SAND2016-5614PE

GLOBAL HYDROGEN RESOURCE ANALYSIS FOR THE TRANSPORT SECTOR

Thomas Drennen

Hobart and William Smith Colleges

Sandia National Laboratories

Susan Schoenung

Longitude 122 West, Inc.

USAEE/IAEE North American Conference

New York City

June 15 – 18, 2014

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

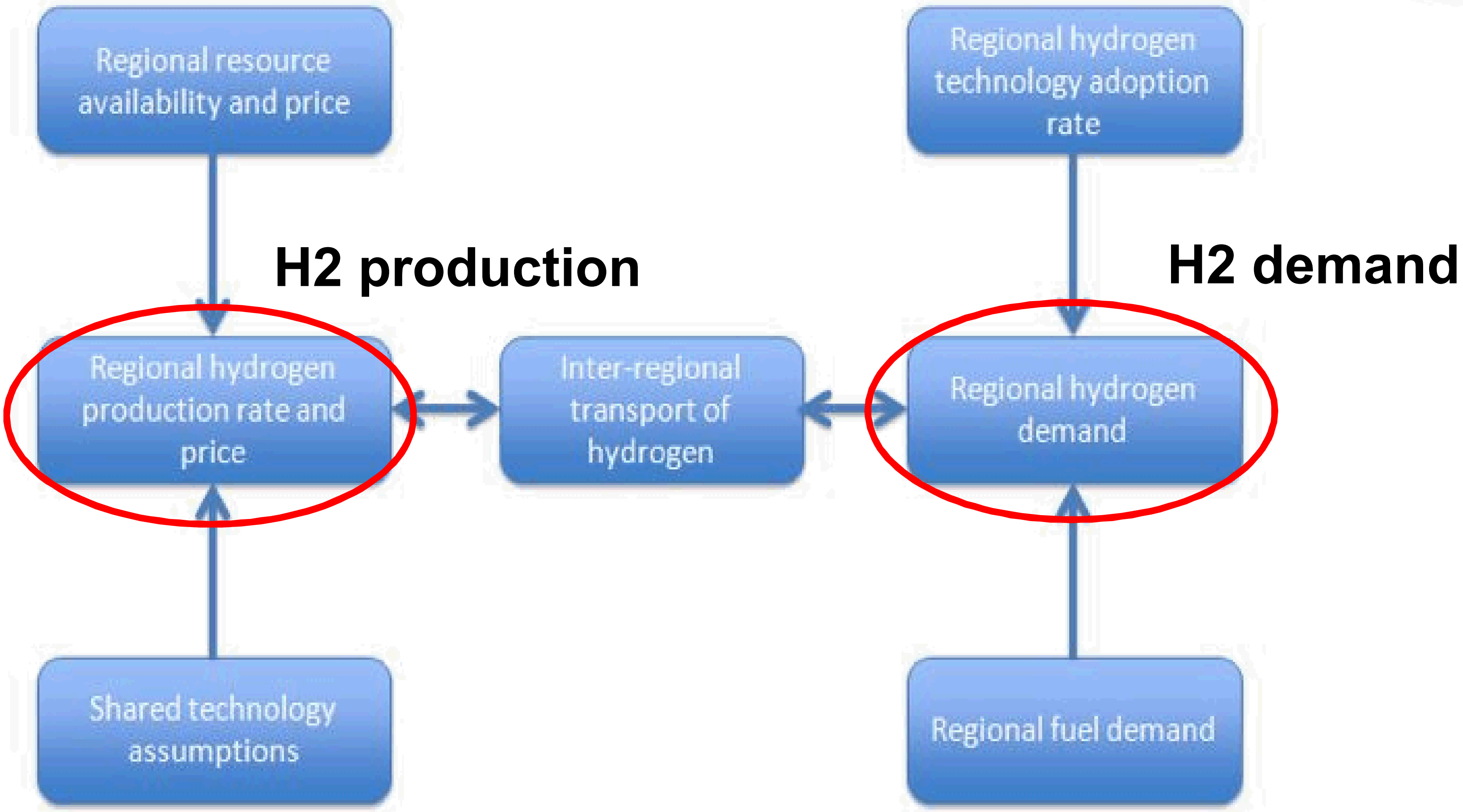
Global Hydrogen Resource Analysis

- This project is a subtask of the International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) Task 30 (Global Hydrogen Systems Analysis).
- The overall objectives of Subtask 30A (Global Hydrogen Resource Analysis) are to:
  1. Analyze potential hydrogen production and distribution pathways for participating countries
  2. Develop a user-friendly pathways analysis tool that allows users the ability to:
     - Understand the resource options and constraints to meeting future hydrogen demand for various fuel cell vehicle market shares; and to
     - Estimate potential petroleum savings and greenhouse gas emission reductions associated with various scenarios.
  3. Collaborate with IEA analysts as appropriate to support global hydrogen resource analysis.

Approach

- The Global Pathways Resource Analysis Tool (GPAT) calculates least-cost pathways for H2, including consideration of: feedstock, conversion, regional and long-distance distribution, and carbon costs.
- For each country, hydrogen demand is calculated based on assumptions about future hydrogen vehicle market shares.
- Hydrogen production costs are calculated based on country-supplied data on feedstock availability for hydrogen production by type, cost, and quantity from 2010 to 2050, and assumptions about hydrogen production technology assumptions (efficiencies, costs, etc.).
- A key feature of the Global Pathways Resource Analysis Tool is the ability for users to vary key assumptions, including resource availability and price, vehicle shares and efficiencies, carbon taxes, and renewable portfolio standards, and view real-time results, making the tool ideal for policy-level discussions.

Global Pathways Resource Analysis Tool



Key Assumptions

Delivered H2 costs include:

- Feedstock costs
- Production (or conversion) costs
- Distribution costs within region
- Long distance distribution costs between countries
- CO_2 prices (default is zero)

Feedstock Costs

Feedstock costs

- Countries supplied feedstock prices and resources available over time
- H2 costs ($\$/GJ_{H2}$) = feedstock cost ($\$/GJ_{input}$)/conversion efficiency($GJ_{H2}/GJ_{input}$)
- Conversion efficiencies based on U.S. analysis pending completion of Task 30B (H2A 3.0)
- Example: Coal costs – 4.28 $/GJ. H2 Feedstock costs = 4.28/.536 = 7.98 $/GJ

Technology	Assumed Efficiency (%)
Onsite natural gas (SMR)	71.9
Centralized natural gas	72.7
Electrolysis	72.5
Biomass	49.6
Centralized Coal	53.6

Production Costs

Production costs

- Include all production/conversion costs other than feedstock costs
- With exception of Japan, production costs are based on a previous U.S. analysis **pending completion of Task 30B** (H2A Systems Analysis, version 3.0)

Technology	Production Costs ($/GJ)
Onsite natural gas (SMR)	6.67
Centralized natural gas	3.25
Centralized coal	10.75
Centralized coal with CCS	14.67
Biomass gasification	8.92
Electrolysis	5.25

Distribution costs (within region)

Distribution costs

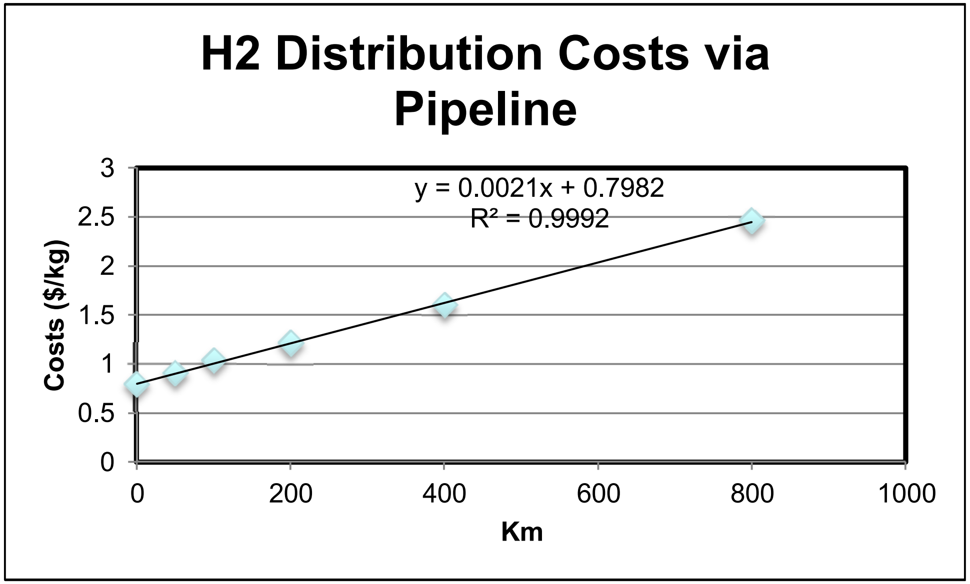
- Includes all costs from plant gate to end use
- With exception of Japan, distribution costs based on H2A Systems Analysis Model.
- Onsite options: 13.75 $/GJ
  - Includes compression, storage, and dispensing
  - Based on natural gas reforming 1500 kg/day H2 production capacity
  - Capital (55%), fixed O&M (23%), and variable O&M including utilities (22%)
- Centralized options: 21.50 $/GJ
  - Includes compression (25%), storage (26%), pipeline transport (32%), liquefaction (8.3%), and refueling station (7.9%)
  - Assumes pipeline transport within an urban setting with more than one million people, market penetration of 50%, 700 bar cascade, and liquid storage
- GPAT does allow for annual changes in these numbers (used in Japanese case)

Long-distance distribution costs

Long-distance distribution costs

- Includes costs of pipeline distribution between regions/countries
- Cost equation estimated using H2A Delivery Scenario Analysis Model (HDSAM) model:

Costs ($/kg) = 0.7982 + 0.00206*Distance (km)



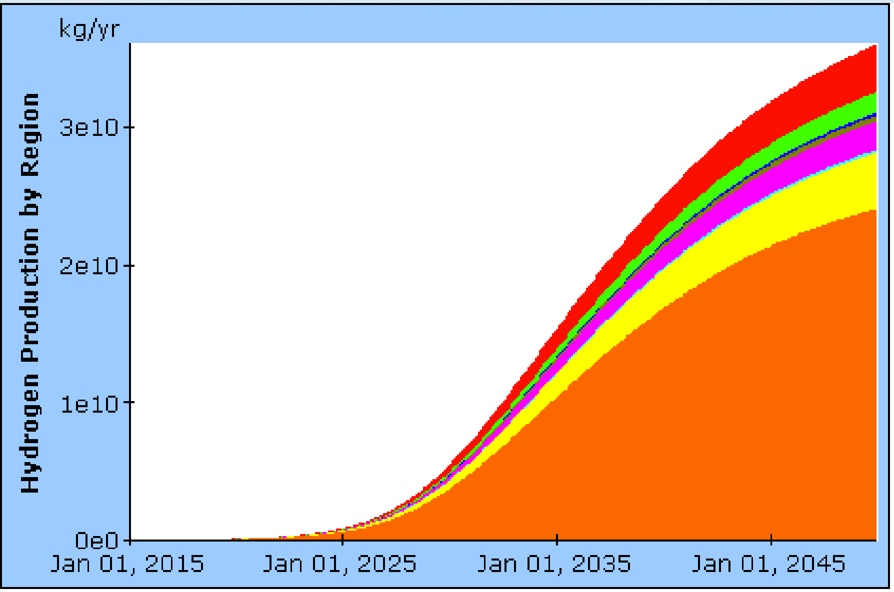
Key Assumptions (continued)

- Default assumption is that H2 production is based on **least cost option**
- Countries can require certain percent come from domestic or non-CO2 emitting sources
- As new options become economically competitive:
  - More expensive domestic sources phased out over 10 years
  - Instantaneous switching from non-domestic sources (if France is purchasing H2 from Germany and the Spanish source become cheaper, switches to Spanish source)
- Base cases assume German policy mandating 20% of H2 produced from renewable resources.
- H2 demand based on assumptions about light-duty vehicle fleet. Default assumes 40% market share of new vehicle sales for fuel cell vehicles by 2050.
  - Exception: France assumes 20% market share

Results

- The analysis shows that there are a large number of potential pathways for providing hydrogen to fuel a significant vehicle fleet and that **resource availability is not the limiting factor in a hydrogen economy**.
- Using GPAT, each participating country has identified multiple options for producing hydrogen domestically.
- Two scenarios presented:
  - Scenario 1: Each country produces sufficient H_2 domestically to meet demand (no trading between countries).
  - Scenario 2: Interregional trading and 100 $/ton CO_2e by 2025.

Case 1: No Interregional H2 Trading, Global Results



Delivered H2 prices in 2050 ($/GJ)

Delivered H2 Price	US	Canada	Germany	Norway	Spain	Sweden	Denmark	France	Japan
US	30.81	-	-	-	-	-	-	-	-
Canada	-	-	-	-	-	-	-	-	-
Germany	-	-	40.23	75.05	79.00	65.59	67.61	69.74	-
Norway	-	-	61.34	53.94	87.94	54.01	66.08	85.13	-
Spain	-	-	79.07	101.72	40.16	91.50	79.96	69.98	-
Sweden	-	-	65.66	68.87	91.50	40.16	66.77	88.16	-
Denmark	-	-	56.73	68.91	69.00	55.81	51.12	79.16	-
France	-	-	59.95	89.05	60.12	78.30	80.25	50.03	-
Japan	-	-	-	-	-	-	-	-	47.84

Columns are Supply and Rows are Consumption (Vertically it is the price supplied to the horizontal country)

Result pages show:

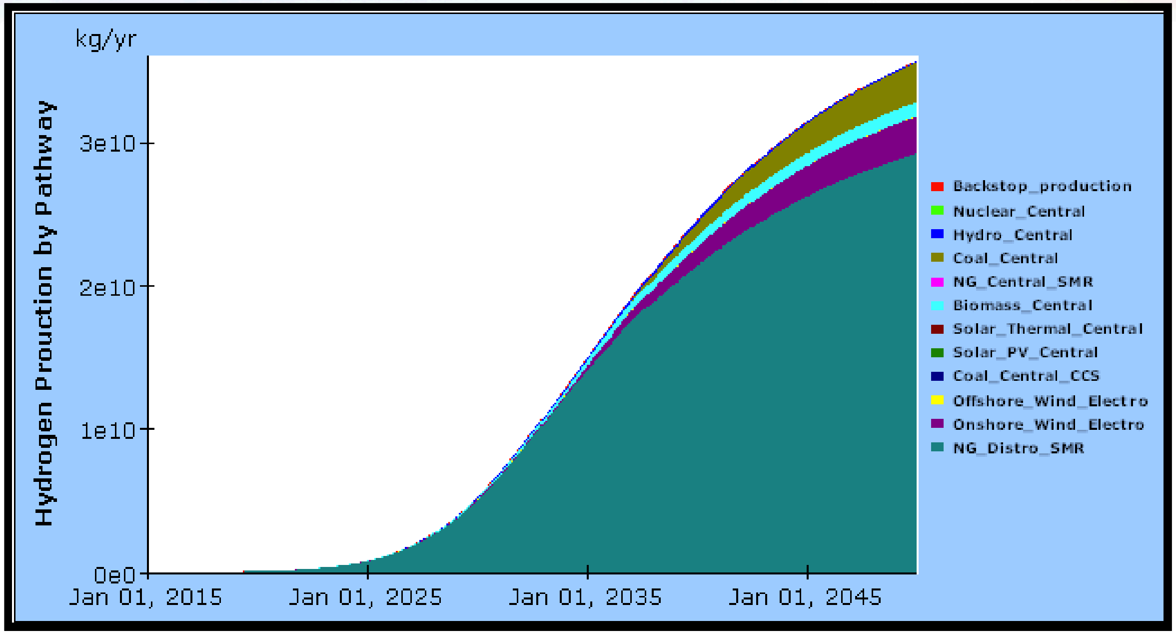
- Hydrogen production (above left) and consumption by region (production = consumption for Case 1)
- Total delivered costs (above right) and in stacked bar format by country
- Production pathways
- CO2 emissions from vehicles
- Comparison of increased feedstock demand due to H2 production compared to 2009 primary energy demand.

Sandia National Laboratories

Case 1: No Interregional H2 Trading, Global Results

Production Pathways:

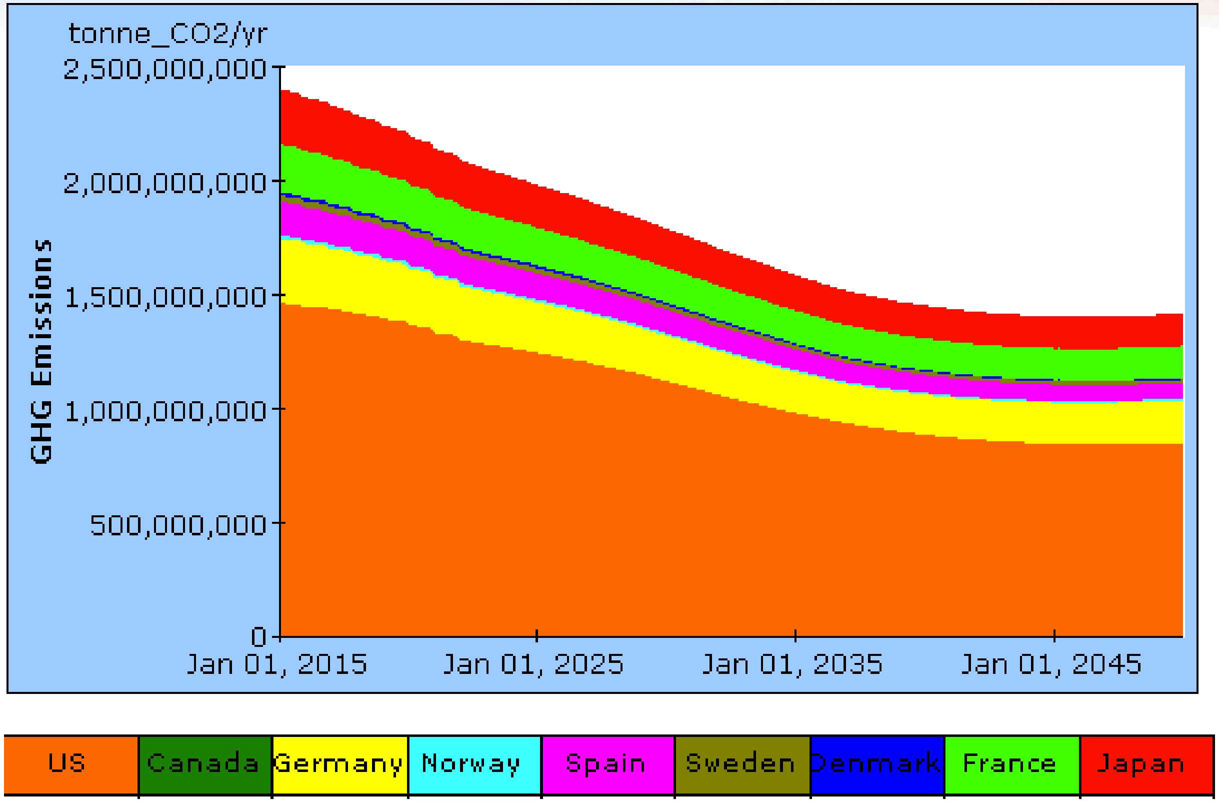
- Includes US, select European countries, and Japan
- H2 production dominated by on-site natural gas SMR
- Small contributions from onshore wind, biomass, and centralized coal



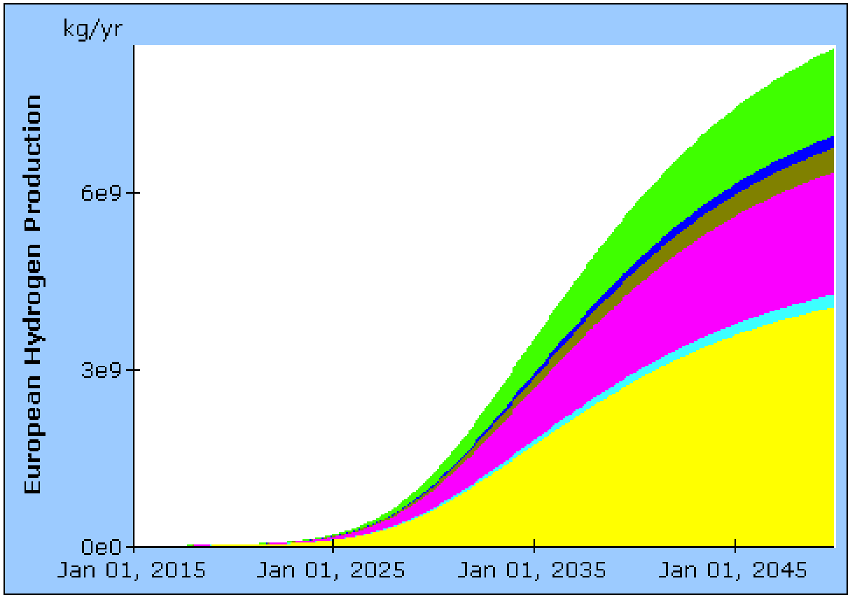
Case 1: No Interregional H2 Trading, Global Results

GHG emissions from light duty vehicles

- GHG emissions fall over time as:
  - Fleet efficiencies improve (gasoline and diesel)
  - Fuel cell vehicle share increases
- Emission decline plateaus as the 40% FCEV market share is reached.



Case 1: No Interregional H2 Trading, European Results



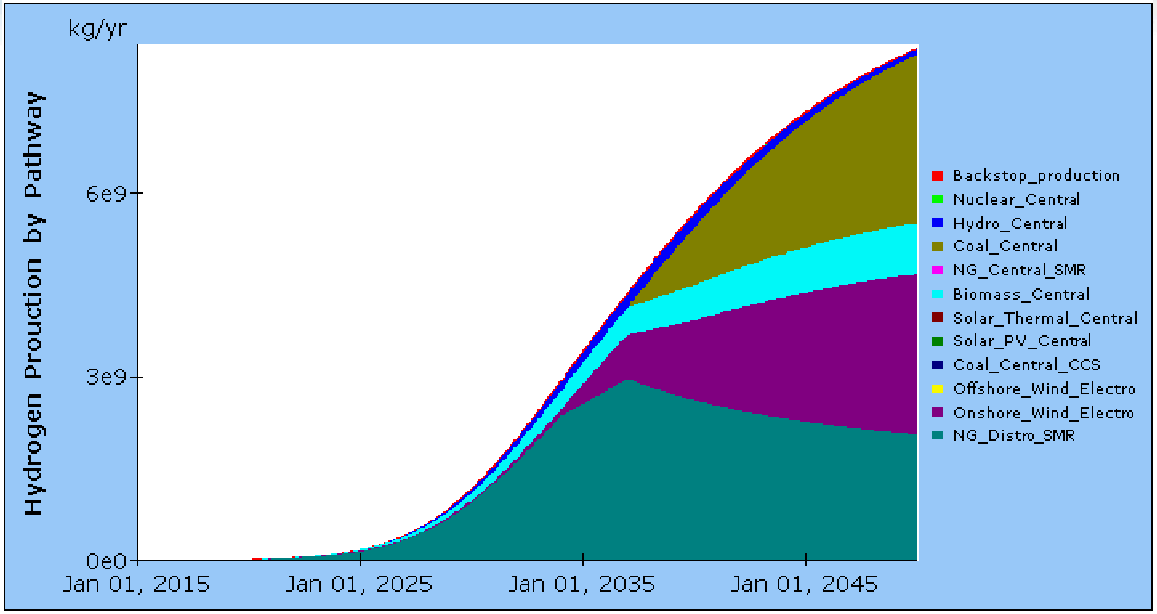
Delivered H2 prices in 2050 ($/GJ)

Delivered H2 Price	Germany	Norway	Spain	Sweden	Denmark	France
Germany	40.23	75.05	79.00	65.59	67.61	69.74
Norway	61.34	53.94	87.94	54.01	66.08	85.13
Spain	79.07	101.72	40.16	91.50	79.96	69.98
Sweden	65.66	68.87	91.50	40.16	66.77	88.16
Denmark	56.73	68.91	69.00	55.81	51.12	79.16
France	59.95	89.05	60.12	78.30	80.25	50.03

Columns are Supply and Rows are Consumption (Vertically it is the price supplied to the horizontal country)

- Shows H2 production by country and prices for delivered hydrogen (each country produces just enough H2 for domestic use)
- For example, Germany’s cost is 40.23 $/GJ; delivered H2 from France to Germany would cost 69.74 $/GJ (costs shown in 2050)

Case 1: No Interregional H2 Trading, European Results

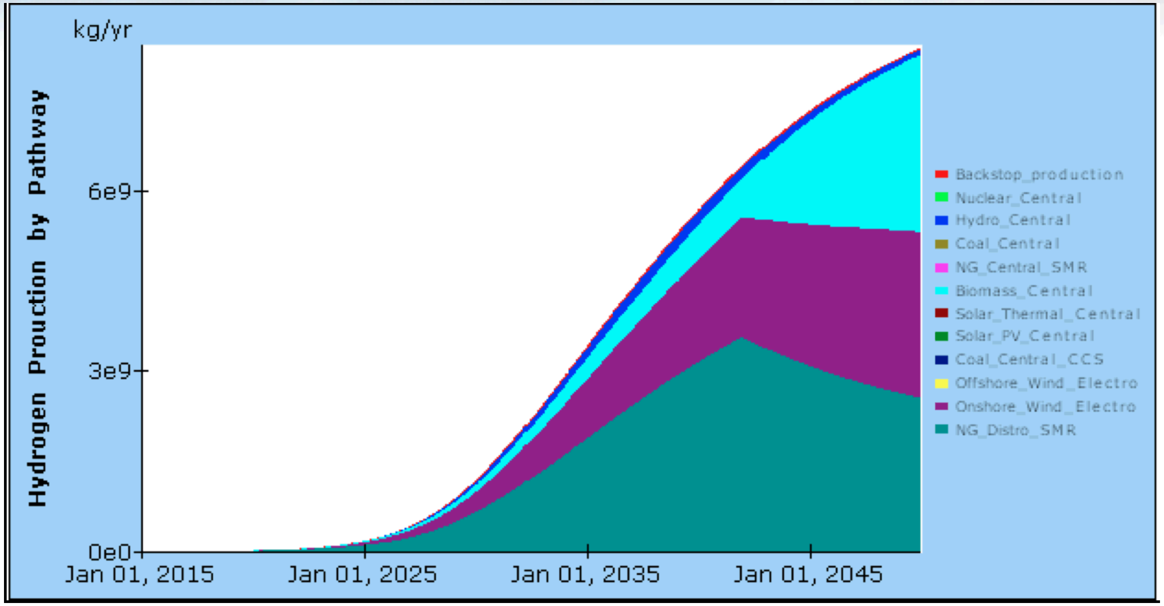


Hydrogen Pathways

- In the early years, hydrogen is produced using onsite natural gas reformation. The share produced from natural gas levels declines after 2035 as onshore wind, biomass, coal, and hydro capture market share as their costs drop relative to natural gas.
- Total hydrogen demand reaches 8.3 billion kg H_2/year by 2050, equivalent to 165 million barrels of oil per year.

Sandia National Laboratories

Case 2: Interregional trading and 100 $/ton CO_2e by 2025, European Results

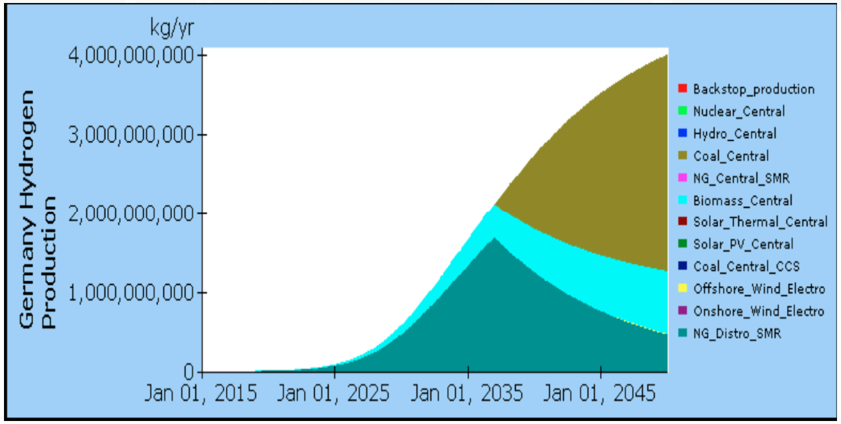


Hydrogen Pathways

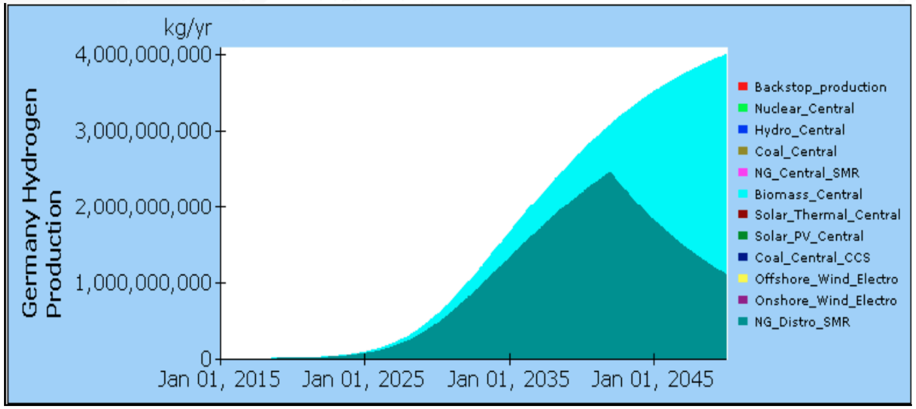
- The inclusion of a price on CO_2 drives out the use of coal gasification in favor of biomass gasification. Greenhouse gas emissions are further reduced by the elimination of coal gasification; emissions are 44% below 2015 levels by 2050.
- Each country still produces their own hydrogen. With higher natural gas prices or higher CO2 prices, begin seeing movements of H2 between regions.

Sandia National Laboratories

Example of Country-Specific Results: Germany



Production pathways for Germany (Scenario 1).

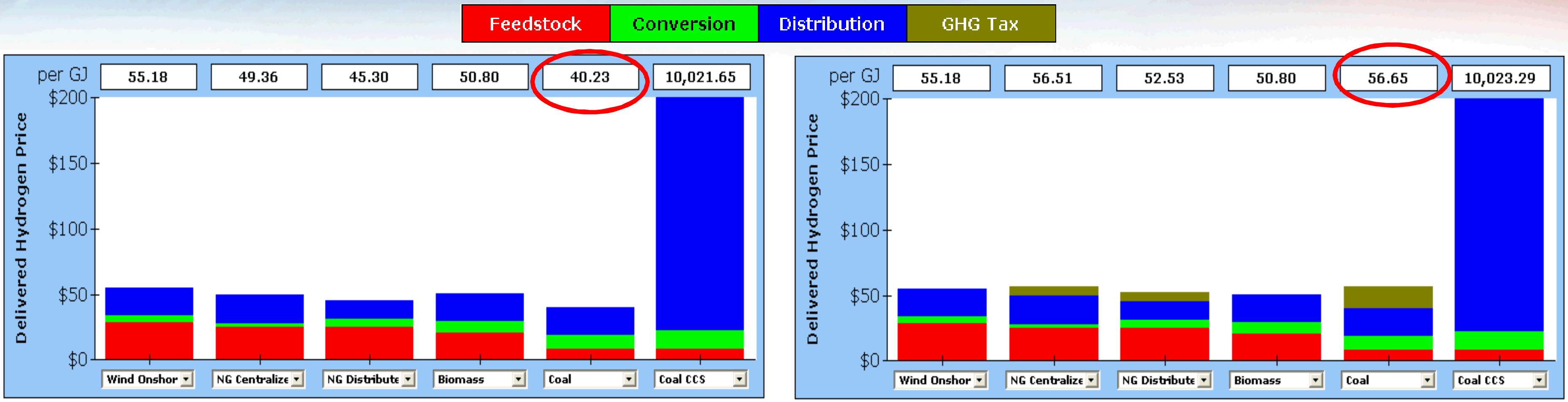


Production pathways for Germany (Scenario 2).

Hydrogen Pathways

- The inclusion of a price on CO_2 drives out the use of coal gasification seen in Scenario 1 in favor of biomass gasification.
- Greenhouse gas emissions are further reduced by the elimination of coal gasification; emissions are 44% below 2015 levels by 2050.

Example of Country-Specific Results: Germany



H2 Production costs for Germany (Scenario 1).

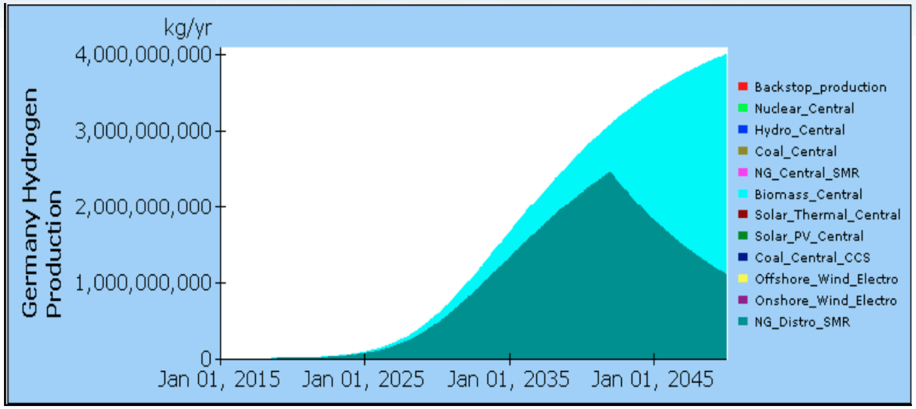
H2 Production costs for Germany (Scenario 2).

Hydrogen Pathways

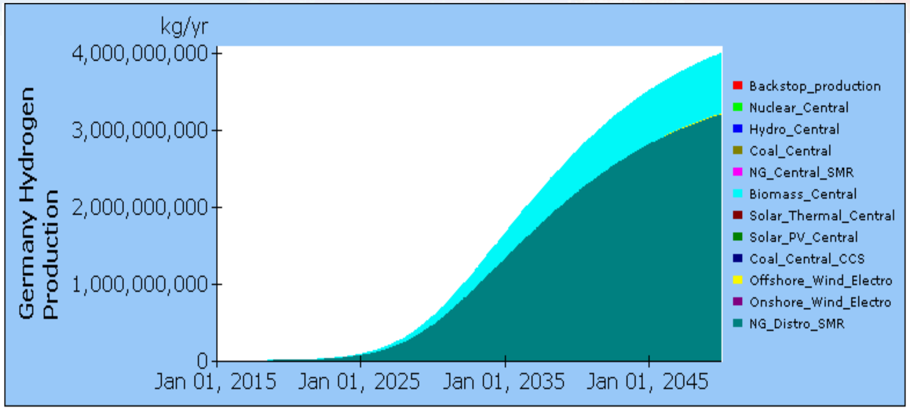
- The inclusion of a price on CO_2 drives out the use of coal gasification seen in Scenario 1 in favor of biomass gasification.
- Greenhouse gas emissions are further reduced by the elimination of coal gasification; emissions are 44% below 2015 levels by 2050.
- Germany says they will not use CCS technologies, so set arbitrarily high so not part of the solution.

Sandia National Laboratories

Example of Sensitivity Analysis: Germany



Production pathways for Germany (Scenario 2).



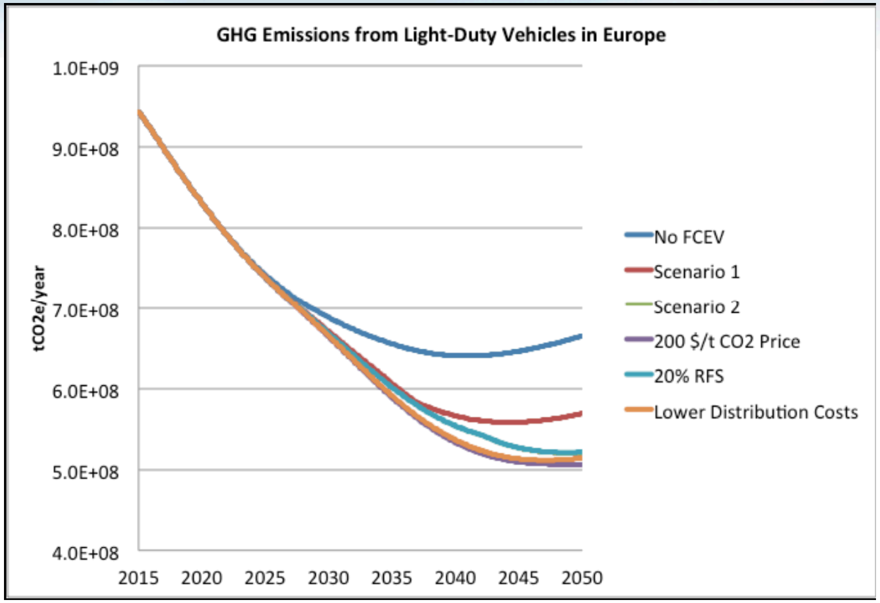
Sensitivity Analysis for Germany, Scenario 2: Biomass 20% more costly.

Hydrogen Pathways

- Results are very sensitive to assumptions about the price of the biomass resource. GPAT allows the user to easily test these sensitivities.
- A 20% increase in the assumed price of biomass results in a solution where natural gas captures the market share not required to come from renewables.

Sandia National Laboratories

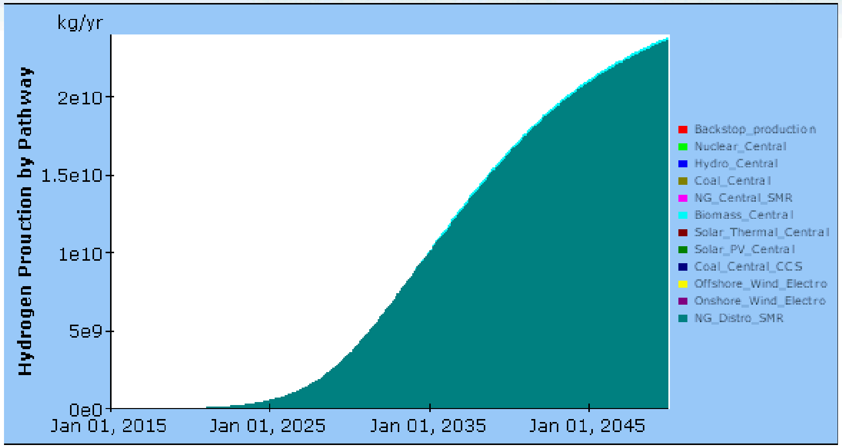
GHG emissions: Europe



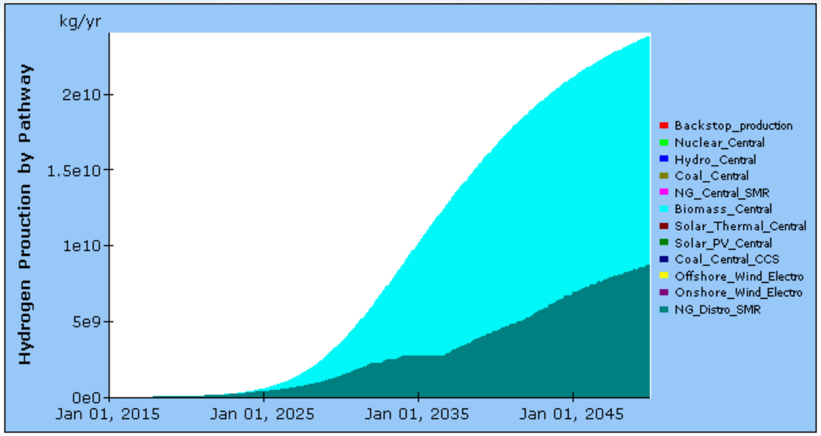
- GHG emissions will decrease even without the introduction of FCEVs as fuel efficiencies improve.
- The introduction of FCEVs can result in significant additional reductions, especially if countries require a certain percentage of the hydrogen be produced from renewable sources.
- Emissions plateau as the 40% market share is achieved. Achieving further decarbonization could be achieved with a larger scale introduction of FCEVs or other non-CO2 emitting vehicle options.

Sandia National Laboratories

Country Specific Results: U.S.



Production pathways for U.S. (Scenario 1)



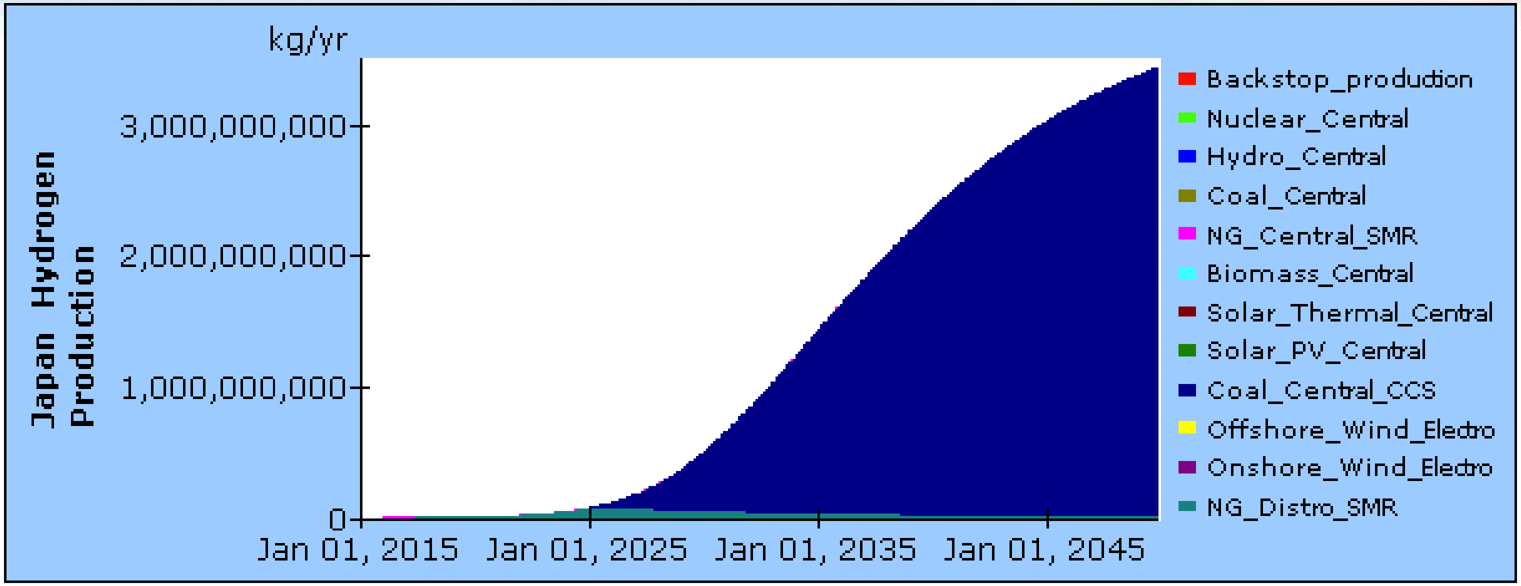
Production pathways for U.S. (Scenario 2)

Hydrogen Pathways

- The United States is modeled by sub-region, with results available at either the regional or aggregate level. Aggregate results shown here.
- Without higher gas prices or carbon prices, low-cost natural gas is used for hydrogen productions (Scenario 1).
- Carbon taxes lead to increased role of biomass gasification (Scenario 2).

Sandia National Laboratories

Country specific results: Japan



- The Japanese included option of long-distance transport of H2 produced using brown coal gasification with CCS in Australia.
- Japanese provided estimates for Australian production and shipping by ship.
- This option becomes the least-cost option after 2025 for Japan, even with CO2 taxes as they assume a 95% carbon capture and sequestration rate.

Lessons Learned

- Large number of potential pathways for providing hydrogen to fuel significant HFCV fleet: resources are **not** the limiting factor.
- Global Pathways Analysis Tool (GPAT) is a powerful discussion tool, providing insight about possible pathways.
- Every country has identified multiple options for producing hydrogen domestically.
- Distribution costs an important consideration – costly to move H2 between countries or even long distance within countries.
- CO2 policies/prices will have large impact but in a low natural gas price world, takes a large CO2 price to drastically change results.

Backup slides

Sandia National Laboratories

Country-level screen layout

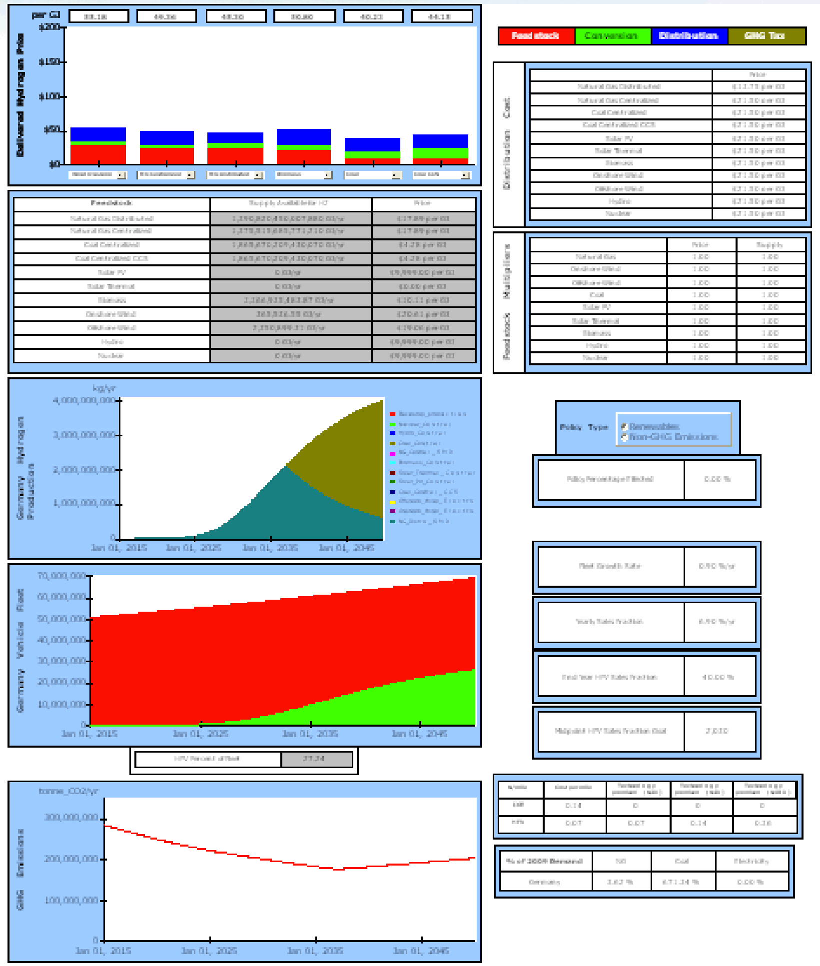
Total H2 prices

Feedstock supply & cost

H2 Pathways

Vehicle fleet

GHG emissions



Regional Distribution costs

Feedstock sensitivity

Renewable/No GHG Policies

Fleet assumptions

Cost per mile

Resource increases over 2009