Global Current Status & Prospects of Hydrogen Energy

MAY 9, 2019 | PROF. DETLEF STOLTEN

International Hydrogen Forum 2019
PyeongChang Alpensia Resort Convention Center, Korea

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IEK-3: Institute of Electrochemical Process Engineering
What are the Drivers Behind the Energy Transition?
The Main Culprits

Climate change → CO₂ equivalent

- Rising sea levels are posing a menace to the world economy
- Storms increase in intensity, size, duration and water load
- Extreme weather events like flooding and droughts increase
- Harvests are going to decline (at the same time when the world population is expanding)

Local emissions

- PM2: small particulate matter reduces life quality and can reduce lifetime and cause cancer
- NOx

Business opportunities

- Harnessing business opportunities through new and more efficient products
- Legal and regulatory support is necessary since the system is tailored to the incumbents

The energy transition triggers great business opportunities

Observation:
If climate change gets tackled appropriately other issues are solved “by default“
Basic Requirements for a Future Energy System

- According to COP21 requirements as for 2050 global temperature rise shall be curbed to +1.5 to 2°C, translating into \( \text{CO}_2 \text{ emissions reductions of 80-95\%} \) based on 1990
- After the transition period energy should **not be more expensive** than today
- **Limited emissions** shall be reduced
- Electricity, fuels and heat must be available with **high reliability**
- **All energy sectors** need **to be addressed to achieve these goals**
- Teratogenic, carcinogenic and poisonous substances shall be avoided
- Nuclear hazards and extremely high cost of new nuclear plants to be considered
- Radiative forcing to be considered (e.g. methane > 26) for new energy pathways
Deconvoluting the Energy Storage Options

- The simplest applicable energy pathways will in most cases turn out to be the most efficient, effective and cost effective.

- **Direct use of power**
- **Storage in batteries (grid stabilization)**
- **Hydrogen storage (long-term storage, seasonal storage)**
- **Methane storage**
- **Liquid fuel production**

- Power to chem comes in parallel
- Quantitative storage requirements will probably be much higher than we anticipate today
- All of the above mentioned storage options will be needed, owing to the limited applicability of the easier ones (e.g. liquid jet fuel for aviation)
- The complete energy chain needs to be considered for future decisions
- **Energy security requires large amounts of storage – as we have implemented today**
Where are we today?

Energy transition

Scope
Targets
Timeline
Constraints and Implications
Barriers (from incumbents’ resistance via markets and regulations down to technologies)

Hydrogen

Generation Technologies
Transmission & Distribution and Storage Technologies
Application Technologies
Hydrogen Safety

Hydrogen Energy Pathways w/r to efficiency and cost
Hydrogen Markets @ Entry Level, Penetration Level and
Hydrogen Energy Services
Business and Citizen Participation Models
Phase-in into Industry 4.0 and Extend to Energy 4.0
Hydrogen as a tradeable commodity for sector coupling
Economic and quantitative constraints
Barriers
Hydrogen in the Energy System
Excess Power is Inherent to Renewable Power Generation

Power Generation → Electrolysis → Power Grid

Positive residual load

Negative residual load

Excess Power is Inherent to Renewable Power Generation

Power to Fuel
Power to Gas (H₂)
Power to Gas (CH₄)
Power to Chem

Household
Transportation
Industry

Demand

Jan

Power, GW

0 50 100 150 200
0-Jan 2-Jan 4-Jan 6-Jan 8-Jan 10-Jan 12-Jan 14-Jan

PV
On-shore
Off-shore
Other RE
Vertical Grid Load

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Linking the Power and the Transport Sector

Residual energy [MWh/km²]
-3000000 - -2500
-2500 - -1700
-1700 - -1200
-1200 - -830
-830 - -460
-460 - -120
-120 - 175
175 - 545
545 - 1535
1535 - 50600

Negative residual energy (Surplus)
Positive residual energy
Continuous Power Production Turns from being a Pillar to a Nuisance in the Grid @ High Shares of Renewable Energy

Back-up power production with gas turbines needed
- First fed with natural gas
- Later fed by hydrogen

Projected Input of Off-shore Power into the German Power Grid
Investments for Electrolysis: Current Status and Expected Development

Status as of 2019

→ CAPEX 1500 - 2000 €/kWₑ

→ Cost reduction through:
  • R&D stack and systems concepts
  • Production scale-up

Until 2030

→ Bottom-up cost analysis: 340-410 €/kWₑ
  • R&D and production progress considered
  • CAPEX of stack, system, compression to 100 bar, housing/building, land

→ Assuming 70% efficiency 490-580 €/kWₑ70%-LHV

[Graph showing projected CAPEX for PEM electrolysis with detailed breakdown of costs for different components like Land, Building, Trafo, AC/DC, Stack, Compressor, and others.

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Hydrogen Storage
## Gaseous Hydrogen: Geologic Gas Storage Facilities Preferred

<table>
<thead>
<tr>
<th></th>
<th>Depleted oil / gas fields</th>
<th>Aquifers</th>
<th>Salt caverns</th>
<th>Rock caverns / abandoned mines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working volume [scm]</strong></td>
<td>10^{10}</td>
<td>10^{8}</td>
<td>10^{7}</td>
<td>10^{6}</td>
</tr>
<tr>
<td><strong>Cushion gas</strong></td>
<td>50 %</td>
<td>up to 80 %</td>
<td>20 - 30 %</td>
<td>20 - 30 %</td>
</tr>
<tr>
<td><strong>Gas quality</strong></td>
<td>reaction and contamination with gases present, microorganism and minerals</td>
<td>saturation with water vapor</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Annual cycling cap.</strong></td>
<td>only seasonal</td>
<td>seasonal &amp; frequent</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Liquid Hydrogen

Great mass storage option, if
- Geology does not allow for (salt) caverns
- $\text{H}_2$ gets imported via ship or train

Liquefaction
- Current energy loss of liquefaction >30% of hydrogen energy content
- Future systems have a potential of 7 kWh/kg or 21% loss
- Current plants 150 l/h – 20000l/h
- Specific evaporation low for large storage tanks
- Evaporated $\text{H}_2$ can be used and is not lost in most cases
- Current plants amount to at most 40 MW H2
- Hence, current $\text{H}_2$ liquefaction is NOT central in the sense of energy systems
Transmission and Distribution Technologies
## Power Line and Gas Pipelines Compared

<table>
<thead>
<tr>
<th></th>
<th>380 kV overhead line</th>
<th>Natural gas pipeline</th>
<th>Hydrogen gas pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>4 x 564/72 double circuit</td>
<td>DN 1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_{in} = 90$ bar</td>
<td></td>
</tr>
<tr>
<td><strong>Energy transport capacity</strong></td>
<td>1.2 $GW_{el}$</td>
<td>16 $GW_{th}$</td>
<td>12 $GW_{th}$</td>
</tr>
<tr>
<td><strong>Investment cost in M€/km</strong></td>
<td>1 - 1.5</td>
<td>1 - 2</td>
<td>1.2 - 3</td>
</tr>
</tbody>
</table>
Reassignment of Pipelines

- Reassignment of existing NG or old city gas transmission pipelines saves 80% of pipeline CAPEX.
- Routing of H₂ transmission pipelines would look very similar to today's NG pipeline routing.
- Reassignment fostered by decreasing demand & L to H gas conversion.
- Early opportunities at two or three-fold pipeline strings.
Example of NG Pipeline Reassignment Potential for Germany
Only Multiple Tube Pipelines Considered

Distance: ~420 km
2020-2025

Marktpotenzial (Umkreis 50km):
Bevölkerung (2017):
~23,5 Mio. (~28%)
BIP (2017):
~800 Mrd. € (~27%)
Abnahmepotenzial: X kt\textsubscript{H2}/a
CO\textsubscript{2}-Vermeidungspotenzial:
X Mt\textsubscript{CO2}/a

Distance: ~2600 km
2035-2040

Marktpotenzial (Umkreis 50km):
Bevölkerung (2017) [1]:
~67 Mio. (~81%)
BIP (2017) [2]:
~2.500 Mrd. € (~83%)
Abnahmepotenzial: X kt\textsubscript{H2}/a
CO\textsubscript{2}-Vermeidungspotenzial:
X Mt\textsubscript{CO2}/a

## Hydrogen Transport

<table>
<thead>
<tr>
<th>H₂ Pipeline</th>
<th>Property</th>
<th>Today</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity tₜₑₜₕ / h</td>
<td>2.4</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>CAPEX €/m</td>
<td>500</td>
<td>3400</td>
<td></td>
</tr>
<tr>
<td><strong>TRL</strong>: 8-9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Advantages</strong>:</td>
<td>High throughput capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low space demand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low specific cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong>:</td>
<td>High upfront cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projects:</td>
<td>Leuna (DE)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texas (US)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gaseous H₂ Trailer</th>
<th>Property</th>
<th>Today</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity kgₜₑₜₕ</td>
<td>400</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>CAPEX €/kgₜₑₜₕ</td>
<td>500</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td><strong>TRL³</strong>: 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Advantages</strong>:</td>
<td>No liquefaction required</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low investment cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Established technology³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong>:</td>
<td>Low transport capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projects:</td>
<td>London (UK)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oslo (NOR)</td>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Liquid H₂ Trailer</th>
<th>Property</th>
<th>Today</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity kgₜₑₜₕ</td>
<td>4300</td>
<td>4300</td>
<td></td>
</tr>
<tr>
<td>CAPEX €/kgₜₑₜₕ</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td><strong>TRL</strong>: 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Advantages</strong>:</td>
<td>No liquefaction required</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low investment cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High transport capacity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Established technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong>:</td>
<td>Requires liquefaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Projects:</td>
<td>London (UK)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vancouver (CAN)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Advantages**: High throughput capacity, Low space demand, Low specific cost

**Disadvantages**: High upfront cost

**Projects**: Leuna (DE), Texas (US)

**Projects**: London (UK), Oslo (NOR)

**Projects**: London (UK), Vancouver (CAN)

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**TRL**: Technology Readiness Level

**CAPEX**: Capital Expenditure

1: Pipeline diameter = 100 mm
2: Pipeline diameter = 1000 mm
3: Trailer pressure = 200 bar
4: Trailer pressure = 500 bar
Final Geospatial Results:
Scenario 20 million FCV

GH₂-Pipeline  GH₂-Trailer  LH₂-Trailer  GH₂-Pipeline  GH₂-Trailer

Legende
Hydrogen production [t/a]
- 908 - 50000
- 50000 - 100000
- 100000 - 150000
- 150000 - 200000
- 200000 - 250000
- 250000 - 300000
- 300000 - 332157

Transmission Pipeline [mm]
- 97.2 - 100.0
- 100.0 - 200.0
- 200.0 - 300.0
- 300.0 - 400.0
- 400.0 - 500.0
- 500.0 - 600.0
- 600.0 - 700.0
- 700.0 - 800.0
- 800.0 - 815.0
- Distribution Pipeline
- Trailer Distribution
- Trailer
- Fuelingstations
Total Investment

- **Production**
- **Storage and Distribution**
- **Fueling**

<table>
<thead>
<tr>
<th></th>
<th>GH2 Trailer</th>
<th>GH2 Pipeline</th>
<th>Pipe/Trailer</th>
<th>LH2 Trailer</th>
<th>GH2 Trailer</th>
<th>GH2 Pipeline</th>
<th>Pipe/Trailer</th>
<th>LH2 Trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 million FCEV</td>
<td>0.5</td>
<td>5.5</td>
<td>4.2</td>
<td>0.6</td>
<td>1.9</td>
<td>8.4</td>
<td>6.1</td>
<td>2.5</td>
</tr>
<tr>
<td>1 million FCEV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 million FCEV</td>
<td>44.1</td>
<td>46.3</td>
<td>40.0</td>
<td>43.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results – Hydrogen Pipeline Connections

- Pipeline connections that are built in each wind year as a result of the optimization (red lines)

Occasionally connected regions:
- Regions in which wind turbines are installed changes within France due to full load hour variation in each wind year

Perpetual pipeline connections can be seen (red lines)

A robust pipeline design can be attained for crucial connections

Number of repetitions
- 1 – 4
- 4 – 9
- 9 – 15
- 15 – 22
- 22 – 36

Repetition of pipeline connections as a result of optimization
Estimates for Korea
Open Field PV Potential in South Korea VK1.0

- Land eligibility specifies the available areas
  - 37 constraints for every 300x300m
- Full physical simulations
  - “2050” context module design
  - Optimally-tilted PV modules
  - Climate model weather data
- No max. slope constraint, max. forest cover of 40%

**Availability and Performance**

**National Solar Potentials**
- Available land: 18,284 km²
- Capacity: 914 GW
- Generation Ø: 1138 TWh/a

**Regional Potential**
- TWh

**Regional Potential**
- FLH
  - 1450
  - 1400
  - 1350
  - 1300
  - 1250
  - 1200

**Available land**: 18,284 km²
**Capacity**: 914 GW
**Generation Ø**: 1138 TWh/a
Impact of Slope Constraints on Wind Land Eligibility (VK1.0 → VK2.0)

- **Eligible Area in %**
  - VK1.0: 35%
  - VK2.0: 10%
- **Reduction by factor of 4**
- **Energy Potential (TWh/yr)**
  - VK1.0: 221.5
  - VK2.0: 53
- **Capacity (GW)**
  - VK1.0: 53
  - VK2.0: 10

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Onshore Wind Potential in South Korea VK2.0

- Land eligibility specifies the available turbine locations
  - 36 constraints for every 300x300m
  - 800 m separation
- Full physical simulations
  - “2050” context turbine design:
    - 3200 kW
    - 186 m hub height
    - 136 m rotor diam.
  - Climate model weather data
- Max. allowed slope of 10°

National Wind Potentials

- Available land 7,703 km²
- Capacity 74.76 GW
- Generation Ø 117.5 TWh/a

Regional Potential
Open Field PV Potential in South Korea VK2.0

- Land eligibility specifies the available areas
  - 37 constraints for every 300x300m
- Full physical simulations
  - “2050” context module design
  - Optimally-tilted PV modules
  - Climate model weather data
- Max. allowed slope of 15°, max. forest cover of 15%

National Solar Potentials

- Available land: 2,818 km²
- Capacity: 140.9 GW
- Generation Ø: 229.2 TWh/a

Regional Potential

Availability and Performance

- FLH
  - 1730
  - 1700
  - 1600
  - 1500
  - 1400

- TWh
  - 10
  - 8
  - 6
  - 4
  - 2
  - 0

Aggregate
Potential in Gangwon-do
Wind Energy Potential in Gangwon-do VK2.0

**Future design 2050**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>3200 kW</td>
</tr>
<tr>
<td>Height</td>
<td>186 m</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>136 m</td>
</tr>
<tr>
<td>Turbine distance</td>
<td>800 m</td>
</tr>
<tr>
<td>Invest</td>
<td>1000 €/kW</td>
</tr>
</tbody>
</table>

**Cost of Energy (€-ct/kWh)**

- FLH: 4110 → LCOE = 2.96 €-ct/kWh
- FLH: 3000 → LCOE = 4.06 €-ct/kWh
- FLH: 2000 → LCOE = 6.09 €-ct/kWh
- FLH: 1000 → LCOE = 12.2 €-ct/kWh
- FLH: 128 → LCOE = 95.2 €-ct/kWh
Wind Energy Potential in Gangwon-do VK2.0

Regional Wind Potentials (1980 – 2016)
- Availability: 1763 turbines (3.2 MW)
- Capacity: 5.64 GW
- Generation Ø: 7.32 TWh/a

Map showing regional wind potentials with color coding indicating GWh values from 0 to 1000.
Expl. H₂ Supply Chain Based on Wind Energy VK2.0

min. 1000 FLH = 3.3 GW_{\text{Wind}}

- Wind turbines
- Microgrid
- Electrolyzer
- H₂ Pipeline
- Liquefaction + storage

Seoul
### Offshore Wind Potential in Gangwon-do

- Locations deeper than 1000 m are excluded.
- Turbine model: GE Haliade-X 12 MW
  - Capacity: 12 MW
  - Rotor diameter: 220 m
  - Hub height: 150 m
- Turbines are separated by 8 x rotor diameter
- Climate weather data is used
- Average full load hours (FLH) is determined between 1980-2016 by a simulation scheme[1]

![Map of Gangwon-do with offshore wind potential areas]

<table>
<thead>
<tr>
<th>Shore Distance Constraint [km]</th>
<th>Capacity [GW]</th>
<th>Generation [TWh]</th>
<th>Average FLH [h/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35.6</td>
<td>106.2</td>
<td>2982</td>
</tr>
<tr>
<td>5</td>
<td>31.9</td>
<td>97.2</td>
<td>3045</td>
</tr>
<tr>
<td>10</td>
<td>28.2</td>
<td>87.9</td>
<td>3112</td>
</tr>
<tr>
<td>15</td>
<td>24.7</td>
<td>78.7</td>
<td>3185</td>
</tr>
</tbody>
</table>

Open Field Fixed-tilt PV Potential in Gangwon-do VK2.0

PV module parameters
- Capacity: 20 m²/kW
- Fixed tilt: 34 – 37°
- Invest: 500 €/kW

LCOE (€-ct/kWh)
- 1472: 4.14
- 1500: 4.06
- 1550: 3.93
- 1600: 3.81
- 1650: 3.69
- 1686: 3.61
Open-field PV Potential in Gangwon-do VK2.0


Availability 257 km² (20 m²/kW)
Capacity 12.85 GW (fixed tilt)
Generation Ø 21 TWh/a
### H₂ Supply Cost Curve based on Open-Field Fixed-tilt PV VK2.0

#### Scenario (min. FLH)

<table>
<thead>
<tr>
<th>Scenario (min. FLH)</th>
<th>1471</th>
<th>1521</th>
<th>1571</th>
<th>1621</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. solar power curtailment</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Energy loss</td>
<td>8.8%</td>
<td>8.8%</td>
<td>9.1%</td>
<td>9.6%</td>
</tr>
</tbody>
</table>

#### PV capacity expansion in GW
- Opt. solar power curtailment: 7.03, 11.25, 12.39, 12.42
- Energy loss: 5.74

#### H₂ potential in kt/a
- Minimum of FLH: 1471, 1521, 1571, 1621
- Supply costs (€/kg): 1.12, 0.36, 5.74

#### Capacity expansion
Capacity expansion = Degree of potential utilization
Expl. H$_2$ Supply Chain Based on Open-field Fixed-tilt PV VK2.0

min. 1521 FLH = 12.4 GW$_{PV}$
Expl. $H_2$ Supply Chain Based on Wind Energy VK2.0

min. 1000 FLH = 3.3 $GW_{\text{Wind}}$

- Wind turbines
- Microgrid
- Electrolyzer
- $H_2$ Pipeline
- Liquefaction + storage

Seoul
Energy Security Considering RE Input Lulls
Annual Probability of Lull Occurrence Depending on the Size of the Region

Constraints:

- Lull means a time period where electricity generation from wind, PV, biomass, hydro, and imports cannot offset internal electricity demand and electricity exports
- Power flow across Europe (including within regions) is considered

► Bulk Storage of Renewable Energy (via Gas) is Needed
International Import
Pipeline through Patagonia to Punta Arenas

- Detour factor of 1.2
- 5 tributary pipelines, 500 km each

→ Pipeline length ~ 4,500 km

Global Energy Supply Systems for Hydrogen

- Japan: Patagonia wind potential 10x Japan’s mobility demand
  - Potential of 18 Mt/a of hydrogen for assumed demand of 1.85 Mt/a for 2050 (passenger cars)

- H2 cost at fueling station: 6.70 €/kg\(_{\text{H2}}\)
  (H2: 20.1 €-ct/kWh; gasoline: 6.3 €-ct/kWh)

- Wind-generated hydrogen from Patagonia can be economically competitive to conventional fuels in Japan; pre-tax
Cost of Hydrogen Import from Strong Wind Regions to Germany

Production (Onshore wind, electrolysis) | Transport (Pipeline, ship, truck) | Provision (Fueling station)

Final fuel costs in €-ct/kWh for DE

- Argentina
- Chile
- Iceland
- Norway
- United Kingdom
- Ireland

Gasoline benchmark excl. taxes [1]
Gasoline benchmark incl. taxes [1]

* LDV / HDV: Light / Heavy Duty Vehicle
Selected Solar Locations of Saudi Arabia

Analyzed PV potential in Saudi Arabia
~ 70,100 km² eligible land
~ 76,720 PV locations
~ 3,505 GW capacity

Additional restrictions:
• Best 5% of all possible locations
• Minimum of full-load hours = 1900

Full-load hours
- 2328 – 2350
- 2350 – 2400
- 2400 – 2450
- 2450 – 2486
Exemplary Results for Saudi Arabia

- Installed PV capacity in GW:
  - 2328: 3,413
  - 2353: 3,400
  - 2378: 2,848
  - 2403: 974
  - 2428: 415
  - 2453: 100

- LCOE in €ct/kWh:
  - 2.1
  - 2.2
  - 2.3
  - 2.4
  - 2.5
  - 2.6
  - 2.7
  - 2.8
  - 2.9

- Min of FLH

- Expansion states in Saudi Arabia scenarios with declining capacity

**Legend:**
- Blue: Installed capacity
- Green: LCOE
- Black: LCOE (curtailed)
Acknowledgement to the Systems Analysis Team
Thank You for Your Attention!

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