The Knowledge Framework for Power Sector Transformation
Introduction

» Why is a knowledge framework necessary?
   ✓ To learn from successful measures put in place by front runners
   ✓ Need to locate measures in time
   ✓ Understand applicability of measures to other countries based on common enablers

» Is it technically feasible to go 100% without certain enablers in place?

» Is a transition to 100% RE power system possible?
   ✓ Hydro and PV + Battery exist today

» Is there a single pathway or recipe for the transition?
   ✓ No, depends on enablers and specific country conditions.

» What is changing to make it feasible?
   ✓ New technologies, cost reduction and enablers (e.g. storage, power electronics)
   ✓ Learning by doing on policies, regulations and system operations as low-cost, high-impact

VRE Integration
• Carrying capacity (from which VRE “breaks” the grid)
• Nearly always there is a technical solution
• Focus on economic carrying capacity as metric
  • Operational improvements are key and should come first

Transfer of measures and Optimization
• Typically a product of “learning-by-doing”
• Learning from Country A may be applied on country B, provided similar enabling condition/profiles are in place
Introduction

High Cost
- Supply-side flexibility
- Demand-side flexibility
- Flexibility from storage
- Grid infrastructure
- Improved operations

Low Cost
- Demand response
  - Residential
  - Industrial
- Retrofitting existing thermal units
  - Decreasing minimum load
  - Decreasing start-up times
  - Increasing ramp rates
- More efficient hydro-thermal co-optimisation
- Shorter dispatch intervals, intra-day markets
- Revised ancillary services requirements (and market)
- Improved VRE forecast, updated regularly and closer to generation

Share of VRE

Source: based on Denholm et al., 2010
Different Transition Pathway based on Countries Profiles

Front runners: DK: 40% / IE: 20%
   » Low domestic storage
   » High PPs Flexibility

Size of national grid compared to synchronized power system (2015)
   » DK: 1.28% <-> IE: 74%

Interconnectors (2015)
   » DK: 50% <-> IE: 7%

• Same measures but at different times
• But also different measures

DK

<table>
<thead>
<tr>
<th>2.2%</th>
<th>3.5%</th>
<th>3.8%</th>
<th>8.3%</th>
<th>13.9%</th>
<th>15.6%</th>
<th>18.4%</th>
<th>19.8%</th>
<th>24.4%</th>
<th>30.9%</th>
<th>35.8%</th>
<th>46.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Flex (CHP Plants)</td>
<td>First grid code for wind</td>
<td>Regulation Power Market</td>
<td>Wind in Regulation Market</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IE

<table>
<thead>
<tr>
<th>0.2%</th>
<th>1.1%</th>
<th>2.6%</th>
<th>7.1%</th>
<th>8.4%</th>
<th>10.5%</th>
<th>16.2%</th>
<th>15.5%</th>
<th>17.3%</th>
<th>19.6%</th>
<th>24.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intention for first grid code (general)</td>
<td>Specific grid code for Non-Synchronous</td>
<td>Potential Technical-Max SNSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Integration should not be approached by one-dimension only – VRE generation share – but in a multi-dimensional way
Goal: provide tailored advice to countries facing integration challenges by mining a database of measures based on the experience from front-runners

Provide a semi-automated quick insight to countries on where to look next

Define a set of quantitative indicators to identify country-specific profiles/enablers

Link countries experiencing challenges with front-runners that solved such issues

What was the measure, year and impact on key indicator?

Identify RE integration challenges that have been resolved by front-runners

Identify key measures used to resolve the challenges

Measure the impact of such measures on integration indicators

Estimate the applicability of each measure based on enabling conditions

- Line Congestion
- Lack of system Inertia
- Dynamic Line rating
- Synchronous condensers
- Curtailment variations
- Negative prices
- Filter Measures:
  - Statistical Inference
What can IRENA do for its Members using the Knowledge Framework?

Synergies with other IRENA Products

» Enhance a plan for a target year by suggesting measures

IRENA FLEXTOOL CASE STUDY

» Identify the need for a flexibility assessment

Integration Costs Discussion

» Identify first and likely low-cost measures in a country’s pathway

Workshops: Sharing of best practices

- Incentives to Increase Demand
- Improve Flexibility
- Nodal Pricing

Country A

Country B

Country C

Country D

Country E facing Challenge

IRENA Reports and others relevant literature

- Incentives to Increase Demand
- Improve Flexibility
- Nodal Pricing
Knowledge Database
Knowledge Framework – Profiles and Measures Database

• Country Profile in year Y
  • Indicator A_y
  • Indicator B_y
  • Indicator C_y

• Solution applied in year Y
  • Year Y
  • Indicators
  • Enabling Conditions (can be a solution previously applied)

• Country Profile in year Y + 1
  • Indicator A_{y+1}
  • Indicator B_{y+1}
  • Indicator C_{y+1}

• Solution applied in year Y+1
  • Year Y
  • Indicators
  • Enabling Conditions (can be a solution previously applied)

• Country Profile in year Y + n
  • Indicator A_{y+n}
  • Indicator B_{y+n}
  • Indicator C_{y+n}

• Solution applied in year Y + n
  • Year Y
  • Indicators
  • Enabling Conditions (can be a solution previously applied)

Country Profile following years
Knowledge Framework – Profiles (Indicators) Examples

Total: 44 indicators

• Flexibility (8 indicators)
  • Temperature-wind correlation
  • CHP generation to total

• Transmission and Distribution grids (7 indicators)
  • Mismatch Index (Supply-demand energy balance)

• Interconnection (4 indicators)
  • Storage in neighbor countries

• Operation (14 indicators)
  • VRE capacity/primary reserve

• Market (7 indicators)
  • Prices are allowed to go negative

  • Demand Response (4 indicators)
  • Storage (1 indicator)
### Profile indicators are Numbers: Flexibility Example

<table>
<thead>
<tr>
<th>Profile Indicators</th>
<th>China</th>
<th>Denmark</th>
<th>Germany</th>
<th>Ireland</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heating coupling</strong></td>
<td>Temperature-VRE Correlation</td>
<td>- 0.49</td>
<td>- 0.81</td>
<td>- 0.73</td>
</tr>
<tr>
<td></td>
<td>Combined Heat Power share – Heat (%)</td>
<td>46</td>
<td>73 -&gt; 67</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Combined Heat and Power share - ELE (%)</td>
<td>13 -&gt; 17</td>
<td>40 -&gt; 79</td>
<td>12 -&gt; 15</td>
</tr>
<tr>
<td><strong>Best avail. thermal plant</strong></td>
<td>Minimum Stable Level (%)</td>
<td>50 -&gt; 35%</td>
<td>35 -&gt; 15%</td>
<td>40 -&gt; 12%</td>
</tr>
<tr>
<td></td>
<td>Ramp (%/min)</td>
<td>-</td>
<td>1 -&gt; 4</td>
<td>1.5 -&gt; 6.0</td>
</tr>
<tr>
<td><strong>Flexible fleet</strong></td>
<td>Flex Capacity Share (%)</td>
<td>21 (national) ; 5 (north)</td>
<td>&gt;50</td>
<td>8.7 -&gt; 8.1 (national); 2 (north)</td>
</tr>
<tr>
<td></td>
<td>Flex Generation Share (%)</td>
<td>17 -&gt; 19</td>
<td>&gt;50</td>
<td>9.4 -&gt; 8.8</td>
</tr>
<tr>
<td></td>
<td>Ratio VRE-Flex capacity:</td>
<td>0.27 -&gt; 0.83</td>
<td>0.96</td>
<td>3.67 -&gt; 4.92</td>
</tr>
</tbody>
</table>

Flexible fleet includes hydropower.
Knowledge Framework – Indicators x Measures

Measures related to countries profiles

- **High share of small-scale PV systems**
  - Italy enlarged the operation frequency range for PV systems to prevent massive tripping.
  - Germany requires PV systems to not trip all at a same frequency.
  - Strict requirements on voltage quality and control in Germany.

- **Bottlenecks over the transmission network may prevent the best use of power assets**
  - German DSOs have applied measures to increase the hosting capacity of low-voltage grids.
  - PV on the Italian distribution grid may be dispatched-down/shutdown.

Small-scale PV share in total PV

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>Italy</th>
<th>UK</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV Share</td>
<td>N-NE China</td>
<td>Flexibility in North-Northeast region (wind dominated) almost 5 times lower than National</td>
<td>Retrofit of CHP Plants</td>
<td>2017</td>
</tr>
<tr>
<td>VRE Share</td>
<td>N-NE China</td>
<td>Flexibility in North-Northeast region (wind dominated) almost 5 times lower than National</td>
<td>Retrofit of CHP Plants</td>
<td>2017</td>
</tr>
</tbody>
</table>

**Note:**
- The diagrams show the share of solar PV compared to total PV and the share of VRE compared to total energy.
## Knowledge Framework – Filtering measures by country profile

### Main Table

#### Output

<table>
<thead>
<tr>
<th>Measure Description</th>
<th>Challenges Addressed</th>
<th>Likelihood</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand response projects</td>
<td>EI</td>
<td>67%</td>
<td>GE, UK, IE</td>
</tr>
<tr>
<td>Synchronous compensator</td>
<td>IAS, ESI, VFD</td>
<td>66%</td>
<td>IT, DK, ERCOT</td>
</tr>
<tr>
<td>Frequency criteria in forecast</td>
<td>VFD</td>
<td>64%</td>
<td>IE</td>
</tr>
<tr>
<td>Wind plants to provide reactive power</td>
<td>VFD</td>
<td>63%</td>
<td>ERCOT</td>
</tr>
<tr>
<td>Study grid stability and curtailment</td>
<td>VFD</td>
<td>61%</td>
<td>IE</td>
</tr>
<tr>
<td>Enlarge frequency to trip (PV and Wind)</td>
<td>VFD</td>
<td>60%</td>
<td>IT</td>
</tr>
<tr>
<td>Enabling demand to participate in the market</td>
<td>EI</td>
<td>59%</td>
<td>IT</td>
</tr>
<tr>
<td>Power Plant retrofitting</td>
<td>EI</td>
<td>58%</td>
<td>CN, DK, IE</td>
</tr>
<tr>
<td>Stability study to evaluate VRE integration</td>
<td>VFD</td>
<td>57%</td>
<td>Ireland</td>
</tr>
<tr>
<td>Wind forecast</td>
<td>EL, UV</td>
<td>55%</td>
<td>DK, IE, USA (ERCOT)</td>
</tr>
<tr>
<td>Real-time inertia monitoring</td>
<td>VFD</td>
<td>53%</td>
<td>ERCOT</td>
</tr>
<tr>
<td>Load resources for reserve requirements</td>
<td>VFD</td>
<td>52%</td>
<td>ERCOT</td>
</tr>
<tr>
<td>Incentives to Demand Response</td>
<td>EI</td>
<td>51%</td>
<td>DK</td>
</tr>
<tr>
<td>Regional Market</td>
<td>EI</td>
<td>49%</td>
<td>IE, DK</td>
</tr>
<tr>
<td>VRE have dispatch priority up to a given value</td>
<td>ITC</td>
<td>48%</td>
<td>China</td>
</tr>
<tr>
<td>Wind to participate in Regulation</td>
<td>EI</td>
<td>46%</td>
<td>DK, GE</td>
</tr>
<tr>
<td>Ensure VRE do not trip at a same frequency</td>
<td>VFD</td>
<td>44%</td>
<td>GE, IT</td>
</tr>
<tr>
<td>Transmission expansion</td>
<td>ITC</td>
<td>43%</td>
<td>GE, IT, UK, PT, CH, IE, ERCOT</td>
</tr>
</tbody>
</table>

### Most to less suitable measures based on country profile

**Challenges**

- **II** - Insufficient Interconnectors
- **EI** - Energy imbalance
- **IAS** - Insufficient Ancillary Services
- **IET** - Inefficient use of existing transmission lines
- **IF** - Insufficiency Flexibility
- **ITC** - Insufficient transmission capacity
- **IS** - Insufficient Storage
- **UV** - Unforeseen variability
- **ESI** - Ensure short-circuit power and Inertia

**Fictional Example, not related to any existing case**
Knowledge Framework – Assessment Flowchart (China)

Integration Challenges

- **Flexibility**
  - Incentives for generators to operate flexibly

- **Transmission**
  - Energy congestion throughout the grid

- **Operation**
  - Address current and potential voltage stability

Key measures applied in countries

- Brazil
- Denmark
- Germany
- Ireland
- Italy
- Portugal
- United Kingdom
- United States of America (ERCOT)

Assessment Flowchart

1. Identify challenges faced by country A
2. Identify measures applied in other countries to address such challenges
3. Filter measures by their applicability to country A
4. List of applicable measures
5. Methodologies and best practices for the implementation of the selected measures
6. Discussion with Member Country A on each identified measure
7. Support and advice for implementation
8. Any selected measures?
9. Yes → Enablers for each measure
10. No → New measures becoming available due to new enablers
Key Takeaways from identified Measures

- **Flexibility**
  - Include flexibility requirements in grid codes
  - Retrofitting may be instrumental under specific cases
  - Flexible sector coupling is essential, especially in countries with cold winters

- **Transmission**
  - Planning is critical
  - Grid capacity maps can signal suitable spots for VRE
  - DLR make the best use of existing assets
  - Ultra-High Voltage DC lines is a game changer but their implementation requires carefulness
  - Voltage stability may limit the capacity (active) of long transmission lines.

- **Storage**
  - Storage technologies can provide a variety of services, including FFR, and increase flexibility in the system

- **Demand Response**
  - Regulations and Markets should be adjusted to enable demand assets to provide flexibility.
Key Takeaways from identified Measures

• Interconnectors
  • Regional market facilitates the efficient use of interconnection assets

• Markets
  • The closer to real time the market is cleared the more precise are participant positions.
  • The highest the market resolution, the more efficient (less balancing), favoring flexible units.
  • Proper regulatory and market settings are essential to unlock flexibility.

• Operations
  • Accurate forecast has proven essential
  • Frequency and voltage response should be included in grid codes asap. Ramping limits may also be considered.
  • Reserve set dynamically may reduce reserve requirement and associated costs
  • Batteries’ role to provide very fast response is prone to increase as synchronous generators are displaced in power systems, especially together with grid forming inverters
  • Synchronous compensators have reduced the number of synchronous generators committed as technical must run by adjusting reactive power at strategic points in the grid and keeping a minimum amount of inertia at all times
Thank you!

Raul Miranda  
RMiranda@irena.org

Emanuele Taibi  
ETaibi@irena.org

www.irena.org  
www.twitter.com/irena  
www.facebook.com/irena.org

www.instagram.com/irenaimages  
www.flickr.com/photos/irenaimages  
www.youtube.com/user/irenaorg