Drivers for progress in PV based on LCOE simulations – past, present & future

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Objective

The aim of this work was to analyse whether it is possible to predict future developments in photovoltaics based on the analysis of LCOE. Starting from a retrospective view, a look into the future is taken.
Outline

Stages of the PV industry

- Beginning of industrialization
- Beginning of mass production
- Mass production and technology maturity

1990 2000 2010 2020 2024

What comes next?
Phase 1: Beginning of industrialization
LCOE calculation

The intention of analysing the LCOE in this presentation is to predict trends over longer periods.

**Assumptions:**
Reference system size 1kWp
Location central Europe (Switzerland)
Yearly in-plane irradiation (optimized tilt angle and azimuth): 1346 kWh/m²
Specific energy yield (first year): ~1091 kWh/kWp (no shading)

Differentiation between area- and non-area related cost:

\[ I_o(\eta) = I_o(\eta_0) - \left(1 - \frac{\eta_0}{\eta}\right)I_{0\text{,area}} \]

=> Reduction of area related investment cost with increasing efficiency

Example: \( \eta_0=16\% \)
Increasing \( \eta \) to 32\% would lower the area related cost 50\%
Investment for area is included in the calculation

A linear degradation was assumed
Phase 1: Beginning of industrialization
The 90s

Learning curve for module price as a function of cumulative shipments

Module price ~ 10 USD/Wp

Total annual production capacity below 225 MWp c-Si (>70% of the market)

 Biggest producers Siemens, Kyocera, BP Solarex

Source: ITRPV Roadmap
https://www.vdma.org/international-technology-roadmap-photovoltaic
Phase 1: Beginning of industrialization
The 90s

PV system costs (3 kWp system)

System price ~15 USD/Wp
Module price ~10 USD/Wp
=> 75% cost for module
=> 25% BOS

Source:
TY - BOOK
AU - Anderson, Jason
AU - Bassi, Samuela
AU - Stantcheva, Emilia
PY - 2006/10/04
SP -
T1 - INNOVATION CASE STUDY: PHOTOVOLTAICS
Phase 1: Beginning of industrialization
The 90s - LCOE

20 years lifetime, 1% linear degradation, module price
$TF = 0.5 \times C\text{-}Si$, $I_0 = 15000 \text{ USD}$, $A_t = 1.3\%$ of $I_0$, $i = 4\%$

Conclusion
A reduction of USD/Wp of the module was the driver for lowering the LCOE

Area related components of the system (sub-construction, …) represent a small proportion of the total costs

A thin film or ribbon-based technology saving 50% of module cost would be winner, “no matter” at which efficiency level

Module lifetime and degradation were not the focus of customers
Phase 1: Beginning of industrialization
The 90s

c-Si
Cell size 10 x 10 cm²
Industrial solar cell efficiency 13 - 18%
Si technology: Ag backside metallization => Al backside, Al-BSF
TiO₂ ARC => SiN ARC and front side passivation (end 90s)

a-Si
Efficiencies < 10%
Phase 1: Beginning of industrialization
The 90s

Two main drivers for reducing USD/Wp of the module

a) Cost reduction of the module or

b) Enhancement of Wp
Phase 1: Beginning of industrialization
The 90s- major research topics

a) Lowering the cost of the module (USD/Wp)

Ribbon technologies (huge research effort):

<table>
<thead>
<tr>
<th>Wafer process/year started</th>
<th>1990</th>
<th>2000</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Status</td>
<td>Level</td>
<td>Status</td>
</tr>
<tr>
<td>EFG/1971</td>
<td>Pilot</td>
<td>1.5MW</td>
<td>Production 12MW</td>
</tr>
<tr>
<td>Dendritic Web/1967</td>
<td>R&amp;D</td>
<td>&lt;0.1MW</td>
<td>R&amp;D &lt;0.2MW</td>
</tr>
<tr>
<td>String Ribbon/1980</td>
<td>R&amp;D</td>
<td>–</td>
<td>Pilot &lt;0.5MW</td>
</tr>
<tr>
<td>Silicon Film/1983</td>
<td>R&amp;D</td>
<td>–</td>
<td>Pilot 1–2MW</td>
</tr>
<tr>
<td>RGS/1983</td>
<td>R&amp;D</td>
<td>–</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>

Target: Reducing cost for the solar cell by saving the cost for wafer dicing & kerf loss

Challenges: material quality, yield

None of these technologies survived

Last approach 1366 technologies
Phase 1: Beginning of industrialization
The 90s- major research topics

b) Enhancement of Wp

Technical improvements c-Si technology:

SiN-ARC, (H-pass)  AI-BSF  mc-Si texturing
Phase 1: Beginning of industrialization
The 90s- major research topics

b) Enhancement of Wp

- Buried contact solar cells (UNSW) - BP Solar
- Copper contacts, heavy diffusion in the contact area, LPCVD nitride ARC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jsc (mA/cm²)</td>
<td>36.28</td>
</tr>
<tr>
<td>Voc (mV)</td>
<td>625.1</td>
</tr>
<tr>
<td>FF</td>
<td>806</td>
</tr>
<tr>
<td>Eff. (%)</td>
<td>18.3</td>
</tr>
<tr>
<td>Area (cm²)</td>
<td>147.5</td>
</tr>
</tbody>
</table>

Source: Stuart R. Wenham and Martin A. Green 1988
Source: https://www.pveducation.org


12.04.2024, Prof. Dr. Hartmut Nussbaumer, SPREE Seminar
Phase 2: Beginning of mass production
2000 – 2010 LCOE

Module price 7 USD/Wp => 0.8 USD/Wp

For the LCOE calculations:
C-Si: $I_0 \sim 4000 - 5000$ USD
TF: $I_0 \sim 3000$ USD

$A_t = 1\% \, \text{of} \, I_0$

$i = 4\%$

Yearly degradation 1\%
Phase 2: Beginning of mass production
2000 – 2010 LCOE

- Thin film modules are of interest, because of the lower USD/Wp potential, however only with similar lifetimes and degradation! => a-Si hype, CdTe

- A change in the perspective from USD/Wp to USD/kWh started, however still module counted for around 50% of the system cost and therefore reduction of USD/Wp remained the biggest driver for lowering LCOE

- High efficiency modules were restricted to high quality residential & niche markets
Phase 2: Beginning of mass production
2000 - 2010

2000: Renewable Energy Sources Act or EEG in Germany (Favourable loans & fixed feed in tariffs for 20 years) => strong market push, module lifetime Q-Cells, Solarworld,… in Europe

Cell sizes 12.5 x 12.5 cm² and 15.6 x 15.6 cm²
Industrial solar cell efficiencies 16-22.4% (SunPower, IBC)

~2004 Beginning production in China
(technology transfer centrotherm, Roth&Rau, Meyer Burger, Schmid)

Thin film technologies:
First Solar CdTe, a-Si hype with Oerlikon and Amat
Phase 2: Beginning of mass production 2000 - 2010

C-Si
Reduction of USD/Wp due to increased wafer size for higher productivity 156 x 156 mm$^2$ (M0)

Al-BSF c-Si solar cell

Approaches to increase efficiency
- Selective emitter
- Fine line screen printing & paste improvement
- Laser opening ARC and plating

https://www.hahn.uni-konstanz.de/en/research/research-groups/process-technology/
Phase 2: Beginning of mass production
2000 - 2010

Silicon feedstock shortage, foreseen end of 90s

Source: Solar grade silicon feedstock supply for PV industry
Peter Woditsch a, *, Wolfgang Koch

Source: ITRPV Roadmap
https://www.vdma.org/international-technology-roadmap-photovoltaic
Phase 2: Beginning of mass production
2000 - 2010

- Disruptive technology changes were not the strong driver
- Continuous improvements and economy of scale resulted in significant reduction of USD/Wp on the module level
- The silicon shortage resulted in a module price increase and slowed down the market development
Phase 3: Mass production and technology maturity 2010-now

Module prices below 1 USD/Wp

Current market prices 0.11 USD/Wp (depending on technology, wholesaler prices)

Source: ITRPV Roadmap
https://www.vdma.org/international-technology-roadmap-photovoltaic
Phase 3: Mass production and technology maturity 2010-now

Fraunhofer ISE: LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES JUNE 2021

LCOE calculation
2024: module USD/kWp
I₀ = 750 USD/kWp
Aᵣ = 1% of I₀
i = 1%

CAPEX | PV rooftop small (≤ 30 kWp) | PV rooftop large (> 30 kWp) | PV utility-scale (> 1 MWp) |
---|---|---|---|
Unit | [EUR/kWp] | [EUR/kWp] | [EUR/kWp] |
2021 low | 1000 | 750 EUR/kWp | 530 |
2021 high | 1600 | 1400 EUR/kWp | 800 |
Phase 3: Mass production and technology maturity 2010-now

The economy of scale in production of silicon solar modules and the resulting cost reduction led to the disappearance of a-Si modules on the market.

Higher efficiency modules can further reduce the LCOE but on an already low level (only if degradation levels and lifetimes can be kept at a similar level).
Degradation rate has a much higher sensitivity on LCOE compared to efficiency. Even for constant area cost of the tandem module with a 9% absolute higher efficiency the LCOE is not lower if the degradation rate is 2% instead of 0.4%.
Phase 3: Mass production and technology maturity
2010-now

Assuming same cost of USD/Wp for c-Si and tandem.
~0.5 cent/kWh per ~10% η
~0.5 cent/kWh per 1% deg
=> ~10% η-gain abs. can be lost by a +1% degradation
=> The tandem technology can only be competitive when achieving similar low degradation rates compared to c-Si technologies
=> An η-increase of 6% absolute at same USD/Wp module cost would tolerate a 0.7% higher degradation rate (20 years lifetime)
Phase 3: Mass production and technology maturity 2010-now

5.2% $\eta$ per 1% deg. at no additional cost for higher efficiency, cost of 2021

$=>$ we are much more sensitive to degradation now

Allowance of ~2$ per cell additional cost for 32% tandem

$=>$ LCOE comparable to PERC

Baseline cell: 244cm², 22.5%, 0.26 $/Wp on module level

Lifetime second highest sensitivity after irradiance


Phase 3: Mass production and technology maturity 2010-now

Since the implementation of PERC into mass production technology progressed fast - typical roadmap of a tier 1 producer

Technical Roadmap: Development trend

Limits for single junction c-Si

HJ is gaining interest, bifacial modules are established

Maybe a roadmap for lowering degradation and enhancing lifetime would make a lot of sense?

Johanna Bonilla, Challenges & Experiences in Scaling up TOPCon n-Type Manufacturing
Phase 4: What comes next?
Status quo

- c-Si single junction technology full potential reached
- In some regions PV cheapest source of electric energy
- Degradation and lifetime of the modules is of high sensitivity for LCOE
- Sub-construction, labour cost for installation and cost for area represent an increasing cost share
- Time dependent value of energy during the day and seasonal dependence

https://energy-charts.info/charts/power/chart.htm?l=en&c=DE&year=2023&week=23
Phase 4: What comes next?

One direction: obvious

**Higher efficiencies** – tandem, multi-junction solar cells, up- & down conversion

Target: Lowering LCOE by increasing kWh- or even USD/Wp?

Only if long term stability is proven and the technology is bankable (how long will it take?)

Avoidance of shortages (Ag)

Research on long term stability and degradation mechanisms for the latest products

Increasing the energy yield per ground or roof area ✨

Multiple use of land and building- PV and green roof, Agri PV, BIPV ✨

Producing energy when there is a lack of energy, controlling of the power output over the day (tracking systems) ✨
Phase 4: What comes next?
Increasing the energy per ground or roof area

Typical system on a flat roof: Highest GCR

Is there a way to further increase the energy yield, lower LCOE or create higher revenues?
Phase 4: What comes next?
Increasing the energy per ground or roof area

- **a) Simple HSAT systems**
- **b) Ground Sculptures**
- **c) Dynamic reflectors**
Phase 4: What comes next?
Increasing the energy per ground or roof area
a) HSAT on roofs?

Power simulation

High GCR!

Simple «Flip-Flop»-Tracker?

Tracking angles of -10° in the morning until 10 am
0° from 10am to 2pm
+10° starting from 2pm
Phase 4: What comes next?
Increasing the energy per ground or roof area
a) HSAT on roofs?

Yearly specific energy yield simulation using for Winterthur, Switzerland

For same GCR simple tracking systems can achieve higher energy yields

More information: see upcoming EUPVSEC 2024
Phase 4: What comes next?
Increasing the energy per ground or roof area
b) Ground Sculptures?

Results of Khan et. al.
For regions with low annual mean-clearness index and high latitudes GvBF design is resulting in superior annual yield per area compared to a south orientated monofacial system.

Phase 4: What comes next?
Increasing the energy per ground or roof area
b) Ground Sculptures?

⇒ GvBF reveals higher yields compared to mono south for overcast days

\[ 1 \leq \frac{E_{GvBF}(\text{day})}{E_{vBF}(\text{day})} \leq 1.17 \]

1.13 Daily yield ratio GvBF/mono

⇒ There is a higher yield in partly cloudy days, where in future the price for electricity is higher

More information available: H. Nussbaumer et al. Comparative energy yield study of vertically installed bifacial PV modules measured by a miniturized test rig, 38th EUPVSEC, 2021
Phase 4: What comes next?
Increasing the energy per ground or roof area
c) Dynamic movable reflectors

- At up to three sides of a system. Here 3x module height. Center modules.
- E/W reflector-change dependent on time. North fix. Also for non-vertical

Effect here ~ + 30 %!
Phase 4: What comes next?
Multiple use of land and building

Green roof
- Water retention
- Additional building insulation
- Cooling of the building / urban heating
- Air humidification
- Enhancement of bio diversity

Photovoltaic roof
- Generation of renewable electrical energy
Phase 4: What comes next?
Multiple use of land and building

Vertical bifacial modules
GCR 0.5, Green roof area 100%

Modules under low tilt angles
GCR 0.5, Green roof area 50%

GCR 0.5, Green roof area >50%

GCR 1, Green roof area 100%

GCR 1: No green roof

GCR 1 Green roof area?

Increased self-shading

No self-shading

Increased self-shading
Phase 4: What comes next?
Multiple use of land and building

- Dense arrangements of vertically orientated bifacial modules have been analysed in order to optimize the energy generation while maintaining the green roof character (minimizing the area covered by modules)

- The energy yield **per area** can reach comparable values to those of systems with modules under low tilt angles

More information available:

Phase 4: What comes next?
Multiple use of land and building- Agrivoltaics

https://www.bmel.de/DE/themen/landwirtschaft/klimaschutz/Agri-PV.html

Phase 4: What comes next?
Multiple use of land and building- Agrivoltaics

Phase 4: What comes next?
Producing energy when there is a lack of energy

Slanted S/N

Vertical E/W

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H. Nussbaumer, Swiss PV conference 2019
Phase 4: What comes next?
Controlling of the power output over the day

HSAT systems could be used for controlling the energy output. Concerning lowest LCOE they compete with systems using higher GCR like 5B

https://www.arctechsolar.us/china/

https://5b.co/projects/happy-valley
Summary & conclusion

LCOE analysis help to predict future developments

However, LCOE analyses alone cannot predict the whole range of developments. PV in combination with further utilisation of the area will be important in the future.

LCOE is very sensitive on degradation and system lifetime
~10% η-gain absolute can be lost by a +1% degradation
An efficiency increase of 6% absolute at same USD/Wp module cost would tolerate a 0.7% higher degradation rate (20 years lifetime)

Understanding and lowering degradation should be major task in research
Acknowledgement

Thank you for allowing me to work here at SPREE in such a wonderful, friendly environment.

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Thanks also to my colleague Roger Hiltebrand, who wrote a Matlab program for the LCOE simulations and all other colleagues Markus Klenk & Selina Pfyffer

Thanks to my school ZHAW for supporting this research stay

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*PV systems on flat roofs with highest energy yields per area, SI/502309-01*

*Development and comparative test of a complete solution for bifacial PV systems on green roofs, SI/502213-01*
Thank you for your attention!