On the Economics of Renewables

5th Atlantic Workshop on Energy and Environmental Economics

Toxa (Spain), 25 – 26 June 2012

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Brigitte Knopf, Michael Pahle, Eva Schmid, Falko Ueckerdt
Overview

1. Has global warming stopped?
2. Scope of the challenge
3. The role of renewables in mitigation scenarios
4. System integration from a technical perspective
5. System integration from a cost perspective
6. System integration from a market perspective
7. How to cure market failures
1. HAS GLOBAL WARMING STOPPED?
Has global warming stopped?

• Looking at last 10 years, global warming seems to have slowed down or even stopped.

• Has the IPCC made a major mistake?

• Is global warming real?
The influence of cutting the data!

- Multiple reasons for stable temperatures last decade:
  - “Slow down” last decades within natural variation
  - 1997/98 exceptionally warm due to El Nino
  - Cooling effect of increasing air pollution, particularly sulphur
    - Temperatures likely to increase once clean air policies are commissioned also in newly industrializing countries
- Looking at longer trends makes obvious that global warming has not stopped at all
Long term trends show clear evidence

- Temporal slow downs of global warming have occurred already in the past
- Recent independent examination of IPCC results (Berkeley Earth Surface Temperature Project) has confirmed results
2. THE SCOPE OF THE CHALLENGE
GHG emissions resulting from the provision of energy services contribute significantly to the increase in atmospheric GHG concentrations.

SRREN (IPCC, 2011)
We are not on Track – Renaissance of Coal!

Kaya decomposition of global CO2 emissions.

SRREN (IPCC, 2011)
Renaissance of Coal?

Prices of Energy Commodities
(U.S. dollars a barrel of oil equivalent)

- Asian liquefied natural gas
- U.S. gas
- Australian coal
- Oil

Source: IMF (2011)
The BAU Scenarios could exceed the Level of Greenhouse Gas Concentration of 600ppm (~4°C Temperature Increase)

SRREN (IPCC, 2011)
The Atmosphere as a Global Common

Atmosphere: Limited Sink
~ 230 GtC

Resource Extraction
> 12,000 GtC
3. THE ROLE OF RENEWABLES FOR MITIGATION
The Current Global Energy System is dominated by Fossil Fuels

Shares of energy sources in total global primary energy supply in 2008.

SRREN (IPCC, 2011)
Global RE Primary Energy Supply from 164 Long-Term Scenarios versus Fossil and Industrial CO₂ Emissions

SRREN SPM, Figure SPM.9

SRREN (IPCC, 2011)
Global RE Primary Energy Supply from 164 Long-Term Scenarios versus Fossil and Industrial CO$_2$ Emissions

2050

Renewable Primary Energy Supply [EJ/yr]

CO$_2$ Emissions from Fossil Fuels and Industrial Processes [Gt CO$_2$/yr]

CO$_2$ Concentration Levels
- Green: Category I (<400 ppm)
- Orange: Category II (400-440 ppm)
- Red: Category III (440-485 ppm)
- Blue: Category IV (485-600 ppm)
- Black dots: Baselines

N=164

2007

SRREN SPM, Figure SPM.9

SRREN (IPCC, 2011)
Global RE Primary Energy Supply from 164 Long-Term Scenarios versus Fossil and Industrial CO₂ Emissions

2050

CO₂ Concentration Levels
- Category I (<400 ppm)
- Category II (400-440 ppm)
- Category III (440-485 ppm)
- Category IV (485-600 ppm)
- Baselines

More RE

SRREN SPM, Figure SPM.9

SRREN (IPCC, 2011)
The Importance of RES depends on the Availability of other Options

- Without the availability of CCS, Renewables become more important

IPCC 2011
Macroeconomic Effect of Renewables

- without further deployment of Renewables costs increase for medium climate targets...
- ...and ambitious targets are not feasible any more
### Scenario Classification Matrix

<table>
<thead>
<tr>
<th>Modeling Approach</th>
<th>Costs Dimension</th>
<th>Energy System (Capacities, Fuels, Infrastructure)</th>
<th>System Integration (Grid, Storage, Backup)</th>
<th>Macroeconomy / Welfare (Factor Market Dist., Consumption Losses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>Partial Equilibrium</td>
<td>Recursive General Equilibrium</td>
<td>Dynamic General Equilibrium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lower flexibility</td>
<td>Less RES deployment potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario A</td>
<td>increasing scope</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Scenario B</td>
<td></td>
<td></td>
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<tr>
<td>Scenario C</td>
<td></td>
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</tbody>
</table>
4. SYSTEM INTEGRATION FORM
A TECHNICAL PERSPECTIVE
Numerical Limitations of Integrated Assessment Models

**Time resolution:**
Time steps of several years

\[ \rightarrow \] Fluctuations of renewables neglected

**Geographical resolution:**
Aggregate world regions

\[ \rightarrow \] Infrastructure neglected (e.g. grids)

**Technological challenge with large shares of fluctuating renewables:**

The electricity grid requires an exact match of supply and demand at **any time** and at **any place**.
# Integration characteristics for a selection of RE electricity generation technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Plant size range</th>
<th>Variability: Characteristic time scales for power system operation</th>
<th>Dispatchability</th>
<th>Geographical diversity potential</th>
<th>Predictability</th>
<th>Capacity factor range</th>
<th>Capacity credit range</th>
<th>Active power, frequency control</th>
<th>Voltage, reactive power control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioenergy</td>
<td>0.1–100 MW</td>
<td>Seasons (depending on biomass availability)</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>50–90</td>
<td>Similar to thermal and CHP</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>PV</td>
<td>0.004–100 MW</td>
<td>Minutes to years</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>12–27</td>
<td>&lt;25–75</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>CSP with thermal storage</td>
<td>50–250</td>
<td>Hours to years</td>
<td>++</td>
<td>+**</td>
<td>++</td>
<td>35–42</td>
<td>90</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Geothermal energy</td>
<td>2–100 years</td>
<td>Years</td>
<td>+++</td>
<td>N/A</td>
<td>++</td>
<td>60–90</td>
<td>Similar to thermal</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Hydropower Run of river</td>
<td>0.1–1,500</td>
<td>Hours to years</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>20–95</td>
<td>0–90</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Reservoir</td>
<td>1–20,000</td>
<td>Days to years</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>30–60</td>
<td>Similar to thermal</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Ocean energy Tidal range</td>
<td>0.1–300</td>
<td>Hours to days</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>22.5–28.5</td>
<td>&lt;10</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Tidal current</td>
<td>1–200</td>
<td>Hours to days</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>19–60</td>
<td>10–20</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Wave</td>
<td>1–200</td>
<td>Minutes to years</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>22–31</td>
<td>16</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Wind energy</td>
<td>5–300</td>
<td>Minutes to years</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>20–40 onshore, 30–45 offshore</td>
<td>5–40</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>

* Assuming CSP system with 6 hours of thermal storage in US Southwest.
** In areas with Direct Normal Irradiation (DNI) > 2,000 kWh/m2/yr (7,200 MJ/m2/yr)
Capacity credit is an indicator for the reliability of a generation type to be available during peak demand hours.

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<th>Capacity credit range</th>
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<td>Bioenergy</td>
<td>Similar to thermal and CHP</td>
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<tr>
<td>Direct solar energy</td>
<td></td>
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<tr>
<td>PV</td>
<td>[...]</td>
</tr>
<tr>
<td>CSP with thermal storage*</td>
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If a type of generation has a low capacity credit, the available output tends to be low during high demand periods.

IPCC 2011
### Integration Options for Renewables

- **Improved weather forecast**  
  → better planning of renewable electricity feed-in

- **Demand side management**  
  → adjust demand to renewable electricity feed-in

<table>
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<th>Flexible power plants</th>
<th>Important Supply Side Options</th>
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<tbody>
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<td>→ provide residual load</td>
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- **Grid extension**  
  → large area pooling of uncorrelated fluctuations (>300km): Import / Export between countries

- **Energy storage**  
  → remove electricity from the grid in times of high renewable generation and feed-in electricity in times of low generation
Impact of Considering Fluctuations in an Energy System Model of Germany

Most models do not take into account fluctuations explicitly:

- Nuclear
- Lignite
- Coal
- 100% Renewables
- PV
- Wind-offshore
- Wind-onshore
- Geo
- Bio & Hydro

Scenario: 80% domestic CO₂ emission reduction in 2050 vs. 1990

Mitigation Costs rise by 20% when considering the fluctuations of renewables!

(Ueckerdt et al., 2011)
Integration Options for Renewables

• **Improved weather forecast**
  → better planning of renewable electricity feed-in

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generation and feed-in electricity in times of low generation
Aggregated Transmission in 2050 in an Electricity Sector model of Europe

Baseline, no climate policy:

90% CO₂ reduction in electricity sector:

Haller et al., 2012
Deployment pathways are not linear

- Regime A (wind)
- Regime B (wind + solar)

Haller et al., 2012
Germany 2050: Electricity production with network expansion (European Interconnectors)

About 50% of demand covered by imports

Large capacities of natural gas power plants required, especially in winter

Scenario: 90% CO₂ emission reduction in electricity sector
Integration Options for Renewables

• **Improved weather forecast**
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Germany 2050: Electricity production without network expansion (Autarkic Germany)

Large storage capacities required

- Storage outflow
- Import
- Production

- Export
- Storage inflow

Large capacities of natural gas power plants required, especially in winter

Scenario: 90% CO₂ emission reduction in electricity sector

(Haller et al., 2012, Energy Policy)
Large back-up capacities of flexible gas power plants are required to provide residual load in extended times of low renewable electricity generation (European winter)…

…even with a European integrated electricity grid

…even with large day/night or medium-term storage capacities (e.g. pumped hydro)

What are the implications for the costs of renewables?
5. SYSTEM INTEGRATION FROM A COST PERSPECTIVE
The Costs of Renewables are often still higher than those of Non-Renewables but…

IPCC SRREN (2011)
...some RE Technologies are already competitive

- Small scale CHP (steam turbine)
- Binary cycle plant
- Domestic pellet heating system
- Palm oil biodiesel

IPCC SRREN (2011)
Learning-by-Doing

![Graph showing the relationship between average price and cumulative global capacity for different types of energy generation. The graph includes data points for 1976, 1984, 1981, 2010, and 2009, indicating significant decreases in average price over time. Key data points include:

- **1976**: [65 USD/W]
- **1984**: [4.3 USD/W]
- **1981**: [2.6 USD/W]
- **2010**: [1.4 USD/W]
- **2009**: [1.9 USD/W]

Legend:
- Blue diamonds: Produced Silicon PV Modules (Global)
- Red squares: Onshore Wind Power Plants (Denmark)
- Brown diamonds: Onshore Wind Power Plants (USA)]
What are the total costs of variable renewables (VRE)?

Total costs of variable renewables = Generation Costs (standard LCOE) + System Costs

Additional system costs can be crucial. LCOE indicator needs to be extended.
“System LCOE" cover the arguments of Joskow and Hirth from a cost perspective

<table>
<thead>
<tr>
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<th>Private perspective</th>
<th>System perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Standard LCOE</td>
<td>System LCOE</td>
</tr>
<tr>
<td><strong>Value/ Benefit</strong></td>
<td>VRE investor’s profits depend on price distribution (Joskow’s 2011)</td>
<td>Market value of VRE decreases with increasing shares (Hirth 2012)</td>
</tr>
</tbody>
</table>
System LCOE increase with higher share of variable renewables

- huge challenge with high shares: VRE LCOE increase due to curtailment

German data (2008), wind:solar=3:1,
No climate externality, no flexibility options
System LCOE increase with higher share of variable renewables

- huge challenge with high shares: VRE LCOE increase due to curtailment

<table>
<thead>
<tr>
<th>Share of variable renewables (%)</th>
<th>System LCOE (€ct/kWh)</th>
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German data (2008), wind:solar=3:1, No climate externality, no flexibility options
System LCOE increase with higher share of variable renewables

- huge challenge with high shares: VRE LCOE increase due to curtailment
- fossil system LCOE increase with VRE

German data (2008), wind:solar=3:1, No climate externality, no flexibility options
System LCOE increase with higher share of variable renewables

- huge challenge with high shares: VRE LCOE increase due to curtailment
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- these additional system costs are small (~10%) when added to VRE generation LCOE

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- these additional system costs are small (~10%) when added to VRE generation LCOE
- with variability: medium increase of VRE LCOE (for shares <50%, in Germany)

German data (2008), wind:solar=3:1, No climate externality, no flexibility options

System LCOE (€ct/kWh)

Share of variable renewables (%)
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- with variability: medium increase of VRE LCOE (for shares <50%, in Germany)
- total system LCOE increase with high shares of VRE
System LCOE increase with higher share of variable renewables

- huge challenge with high shares: VRE LCOE increase due to curtailment
- fossil system LCOE increase with VRE
- these additional system costs are small (~10%) when added to VRE generation LCOE
- with variability: medium increase of VRE LCOE (for shares <50%, in Germany)
- total system LCOE increase with high shares of VRE

- system implication fully considered
- social cost perspective → indicator for policy maker
- method not very simple → improve framework
Impact of Considering Fluctuations in an Energy System Model of Germany

Most models do not take into account fluctuations explicitly:

Same scenario with consideration of fluctuations:

Mitigation Costs rise by 20% when considering the fluctuations of renewables!

Scenario: 80% domestic CO₂ emission reduction in 2050 vs. 1990

(Ueckerdt et al., 2011)
6. SYSTEM INTEGRATION FROM A MARKET PERSPECTIVE
The Current Market System: Merit Order Pricing

Marginal Cost

Price without nuclear plants

Price with nuclear plants

Electricity demand

Capacity (performance)

Exit from nuclear energy

Marginal Cost

Price without replacement

Price with replacement

Electricity demand

Increasing penetration of renewables

Capacity (performance)
Wholesale Market Prices

Merit-Order effect of increasing shares of renewables: Decreasing power prices

(Knopf et al., 2011)
Wholesale Market Prices

Well designed capacity markets necessary?

Market design for integration of renewables?

- Uncertainty due to further development of exogenous drivers, e.g. gas price
- Uncertainty due to market design for renewables

Knopf, Pahle, Edenhofer (2012)
- Demand: Fluctuating, Supply: Conventional only
- Price set by marginal plant, mostly natural gas
- Avg. price close to marginal cost of natural gas plants
- High price span due to supply curve curvature
The Energy Transformation in Germany: Increasing Share of Renewable Energy in Electricity Generation

X: government target
• **RES** entering the market at zero marginal costs
  → Peaking plants and less efficient natural gas no longer needed: Plants **decommissioned**
  → Low **average price** reduces invest. incentive for **plants**
  → Low **price span** reduces invest. incentive for **storage**
• But: **Fluctuations** matter if share of RES is high!
  → “**Left shift**” of convent. supply if RES supply is low
  → Insufficient supply if demand is high at the same time
  → **Reliability/security of supply** endangered
Negative Spot Prices: Indicator for a Market Failure

![Graph showing negative spot prices]

- 2009 EEX day-ahead Spotmarkt [€]
- Stunden

- Histograms for 2009 EEX day-ahead Spotmarkt [€]
System Integration

- Challenge **long-term** scale: Delivering **adequate capacity**
  - Possible solution: **Capacity mechanism**

- Challenge **short-term** scale: Delivering **flexibility**
  - Possible solution: Storage, DSM, Grid, Plant flexibility

FAST: Flexibility Assessment Method (IEA 2011)
7. MARKET FAILURES – AND HOW TO CURE THEM
Externalities & Implied Policies along Innovation Chain

- **Applied R&D**
- **Basic R&D**
- **Demonstration**
- **Niche Markets**
- **Diffusion / Integration**

**Network / Coordination Ext.**
(e.g. building up supply chain)

**R&D Spillovers**

**Learning Spillovers**

**Information Ext.**
(e.g. cost uncertainties, imperfect capital market)

**Technology Push Policy**

**Market Pull Policy**

- **Externalities: Empirical evidence and relevance?**
- **Implications for RES support scheme design (FIT, CfD, TGC, Auction)?**

Source:
- Jaffe et al. (2005)
- Rodrik (2004)
- Fischer & Newell (2008)

Case 1: Carbon Pricing is necessary and sufficient

Edenhofer et al. 2007
Case 2: Additional Promotion of Renewables is *not* reasonable

► Several stable equilibrium points (PE3 and PE1) are possible if the supply curves show a non-convex behavior (PE2 is not stable).

► Without additional policy support, the system will steer towards the neighboring equilibrium point PE3.

► PE3 > PE1: the system is efficient.

Edenhofer et al. (2007)
The internalization of the social costs of energy supply (e.g. via a cap and trade system) improves the competitiveness of renewable energies.

As long as the cross-over point $PE_3$ does not vanish, this, however, still results in an inefficient state.

Edenhofer et al. (2007)
FROM MARKET FAILURES TO POLICY INSTRUMENTS
Robustness of Policy Instruments

Consumption losses relative to the 1st-best optimum of optimal and “close-to-be-optimal” instruments that deviate by $+1\%$ and $-1\%$ from the optimal value.

Kalkuhl, Edenhofer, and Lessmann 2012
2nd Best-Technology Policy

Welfare losses in BGE consumption losses [%]

Kalkuhl, Edenhofer & Lessmann 2011
http://srren.ipcc-wg3.de/report