Experience curves as policy tool
The case of PV

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Contributions by Project Partners: GENEC (F), FhG-ISE (D), ISET (D), UU-STS (NL), CESI (I), ECN Solar Energy (NL)

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Photex

• General objective
  – to further develop experience curve approach as a policy and analysis design tool

• Specific objectives and characteristics
  – focus on one technology and its components (PV)
  – study the effects of different policy schemes on technology progress
  – advise on a right balance between R&D and D&D spending
  – analyse sources and mechanisms of technology learning
PV has experienced a very fast growth over recent years

Cumulative module shipments (MWp) (Maycock, 1990-2000)

<table>
<thead>
<tr>
<th>Year</th>
<th>Growth rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>35%</td>
</tr>
<tr>
<td>1987</td>
<td>27%</td>
</tr>
<tr>
<td>1988</td>
<td>24%</td>
</tr>
<tr>
<td>1989</td>
<td>23%</td>
</tr>
<tr>
<td>1990</td>
<td>22%</td>
</tr>
<tr>
<td>1991</td>
<td>21%</td>
</tr>
<tr>
<td>1992</td>
<td>18%</td>
</tr>
<tr>
<td>1993</td>
<td>16%</td>
</tr>
<tr>
<td>1994</td>
<td>16%</td>
</tr>
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<td>1995</td>
<td>15%</td>
</tr>
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<td>1996</td>
<td>15%</td>
</tr>
<tr>
<td>1997</td>
<td>19%</td>
</tr>
<tr>
<td>1998</td>
<td>20%</td>
</tr>
<tr>
<td>1999</td>
<td>21%</td>
</tr>
<tr>
<td>2000</td>
<td>25%</td>
</tr>
<tr>
<td>2001</td>
<td>27%</td>
</tr>
</tbody>
</table>

Module Shipments (Maycock, 1990-2001)

<table>
<thead>
<tr>
<th>Year</th>
<th>Growth rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>19.1%</td>
</tr>
<tr>
<td>1991</td>
<td>4.5%</td>
</tr>
<tr>
<td>1992</td>
<td>5.2%</td>
</tr>
<tr>
<td>1993</td>
<td>14.0%</td>
</tr>
<tr>
<td>1994</td>
<td>11.8%</td>
</tr>
<tr>
<td>1995</td>
<td>14.2%</td>
</tr>
<tr>
<td>1996</td>
<td>42.0%</td>
</tr>
<tr>
<td>1997</td>
<td>23.1%</td>
</tr>
<tr>
<td>1998</td>
<td>30.0%</td>
</tr>
<tr>
<td>1999</td>
<td>42.9%</td>
</tr>
<tr>
<td>2000</td>
<td>35.8%</td>
</tr>
<tr>
<td>2001</td>
<td>35.8%</td>
</tr>
</tbody>
</table>
What progress ratio do we need?

Effects of different progress ratios on break-even costs and cumulative production (Van der Zwaan and Rabl, 2002)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>23</td>
<td>0.7%</td>
<td>15</td>
</tr>
<tr>
<td>0.75</td>
<td>48</td>
<td>1.5%</td>
<td>27</td>
</tr>
<tr>
<td>0.8</td>
<td>148</td>
<td>4.5%</td>
<td>64</td>
</tr>
<tr>
<td>0.85</td>
<td>957</td>
<td>29%</td>
<td>288</td>
</tr>
<tr>
<td>0.9</td>
<td>39700</td>
<td>1200%</td>
<td>7110</td>
</tr>
</tbody>
</table>

Assumptions: Current costs $5/Wp; break-even costs $1/Wp (implies kWh cost of 0.05 – 0.01 $/kWh); initial cumulative production is 1 GWp

Progress ratio should be between 0.75 and 0.8?
First progress ratio results from Photex

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (kWp)</th>
<th>Cost (€/Wp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>2002</td>
<td>6.4</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>2000</td>
</tr>
</tbody>
</table>

PR = 88%
# Systems in Germany

(Source: ISET)

<table>
<thead>
<tr>
<th>Timeframe</th>
<th>Progress Ratio</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988-2001</td>
<td>94%</td>
<td>Current Photex</td>
</tr>
<tr>
<td>1990-2001</td>
<td>91.6%</td>
<td>Photex price + general capacity data</td>
</tr>
<tr>
<td>1991-2001</td>
<td>93%</td>
<td>ISET</td>
</tr>
</tbody>
</table>
IEA-PVPS, Task 1

Capacity between 1992 and 2001 grown 5 times;
Prices from about 10 $/kWp to 7 $/Wp;
Progress ratio 93%
(Preliminary) intermediate conclusion

- To keep costs and deployment efforts to a reasonable level, the PV-progress ratio should not be higher than 80%.
- Current PV-systems progress ratio seems to be slightly above 90%.
- **Current progress ratio PV-Systems seems to be too high!**
  - if price developments reflect cost developments!
Precautions to the conclusion

• Do price developments reflect cost developments?
• It has been difficult to gather a substantial amount of reliable data. Monitoring activities such as done in IEA-PVPS is therefore essential and should be intensified!
Do costs reflect prices?

Cumulative production

Cost or prices in logarithmic scale

Normal price development

PV-case?
(small sector led by giant companies?)
Photex data: Database overview: status December 2002 (Source UU-STS)
Photex data: System cost data
(Source UU-STS)

System cost (Euro-2000/Wp)

- P<3 kWp (N=1180)
- 3<P<10 kWp (N=665)
- P>10 kWp (N=35)
Photex data: increasing the database

- Projects before 1990 (possibly via EU-DGTREN)
- Module data: Strategies Unlimited report
- Incorporating IEA-PVPS Task 2 data
Differences in BOS and module learning in past decade

• Module prices have come down slightly
• BOS prices have come down substantially
Module prices
(Source UU-STS)

An increase since 1999
BOS prices in Germany
(Source ISET)

BOS cost experience curve
(Residential systems in Germany, 1992-2000)

PR = 0.78
$r^2 = 0.87$
BOS prices Photex database
(Source UU-STS)

![BOS cost graph](chart.png)

- **P<3 kWp (N=17)**
- **3<P<10 kWp (N=13)**
- **P>10 kWp (N=28)**
BOS is learning fast, especially in Germany  
*(Source: FhG-ISE)*

### Cost distribution of residential PV systems (1999/2002)

<table>
<thead>
<tr>
<th>System size</th>
<th>1 kWp</th>
<th>5 kWp</th>
<th>2 kWp</th>
<th>3 kWp</th>
<th>5 kWp</th>
<th>50 kWp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Euro</td>
<td>%</td>
<td>Euro</td>
<td>%</td>
<td>Euro</td>
<td>%</td>
</tr>
<tr>
<td>modules</td>
<td>4000</td>
<td>48</td>
<td>3800</td>
<td>56</td>
<td>4100</td>
<td>68</td>
</tr>
<tr>
<td>inverter</td>
<td>1100</td>
<td>13</td>
<td>900</td>
<td>13</td>
<td>650</td>
<td>11</td>
</tr>
<tr>
<td>mounting structure,</td>
<td>1400</td>
<td>17</td>
<td>1100</td>
<td>16</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>installation material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>installation labour</td>
<td>1270</td>
<td>15</td>
<td>780</td>
<td>11</td>
<td>650</td>
<td>11</td>
</tr>
<tr>
<td>planning,</td>
<td>500</td>
<td>6</td>
<td>250</td>
<td>4</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>documentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total [Euro]</td>
<td>8270</td>
<td>6830</td>
<td>6000</td>
<td>5800</td>
<td>5500</td>
<td>&lt; 5000</td>
</tr>
</tbody>
</table>

• Similar trends e.g. in NL and US: the result of reaching a critical mass in volume sales!
Relative cost distribution of residential PV systems-installer in Germany

(Source: FhG-ISE)
Sources of BOS cost reduction in Germany
(Source: FhG-ISE)

• Standardisation
  – 2 kW standard mounted roof system has lowest installation costs in Germany
    • standardised planning procedures
    • standardised mounting procedures
    • standardised material
    • installation knowledge widespread also to low-cost personnel

• Further reduction in BOS possible, expected and needed
  – inverters (volume)
  – DIY-kit for installation
  – further (small) innovations and learning
Questions with regard to BOS-costs

• Is BOS-learning local or global in character?
  – Inverter part is at least (partially) international market
    • Several manufacturers deliver inverters to several countries in Europe
    • Different national standards for dealing with islanding
    • Different national standards for connectors
  – Differences in building norms and practices and policy result in non-ideal spill-over effects between countries
    • e.g. mounted roof systems versus building integrated PV

• Positive effect on costs expected from more EU-wide harmonisation on standards and policy
How to reduce module prices?

• Observations
  – Module prices have come down barely during the last 5 years
  – Module prices constitute 70%-80% of system prices

• Uncertainties
  – Have module costs come down?
  – Are module producers still not making a profit?
Latest news on module price developments (Source: solarbuzz.com)
Cost Break Down x-Si (90% of market)

(Note: Direct manufacturing cost do not include overhead such as R&D, Sales, Maintenance and Staff Departments)
Analysis of cost reduction x-Si

Wafer cost

Feedstock 30% Scrap from IC Industry
20 - 30 €/kg Fluctuating
Independent supply needed
=> 15 - 20 €/kg Si (mg Si 2 $/kg)
Silicon content 2000 17 g/Wp
2010 10 g/Wp
sheets (EFG, RGS), wafer thickness
Crystallisation cast, sheets
Wafering
Si feedstock for PV: supply and demand
(Source: ECN Solar Energy)
Analysis of cost reduction x-Si

Cell Processing
Labour, Equipment
Efficiency, (yield, uptime)
Plant size

Efficiency 12-14% → 15-18%
2000 2010

Plant Size 1990 1 - 5 MWp 50 MWpa
2000 10 - 25 MWp 300 MWpa
2010 25 - 100 MWp 2 GWpa
Analysis of cost reduction x-Si

Effect of Plant Size on Price

ECU'96/Wp

MWp/Year

Source, Alonso et al., 1995 (Music-FM study)
Analysis of cost reduction x-Si

Module Assembly
Materials, Labour

Yield

Scale-up
Laminates
New encapsulants
Back contact cells

Maycock 2000

$0.86

Module Assembly

Depreciation
Yield Losses
Labor
Materials
Some conclusions

- PV-systems prices do not go down fast enough
- PV-BOS prices have come down very fast, especially in high volume markets
- PV-BOS prices still need to come down further
- Module prices make up 70%-80% of systems and need most focus for cost reduction efforts
- Material costs most important part of module costs
- Building up an own feedstock production is absolutely necessary for PV-industry
- Insecure relationship with ICT-industry will remain: needs more analysis
Implications for policy: how to get progress ratio back on track?

- Progress ratio is a statistical correlation between costs (prices) and cumulative production as a result of a learning process
- Progress ratio can be enhanced by
  - Establishing a better balance between R&D and deployment efforts
    - Enhancing R&D-efforts on PV
    - Ensuring a healthy growth rate of PV
      - Too fast: what is learned cannot be implemented timely in practices of production and use, resulting in prohibitive progress ratio
      - Too slow: learning process stops or reverses (e.g. BOS-learning experience shows learning needs minimum critical mass)
  - Improvement of the learning process itself
    - analyse the learning process
    - improve learning feed-back loops and geographical spill-over
Improving the learning cycle for PV: a first try to describe it
(Source: *UU-STS*; with a few additions from ECN PS)

**Dynamic model of PV technology investments and learning**

- **Public R&D funding** → **R&D efforts** → **Learning by searching** → **PV system production** → **PV system purchase & installation** → **PV system operation** → **Energy output / CO2 reduction** → **Learning by doing** → **Stock of technological know-how**

- **Private R&D funding**

- **PV industry profits**

- **Public expenditure**

- **Private expenditure**

- **R&D efforts**

- **PV system production**

- **PV system purchase & installation**

- **PV system operation**

- **Learning by using (local?)**

- **Energy output / CO2 reduction**

- **Capital investments in production facilities**

- **Energy + material input / CO2 emissions**

- **Labour**

- **Learning by doing**

- **Material, energy, labour**

- **Money**

- **Information**
In conclusion

• The case of PV demonstrates the importance of an experience curve approach to policy analysis and design
  – shows need for *combined* RD&DD efforts
    • most substantial cost reduction in BOS by learning by doing induced by aggressive deployment strategies
  – shows need for *balanced* RD&DD efforts
    • If DD gets over R&D too much, it effects progress ratio negatively, to an extent cumulative costs become prohibitive.