Model taxonomy for hydrogen energy systems

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Agenda

2-minute version of the work

Longer version with more details
Approach

Define a model taxonomy for archetypes of hydrogen models

Define the archetypes of hydrogen models commonly used in literature

Characterize the archetypes using the taxonomy

Identify commonalities, gaps, and challenges
Key messages

1. **No single model can cover all** the perspectives and **soft-linking** multiple models is **necessary** to give a holistic answer.

2. **Hydrogen** is a versatile energy carrier that **requires special features for modeling**. These include system-wide scope, flexibility to the power sector, need for high temporal resolution, no end use GHG emissions, consumer behavior, among others.

3. **Some** of the modeling **categories** (e.g., renewable hydrogen production) are **well covered across all archetypes**, while others (e.g., environmental impact) are only covered by one or few archetypes.

4. The characterization allowed identifying **correlations between the archetypes** to identify which ones are the most **complementary** to each other.

5. In terms of **gaps**, **environmental impact**, the **innovation** cycle, **market design** and **policy** levers to promote deployment are much less covered.

6. Hydrogen technologies are relatively new in some archetypes (e.g., IAM) and a **consistent and validated set of data for use across models** is lacking.
Agenda

2-minute version of the work

Longer version with more details
There are 6 major categories that can be used to characterize the most important features of an energy model

This taxonomy is applicable to any energy model

**Complexity**
Factors that make the model more realistic
- Irrationality of agents
- Uncertainty analysis
- Market representation

**Spatio-temporal features**
Coverage and resolution across space and time
- Spatial resolution
- Spatial coverage
- Temporal resolution
- Time horizon

**Structure (topology)**
Conversion pathways covered and input data
- Renewable technology
- Thermal plants
- Hydrogen conversion
- Demand technologies
- Sectors covered
- Input data
- Constraints

**Purpose of the model**
Main intended use of the model
- Policy
- Market
- Environmental
- Forecasting
- Backcasting
- Exploratory

**Solution methods**
Approach to solve the problem and reach the final state
- Analytical approach
- Mathematical approach
- Methodology
- Programming language

**Use and accessibility**
How easy is to access the code and make changes? Is training available?
- Transparency
- Licensing
- Training
## Modeling features required to model hydrogen

<table>
<thead>
<tr>
<th>System-wide scope</th>
<th>Flexibility for power system</th>
<th>Spatio-temporal resolution</th>
<th>No end use GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade-offs across feedstocks and end uses</td>
<td>Electrolyzers compete with other flexibility options such as storage, transmission, demand response</td>
<td>Fine resolution to capture flexibility benefits and model infrastructure expansion</td>
<td>Need to use lifecycle assessment to quantify the upstream impact and beyond GHG emissions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Systemic drivers</th>
<th>Consumer behavior</th>
<th>Development uncertainty</th>
<th>Climate variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Role of hydrogen is influenced by role of other cross-cutting tech like CCS, bioenergy, nuclear</td>
<td>Hydrogen might arise (e.g., FCEV) when other factors beyond cost are considered</td>
<td>Cost decline over time, availability of renewables, CCS can all affect the role of hydrogen</td>
<td>Wind is fundamental for H₂ production and it is affected by the climate year and patterns</td>
</tr>
</tbody>
</table>
Taxonomy is adapted to 4 categories when considering the main modeling features that hydrogen requires

**Methodology**
Role of hydrogen will depend on this
- Optimization vs simulation
- Macro vs micro-economic
- System dynamics
- Multi-criteria

**Spatio-temporal resolution**
Need for models that can model with at least **hourly resolution** to be able to account for the **flexibility** of electrolyzers and with high spatial resolution to make choices about **infrastructure expansion** and consider the specific **renewable potential**

**Complexity**
Hydrogen technology are mostly at an early stage making **innovation (tipping points)**, clear **policy signals and market formation** critical. These are complex aspects that most models do not cover. **Behavioral aspects** could also favor hydrogen and are also overlooked by most models

**Model topology**
Full hydrogen potential can only be assessed when **all the conversion pathways (to derivatives)** are considered, and **all the end uses** (for those derivatives) are included. Multiple feedstocks and trade are also relevant for its full potential
There are 9 archetypes for hydrogen models

**Boundaries and relationships between hydrogen model archetypes**

<table>
<thead>
<tr>
<th>Archetype</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAM</td>
<td>Used for IPCC reports covering the natural system, the human system, and climate</td>
</tr>
<tr>
<td>Energy</td>
<td>Used to outline decarbonization pathways for the entire energy system. Usually exclude economy and land</td>
</tr>
<tr>
<td>Power</td>
<td>Focus on electricity sector with (at least) hourly resolution</td>
</tr>
<tr>
<td>VRE integration</td>
<td>Off-grid optimization of plant configuration (including unit sizes, storage, and hourly operation)</td>
</tr>
<tr>
<td>Sectoral models</td>
<td>Have a better representation of a single sector but omit the interaction with the rest of the energy system</td>
</tr>
<tr>
<td>Cities</td>
<td>Similar to energy models but applied to a city, potentially with a higher spatial resolution</td>
</tr>
<tr>
<td>Islands</td>
<td>Isolated systems with more limited choices for 24/7 electricity supply and storage technologies</td>
</tr>
<tr>
<td>Supply chain</td>
<td>Identify the spatial location of assets (renewables, pipelines, HRS) with fixed assumptions for the rest of the system</td>
</tr>
<tr>
<td>LCA-based</td>
<td>Expand energy model to cover sustainability aspects with more data needed and soft-linking required</td>
</tr>
</tbody>
</table>
There are trade-offs to consider for each archetype and selection should be done based on modeling objective

<table>
<thead>
<tr>
<th>Archetype</th>
<th>Advantages</th>
<th>Challenges</th>
<th>Specificity for hydrogen</th>
<th>Specificity for H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAM</td>
<td>Cover land use, economy, climate, and the entire energy system</td>
<td>Slow update cycle (IAM). Focus on H₂ for road transport. Limited PtX representation. Perfect foresight assumed</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Energy</td>
<td>Consider trade-offs for feedstocks and end use across the entire system and constraints can be added to cope for shortcomings</td>
<td>Limited representation of hydrogen transport and use. Limited to a single year</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Power</td>
<td>Captures flexibility and representation of the power market</td>
<td>No alternative uses for the renewable energy or coupling with hydrogen use</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>VRE integration</td>
<td>Closer to business model of PtX plants with high temporal resolution</td>
<td>Omit technologies with multiple output (e.g., CHP). No possibility of demand curves with multiple sectors</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Sectoral models</td>
<td>Broader set of criteria and range of business models can be included</td>
<td>Ability of granular data. Behavioral aspects</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Cities</td>
<td>Complement urban planning and closer to implementation</td>
<td>Availability of granular data. Behavioral aspects</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Islands</td>
<td>Explore pathways towards 100% RES</td>
<td>Modeling high VRE systems with seasonal storage. Full energy system coverage with high temporal resolution</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Supply chain</td>
<td>Individual sites for renewables and H₂ use can be identified</td>
<td>Exogenous assumptions on hydrogen demand and willingness to pay and fixed renewable input</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>LCA-based</td>
<td>Enriches cost and energy dimensions with environmental impact</td>
<td>Consistency in inventory data (e.g., electricity) and limit to expanding geographical scope</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
No single model covers all the features that are needed

There are archetypes that are close to each other and choice will depend on the study objective.

Correlation between hydrogen model archetypes based on similarities across dimensions of the hydrogen taxonomy

Key insights

- **LCA, energy, and spatial analysis can be complementary**
- **Geospatial analyses** for renewable potential and infrastructure are the least correlated to other archetypes so there are limited choices if that is critical aspect of a study
- **IAM, ESM, power model, city, and off-grid models are highly correlated** given their reliance on cost optimization and the representation of (a part of) the energy system. The specific choice among them will depend on the specific objective of the study
Thanks to all the team!

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