Exploring Rapidly Changing Energy System

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Outline

- Energy Transition
- Incorporating Systems Approach
- Environmental Impact of Renewables
  - Examples from California: Operational changes of existing NG plants
- Status of Carbon Capture, Utilization, and Storage
- Hydrogen for Deep Decarbonization
Energy Transition: Meeting growing demand while reducing carbon emissions
Today’s energy systems are undergoing major transformations, which are leading towards greater convergence and inter-sectoral integration – Understanding the implications of these dynamics requires novel tools that provide deep systems-level insights.
To address this pressing need, we have developed a novel systems-level technology assessment tool to understand the impact of all relevant technological, operational, temporal and geospatial variables to the evolving energy system.
The growing penetration of renewable resources like solar PV on the power system significantly impacts plant-level operations – These dynamics have a range of complex consequence that our tool can help quantify.
Bringing clarity to the real carbon footprint of renewable power technologies is also increasingly important.

Example snapshot of our PV LCA tool

<table>
<thead>
<tr>
<th>What would you like to compare?</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of installation</td>
<td>US (San Francisco)</td>
<td>Germany (Berlin)</td>
</tr>
<tr>
<td>Cell type</td>
<td>multi crystal Si</td>
<td>multi crystal Si</td>
</tr>
<tr>
<td>Installation type</td>
<td>rooftop, typical tilt</td>
<td>rooftop, optimal tilt</td>
</tr>
<tr>
<td>Shading losses</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Lifetime (yr)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Efficiency, STC rated</td>
<td>16.0%</td>
<td>16.0%</td>
</tr>
<tr>
<td>Degradation rate (-/yr)</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Inverter loading ratio</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>GHG emissions of electricity used to make panels (g CO₂-e / kWh)</td>
<td>660</td>
<td>660</td>
</tr>
<tr>
<td>GHG emissions of electricity used to make BOS (g CO₂-e / kWh)</td>
<td>310</td>
<td>480</td>
</tr>
<tr>
<td>If multi-Si, panel prod. typical of:</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td>Shipping distance from panel production to installation (km)</td>
<td>8690</td>
<td>17300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Life cycle GHG emissions (kg CO₂-e/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
</tr>
<tr>
<td>Scenario 2</td>
</tr>
<tr>
<td>AC power per panel area (W/m²)</td>
</tr>
<tr>
<td>Incident irradiance (kWh/m²/yr)</td>
</tr>
<tr>
<td>Panel prod. typical of:</td>
</tr>
</tbody>
</table>

* Standard Test Condition
** Balance of system

Sources: MITEI Analysis
Tracking’s impact on carbon intensity ranges from -12% to +12% - (1) Cloudier or higher latitude → more diffuse light → less power gain from tracking, (2) More module prod. emissions (mc-Si > CdTe) → greater reduction in carbon intensity

Estimating the net impact of higher renewable power penetration is quite challenging – Has solar boom in California achieved its maximum emission reduction potential?

Sources: MITEI Analysis
There is a considerable alteration in how the natural gas power plants have been dispatched over the last decade.

Sources: MITEI Analysis
Aggregate fleet wide studies are incapable of capturing the real world dynamics – For accurate characterization, high temporal and geospatial resolution analysis must be performed.

Source: MIT Analysis
By executing the analysis at hourly generator level resolution the main causes of the deviation from the optimum performance of the units are identified - Higher number of start-ups and more frequent cycling with a profile shift in time of the day are
Although we are seeing real growth in low carbon capacity, the global coal fleet remains large and relatively young – Today, coal supplies ~40% of total electricity from a fleet made up of ~1,600 GWs.

More than 50% of the installed capacity is younger than 20 years.

Sub-critical plants dominate the installed capacity.

Relative to the profound growth witnessed with renewables deployment, CCS has really struggled to gain any momentum – Today’s deployment reality vastly deviates from targets

Current
32 MtCO₂/year
$60/ton CO₂ captured³
25%-35% (HHV) ⁴

Total planned
74 MtCO₂/year

Target
4 GtCO₂/y by 2040²
$10/ton CO₂ capt. by 2035
43%-56% (HHV) in 2035

Missed Targets
2.6-4.9 GtCO₂/y by 2020¹

Target: 125x capacity increase in 20 years!

Plan: 2.3x capacity increase in 8 years!

The majority of today’s operational CCS facilities are linked to gas processing and this accounts for 20 MtCO₂/year of the capacity – Only two power plants have an operational CCS element.

- **Val Verde**
  - Natural gas processing
  - EOR 1972
- **Great Plains**
  - Synthetic gas production
  - EOR 2000
- **Coffeyville**
  - Fertilizer production
  - EOR 2013
- **Lost Cabin**
  - Natural gas processing
  - EOR 2013
- **Petrobas Lula**
  - Natural gas processing
  - EOR 2013
- **Air Products**
  - Hydrogen production
  - EOR 2013
- **Boundary Dam**
  - Power generation
  - EOR 2014
- **Quest**
  - Hydrogen production
  - Dedicated 2015
- **Uthmaniyah**
  - Natural gas processing
  - EOR 2015
- **Abu Dhabi**
  - Iron and Steel production
  - EOR 2016
- **Petro Nova**
  - Power generation
  - EOR 2017

**Graph Details:**
- **Y-axis:** Total Capture Capacity (MtCO₂/year)
- **X-axis:** Number of Operational Projects
- **Categories:** Power Generation, Hydrogen Production, Fertiliser Production, Synthetic Natural Gas, Iron and Steel, Natural Gas Processing

*MITei Analysis*
The relative cost of integrating CCS remains an enormous hurdle for the technology

Sources: Rubin, Davison and Herzog, IJGGC, 2015.
Value capture via CO₂ utilization has the potential to provide some impetus for deployment of capacity over the medium term – For it to be useful from a climate perspective though the utilization will have to support a closed loop.

Achieving current carbon mitigation targets will require utilization with long term storage at the gigatonne scale.

Other than utilization for EOR, the permanent storage with utilization options is questionable.

There is still potential to expand CO₂ use in EOR, but in reality that application is limited in scale.

The integration of renewable power has led to considerable changes in how the fossil-fired power plant fleet is being dispatched relative to a decade ago.
Cycling and a shift from baseload to peaking capacity in combined cycle units are some of the operational changes we will increasingly observe.
The role of CCUS in delivering low-carbon electricity remains unclear, however deep economy-wide decarbonization will likely need other energy carriers (e.g. Hydrogen).

Sources: EIA, 2018
The exact integration of hydrogen into the energy system is uncertain but numerous opportunities exist both on the supply and demand side.
Not all hydrogen are created equal – The role of hydrogen in economy-wide deep decarbonization is dependent on how hydrogen is produced.

Sources: MITEI
The global fuel cell electric vehicle (FCEV) car stock reached 8,000 units in April 2018. The United States represents the largest fleet with 4,500 FCEVs.

Toyota Mirai ($57,500)
Fuel Economy = 106 km/kg H₂
Tank ~ 5 kg
Range = 550 km (340 miles)

Japan has more than twice as many fueling stations relative to the US (100 vs. 38)

Sources: EIA 2019
Exploring the life cycle greenhouse emissions of various hydrogen pathways relative to vehicle types

- Car models chosen to facilitate apples-apples comparisons—i.e., minimize differences in non-powertrain features.

<table>
<thead>
<tr>
<th>Car Model</th>
<th>Interior Volume (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Camry ICEV</td>
<td>115</td>
</tr>
<tr>
<td>Toyota Camry HEV</td>
<td>115</td>
</tr>
<tr>
<td>Honda Clarity PHEV</td>
<td>117</td>
</tr>
<tr>
<td>Honda Clarity BEV</td>
<td>116</td>
</tr>
<tr>
<td>Honda Clarity FCEV</td>
<td>113</td>
</tr>
</tbody>
</table>

Sources: MITEI Analysis
1. BEV emissions per mile ~ 55% emissions of comparable ICEVs.
2. Increased emissions from battery & fuel (electricity) production are more than offset by increased powertrain efficiency (MPG).
3. HEV emissions per mile fall between ICEV and BEV emissions.
4. FCEVS: more later.
Hydrogen value chain should be significantly scaled-up to have an impact in the current energy system – 2018 H₂ production ~10 Mtons (1.2 EJ) vs. 2018 energy demand ~101.2 Quad (106.8 EJ)

Sources: Lawrence Livermore National Laboratory
Key Takeaways

- Understanding the evolving energy system requires new analytical methods and tools that allow exploration of system level interactions and perform cross sectoral comparisons.

- Impacts arising from standard vs. best practices can have a significant impact such as in California’s natural gas fleet.

- The shift in energy system from isolated to integrated and from centralized to distributed is hard to characterize. High temporal and geospatial resolution is a must for any accurate analysis.

- CCUS is essential for deep decarbonization especially for sectors that are hard to electrify.
  - For electric power sector CCUS has a role to play as the global fossil power plant fleet is young.
  - The changes in how the fossil-fired power plant fleet is being dispatched will be a technical challenge for CCUS deployment

- Meaningful climate change mitigation efforts must target all sectors, not just power – the versatility of H₂ makes it an appealing energy carrier to serve traditionally difficult-to-electrify end uses.
  - For light duty transportation (FCEV), hydrogen production determine the ranking among other options. FCEV GHGs ~quadruple with H₂ from coal gasification vs. electrolysis + wind.
  - Due to growth of renewable power, there is a growing need for long-term/seasonal energy storage.
Thank you

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