Key Takeaways and Recommendations

1. **Hydrogen investments in Italy and France look most promising**
   - The total market size is largest in Italy and France; these countries also offer the most diverse end-use applications, minimizing investment risks
   - Expected applications include industry, transportation as well as buildings

2. **Although less attractive in the near-term, Portugal and Spain may become more attractive in the medium to long term for hydrogen investments**
   - The magnitude of hydrogen demand as well as the end-use applications might be more limited

3. **Among the three technology options (grey, blue and green hydrogen), blue seems to be the least viable; a shift from grey hydrogen in the near-term to green hydrogen in the long-term is seen in each country**
   - Stronger climate policy will favor green hydrogen; technological breakthroughs and large-scale deployment of negative emissions technologies could shift the balance to grey hydrogen
   - Emissions from grey hydrogen could be offset by negative emissions technologies

4. **Industrial end-uses might be the safest investment opportunity**
   - These end-uses are typically much harder to electrify to achieve decarbonization; green hydrogen will offer one of the few decarbonization strategies
   - Grey hydrogen in these industries will not be displaced in the near-term
Key Developments to Watch

1. **Evolution of hydrogen costs and emerging climate policy landscape globally**
   - Faster than expected declines in green hydrogen costs could result in grey hydrogen assets being stranded
   - More stringent climate policy sooner could increase near-term opportunities for hydrogen investments
   - Global climate damages incorporated into national decision making will strongly favor green hydrogen even in the near-term

2. **Viability of electrification as a competing decarbonization strategy**
   - Slower technological improvements in energy storage could improve hydrogen’s demand in transportation (freight and heavy-duty transport) and buildings (if electrification is prohibitively expensive)

3. **Infrastructure and network build outs in each country**
   - Large investments in hydrogen infrastructure could signal longer-term investment potential in the countries of interest
   - Opportunities for decentralized hydrogen production may emerge for hydrogen refueling stations

4. **Synergies with negative emissions technologies**
   - Negative emission technologies could result in cheaper grid costs and reduce the costs of green hydrogen; at the same time, they could allow for offsetting grey and blue hydrogen emissions
Italia e Francia avranno un mercato di rinnovabili robusto

**Italia** – Un Economia di idrogeno robusta

- Da fabbriche di pasta a trasporti pesanti, l’Italia può raggiungere un 25% di energia idrogenica entro il 2050
- L’Italia è onorata per il Nazionale Integrato per l’Energia e il Clima (PNIEC), con piani per una decarbonizzazione del 95% (1,5 Deg) entro il 2050

**Francia** – Prima Mover’s Advantage

- Le compagnie francesi sono già le più grandi produttrici e distributrici di idrogeno
- Plan Climat, scenario 2 Deg, l’idrogeno potrebbe alimentare il 20% delle necessità di energia finale entro il 2050
- Focalizzato su trasporto, miscelazione e elettrolisi

*Stanford University*
Portugal and Spain will have important but more limited hydrogen applications

**Portugal – Hydrogen for economic recovery**

- Hydrogen part of post-COVID economic recovery stimulus as part of EN-H2 2030 (Estratégia Nacional para o Hidrogénio)
- Emission reductions of 45-55% by 2030 as part of National Energy and Climate Plan of 2021-2030

**Spain – A push for transportation**

- Through Hydrogen Fuel Cell Electric Vehicles (HFCEV) and Hydrogen Refueling Stations (HRS)
- Under Spain’s 2017 Movalt Plan for revamping green transport
- Currently 6 HRS producing 7200 kg H2/day to ramp up to 24 HRS producing 7200 kg/day
- Relative outlook is weaker than some of the more ambitious country targets


Stanford University
France and Italy expected to lead in total hydrogen demand

- Based on policy and national targets, the largest total demand for hydrogen is expected to be in Italy and France
- At the same time, the markets in Spain and Portugal are also robust
- The key factors determining demand will be:
  - Cost of emissions reductions with hydrogen relative to other technologies
    - Electrification; biofuels; negative emissions technologies
  - Policy and infrastructure support for hydrogen technology deployment
    - Availability of hydrogen charging stations; government support in the form of subsidies; low cost financing
Life cycle assessment accounts for emissions along each step in the system boundary the three considered technologies; emissions influence technology choice.

- **Steam methane reforming (Grey)**
  - Construction and decommissioning of the plant
  - Natural gas production and transport
  - Electricity generation
  - Operation
  - Carbon capture and storage

- **SMR with CCS (Blue)**
  - Construction and decommissioning of the plant
  - Natural gas production and transport
  - Electricity generation
  - Operation

- **Electrolysis with solar (Green)**
  - Manufacture of PV modules
  - Transportation
  - Installation
  - Operation and Maintenance

- **Electrolysis with wind (Green)**
  - Manufacture and operation of turbines
  - Electrolysis
  - Hydrogen compression and storage

Green hydrogen base case assumes 50% solar, 50% wind.
Emissions profiles of hydrogen and climate targets will determine the tradeoffs between grey, blue and green hydrogen.

Green hydrogen has the lowest total emissions.

Note: Electrolysis Base case assumes 50% solar, 50% wind.

Uncertainty does not change relative emissions ranking.
Demand for hydrogen will be driven in part by ambition and design of climate policy in countries

- We constructed two scenarios to capture the range of ‘social cost of carbon’ estimates that could be used to reflect the externalities associated with greenhouse gas emissions:

  ![Graph 1: National Emphasis](image)

  - National accounting of damages

  ![Graph 2: Global Coordinated Action](image)

  - Global welfare-based climate accounting for a uniform externality estimate

  - Value is the same for all countries

- Similar divergence could also result from technological advances in Scenario 1 relative to 2.
How does the levelized cost of hydrogen evolve?

- Current levelized cost of hydrogen
- Aspects of cost
  - Capital charges
  - Fixed O&M
  - Fuel and electricity

<table>
<thead>
<tr>
<th>Technology</th>
<th>2020 LCOH ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMR</td>
<td>1.3</td>
</tr>
<tr>
<td>SMR + CCS</td>
<td>2.5</td>
</tr>
<tr>
<td>Least-cost case electrolysis (Solar PV)</td>
<td>3.2</td>
</tr>
<tr>
<td>Least-cost case electrolysis (Wind)</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Grey (and Blue) Fuel and electricity: 61%, Capital charges: 29%, O&M: 10%

Green Fuel and electricity: 47%, Capital charges: 40%, O&M: 13%
Levelized cost of hydrogen

- Cost projections
  - Technology learning rates
  - Technology transfer
  - System losses
  - Input variability and uncertainty
  - Other factors

<table>
<thead>
<tr>
<th>Hydrogen type</th>
<th>Technology</th>
<th>Learning rate</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey</td>
<td>SMR</td>
<td>11%</td>
<td>+/-6%</td>
</tr>
<tr>
<td>Blue</td>
<td>SMR + CCS</td>
<td>4.50%</td>
<td>+/-2.50%</td>
</tr>
<tr>
<td>Green</td>
<td>Electrolysis</td>
<td>18%</td>
<td>+/-13%</td>
</tr>
</tbody>
</table>
Cost minimization model uses demand scenarios for each country, technology cost and emissions estimates, and policy assumptions for each country to develop optimal portfolios.

**Critical Inputs:**
- $H_2$ demand projections through 2050
- Levelized cost of production of $H_2$
- CO$_2$ emissions for each production technology
- Carbon price projections through 2050
- Industrial discount rate

**Key Assumptions:**
- Demand grows exponentially from 2020 to 2050
- Lowest cost technology chosen every year
- Production technologies have a lifetime of at least 30 years
- Direct emissions are used to calculate social cost of carbon
- All costs are in 2019 dollars
Model provides year on year total hydrogen investments by technology type; blue hydrogen is always dominated by grey or green hydrogen.

Sample model inputs and results: France

(a) Levelized cost of production of $H_2$ from different technologies.

(b) Net present value of investment into different $H_2$ production technologies

(c) Capacity of $H_2$ produced from different production technologies over the next 30 years
Italy and France have the highest expected total investments in both grey and green hydrogen.

Climate damages are calculated using social cost of carbon estimates; Residual emissions can have significant climate damage costs if they are not offset with negative emissions technologies.

Climate damages are only shown for the national case here; the damages will be an order of magnitude higher if global damages are considered.
Reiterating Key Takeaways and Recommendations

1. Hydrogen investments in Italy and France look most promising

2. Although less attractive in the near-term, Portugal and Spain may become more attractive in the medium to long term for hydrogen investments

3. Among the three technology options (grey, blue and green hydrogen), blue seems to be the least viable; a shift from grey hydrogen in the near-term to green hydrogen in the long-term is seen in each country

4. Industrial end-uses might be the safest investment opportunity
Thank You

Questions and comments?
<table>
<thead>
<tr>
<th>Country</th>
<th>Spain</th>
<th>Italy</th>
<th>Portugal</th>
<th>France</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV of investment in grey $H_2$ (billion dollars)</td>
<td>0.21 – 1.31</td>
<td>13.33 – 36.35</td>
<td>16.03 – 21.96</td>
<td>10.00 – 23.38</td>
</tr>
<tr>
<td>NPV of investment in green $H_2$ (billion dollars)</td>
<td>4.17 – 5.17</td>
<td>18.54 – 42.73</td>
<td>1.52 – 16.91</td>
<td>10.65 – 25.24</td>
</tr>
<tr>
<td>Direct emissions (million tons of $CO_2$)</td>
<td>3.3</td>
<td>124.3</td>
<td>327.1</td>
<td>142.0</td>
</tr>
<tr>
<td>Total emissions (million tons of $CO_2$)</td>
<td>4.3</td>
<td>247.0</td>
<td>468.7</td>
<td>269.1</td>
</tr>
<tr>
<td>Climate cost of portfolio (billion dollars)</td>
<td>1.0</td>
<td>68.3</td>
<td>11.2</td>
<td>66.2</td>
</tr>
<tr>
<td>Country</td>
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</tr>
<tr>
<td>Discount rate used</td>
<td>7%</td>
<td>2%</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>Discount rate range</td>
<td>5 – 9%</td>
<td>&lt;5%</td>
<td>5 – 9%</td>
<td>5 – 9%</td>
</tr>
</tbody>
</table>

Source: European Council for an Energy Efficient Economy
Spain main results

(a) Levelized cost of production of H₂ from different technologies.

(b) Net present value of investment into different H₂ production technologies

(c) Capacity of H₂ produced from different production technologies over the next 30 years
Natural gas price uncertainty

(a) Investment portfolio when natural gas prices are 30% higher than predicted

(b) Investment portfolio when natural gas prices are 30% lower than predicted
Italy main results

(a) Levelized cost of production of $H_2$ from different technologies.

(b) Net present value of investment into different $H_2$ production technologies

(c) Capacity of $H_2$ produced from different production technologies over the next 30 years
Natural gas price uncertainty

(a) Investment portfolio when natural gas prices are 30% higher than predicted

(b) Investment portfolio when natural gas prices are 30% lower than predicted
Portugal main results

(a) Levelized cost of production of H$_2$ from different technologies.

(b) Net present value of investment into different H$_2$ production technologies

(c) Capacity of H$_2$ produced from different production technologies over the next 30 years
Natural gas price uncertainty

(a) Investment portfolio when natural gas prices are 30% higher than predicted

(b) Investment portfolio when natural gas prices are 30% lower than predicted
France main results

(a) Levelized cost of production of H₂ from different technologies.

(b) Net present value of investment into different H₂ production technologies

(c) Capacity of H₂ produced from different production technologies over the next 30 years
Natural gas price uncertainty

(a) Investment portfolio when natural gas prices are 30% higher than predicted

(b) Investment portfolio when natural gas prices are 30% lower than predicted
We constructed two scenarios to capture the range of ‘social cost of carbon’ estimates that could be used to reflect the externalities associated with greenhouse gas emissions:

<table>
<thead>
<tr>
<th>Base Case</th>
<th>Sensitivity</th>
</tr>
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<tbody>
<tr>
<td>Cost based accounting of damages within national borders is used</td>
<td>Nested Inequalities Climate Economy (NICE) model used to determine globally optimal climate policy</td>
</tr>
<tr>
<td>Estimates are derived using the Ricke et al (2018) study</td>
<td>Each generation is given equal weight (i.e. “pure rate of time preference” is assumed to be zero)</td>
</tr>
<tr>
<td>2020 damages estimates are expected to grow at 5% every year</td>
<td>Social welfare aggregation assumes a declining marginal utility of consumption (i.e. “inequality aversion” is assumed to have a value of 2)</td>
</tr>
<tr>
<td>Similar to observed policy design for existing carbon pricing policy</td>
<td>Climate damages are expected to be borne disproportionately by the poor</td>
</tr>
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