Evaluating energy technologies against climate targets

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Today’s agenda

- Role of energy systems in climate change mitigation
- Evaluating energy technologies against climate targets
Lecture 2 outline: evaluating energy technologies

• Technology innovation dynamics

• Evaluating technologies against demand patterns
U.S. carbon intensity target


Trancik, Cross-Call, *ES&T*, 2013
Cost-carbon curve

- Coal
- Natural Gas
- Coal with CCS
- Nuclear Fission
- Wind
- PV
- Solar Thermal

2030 electricity target
2050 target

Levelized energy costs (USD$_{2010}$/GJ)

Trancik, Cross-Call, *ES&T*, 2013
Cost and carbon intensity of energy (electricity)
Change in energy technology costs over time

Trancik, Cross-Call, Energy technologies evaluated against climate targets, *ES&T* 2013
The cost of a technology can decrease for many reasons. One important reason is that producers gain experience ('learning') as they produce the technology. This experience leads to improved designs and cost decline. 

Wright's Law states that the cost of a technology will fall with its level of deployment according to a 'power-law' formula. The percentage decrease is a number that varies between technologies, for example due to differences in technology design characteristics, and is usually measured from historical data. Technologies that are modular and small-scale may improve more quickly, though a wide variety of other factors also affect the rate of deployment of a technology. The percentage decrease is associated with a fixed percentage decrease in its cost. The percentage decrease is taken from IPCC AR5 WGIII, IRENA 2015, EIA 2015, and World Energy Council 2013. 

What is important is that the act of deploying the technology itself is what helps lower costs. However, experience is not the only important mechanism; costs are clearly driven down for other reasons as well. Scale economies yield cost reductions from increasing the scale of manufacturing, and work independently of accumulated production experience. 

It is evident that many technologies improve with time and experience. A striking fact about this improvement is that it is, to a large extent, predictable. A long-recognized observation known as Wright's Law states that the cost of a technology will fall with its level of deployment according to a 'power-law' formula. 

Figure 2.7: Determinants of technology cost reduction and implications for emissions.
Determinants of the rate of technology innovation

Are technology costs changing in regular ways?

If so, what equations describe these changes?

How might costs change in future?
Performance curves

\[ c(x) \sim x^{-\alpha} \]

\[ PR = 2^{-\alpha} \]

<table>
<thead>
<tr>
<th>Series</th>
<th>Years</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal plants</td>
<td>1902–2006</td>
<td>( 6.1 \times 10^6 ) – ( 3.1 \times 10^8 ) kW</td>
</tr>
<tr>
<td>Ethanol</td>
<td>1980–2004</td>
<td>( 3.4 \times 10^6 ) – ( 2.7 \times 10^8 ) m³</td>
</tr>
<tr>
<td>PV cells</td>
<td>1975–2003</td>
<td>( 5.4 \times 10^2 ) – ( 2.2 \times 10^6 ) kW</td>
</tr>
<tr>
<td>Transistors</td>
<td>1968–2005</td>
<td>( 2.0 \times 10^9 ) – ( 1.1 \times 10^{19} )</td>
</tr>
</tbody>
</table>

Evaluating competing models

Moore's yearly price history

Wright's experience curve

Goddard's opportunity curve

Moore's prediction errors

Wright's prediction errors

Goddard's prediction errors

Moore's forecast for Photovoltaics2

- exponential trend projection
- expected forecasting error

Limits to tech improvement: commodity cost floors

Technology design and rate of improvement

\[ c(x) \sim x^{-\alpha} \]

\[ \alpha \sim \frac{1}{d} \]

d=number of component dependencies; n=number of components

McNerney, Farmer, Redner, Trancik, PNAS, 2011
Forecasting cost improvement under Paris pledges

Figure 4.8: Comparison between PV LCOE projections and LCOE of fossil-fuel-fired generation. 

Projections for global average LCOE of PV compared to current estimates of the LCOE of coal and natural gas combined cycle (NGCC), coal and NGCC with carbon capture and sequestration (CCS), and coal and NGCC with a $100/t CO₂ carbon tax. Red triangles represent maxima; black circles represent central estimates; blue triangles represent minima. A range of estimates of the external costs of air pollution for these different electricity sources, added to their LCOE, are shown as empty boxes for PV and empty symbols for coal and NGCC. 

Projections for the LCOE of PV in the United States compared to current estimates of the LCOE of coal and NGCC in the United States. Projections for the LCOE of PV in China compared to current estimates of the LCOE of coal in China. External costs from air pollution are estimated by combining emission factors from ecoinvent with cost factors from. External costs from causes other than air pollution are not considered in these estimates. More details on external cost calculations are provided in the Appendix.

Forecasting cost improvement under Paris pledges

Evaluating technologies against demand patterns

- Stationary energy storage
- Electric vehicles
Evaluating stationary storage technologies

Texas
Spring

Solar Out
Wind Out
Solar Gen
Wind Gen
Price

MW/MW Installed

Days

0 1 2 3 4

Balancing the cost and benefit of storage

• Value of energy storage

\[ \chi = \frac{R_{\text{total}}}{C_{\text{gen}} + \dot{E}_{\text{max}}(C_{\text{power}} + hC_{\text{energy}})} \]

annualization factor

wind, solar cost

storage power

storage cost

hours

annual revenue

• Storage system sized to maximize chi

Evaluating stationary storage technologies

Evaluating technologies against demand patterns

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- Electric vehicles
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