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Hydrogen Resource Analysis Update
HIA Task 30
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Agenda: Global Resource Analysis (Subtask A)

- Objectives
- Model overview
- Data overview
- Model results
- McKinsey study
  - Comparison of objectives and results
  - Differentiating factors
- Next steps

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Objectives: Global Resource Analysis (Subtask A)

Objectives

- Analysis of regional resources for hydrogen production given country's individual resources and price structures
- Analysis of potential for hydrogen transport between regions
- Creating a dynamic model populated with country supplied data that allows users the ability to understand the likely options and constraints to meeting future hydrogen demand

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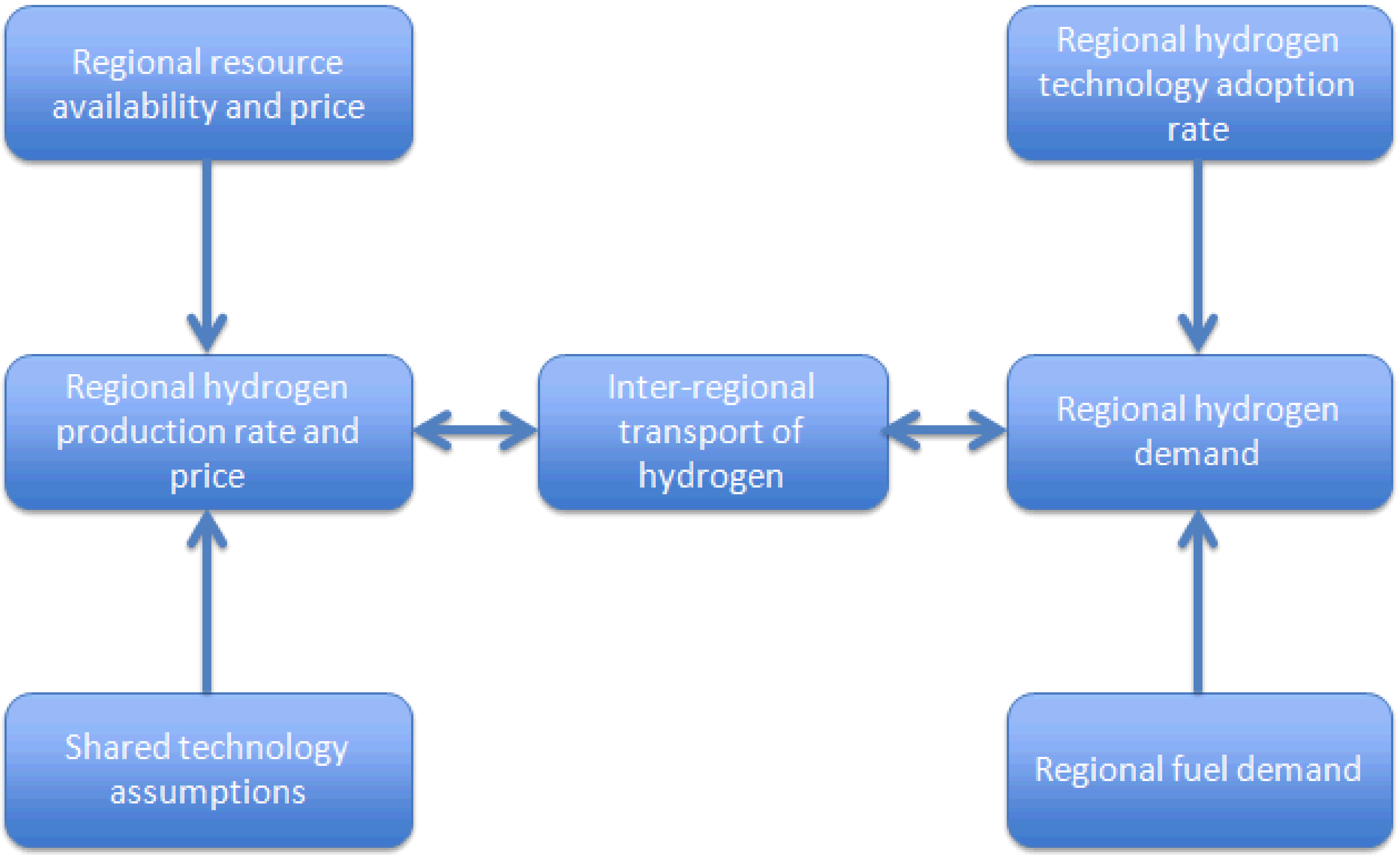
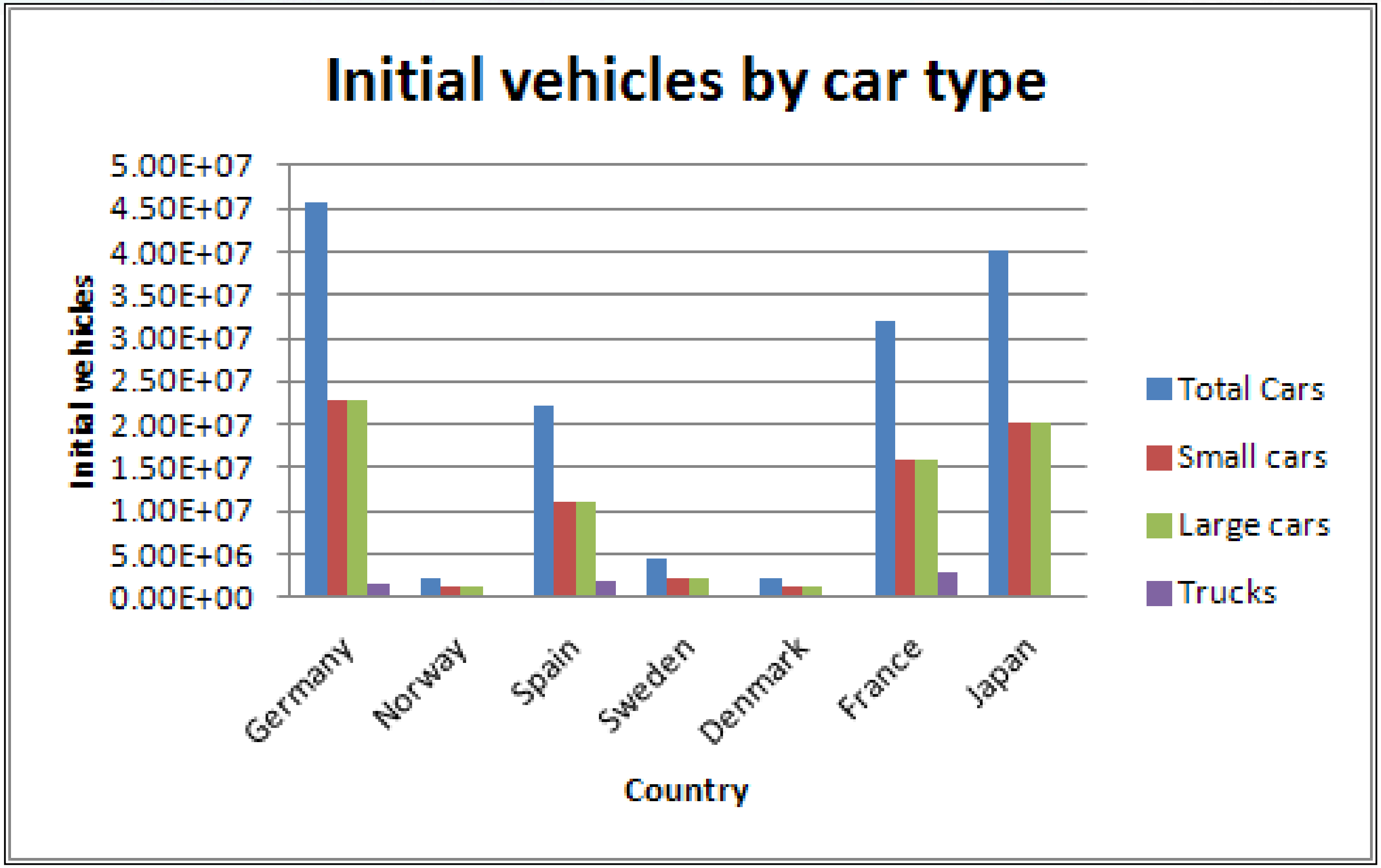
Resource Assessment Model Overview



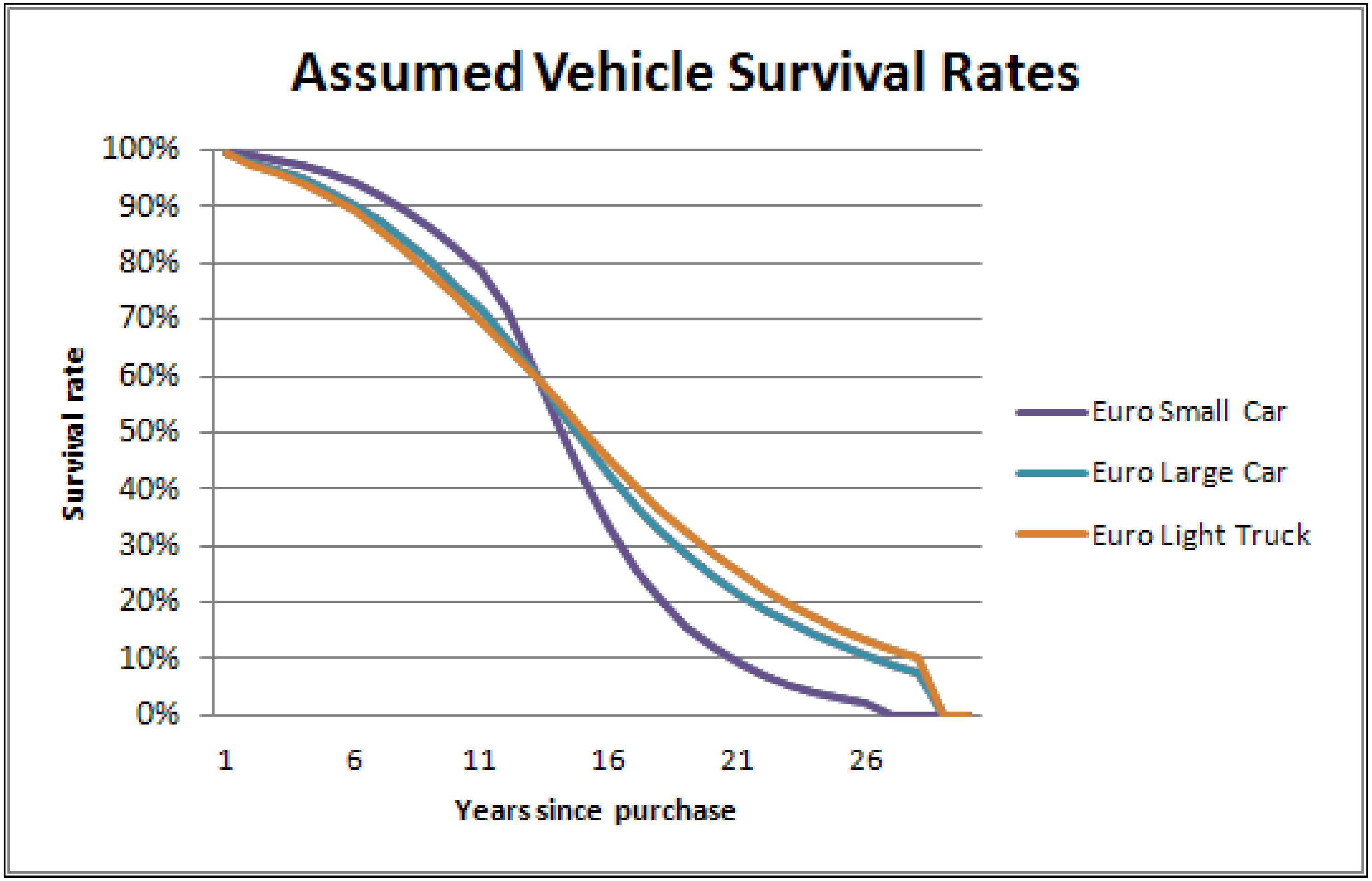
Base case vehicle assumptions

- Assumes 50% of vehicles in 2050 are FCEV
- Three vehicle classes for non-US FCEV fleet (small, large, truck)
  - Small, 10,964 mi/yr, 55 mi/kg (2020) to 71 mi/kg (2045)
  - Large, 11,778 mi/yr, 50 mi/kg (2020) to 66 mi/kg (2045)
  - Truck, 11,803 mi/yr, 35 mi/kg (2020) to 76 mi/kg (2045)
- Scrappage rate: 5.8 %/yr (see next page)
- Sales rate: 6.7%/yr (net growth of 0.9%/yr)
- Initial vehicle stocks from the "TREMOVE" model. (http://ec.europa.eu/environment/air/pollutants/models/tremove.htm)
- Future runs will be differentiated by country.

Base case vehicle stock, 2010



Base case vehicle survival rates



Data Requirements (agreed to at Bethesda meeting, March 2011)

A. **Feedstock availability for hydrogen production**
   1. Cost by type [(€/GJ or $/kWh, 2010,2020, 2050 (min requirement)]
      Examples: coal, wind, refinery byproduct, biomass, solar, natural gas, nuclear
   2. Quantity by type available (GJ/yr)
   3. Consider breaking down feedstock by class (i.e., onshore/offshore wind resources)
   4. Data sources
   5. Important: Only report feedstock likely to be available for hydrogen production
   6. Report all €/GJ or $/kWh in consistent monetary terms (i.e., 2005 €/GJ)

B. **Hydrogen production**
   1. What are assumed technologies
      Example: Centralized SMR for natural gas reformation
   2. Feedstock conversion efficiencies
      Example: SMR efficiency of 0.68 (0.68 MJ H_2 per 1 MJ natural gas)
   3. Estimated hydrogen production costs by feedstock type (€/GJ of €/kg)
   4. Assumptions about government policies in estimates
      Examples: Minimum renewable content standards, carbon taxes, production tax credits
   5. Data sources

Data Requirements (continued)

C. **Vehicles**

1. Quantity of light duty vehicle stocks by type and average efficiency (in mpg or liters/km) (2010, 2020, 2050)

    -- Model will use "average vehicle" derived from this data.

2. Vehicle scrappage rate (vehicle life)

    -- Example: Average vehicle lasts 15 years.

3. Expected annual growth rate in vehicle sales (%/yr)
4. Average distance driven/year (average vehicle km/yr) (2010, 2020, 2050)
5. Projected sales of hydrogen fuel cell vehicles by 2050
    1. Only report if country has specific goals/targets
    2. Example: 40% of all new car sales in 2050
6. Data sources

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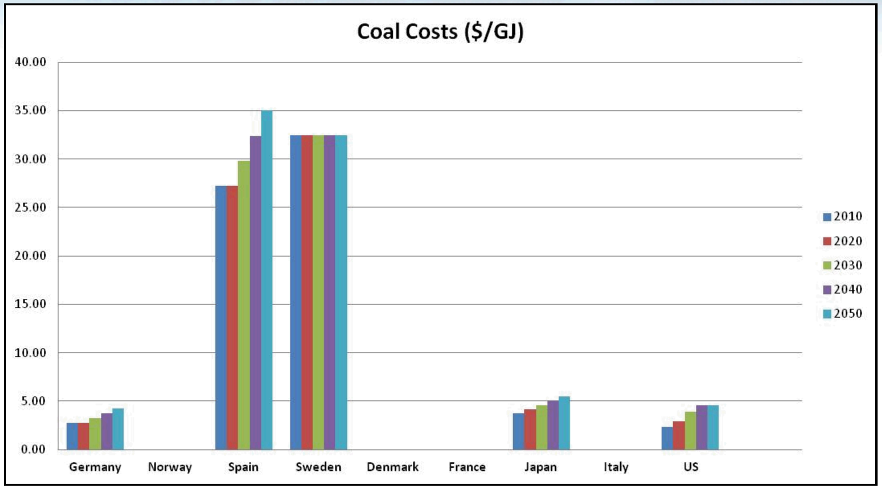
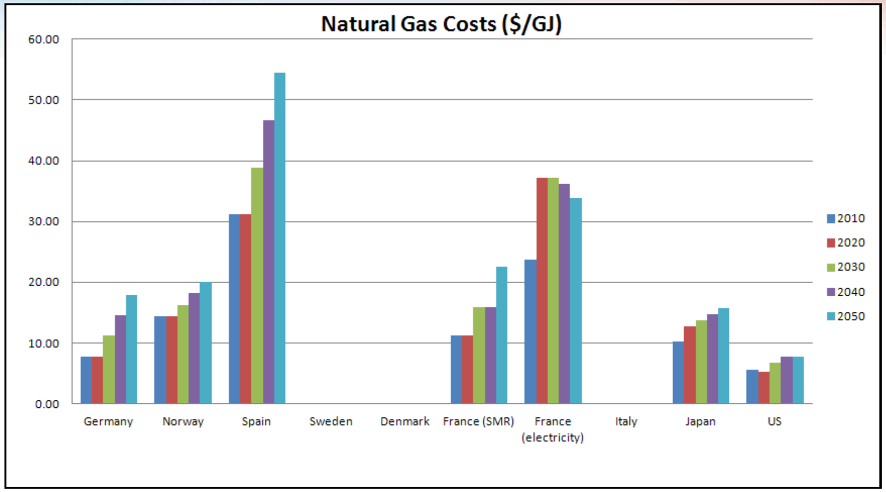
Summary of country-level inputs

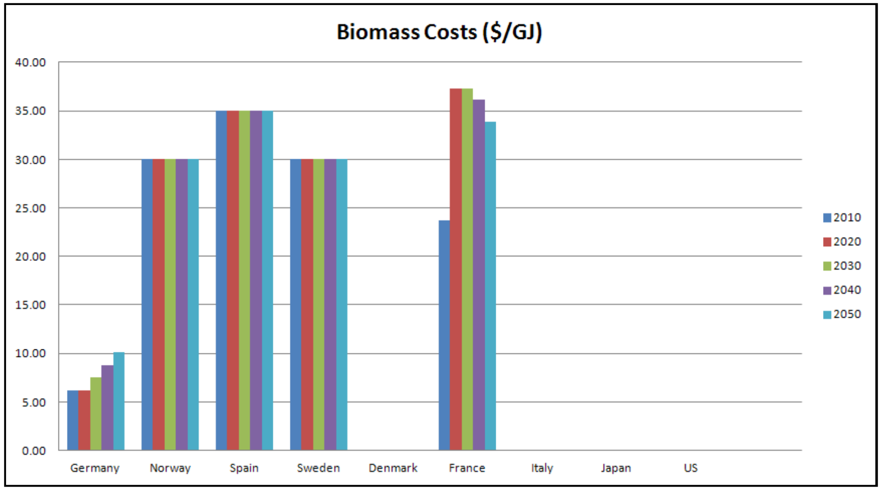
- Data from 9 countries
  - Germany
  - Spain (in review)
  - Norway
  - Denmark
  - Sweden
  - France
  - Japan
  - Italy (preliminary)
  - Canada (preliminary, no longer participating)
- Countries have reviewed aggregated feedstock availability and pricing data and provided comments/qualifications.
  - Data uncertainties remain for several countries (Spain, Italy, Canada)

Self-Reported Feedstock Costs



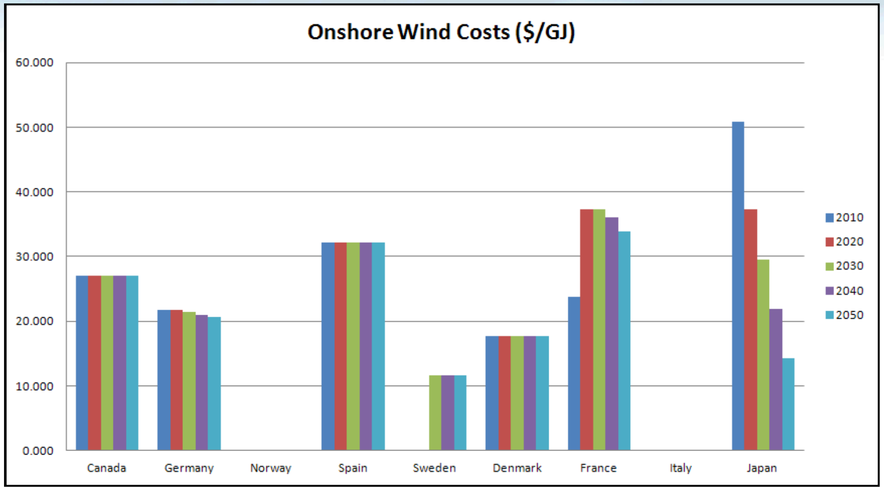


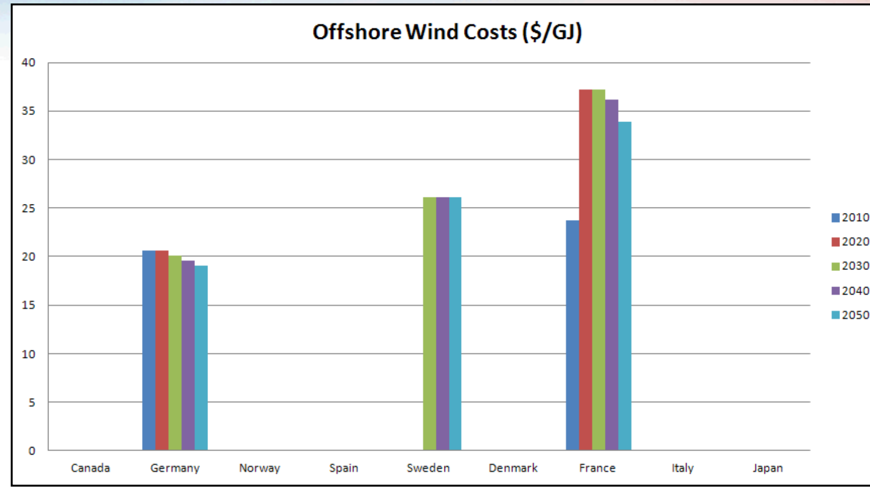
*France reported NG availability for use in SMR and for electricity.



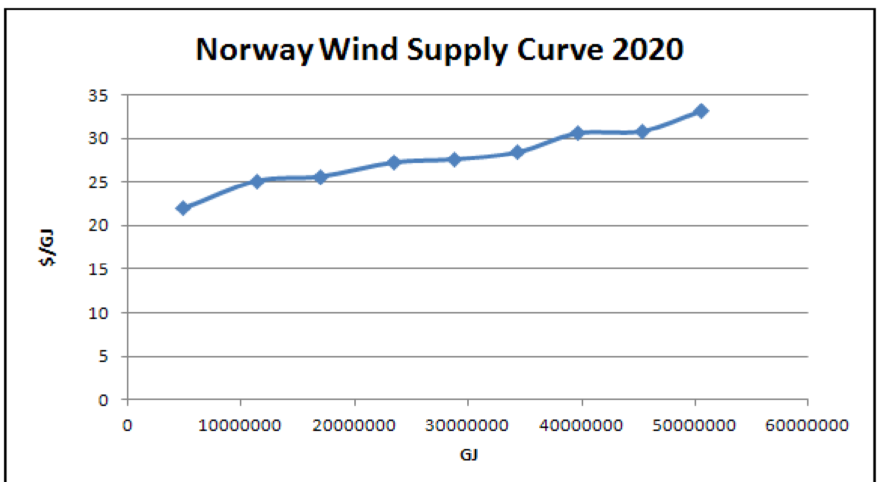
*US biomass supply curves based on supply availability at $60/dry ton.

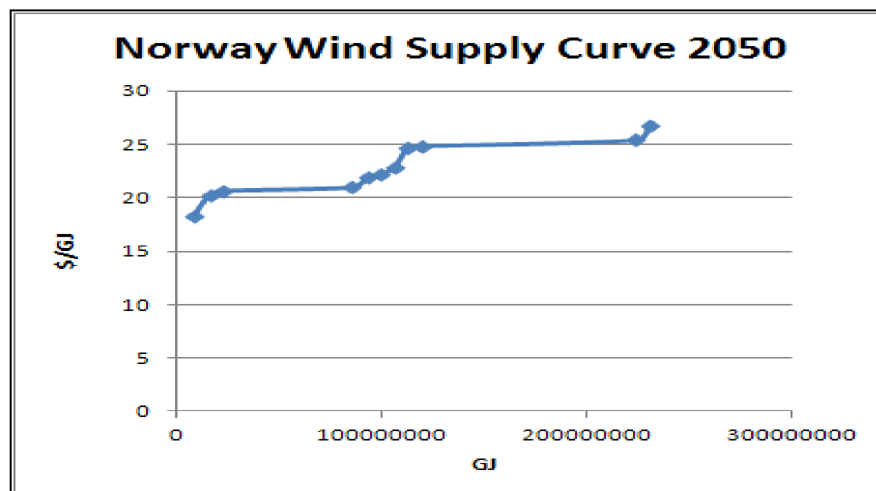
Self-Reported Feedstock Costs





*Norway and US provided wind supply curves (US next page).

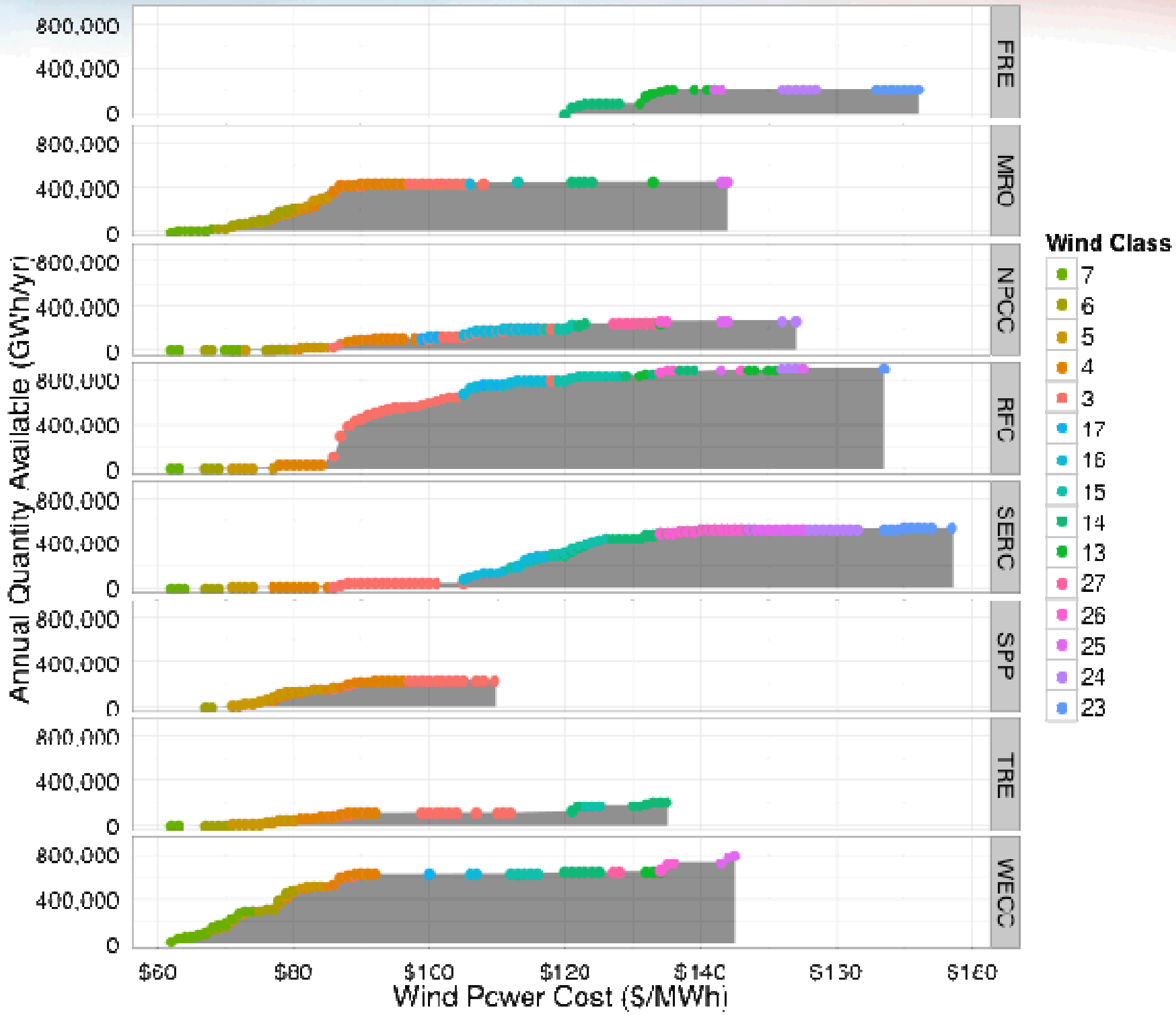




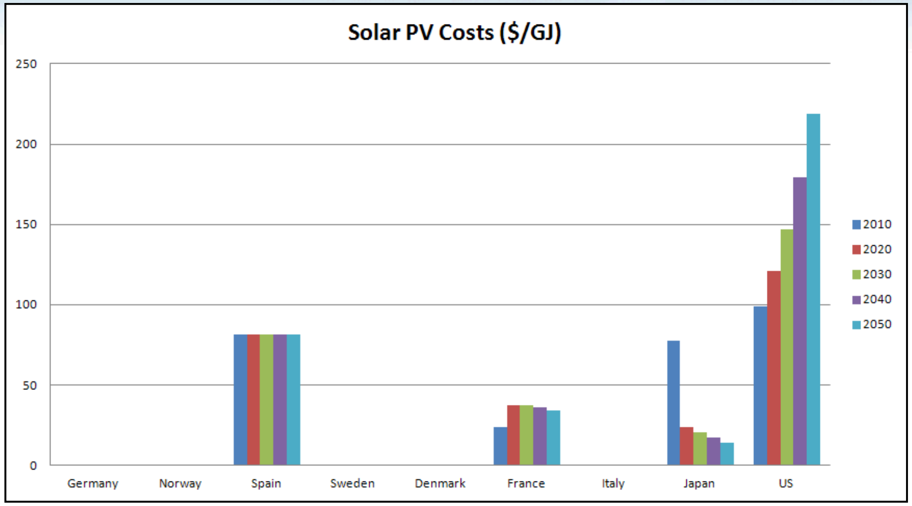
Self-Reported Feedstock Costs: US Wind

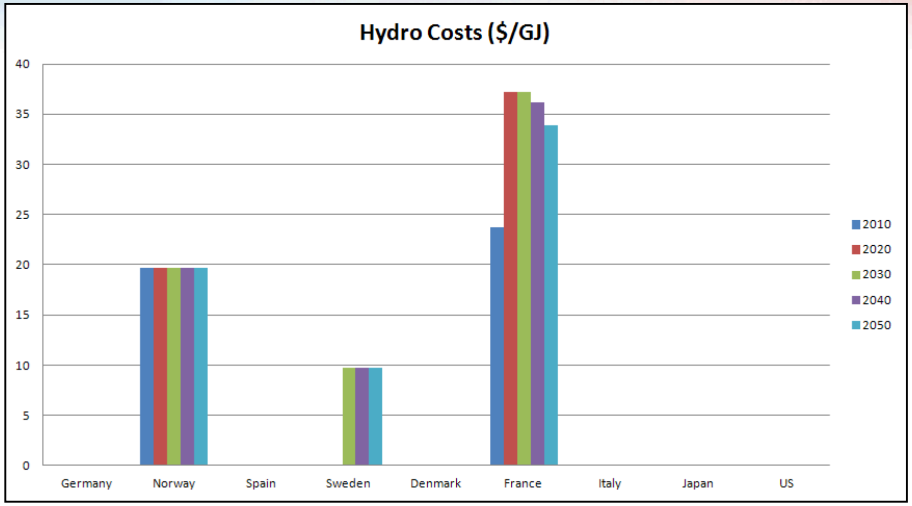
Wind resource

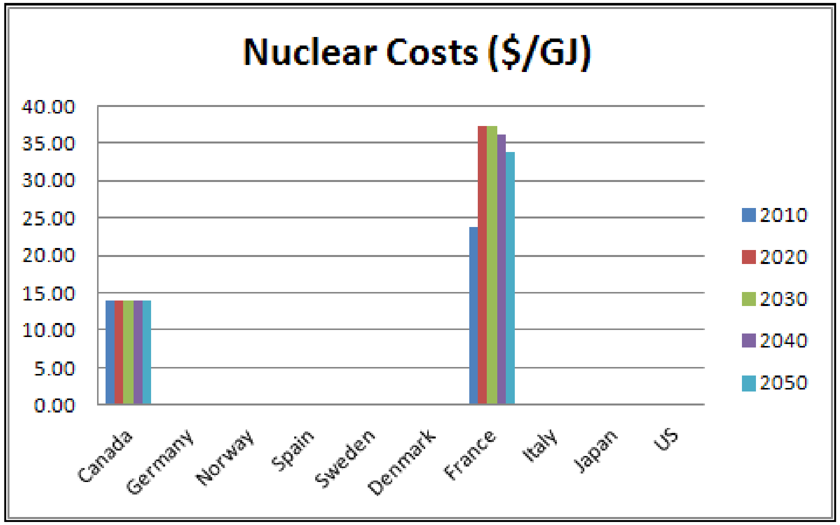
- Regionally differentiated wind supply curves derived from NREL/Black and Veatch "20% Wind" study
- Includes onshore, shallow & deep offshore.



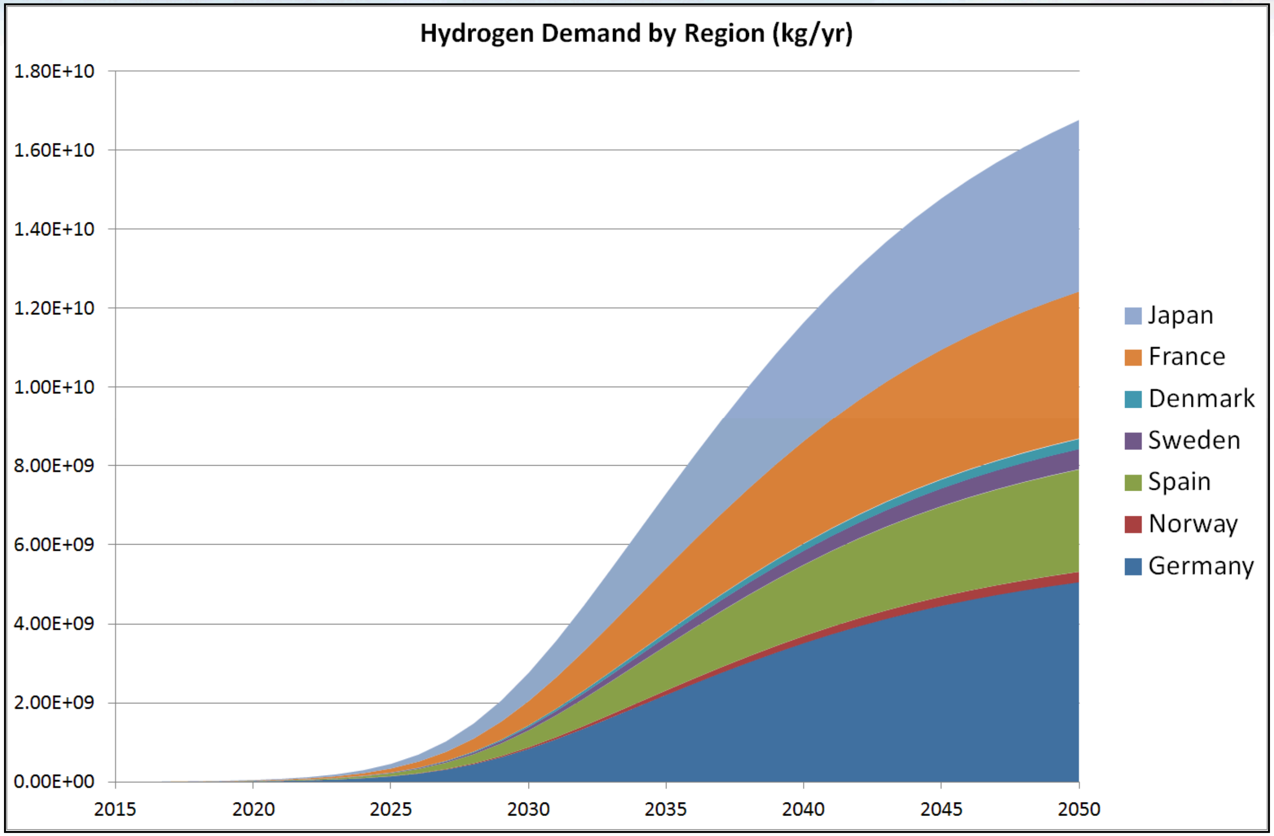
Self-Reported Feedstock Costs



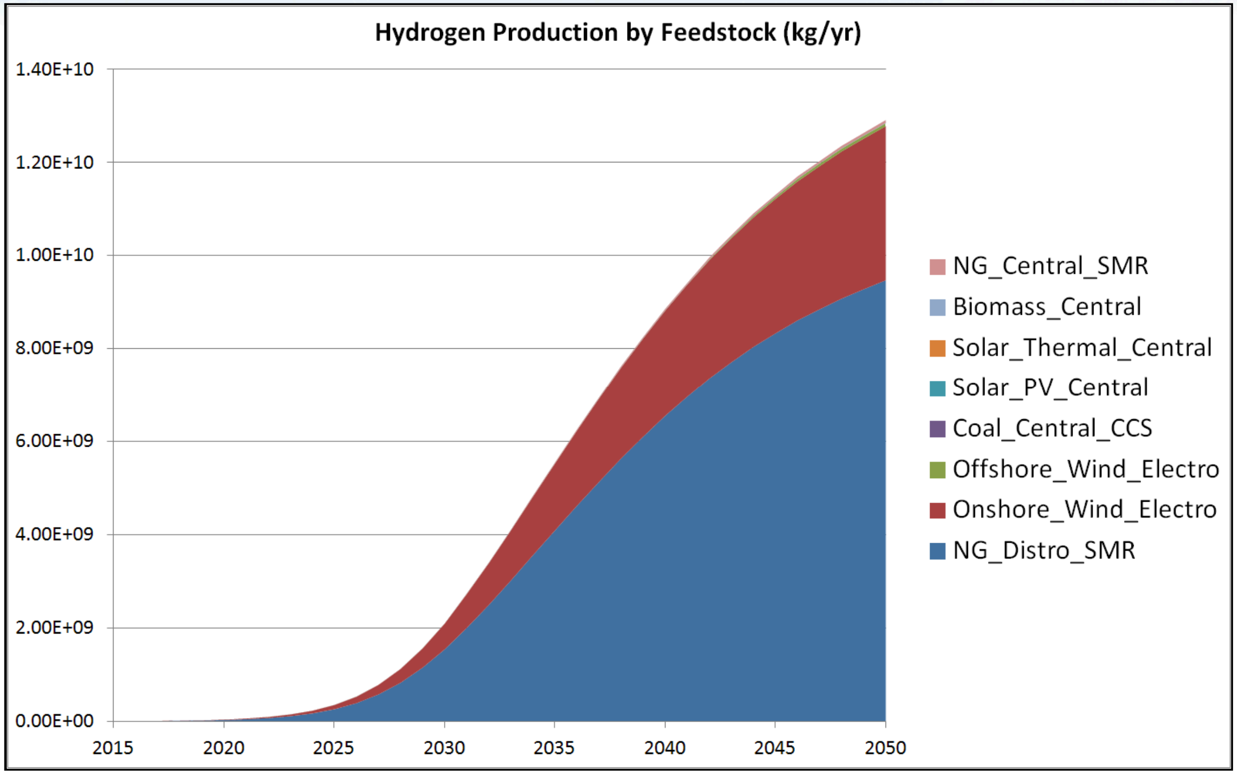




Base case results: H2 demand by country



Base case results: H2 production by source (no trade)



Based on least cost production, main sources of hydrogen production would include (in order of importance in 2050): distributed natural gas, and onshore wind.

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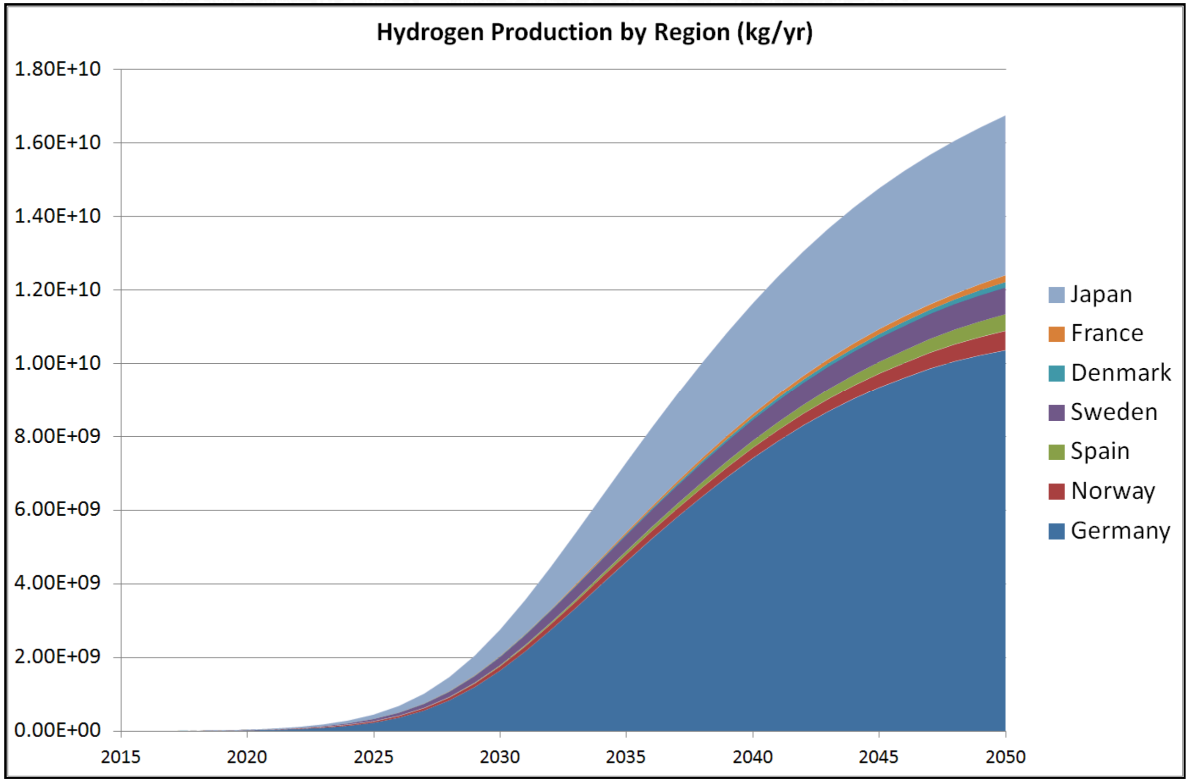
Base case results: H2 production by country of origin (trading allowed)



When trading between countries allowed, Germany becomes major H2 producer for EU countries, using self-reported data about access to inexpensive imports of natural gas.

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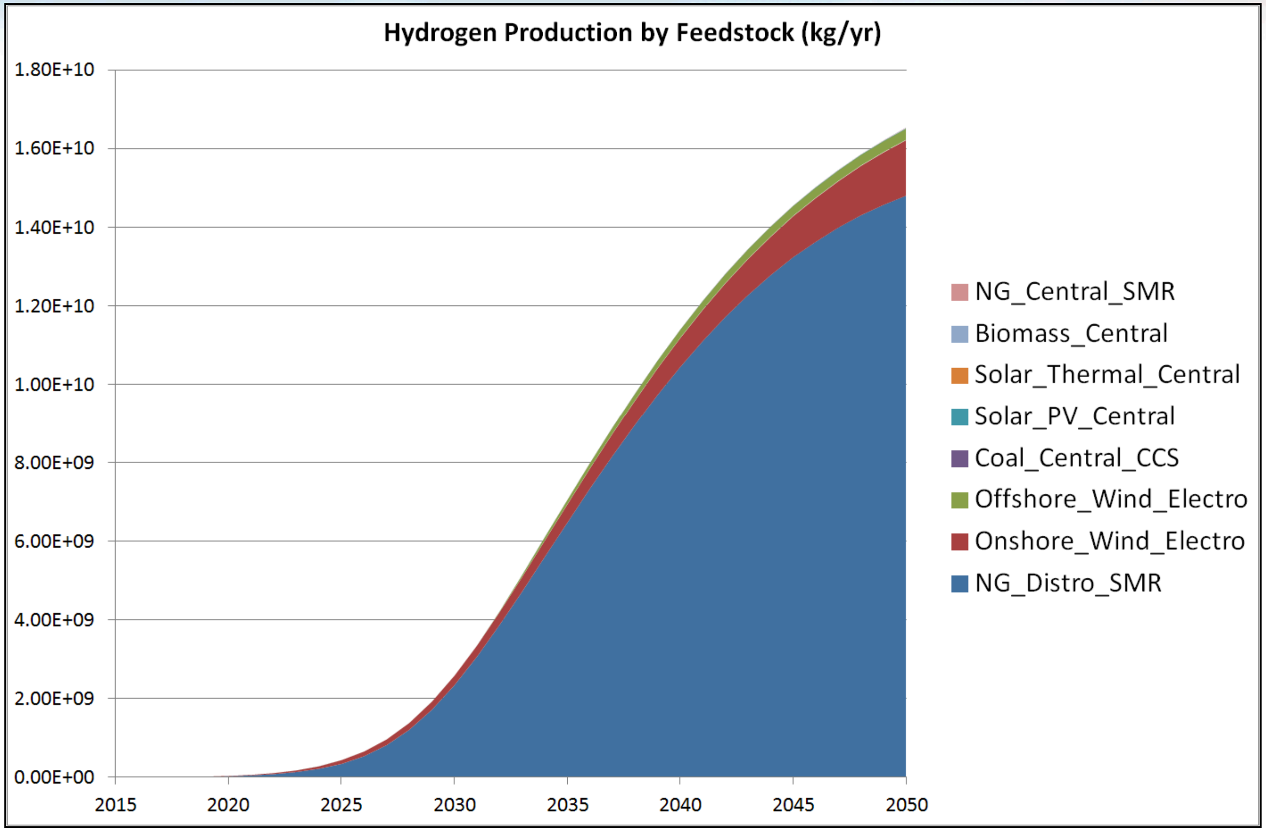
Base case results: H2 production by source (trading allowed)

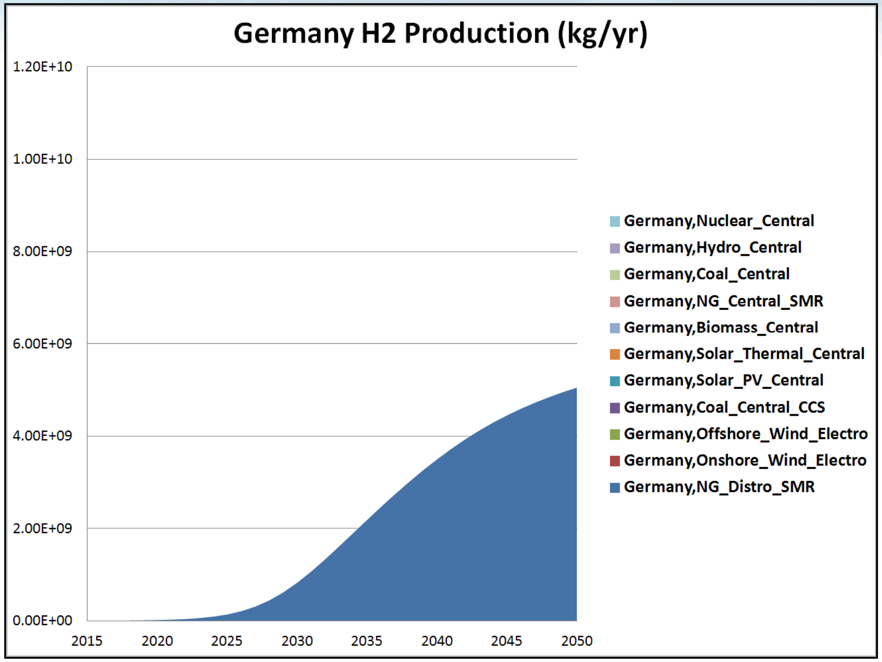


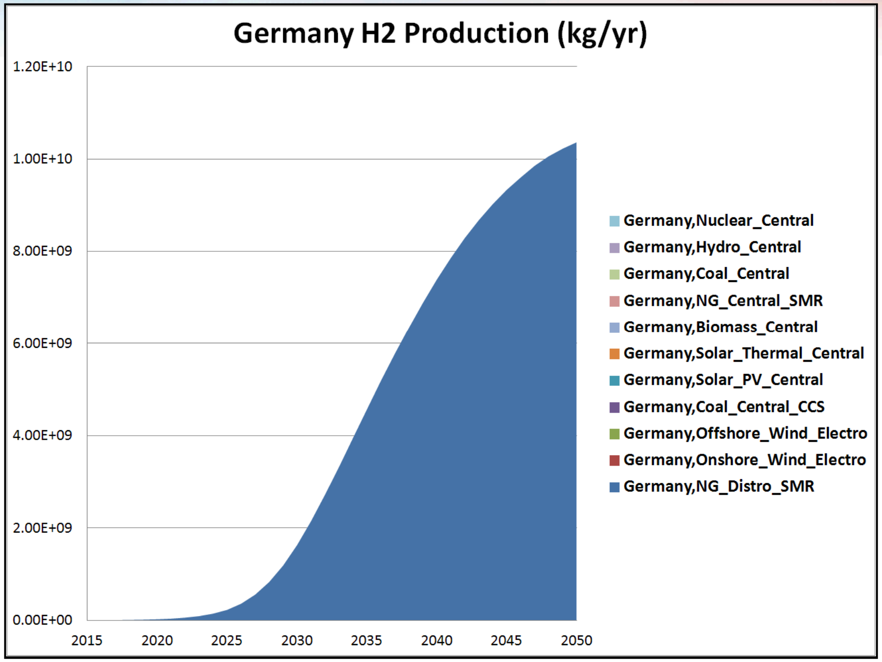
Based on the least cost production methodology, when trading between countries is allowed, H2 is mainly produced from distributed natural gas SMR, followed by onshore and offshore wind.

Base case results

- The following slides show the base case results for each country for two cases:
  - Trading not allowed between regions
  - Trading allowed between regions
    - Assumed costs for pipeline transport of H2 costs: $1.50/kg/1000 km + $2.06/kg fixed costs

Results: H2 production in Germany (no trading/ trading)





Germany becomes major exporter of H2 when trading is allowed using relatively inexpensive natural gas.

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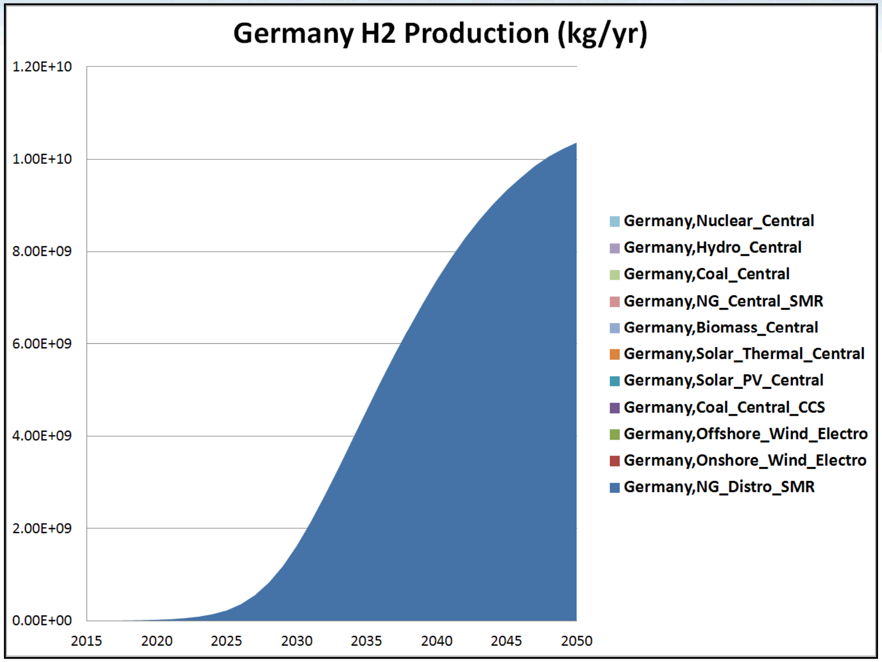
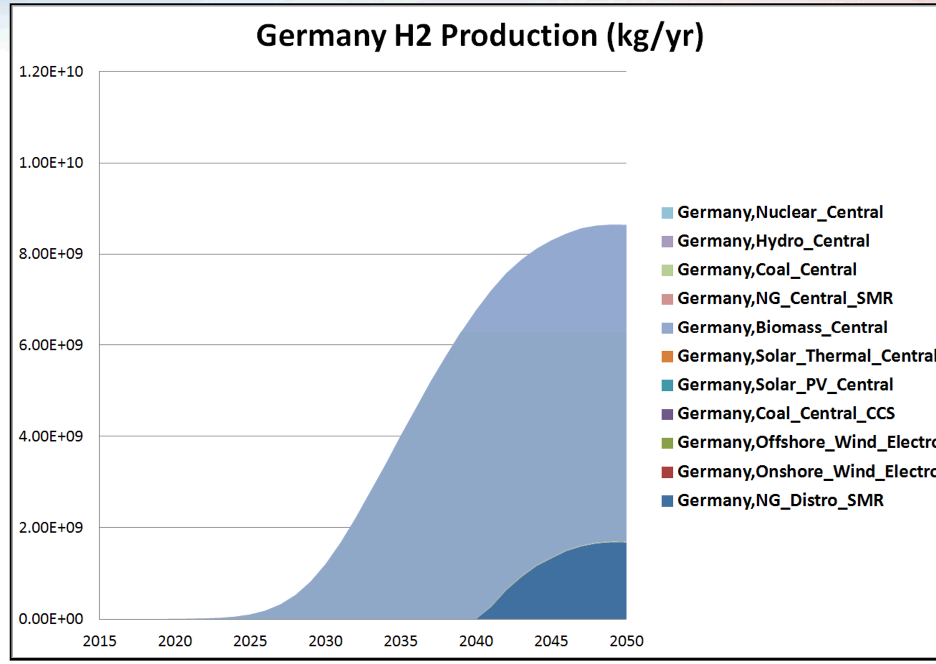
Results: H2 production in Germany (trading, no CO2 tax/CO2 tax)





Germany becomes major exporter of H2 when trading is allowed using relatively inexpensive natural gas.

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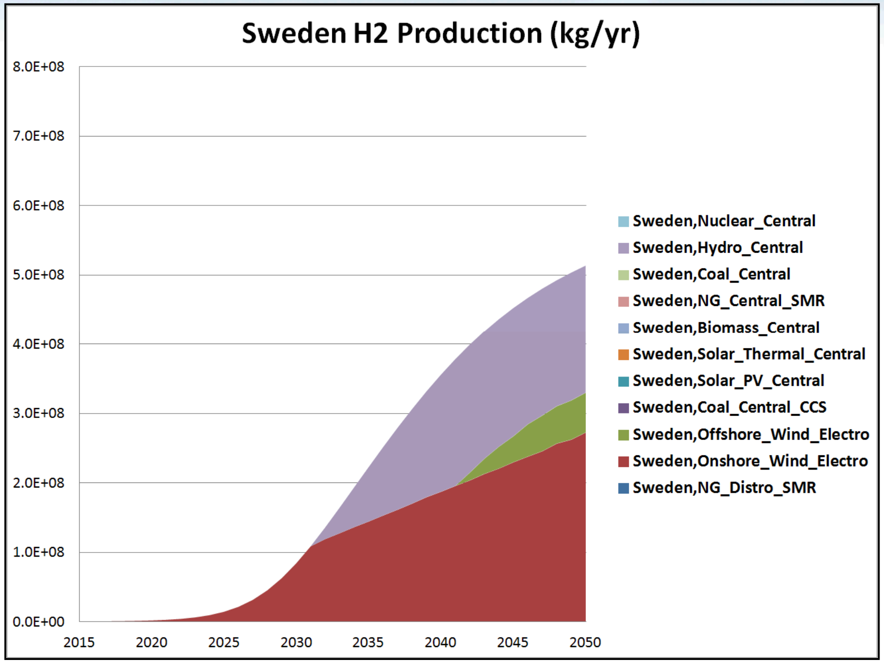
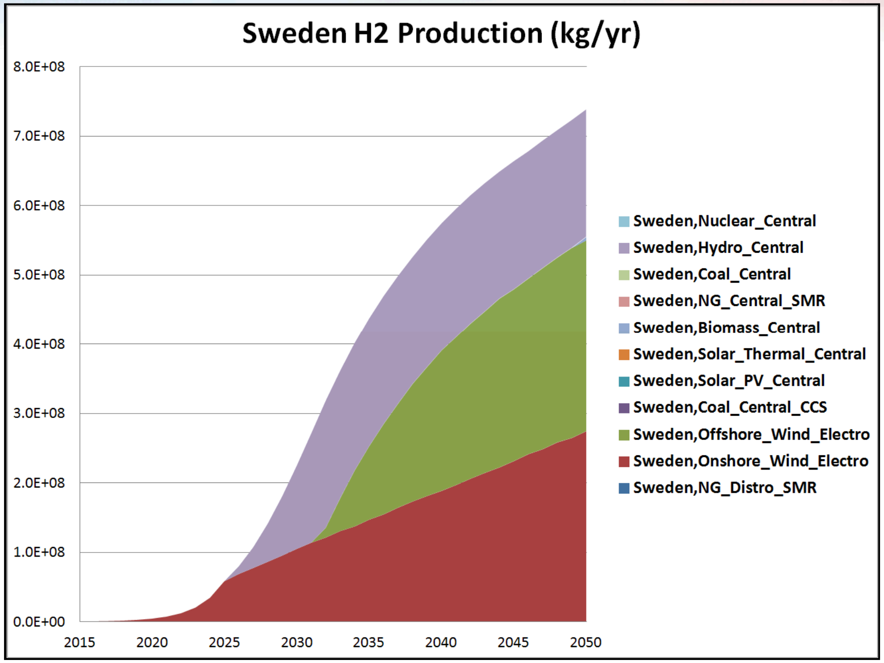
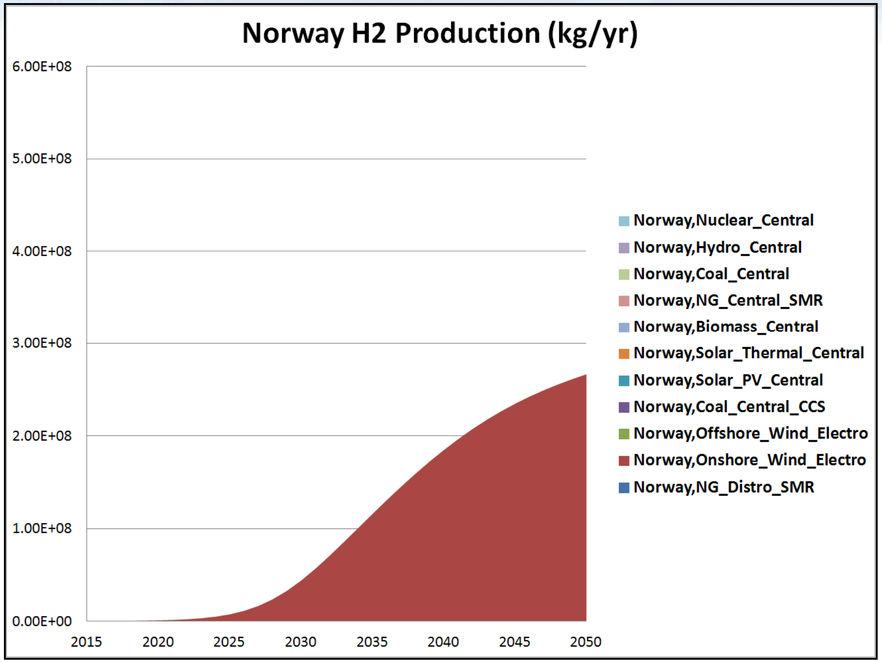
Results: H2 production in Sweden (no trading/trading)

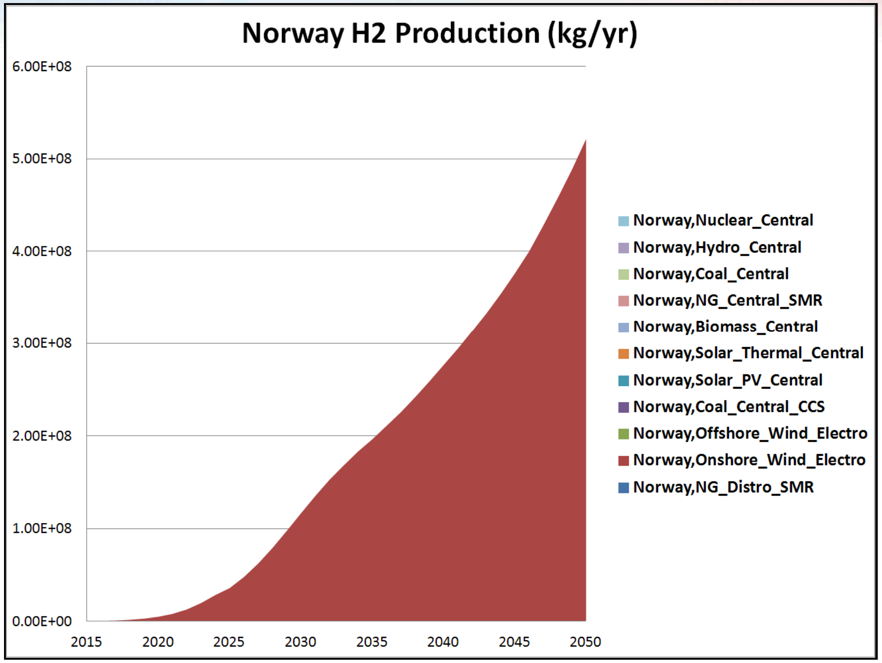




Sweden produces H2 from onshore wind, offshore wind, and hydro. Sweden becomes major exporter when trading is allowed.

Results: H2 production in Norway (no trading/trading)





Norway produces H2 from onshore wind and becomes exporter when trading is allowed.

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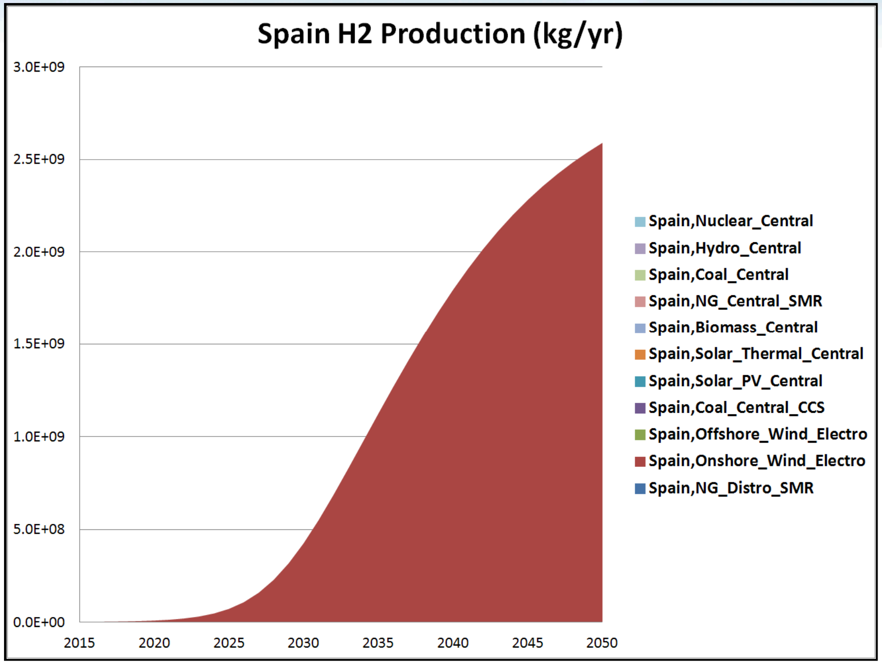
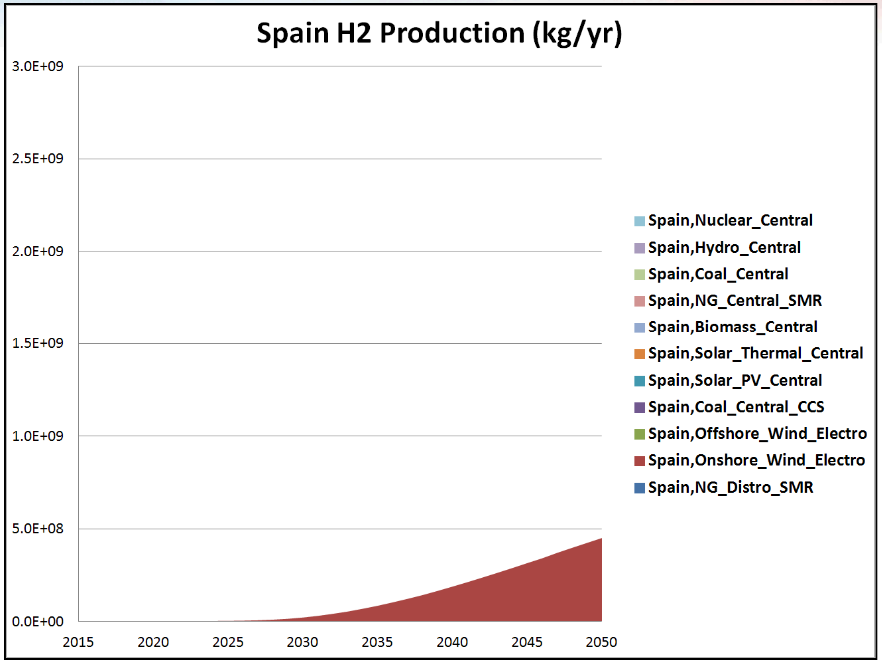
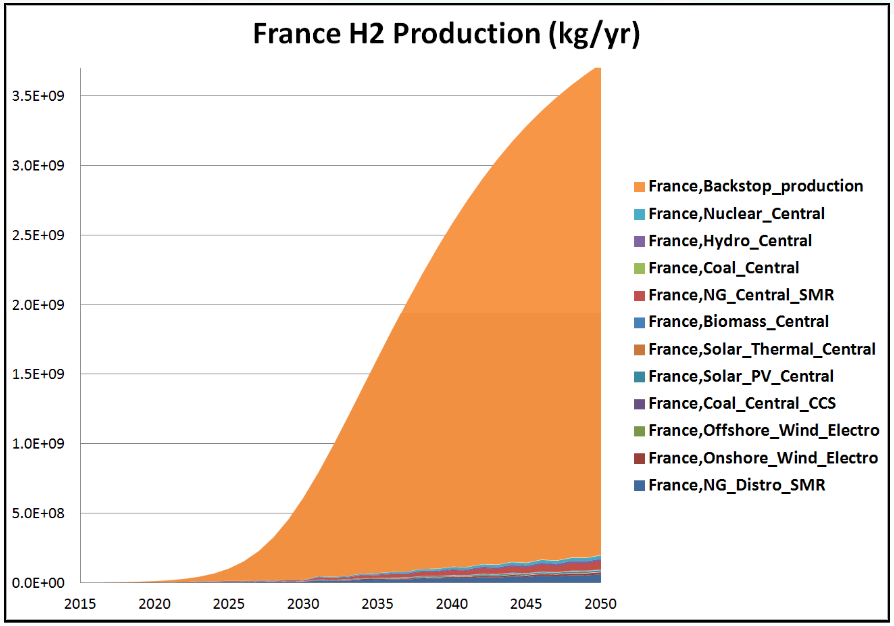
Results: H2 production in Spain (no trading/trading)

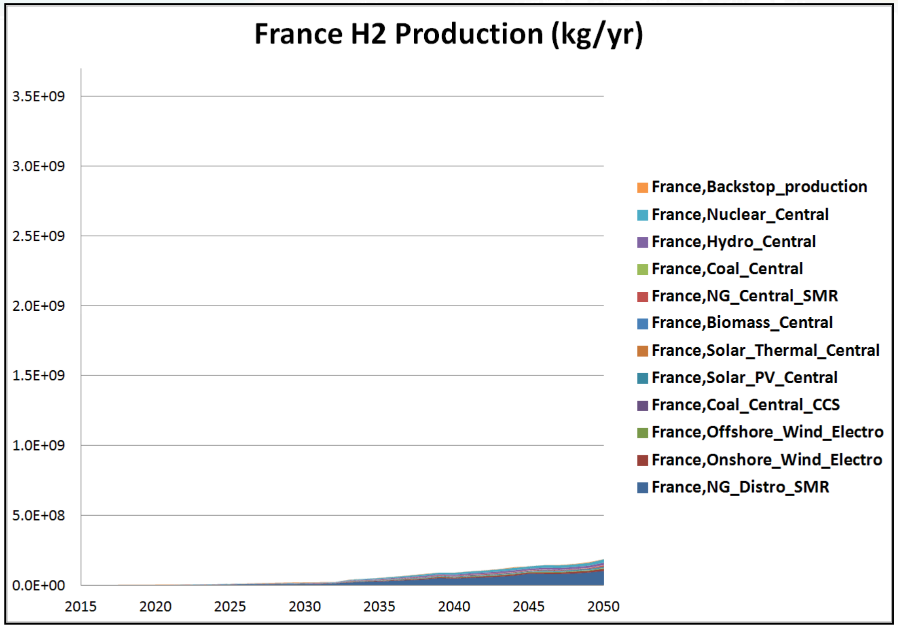




Spain produces H2 from onshore wind resources. If trading is allowed, Spain still produces H2 from wind resources, but becomes a net importer of hydrogen. Note that this analysis will likely change as Spain recently supplied updated resource data.

Results: H2 production in France (no trading/trading)





As currently modeled, France cannot meet domestic H2 demand given reported resources (shortfall shown by “backstop technology.”). When trading is allowed, France becomes major H2 importer. Self-reported data included natural gas used for electrolysis and SMR; the portion available for electrolysis (at grid prices) is not included in this analysis.

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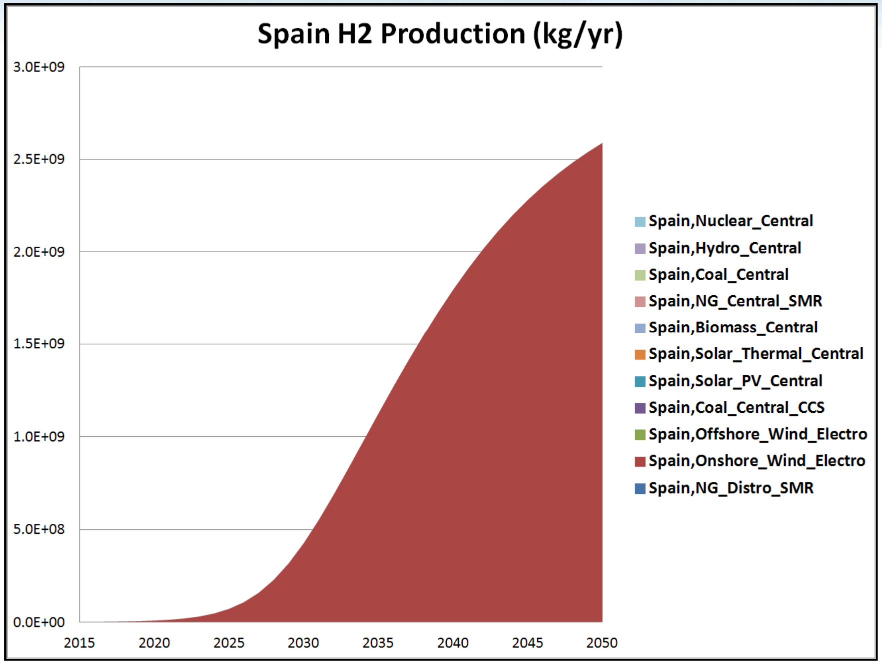
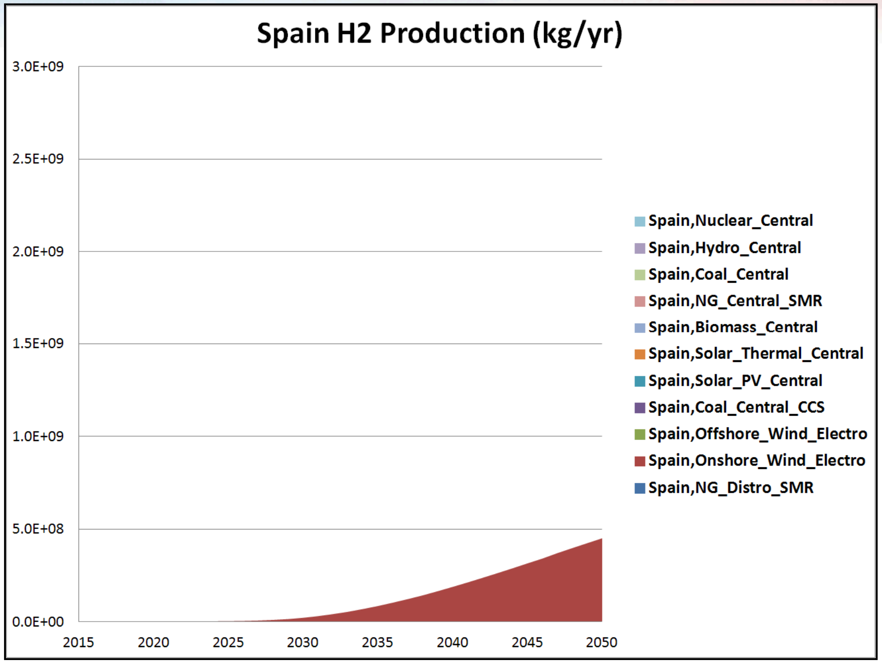
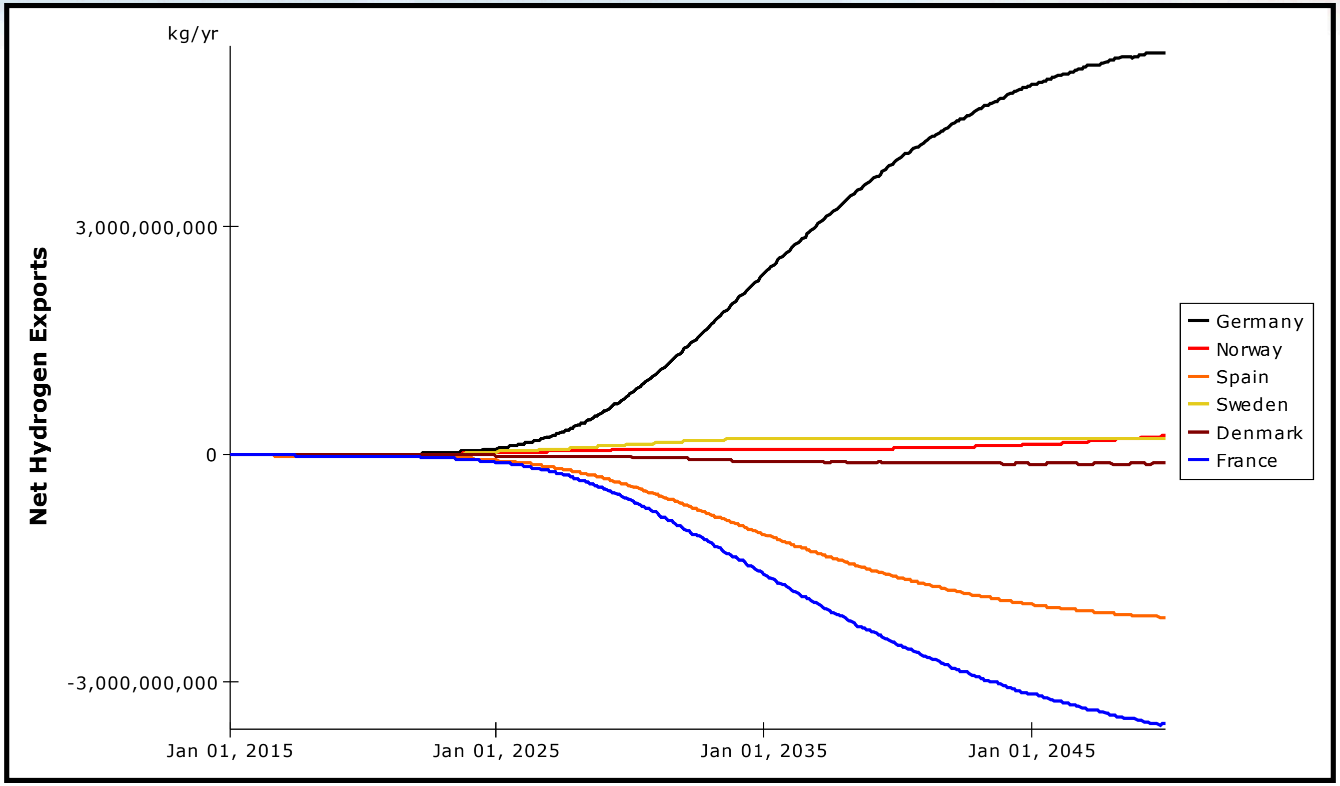
Results: H2 production in Spain (no trading/trading)





Spain produces H2 from onshore wind resources. If trading is allowed, Spain still produces H2 from wind resources, but becomes a net importer of hydrogen. Note that this analysis will likely change as Spain recently supplied updated resource data.

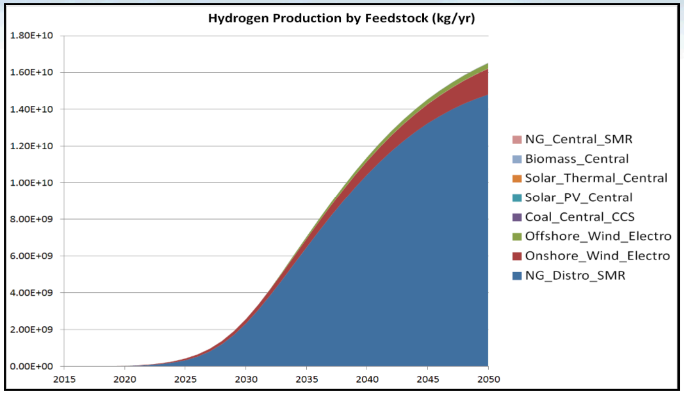
Results: H2 imports/exports by country



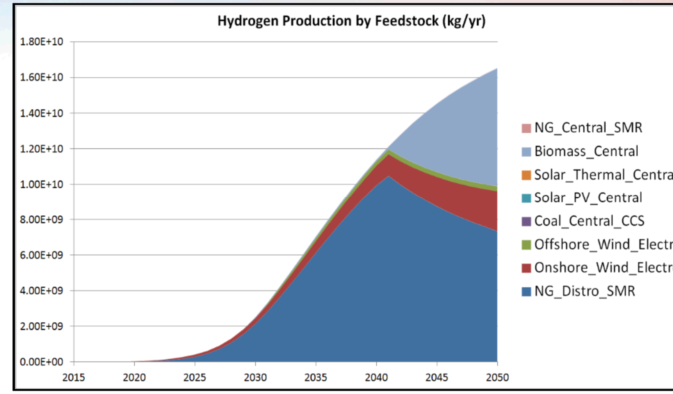
For the base case assumptions, Germany, Norway, and Sweden are exporting countries. France and Spain are major importing countries.

CO2 tax cases: H2 production by source (CO2 tax by 2050 of 0 $/tC02, 100 $/tCO2, 200 $/tCO2, 500 $/tCO2)

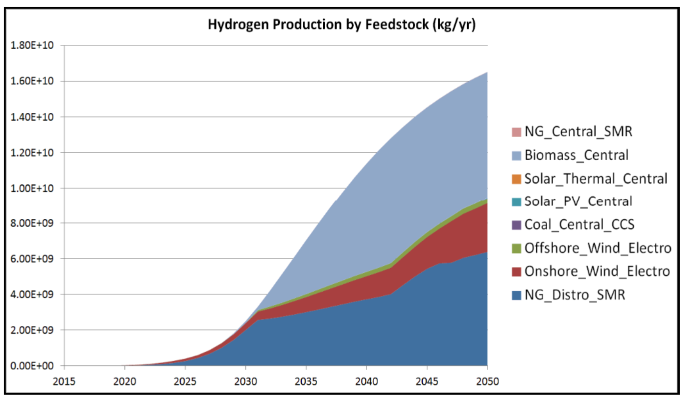
CO2 Tax: 0 $/tCO2



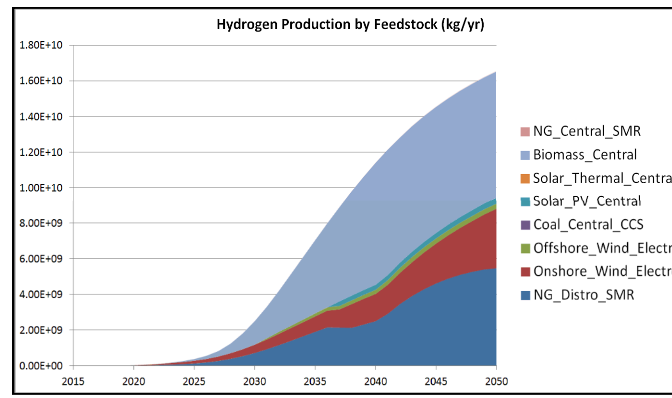
CO2 Tax: 100 $/tCO2



CO2 Tax: 200 $/tCO2



CO2 Tax: 500 $/tCO2



As CO_2 price increases, H2 production shifts from natural gas to wind and biomass.

Discussion of McKinsey Study

- McKinsey study: "A Portfolio of Power-trains for Europe: a fact-based analysis."
- Overall goal: Assumes 95% decarbonization of transport sector by 2050 required to meet EI goal of 80% overall decarbonization goal.
  - Assumes will have to be met by wide-scale introduction of PHEVs, BEVs and FCEVs.
- Purpose of this discussion:
  - What did study assume?
  - What were key findings?
  - Is there general agreement with the findings?
  - What differentiates our study?

McKinsey Study: Key Assumptions

- Collaboration with companies, governments, and NGOs
- Economic comparison of drive trains based on total cost of ownership (TCO). TCO of BEVs and FCEV initially high, but decline rapidly as vehicles gain market share (based on learning rates).
- H2 infrastructure 5% of total costs.
- Considered 9 production paths for H2: (variations of SMR, Electrolysis, Coal)

McKinsey Study: Interesting results

- TCOs of all four power-trains converges around 2025.
- Cost of fuel cell system falls by 90%; BEV by 80% by 2020.
- Sources of H2:
  - Before 2020, 40% Centralized SMR, (CSMR), 30% Decentralized SMR (DSMR), 30% distributed electrolysis (DWE)
  - After 2020, 30% CSMR, 30% IGCC, 15% CWE,15% DWE, 10% coal gasification
  - Distribution starts with gaseous truck, then liquefied on trucks, and eventually pipeline (predominate by 2025).
- H2 production prices:
  - Centralized SMR and coal gasification are lowest-cost options.
  - Electrolysis and DSMR most expensive (see Exhibit 17, included below)

McKinsey Study: Interesting results, H2 production costs

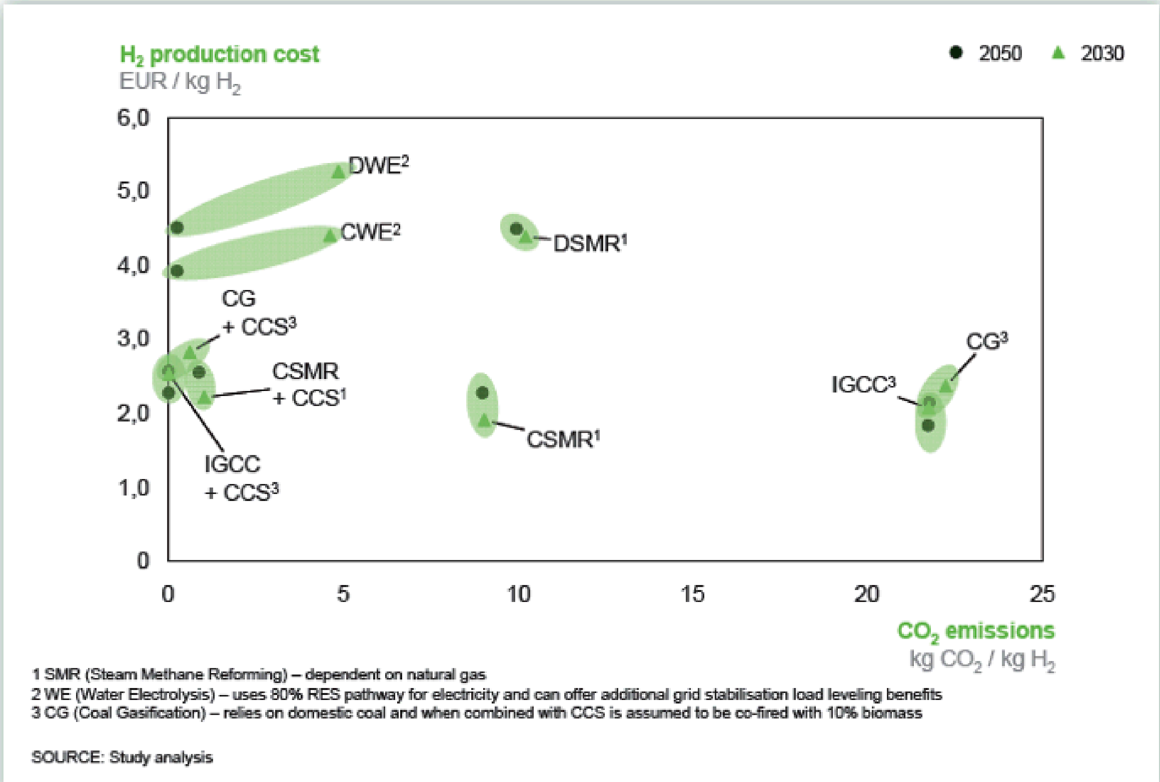


Exhibit 17: A variety of technologies are available to produce CO_2-free hydrogen (future cost levels)

Source: McKinsey Study

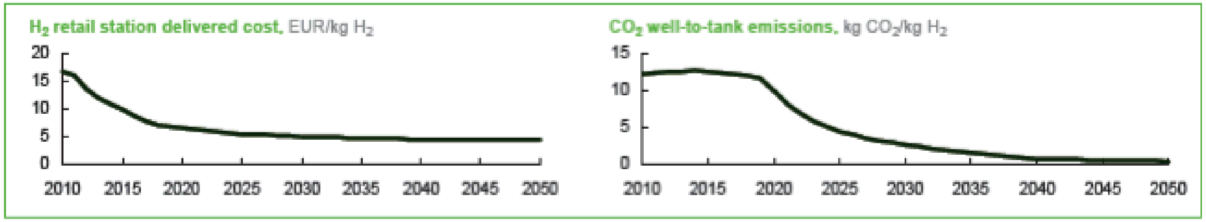
McKinsey Study: Interesting results

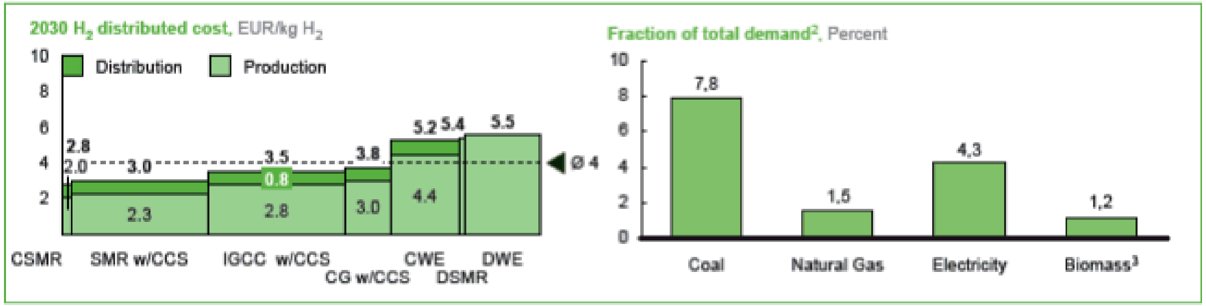
- For a scenario with 25% FCEVs, 35% BEVs, 35% PHEVs, and 5% ICEs in EU by 2050, they conclude:
  - Distributed H2 costs approach 4.50 Euro/kg in 2030
  - H2 demands by 2050 a small fraction of 2008 primary energy consumption (See exhibit 25, attached)
    - 7.8% for coal (primary energy consumption in 2008)
    - 1.5% for natural gas
    - 4.3% for electricity
    - 1.2% for biomass
- They provide an alternative scenario with 100% electrolysis and 80% renewable-based electricity (See exhibit 26, attached)
  - Increases H2 cost to average of about 5.31 Euros/kg in 2030
  - H2 demands by 2050 amount to 11% of 2008 primary energy demand.

McKinsey Study: Interesting results, H2 production costs and sources

Description

- Before 2020, CSMR has 40% and DSMR & DWE each have 30% share of new production
- After 2020, CSMR & IGCC each have 30%, CG has 10% and CWE & DWE each have 15% share of new production
- CCS is applied to all new CSMR, IGCC and CG capacity starting in 2020
- Coal is co-fired with 10% biomass, which costs 3x IEA estimate to account for pre-treatment required prior to gasification[1]
- Coal, natural gas, electricity and biomass are all important for Hydrogen production





1 Co-firing more than 10% biomass with coal in IGCC and CG with CCS can allow negative CO2 emissions
2 Fraction is the amount of primary energy source consumed in 2050 divided by total EU-29 wide consumption in 2008
3 Fraction of biomass is that assumed available to the power generation sector (1,600 TWh/year)

SOURCE: Study analysis

Exhibit 25: The production mix assumed in the study is robust to energy shocks

Source: McKinsey Study

McKinsey Study: Interesting results, H2 production costs and sources

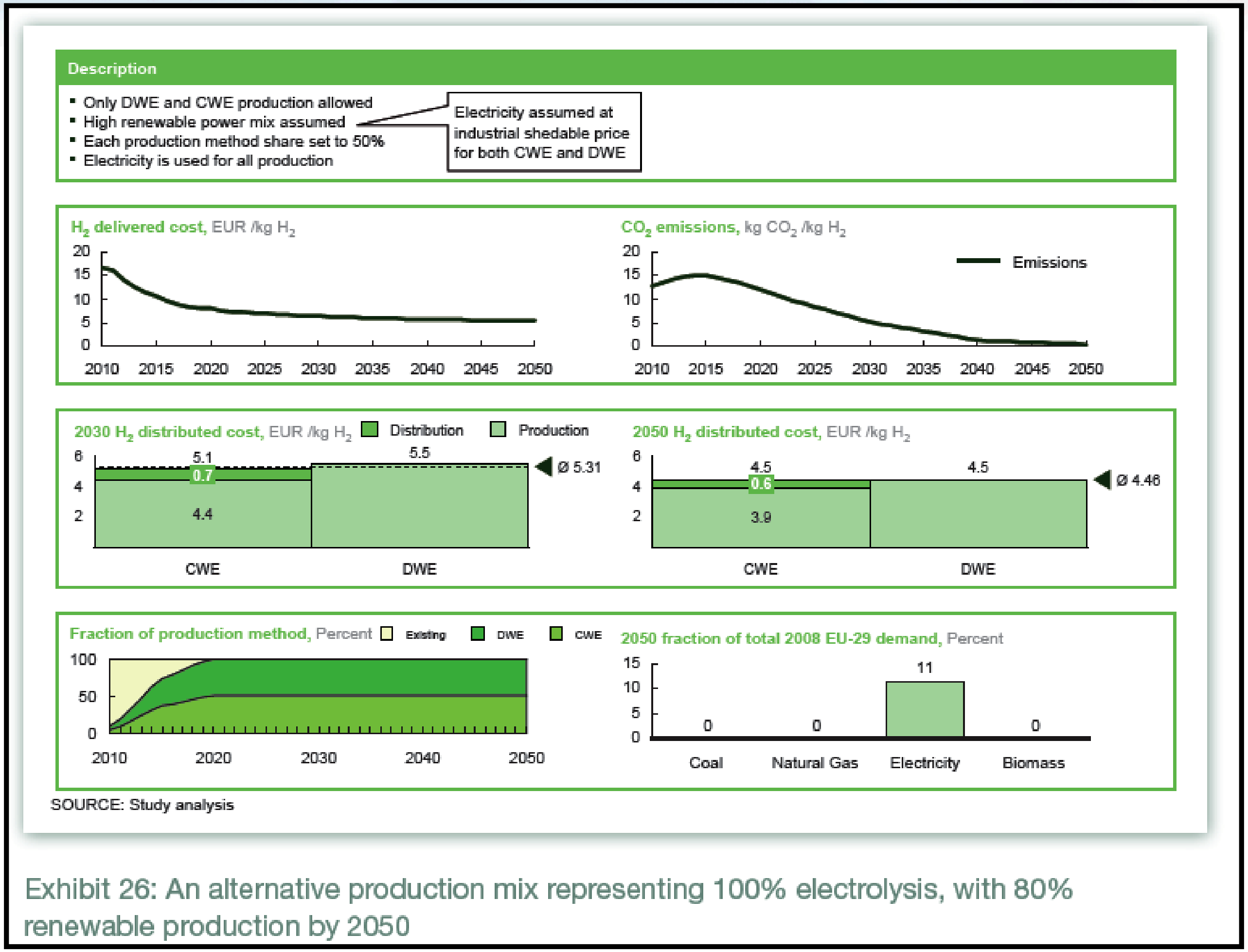


Exhibit 26: An alternative production mix representing 100% electrolysis, with 80% renewable production by 2050

Source: McKinsey Study

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Next steps

- Are countries comfortable with data input? Results?
- Continue modifying model to include updated country-level data on feedstocks and vehicle stocks
- Develop more user-friendly user interface
- Publish results

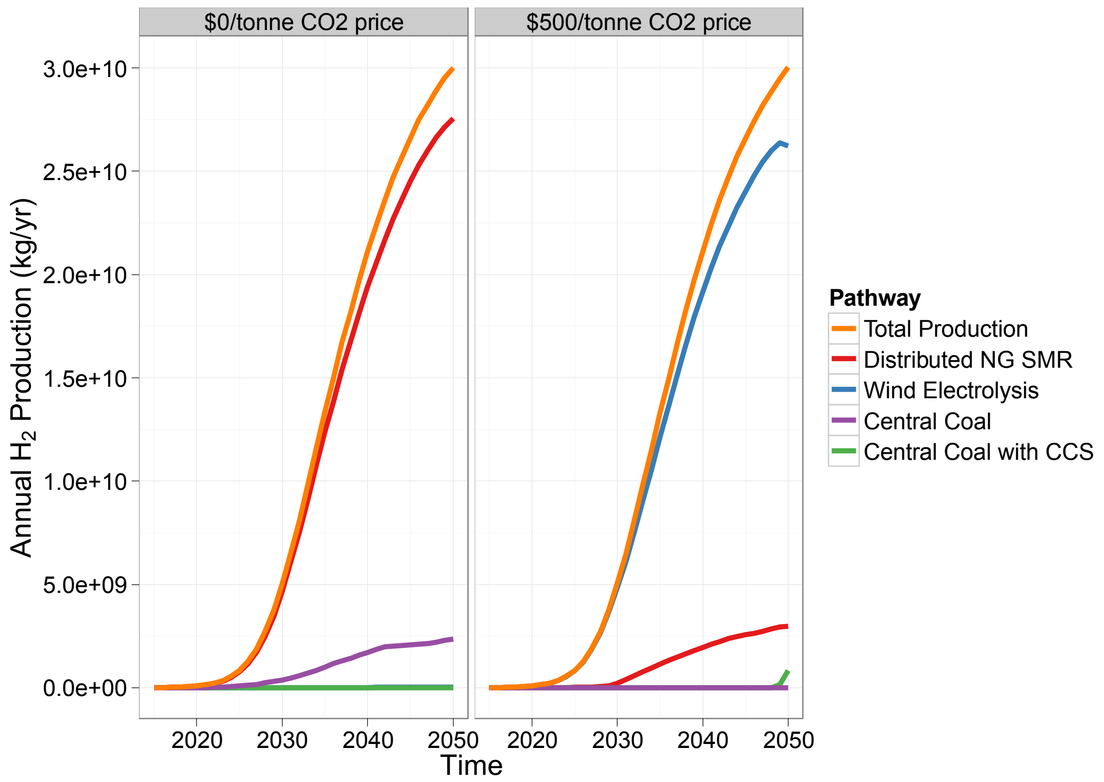
Backup Slides

Update on US Analysis

Results: US Base Case, Hydrogen production

Hydrogen Production

- For 50% HFCV, H2 production reaches 30 billion kg by 2050.
- Without CO_2 price, most of the H2 comes from distributed NG, followed by centralized coal
- At high CO_2 price ($500/ton), wind powered electrolysis replaces natural gas.



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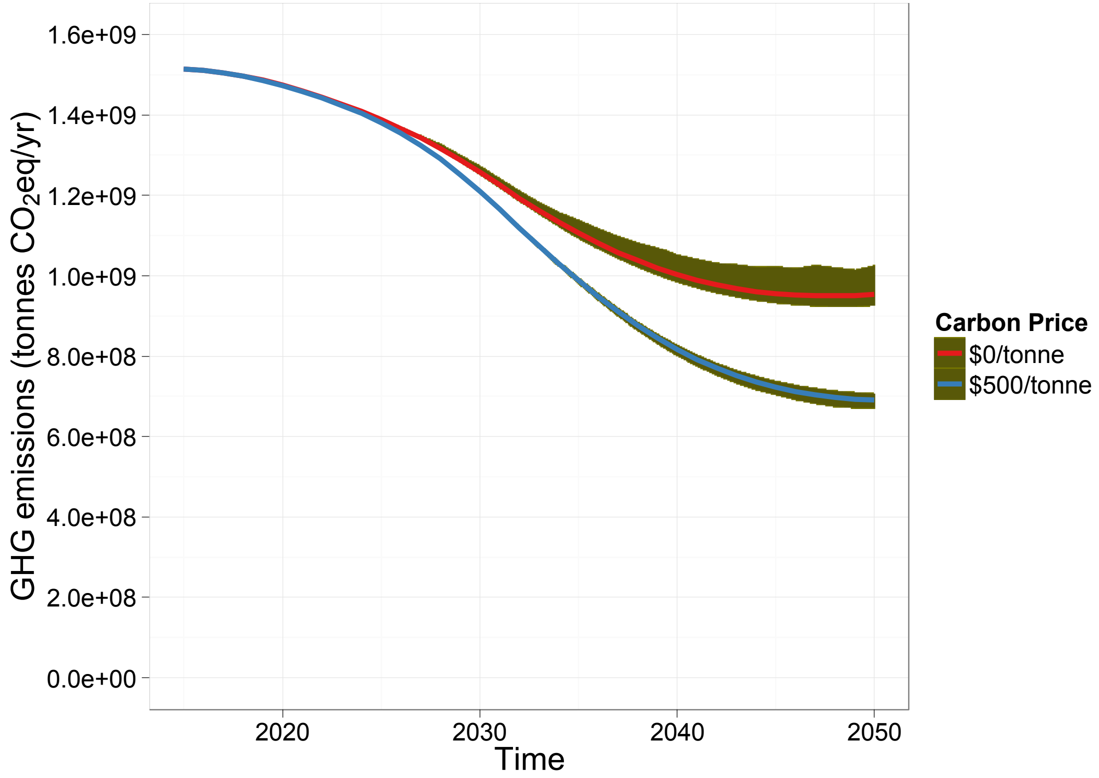
Results: US Base Case, Transport GHG Emissions

Transport GHG emissions

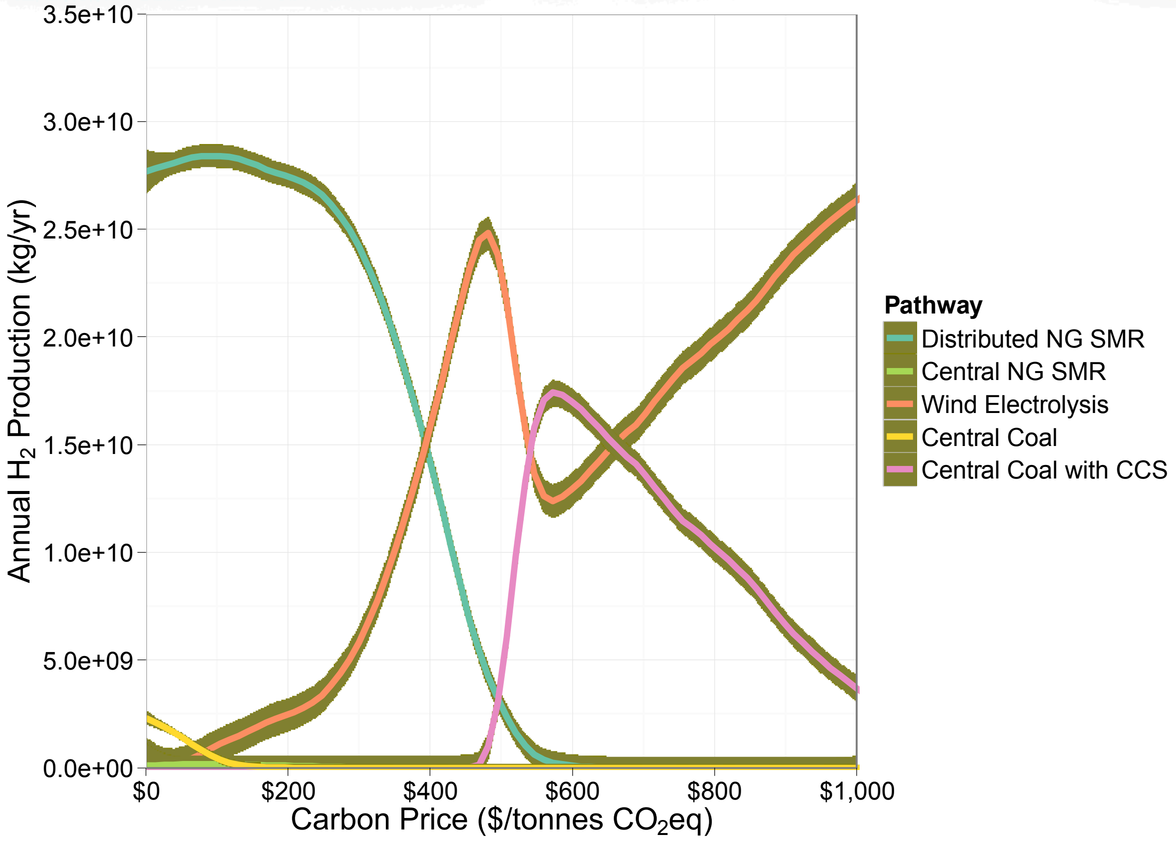
- For 50% HFCV, GHG emissions reduced 37% from 2015 levels by 2050 for the $0/tCO2 case and 54% for the $500/tCO2 case.
- Gray shaded area indicates the 80% confidence interval associated (300 runs).



Results: US Base Case, Carbon Price Sensitivity

H2 Production

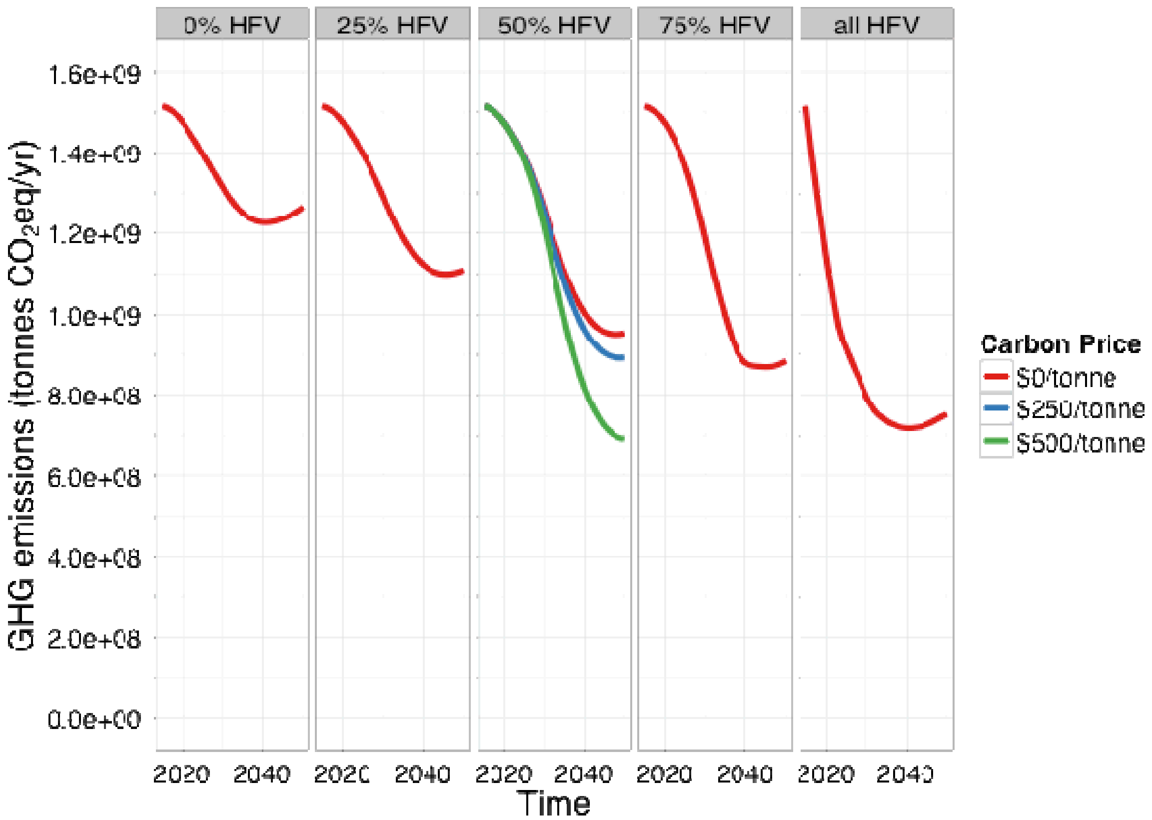
- As carbon price increases, wind replaces natural gas as main source of H2.
- For prices above $500, centralized coal with CCS enters the production mix.
- Gray shaded areas illustrate 80% confidence interval (10,000 runs).



Results: US Base Case, GHG Emissions as function of HFCV Share and Carbon Price

GHG Emissions

- Plots shows transport related GHG emissions as a function of HFCV share.
- For 50% share by 2050, GHG emissions reduced 31 to 54% from 2015 levels (0 to 500 $/tCO2e, respectively).
- At 100% HFCV share by 2050, transport GHG emissions reduced 50% from 2015 levels.



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