Highly efficient multi-junction solar cells using silicon heterojunction and perovskite tandem: prospective life cycle environmental impacts

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Sustainability assessment of 3rd generation photovoltaics

Ecological Life Cycle Assessment

Social Life Cycle Assessment
Social acceptance

Environment

Social

Economics

Levelised cost of electricity (LCOE)
Cost of ownership (CoO)
Highly efficient 3rd generation tandem solar cells (1)

Best Research-Cell Efficiencies

- Multijunction Cells (2-terminal, monolithic)
- Thin-Film Technologies
  - CIGS (concentrator)
  - CIGS
  - CdTe
  - Amorphous Si:H (stabilized)
- Emerging PV
  - Dye-sensitized cells
- Perovskite cells (not stabilized)
- Organic cells (various types)
- Inorganic cells (CZTSSe)
- Quantum dot cells

Crystalline Si Cells
- Single crystal (concentrator)
- Single crystal (non-concentrator)
- Multijunction
- Silicon heterostructures (HIT)
- Thin-film crystal

Single-Junction GaAs
- Single crystal
- Concentrator
- Thin-film crystal

Multijunction Cells (3-terminal, monolithic)
- LM = lattice matched
- MM = mismatched
- IM = inverted, metamorphic
- Three-junction (concentrator)
- Three-junction (non-concentrator)
- Two-junction (concentrator)
- Two-junction (non-concentrator)
- Four-junction (concentrator)
- Four-junction (non-concentrator)
- Four-junction or more (concentrator)
- Four-junction or more (non-concentrator)

Institute of Natural Resource Sciences / Life Cycle Assessment Section

25.04.2018
Highly efficient 3rd generation tandem solar cells (2)

- Perovskite solar cell (PSC): organometallic perovskite layer made of methyl ammonium lead iodide (MALI, CH$_3$NH$_2$PbI$_3$)
- Silicon heterojunction (SHJ): crystalline Si wafer with amorphous and micromorphous silicon layers for passivation and recombination junction
- Monolithic tandem cell SHJ-PSC with extended absorption spectrum, conversion efficiency: >30%

Bush et al. (2017)
**Modules and system boundaries**

- Module prototype with different coatings and colours
- Coated with aluminium, copper and plastics

**Functional Unit:**
1 kWh electricity, AC, low voltage, at power plant

Clua Longas et al. (2017)
Summary parameters and scenarios

Yield 1027 kWh/kWp, slanted-roof installation in Switzerland, PR: 82%
Lifetime 30 years, cell-to-module efficiency ratio: 0.915
Degradation 0.7% per year (avg 10.5% for LT 30 years, eff. yield 919 kWh/kWp
Identical mounting system, module and cell production

Abbreviation | Technology | Efficiency in % | Thickness in micrometer |
---|---|---|---|
| | Cell | Module | Wafer | Kerf |
Mono-Si REF | Mono-crystalline silicon, single-junction | 16.5 | 15.1 | 295 | 145 |
Mono-Si ITRPV | Mono-crystalline silicon, single-junction | 26.0 | 23.8 | 140 | 60 |
Poly-Si REF | Poly-crystalline silicon, single-junction | 16.0 | 14.7 | 295 | 145 |
Poly-Si ITRPV | Poly-crystalline silicon, single-junction | 20 | 18.3 | 150 | 60 |
PSC PESS | Perovskite single-junction | 15.0 | 13.8 | n.a. | n.a. |
PSC OPT | Perovskite single-junction | 20.0 | 18.3 | n.a. | n.a. |
M2T-SHJ-PSC PESS | Monolithic two terminal tandem cell using perovskite and silicon heterojunction tandem | 26.0 | 23.8 | 295 | 145 |
M2T-SHJ-PSC OPT | Monolithic two terminal tandem cell using perovskite and silicon heterojunction tandem | 30.0 | 27.5 | 120 | 60 |

IEA PVPS. (2016)
Prospective life cycle environmental impacts

Greenhouse gas emissions
Ozone depletion
Human toxicity, non-cancer effects
Human toxicity, cancer effects
Particulate matter
Ionising radiation, human health
Ionizing radiation, ecosystems
Photochemical ozone formation
Acidification
Terrestrial eutrophication
Freshwater eutrophication
Marine eutrophication
Freshwater ecotoxicity
Land use
Mineral, fossil & resource depletion
Primary energy demand

* Optimistic lifetime of 30 years for PSC layer
Trade-off in mineral and fossil resource depletion due to use of ITO as TCO

Itten & Stucki (2017)
Contribution analysis GHG

* Optimistic lifetime of 30 years for PSC layer
  • Yield 1027 kWh/kWp, degradation 0.7% per year, 30 year lifetime for all solar cells
  • Identical mounting system, module and cell production
  • Additional layers for SHJ and PSC in same order of magnitude
  • Silicon wafer most important contribution (if used)

Itten & Stucki (2017)
Glass-glass module without frame

1. Front glass
2. Clear interlayer
3. Colour filter
4. Cell matrix (cells, tabbing ribbons, bus-bar ribbons)
5. Black interlayer
6. Back glass
7. Junction box, cables and connectors

Current calculations with framed module with aluminium backside, the final encapsulation will be glass-glass without frame

Cattaneo et al. (2018)
GHG mono-Si vs PSC vs tandem

- Blue lines for mono-Si modules, grey for Poly-Si with fixed lifetime of 30 years
- PSC: Perovskite single-junction, mono-Si: mono-crystalline silicon single-junction
- SHJ-PSC: monolithic tandem perovskite silicon heterojunction

Itten & Stucki (2017)
**Sensitivity degradation**

- Dotted blue and grey lines for mono-Si and poly-Si modules with fixed lifetime of 30 years
- End of Life (EoL) for 10% and 5% annual degradation after 10 and 20 years lifetime

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**GHG emissions per kWh of electricity**

**Lifetime perovskite (PSC) in years**

- Mono-Si REF, eff: 16.5%, deg: 0.7%
- Mono-Si ITRPV, eff: 26%, deg: 0.7%
- Poly-Si REF, eff: 16%, deg: 0.7%
- Poly-Si ITRPV, eff: 20%, deg: 0.7%
- PSC OPT, eff: 20%, deg: 0.7%
- PSC OPT, eff: 20%, deg: 1.5%
- PSC OPT, eff: 20%, deg: 3%
- PSC OPT, eff: 20%, deg: 5%
- PSC OPT, eff: 20%, deg: 10%

- Itten & Stucki (2017)
Surface area requirement and non-renewable energy payback time (NREPBT)

\[
NREPBT = \frac{NRPE_{PV}}{NRPE_{kWh} \times E_{PV}}
\]

according to IEA-PVPS Methodology Guideline for PV

NREPBT: Non Renewable Energy Payback Time

NRPE_{PV}: Non Renewable Primary Energy Demand PV Power Plant

E_{PV}: Annual Yield of the Solar Power Plant in kWh

NRPE_{kWh}: Non Renewable Primary Energy Demand per kWh replaced electricity
Conclusions

• Key parameters: module efficiency, lifetime and degradation
• Less than 10% of GHG from additional layers for perovskite and silicon heterojunction
• Trade-off resource depletion: use of indium for ITO
• If the perovskite layer is stabilized, the area demand for photovoltaic electricity reduction can be reduced up to 20%
• Toxicity: use of heavy metals (Pb and Sn)
Thanks for your attention!

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References


Electricity Demand production

Electricity demand in kWh per m² cell

<table>
<thead>
<tr>
<th>Study</th>
<th>Cell production</th>
<th>PSC layer (or SHJ layer)</th>
<th>Wafer production</th>
<th>Mono-Si production</th>
<th>Polysilicon production</th>
<th>Metallurgical Si production</th>
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<tbody>
<tr>
<td>Serrano-Lujan et al. (2015)</td>
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<td>OPV, Espinosa et al. (2011)</td>
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<td>IEA PVPS (2015)</td>
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<td>Louwen et al. (2015) excl back electrode</td>
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<td>Lunardi et al. (2017)</td>
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</table>
Harmonised comparison with published results

Greenhouse gas emissions in kg CO₂-eq per kWh

- *Serrano-Lujan et al. (2015), eff: 6.4%
- *Espinosa et al. (2015), VD, eff: 15.4%
- *Espinosa et al. (2015), SC, eff: 11.5%
- *Gong et al. (2015), TiO₂, eff: 9.1%
- *Gong et al. (2015), ZnO, eff: 11.0%
- *Celik et al. (2016), HTL, eff: 15%
- *Celik et al. (2016), SB, eff: 15%
- *Celik et al. (2016), VB, eff: 15%
- *Ind., this study, PVD + SDC, eff: 15%

- Lab scale
- Lab to fab

Legend:
- Deposition PSC layer
- Inverter
- Mounting system and module production
## Cell structure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Doping</th>
<th>Thickness</th>
<th>Application</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indium tin oxide</td>
<td></td>
<td>120 nm</td>
<td>Sputtering</td>
<td>Top contact layer</td>
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<tr>
<td>Tin oxide</td>
<td>n</td>
<td>10 nm</td>
<td>Sputtering</td>
<td>Electron transport layer</td>
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<tr>
<td>Methyl ammonium lead iodide</td>
<td>i</td>
<td>500 nm</td>
<td>Thermal evaporation of PbI$_2$ followed by slot-die coating of MAI</td>
<td>Absorber layer</td>
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<tr>
<td>Nickel oxide</td>
<td>p</td>
<td>10 nm</td>
<td>Sputtering or atomic layer deposition</td>
<td>Hole transport material</td>
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<tr>
<td>Silver rear contact</td>
<td></td>
<td>150 nm</td>
<td>Sputtering</td>
<td>Back contact layer</td>
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</table>

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<tbody>
<tr>
<td>Ag front grid</td>
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<td>Ag screen printing</td>
<td>Front grid</td>
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<td>Indium tin oxide</td>
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<td>Top contact layer</td>
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<td>Nickel oxide</td>
<td>p</td>
<td>10 nm</td>
<td>Sputtering or atomic layer deposition</td>
<td>Hole transport</td>
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<tr>
<td>Perovskite</td>
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<td>n-µ-c-Si</td>
<td>n</td>
<td>10 nm</td>
<td>PECVD</td>
<td>Recombination junction</td>
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<tr>
<td>i-a-Si</td>
<td>i</td>
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<td>Passivation</td>
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<tr>
<td>n-Si</td>
<td>n</td>
<td>295 and 120 micron</td>
<td>Base for others layers</td>
<td>Silicon substrate</td>
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<tr>
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<tr>
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