization	tech	Non-EIA
Hydrogen storage costs	Assumptions relating to costs necessary for injecting, withdrawing, and storing hydrogen	none	Non-EIA
Hydrogen storage capacity addition cost	Assumption relating to the cost to build hydrogen storage capacity	none	Non-EIA
Historical hydrogen production capacity	Historical hydrogen production baseline	year,region,tech	Non-EIA
Planned hydrogen production capacity	Hydrogen production capacity set to come online exogenously in a given year	year,region,tech	Non-EIA

3.2. Output data

Table 2 summarizes key outputs from HMM to be used by other NEMS modules. The data are identified by function, dimensions, and module destination. New variables will be created in the restart file prior to testing to allow data connections with other modules. Many of these outputs influence the requirements toward building a minimally viable hydrogen module.

Table 2. Summary of primary output requirements

Requirement	Usage	Dimensions	Destination
Natural gas consumed by SMRs	Volume of natural gas consumed by SMRs for hydrogen production	year,region	NGMM, EPM
Volume of CO_2 captured via CCS in SMRs	Volume for CO_2 market and emissions calculations	year,region	CCATS, EPM

Requirement	Usage	Dimensions	Destination
Grid electricity consumed by grid electrolysis	For electricity generation capacity build decision foresight	hour,year,region,season	EMM
Hydrogen supply curve	Fuel for electricity generation in the electric power sector	year,season,region,step	EMM
Price of hydrogen to industrial sector	End-use price of hydrogen for use in the industrial sector	year,region	IDM
Price of hydrogen to electric power sector	End-use price of hydrogen for use in the electric power sector	year,region	EMM
Price of hydrogen to transportation sector	End-use price of hydrogen for use in the transportation sector	year,region	TDM

Source: U.S. Energy Information Administration

3.3. Data compliance

The NEMS codebase is published every AEO cycle, which includes input files used by individual modules. Although using EIA-owned data for model inputs is preferable, modules frequently must use third-party data. All purchased third-party data used in HMM must be handled appropriately during code publication according to the purchase agreements of said data. The HMM code and data must be able to be published under the NEMS open source license.

3.4. Published data tables

With the implementation of HMM, NEMS will be adding a new fuel—hydrogen—to its sector-level accounting of energy consumption. Furthermore, the production of hydrogen itself is, by definition, manufacturing of base chemicals, specifically industrial gas. So, HMM requires that both the use of hydrogen as a fuel and the energy consumed in its production be added to all published data tables, either in aggregated total or as separate use.

Because the manufacturing of hydrogen gas is categorized as an industrial use of energy, we will require that hydrogen production be created as a new subsector under the industrial sector. The current plan is that hydrogen production will be accounted for, handled, and reported in NEMS analogous to refinery energy use. Like refinery use, consumption will be aggregated into this total, but the energy consumed in hydrogen production will be available within NEMS and in certain publication tables as a separate subtotal. Finally, the last requirement related to publication tables relates to AEO emissions accounting. Steam methane reforming, the current technology used to produce hydrogen, primarily releases industrial process emissions; energy-related emissions (for example, combustion of fossil fuels) are also generated but are a minor component of total emissions. Furthermore, it is the industrial process emissions that are economic targets for CCS. Therefore, the introduction of HMM into NEMS also requires that both the combustion emissions and industrial process emissions released from hydrogen production pathways be consistently accounted for, including in published data tables.

4. Other requirements

The fourth section in Appendix A lists the other system requirements to be met by the new HMM development and implementation process. Several key requirements are expanded on below.

4.1. Performance

HMM must meet three performance requirements: runtime, feasibility, and uniqueness.

To limit extending NEMS runtime, we will ensure that HMM solves in an acceptable amount of time as defined in collaboration with the integration team. The initial requirement will be that total HMM runtime in a given NEMS cycle will not exceed 20 minutes. This requirement ensures that a NEMS run can be completed overnight, allowing for daily reviews of model results by analysts.

We will require that the linear program consistently give feasible results, which means that the model input assumptions and constraints will not need to be regularly modified for the model to solve. If the model gives an infeasible solution, appropriate error messages and validator tests will be triggered.

Finally, we require that the mathematical program have a unique solution that is reproducible given the same restart file and model inputs, which will avoid oscillations that lead to NEMS non-convergence and will indicate that our representation of the U.S. hydrogen market is sufficiently constrained.

4.2. Code quality

In developing and coding HMM, we require that the following best practices be implemented, specifically in the AIMMS optimization model:

- **Discrepancy accounting**. Although the mathematical program will have a constraint that hydrogen supply equals demand, we require that additional discrepancy tracking be included in the code to aid in debugging and ensure both the model solution and any pre- or post-processing steps are correctly applied.
- **Utilization of set logic**. Given that AIMMS is an algebraic programming language, set logic will be used throughout the model structure. Furthermore, set elements and element parameters will be used to avoid hard coding in HMM.
- **AIMMS best practices**. We will require that EIA-established AIMMS coding best practices be used in the development of HMM, including the following features:
  - Case files for data management and saving output results for model debugging
  - Use of procedures in lieu of identifier definitions for setting parameters
  - Use of binary parameters for mappings and other code logic
- **Self-configuration**. Any project options, solver settings, or other AIMMS settings that are required for HMM will be part of the model code to ensure self-configuration after software updates and other NEMS system changes that may reset these options.
- **Python and general programming best practices.** We will follow these best practices with EIA and integration team guidance, including code commenting via docstrings, consistent formatting in data pipelines, and version control.

4.3. Technical reviews

As part of HMM development, we will require that the following technical reviews take place:

- **Mathematical formulation technical review.** This document will be the full, detailed model structure for the optimization model and basic code structure of HMM; therefore, we will require that the Chief Modeler provide a detailed review of the model structure, including the decision objective function, decision variables, constraints, and fundamental set structure. In addition, we will require that all key technical leads, specifically subject matter experts who work on the IDM and EMM, review and sign off on our mathematical program and proposed formulation before coding.

- **Model code peer review**. We will require that all model code, both AIMMS and Python, be regularly reviewed either by another HMM team member or other programmers in the Office of Energy Analysis (OEA) to ensure code documentation, readability, maintainability, and adherence to EIA best practices.
- **Integration team reviews**. We will require biweekly coordination meetings at a minimum with the Long-Term Integrated Products Team, including the Team Lead and all staff responsible for NEMS. We will require their review to ensure that all proposals related to how HMM interfaces and operates within NEMS is properly supported by their team, meets their criteria for acceptable implementation, and is appropriately coordinated with any overarching changes expected in the NEMS system.

4.4. Model documentation

We will require that detailed, thorough model documentation be produced for HMM within 90 days of the AEO2025 public release. The format and review of this documentation will be consistent with the latest OEA guidance.

4.5. Debugging requirements

HMM will be designed in such a way that makes it easy for other modelers to debug model results. HMM needs to be able to run in a *standalone* mode so that all model years can run sequentially without needing to run NEMS. Model output for all model years will be stored in the module to facilitate debugging of model results. Report pages in AIMMS will be created to further aid in debugging.

Appendix A. Table of Requirements

ID	Requirements	Description
1	**Integration**	
1.1	NEMS interface	
1.1.1	Calling AIMMS	Call AIMMS from NEMS via existing framework
1.1.1.1	Years run	Run HMM from first model year through last model year
1.1.1.2	Iterations run	Run HMM at least first iteration, with the capability for running all iterations available
1.1.2	Runtime parameters	
1.1.2.1	Transfer of scedes parameters	Transfer scedes runtime parameters needed by HMM via text file consistent with existing AIMMS models in NEMS
1.1.2.2	Endogenize runtime parameters	Use control parameters from NEMS global data to define the year, iteration, etc.
1.1.3	Restart file variables	
1.1.3.1	Text file variable I/O definition	Use existing framework of two .txt files to list and define the sets of restart file variables to write to AIMMS and read back in NEMS
1.1.3.2	Text file I/O transfer	Exchange restart variable data via .txt files in “toAIMMS” and “fromAIMMS” directories consistent with existing framework
1.1.3.3	Naming conventions	Use variable naming conventions that are consistent (for example, “h2” for hydrogen fuel)
1.1.3.4	Common block	Store HMM output variables in HMMBLK (excluding QBLK, MPBLK, QMORE, and PMORE variables that are part of convergence)
1.1.4	NEMS runtime diagnostics	
1.1.4.1	Error log	Generate a clear log that is understandable to non-HMM users and that provides information about model performance
1.1.4.2	Validator tests	Add multiple relevant validation tests to NEMS validator tool to confirm error-free performance, help diagnose issues with runs
1.1.4.2	Run termination	Crash, or terminate, the NEMS run immediately upon model infeasibility or failure to successfully solve
1.2	Software version	
1.2.1	AIMMS version	Be compatible with and run in the latest AIMMS version used by NEMS
1.2.2	Python version	Ensure compatibility of Python code with latest Python version and package environment in NEMS
1.3	HMM repository	
1.3.1	Data processing files	House and maintain version control of all data files and data processing files within a git repository separate from the NEMS repository
1.3.2	Transfer to NEMS repository	Transfer only files read during runtime from the h2_model repository to the NEMS repository

ID	Requirements	Description
2	**Functional**	
2.1	Model granularity	
2.1.1	Temporal resolution	Solve hourly and seasonally for grid-based production technology and annually for all other technology
2.1.2	Geographic resolution	Meet demand at the census-division level
2.2	Production	
2.2.1	By technology type	
2.2.1.1	SMR	Project production of H_2 via SMR by year and region
2.2.1.2	SMR+CCS	Project production of H_2 via SMR with CCS by year and region
2.2.1.3	Electrolysis fueled by grid, hourly	Project production of H_2 via grid-fueled electrolysis by hour, season, EMM region, and year
2.2.2	Capacity expansion	
2.2.2.1	Life-cycle costs	Include costs over project life cycle in decision to build new H_2 production and storage capacity
2.2.2.2	Learning	Allow for changes in learning rate and cost declines in select H_2 production technologies
2.3	Consumption	
2.3.1	Natural gas consumption	
2.3.1.1	Natural gas feedstock	Project natural gas used as feedstock for H_2 production by year and region
2.3.1.2	Natural gas heat and power	Project natural gas used for heat and power during H_2 production by year and region
2.3.2	Electricity	Project electricity consumption for H_2 production by hour, month, EMM region, and year
2.4	Policy	
2.4.1	45Q	Include 45Q tax credits in evaluating economics of H_2 production technologies with CCS
2.4.2	45V	
2.4.2.1	Regionality	Apply 45V clean H_2 production tax credit assuming regional matching (EMM)
2.4.2.2	Hourly clean electricity matching	Apply 45V clean H_2 production tax credit using hourly matching of generation mix
2.4.2.3	Treasury guidance	Reflect Treasury guidance for Section 45V tax credits, subject to release
2.4.3	Carbon tax	Allow for carbon tax representation in H_2 production, technology, and capacity decisions
2.5	Prices	
2.5.1	H_2 supply price	Project supply price of H_2 by region, technology type, and year
2.5.2	H_2 spot or market price	Project spot or market price of H_2 by region and year
2.5.3	End-use prices	
2.5.3.1	Industrial	Project delivered end-use prices to the industrial sector by census region and year
2.5.3.2	Refinery	Project delivered end-use prices to refineries by census region and year

ID	Requirements	Description
2.5.3.3	Transportation	Project delivered end-use prices to the transportation sector by census region and year
2.5.3.4	Electric power	Project delivered end-use prices to electric power sector by EMM region, season, and year
2.6	Transmission and distribution	
2.6.1	Limited regional transmission	Represent regional H_2 markets with limited transmission across regions
2.6.2	Mass balance	Require all midstream transport of H_2 adhere to mass balance, including losses
2.7	Storage	
2.7.1	Annual injection = withdrawal	Assume storage injections equal storage withdrawals (plus losses) in any year
2.7.2	Costs	Include storage capex and opex costs in delivered end-use prices
2.7.3	Type	Allow for storage type expansion as new technology is developed over time
3	**Data**	
3.1	Input data	
3.1.1	Historical data	
3.1.1.1	Consistency with EIA data	Leverage existing EIA data or estimates where possible, including as inputs to module
3.1.1.2	Output consistent with history	Ensure projections in early model years are consistent with historical data and market trends
3.1.2	External data sources	
3.1.2.1	Ensure realistic assumptions	Ensure any assumptions behind data are realistic with minimum policy goal bias
3.1.2.2	DOE data sources	Leverage existing DOE H_2 work where possible
3.1.3	Input data processing	Process raw data outside the NEMS system and outside of runtime, with input files containing data needing minimal processing within AIMMS
3.2	Output data	Produce all output data expected by other NEMS modules
3.3	Data compliance	Ensure all data in H_2 module are used in accordance with any licensing agreements and may be published, including registering new data sources per OEA guidance
3.4	Published data tables	
3.4.1	Consistency across tables	Add both the use of H_2 as a fuel/feedstock and the energy consumed in the production of H_2 to published data tables, either in aggregated total or as separate use
3.4.2	Energy accounting	Consider energy use in the production of H_2 an industrial use
3.4.3	Emissions accounting	Consistently account for both combustion and industrial process emissions, including in published data tables

ID	Requirements	Description
4	**Other system requirements**	
4.1	Performance	
4.1.1	Runtime	Add no more than 10 minutes per cycle to total NEMS runtime after implementing HMM
4.1.2	Feasibility	Achieve convergence of HMM model outputsunless given values from another module that indicates errors in their solution or operation in NEMS
4.1.3	Unique and reproducible results	Solve HMM such that the results are unique and reproducible
4.2	Software quality attributes	
4.2.1	Discrepancy tracking	Track discrepancy between supply and demand in module
4.2.2	Use of set logic	Use set logic in construction of mathematical program
4.2.3	AIMMS best practices	
4.2.3.1	Case files	Use case files for debugging and saving data
4.2.3.2	Use of procedures	Define identifiers in procedures where possible (that is, *not* in identifier window where identifier is created in AIMMS)
4.2.3.3	Binary parameters	Use binary parameters for mapping between regions and for aggregating and disaggregating data
4.2.3.4	Self-configuration	Ensure AIMMS model self-configures Project Options each time AIMMS is called
4.2.4	Python best practices	Use function docstrings when coding in Python (https://www.programiz.com/python-programming/docstrings)
4.3	Technical reviews	
4.3.1	Technical review of math program	Review mathematical formulation with senior modelers familiar with optimization
4.3.2	Model code peer review	Peer -review all model code
4.3.3	Integration team meetings	Hold biweekly meetings with integration team to communicate updates, issues, and system changes
4.4	Model documentation	Produce mathematical model documentation consistent with AIMMS implementation
4.5	Debugging tools	
4.5.1	AIMMS report pages	Implement basic debugging output in AIMMS to assist in both debugging and model tuning.
4.5.2	Restart file data transfer verification	Transfer NEMS variable inputs into HMM AIMMS identifiers prior to any data processing; only write ouput from HMM to NEMS restart variables after the model runs (that is, NEMS variables not used directly in AIMMS code)
4.5.3	Error handling	Implement error handling in AIMMS code for system crashes
4.5.4	AIMMS standalone operability	Have an entry point such that HMM is testable on its own absent NEMS
4.5.5	NEMS-HMM compartmentalization	Compartmentalize AIMMS HMM code to ease debugging

Source: U.S. Energy Information Administration