Metallization & Interconnection WORKSHOP

Fraunhofer ISE

Low-temperature metallization & interconnection for silicon heterojunction & perovskite silicon tandem solar cells

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Low-temperature processes

Motivation

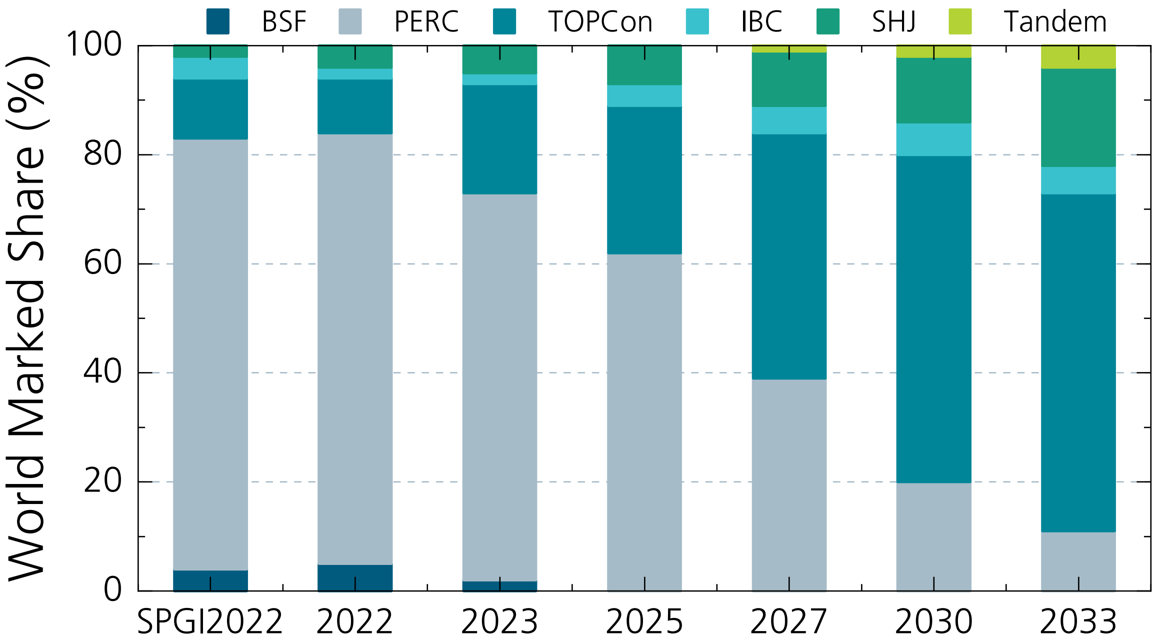
Solar cell trend in PV industry

- **PERC** will be replaced by **TOPCon**
  - Record efficiency TOPCon: 26.1 % [1]
- **IBC**, **SHJ** and **tandem** only minor market share < 30 %

High-efficiency cell concepts

- Beside TOPCon, SHJ and perovskite Si tandem cells offer high photo conversion efficiencies
  - Record efficiency SHJ: 26.8 % [2]
  - Record efficiency Pero Si tandem: 33.2 % [3], on large wafer size: 26.8 % [4]
- But: Temperature-sensitive layers: a-Si, perovskite

➡ Low-temperature (LT) processing required



Taken from ITRPV 2023

What are the challenges for SHJ and tandem for LT metallization & LT interconnection?

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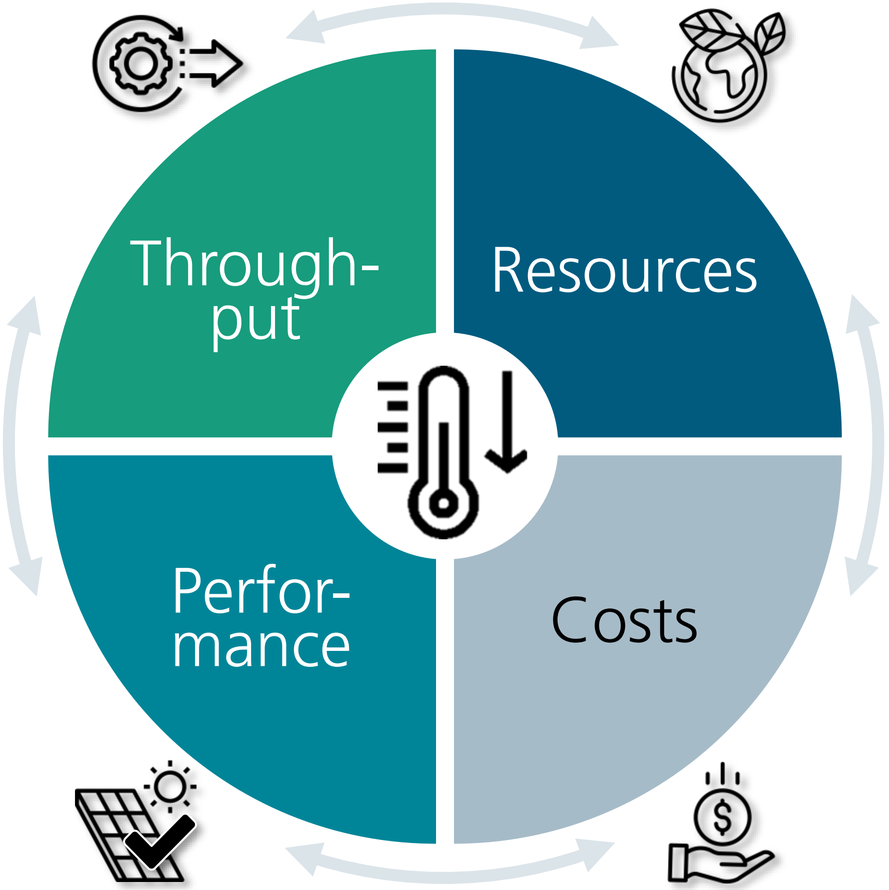
[1] 26.1 % by JinkoSolar in October 2022
[2] 26.8 % by LONGI in November 2022
[3] 33.2 % by KAUST in April 2023
[4] 26.8 % by Oxford PV on large wafer of 274 cm² in November 2021

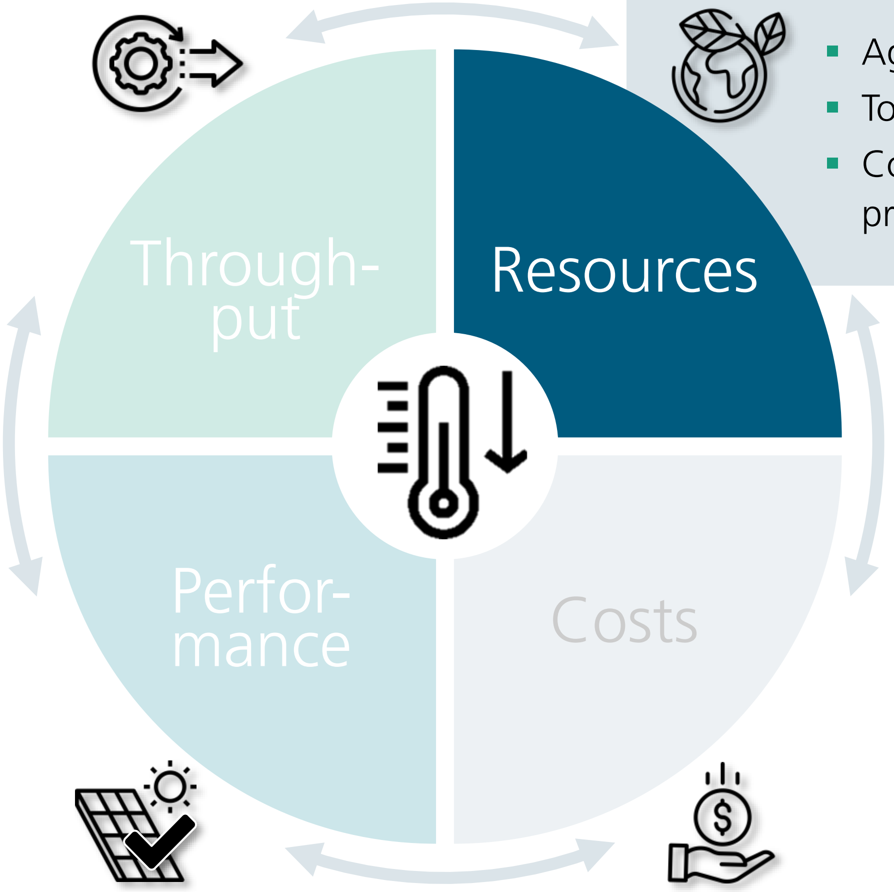
Low-temperature metallization & interconnection

Challenges for industrial application


Throughput
Resources
Performance
Costs

Low-temperature metallization & interconnection

Challenges for industrial application



- Ag & Cu criticality
- Toxicity of Pb
- Commercial availability of products

Resources for LT processes

Criticality, toxicity & availability

Critical resources in PV: Ag, In, Bi, Cu (Si, Ga, As, Cs) [1,3]

LT solder alloys

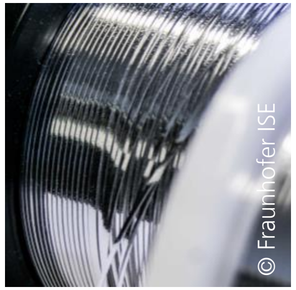
- **Ag-free** interconnection technology
- Substitution of toxic **Pb** is challenging [1,2,3]
- Low-melting alloys contain **Bi** & **In**
- Limited availability of LT solder-coated PV ribbons/wires

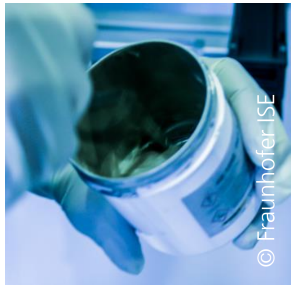
Electrically conductive adhesives (ECAs)

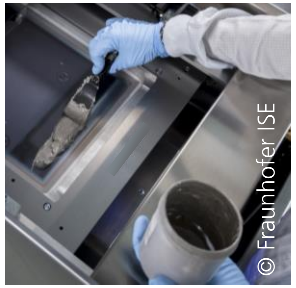
- Commercially available with wide processing window
- Mostly **Ag**-based*, also **Cu**-core/**Ag**-coated versions

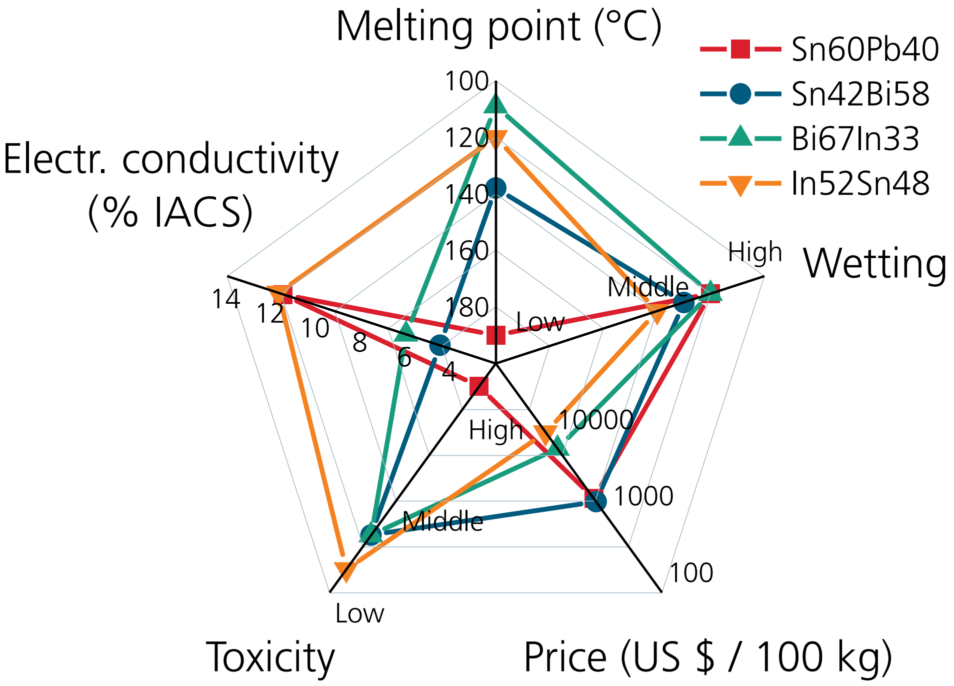
LT metallization pastes

- Various pastes commercially available, esp. from Japan
- Mostly **Ag**-based**, also **Cu**-core/**Ag**-coated versions









Data taken from [4-7]
IACS = Intern. Annealed Cu Standard

*Ag content in ECAs: 30 $\%_{wt.}$ – 70 $\%_{wt.}$ **Ag content in LT pastes: 90 $\%_{wt.}$ – 94 $\%_{wt.}$

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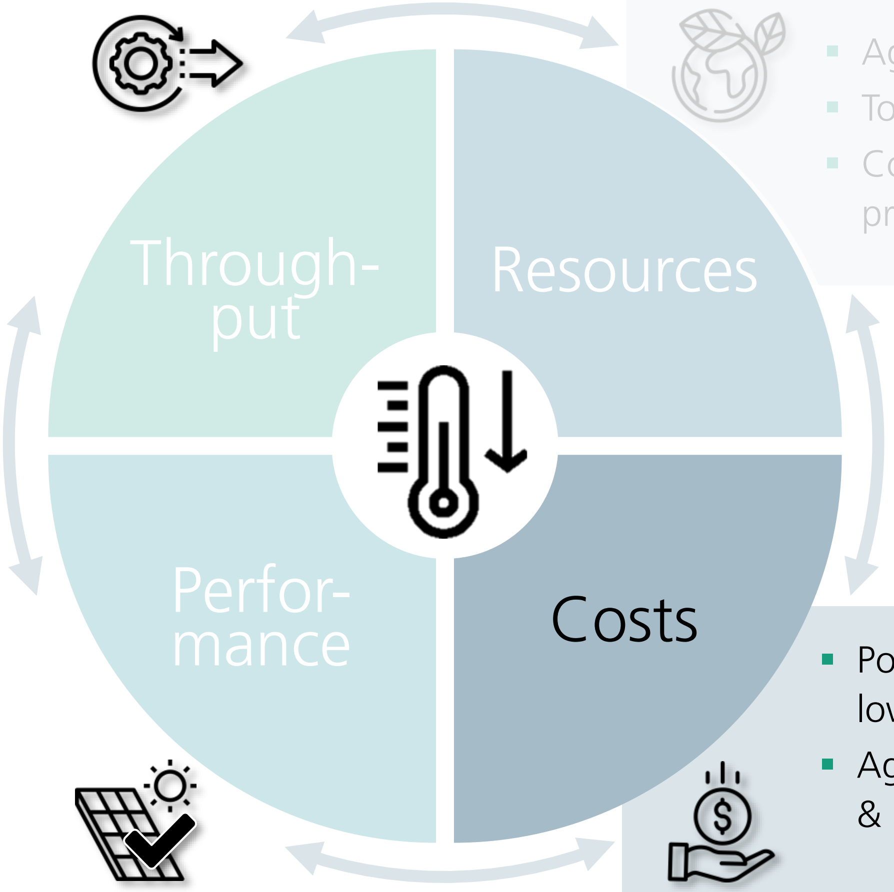
[1] Y. Zhang *et al.*, Design considerations for multi-TW scale manufacturing, 2021, DOI: 10.1039/D1EE01814K
[2] RoHS-Richtlinie 2011/65/EU: Beschränkung der Verwendung best. gefährlicher Stoffe in Elektro-/Elektronikgeräten
[3] E. Gervais *et al.*, Raw material needs for the large-scale deployment of PV, 2021, DOI: 10.1016/j.rser.2020.110589
[4] H. Baker, Alloy Phase Diagrams: ASM Handbook
[5] DERA and GBR, Preismonitor Semptember 2022
[6] J. R. Rumble, CRC handbook of chemistry & physics, 2017
[7] D. C. Adriano, Trace elements in terrestrial environments: Biogeochemistry, bioavailability, and risks of metals, Springer, 2001

Low-temperature metallization & interconnection

Challenges for industrial application



- Ag & Cu criticality
- Toxicity of Pb
- Commercial availability of products

- Power consumption due to low-temperature soldering
- Ag reduction in LT pastes & ECAs

Ag reduction for LT processing

Ag in screen-printed LT pastes

Busbar layout for metallization

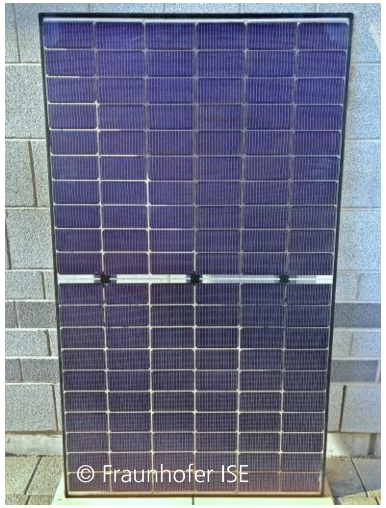
- High Ag consumption for cells with busbars
  - For 5BB M2 SHJ: ~200-300 mg/cell [1,2]

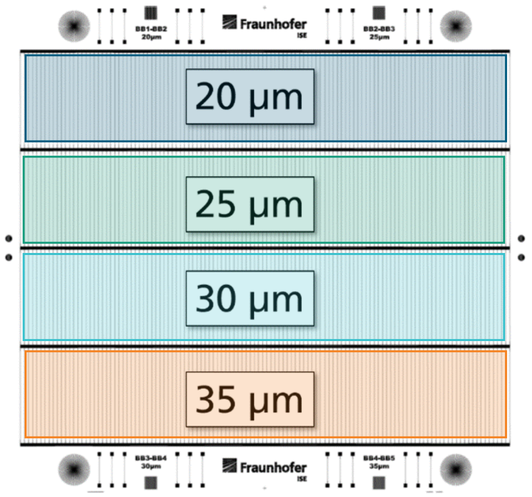
Approaches for Ag reduction

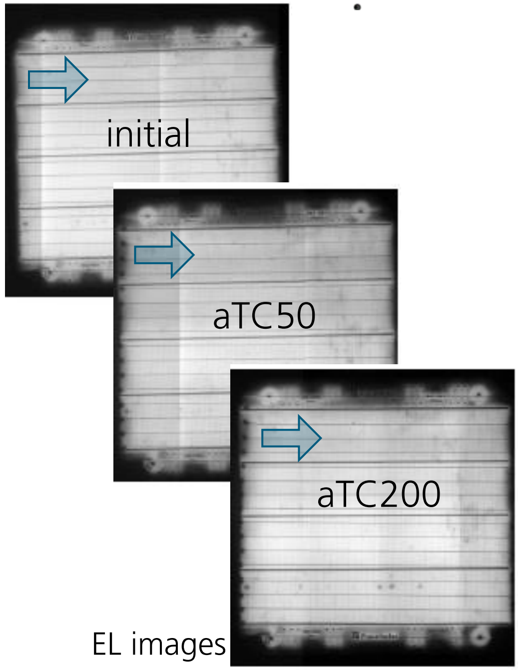
- Substitution of Ag by Cu/Ag pastes [3], increased flooding & printing speed [3], BB-less layouts
- Optimized fine line printing [4]
  - aTC-stable LT fine line fingers with $w_{ch} \approx 25$ µm width on SHJ bottom cells
  - ➡ -43 % Ag reduction

Transfer to perovskite silicon tandem

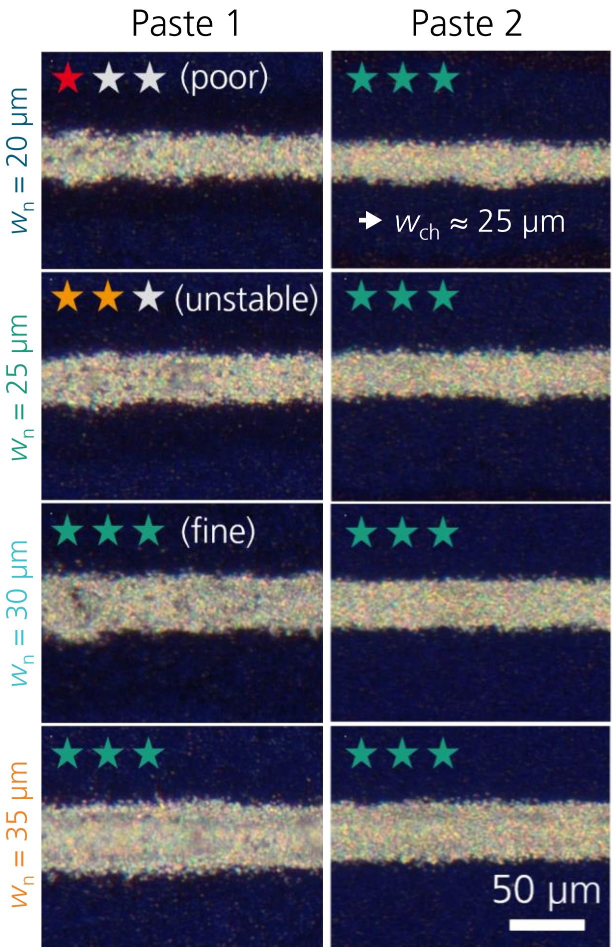
- Prototype-module (~1.8 m^2) with wire interconnection achieving $P_{mpp} > 400$ W







EL images



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[1] Y. Zhang *et al.*, Design considerations for multi-TW scale manufacturing, 2021, DOI: 10.1039/D1EE01814K
[2] S. Pingel *et al.*, Reduction of Scarce Materials in SHJ Cells and Implication son the Performance in Field, Silicon PV, 2023, to be published
[3] S. Pingel *et al.*, Progress on the reduction of silver consumption in metallization of SHJ solar cells, this conference
[4] S. Tepner, A. Lorenz, Printing technologies for silicon solar cell metallization: A comprehensive review, Progr. In PV, 2023, DOI: 10.1002/pip.3674

Ag reduction for LT processing

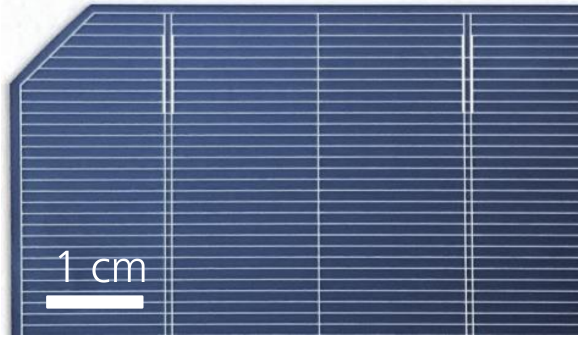
Ag in ECAs for interconnection

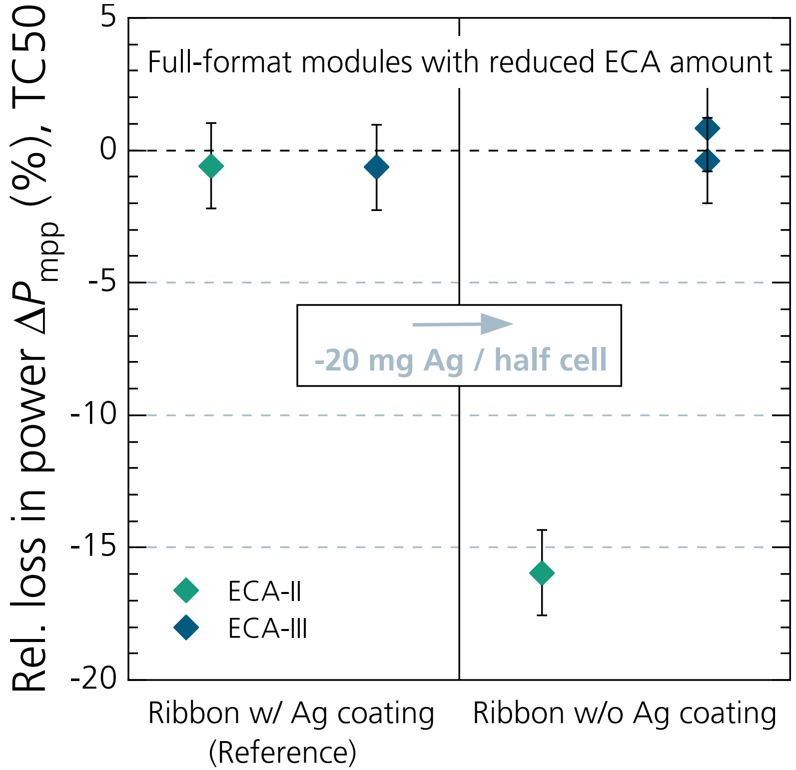
Busbar layout for ECA interconnection

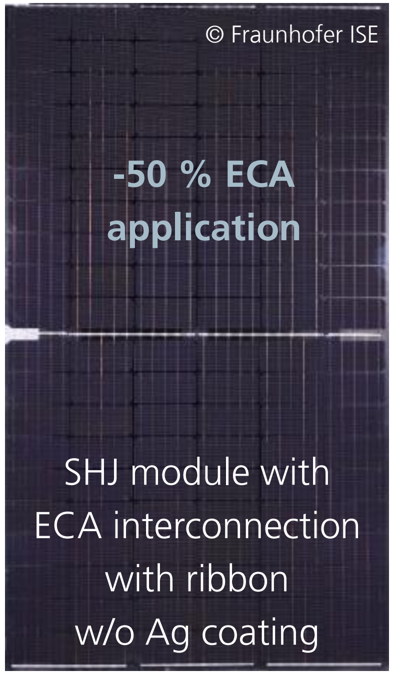
- High Ag consumption for ECA-printing on busbars
  - For 5BB M2 SHJ: ~80-150 mg/cell [1], ~40 mg/cell Ag-coating of Cu ribbon [2]

Approaches for Ag reduction

- Printed patterns instead of continuous application [1]
- ECA-free interconnection for shingling [3]
- Optimized BB layout for ECA interconnection
- Using ribbons w/o Ag coating



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-50 % ECA application

SHJ module with ECA interconnection with ribbon w/o Ag coating

➡ Compatibility of ribbon & ECA is important

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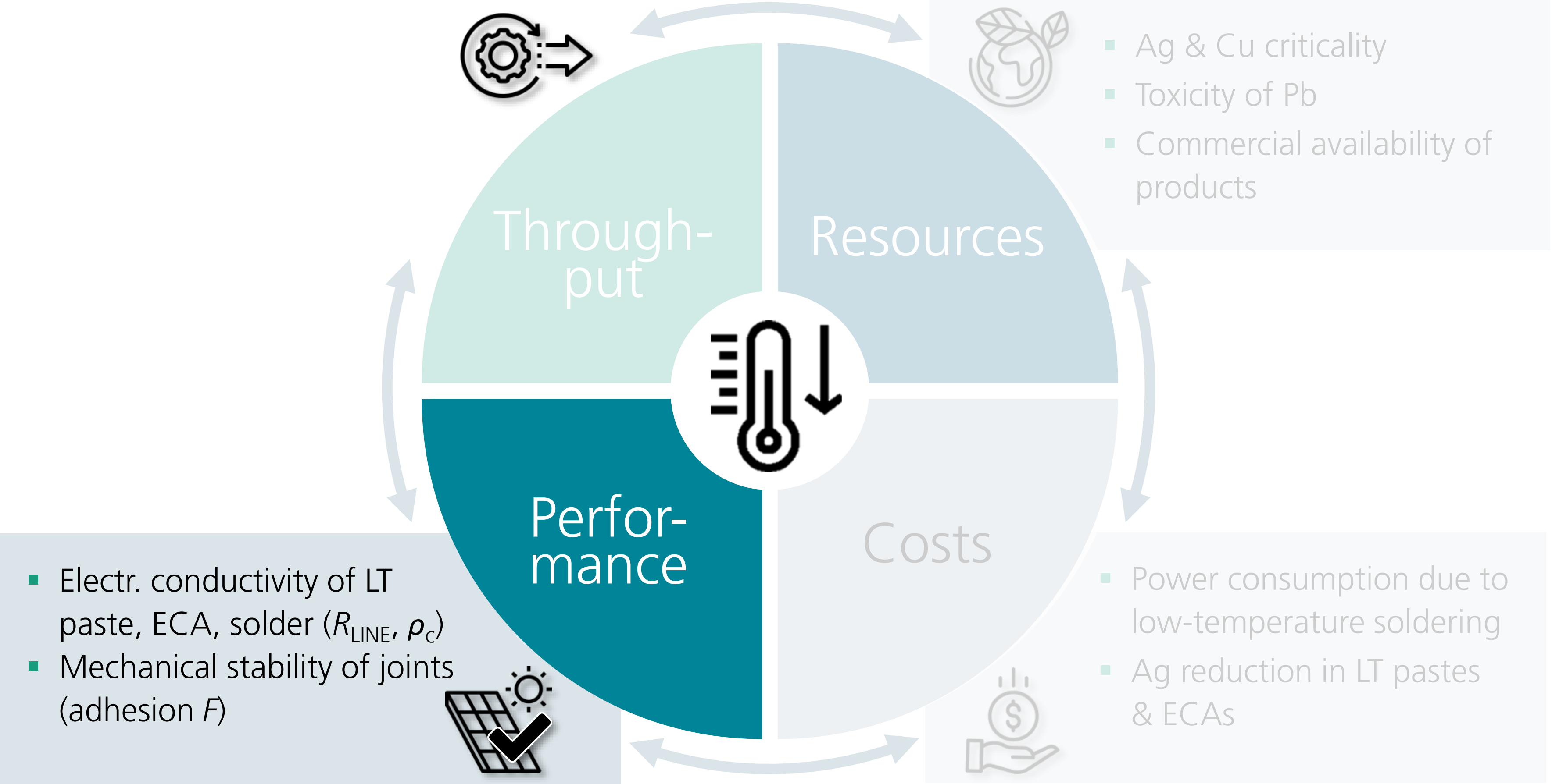
[1] C. Kaiser *et al.*, Reduction of ECA amount for the ribbon interconnection of heterojunction solar cells, 37th EU PVSEC, 2020, DOI: 10.4229/EUPVSEC20202020-4AV.2.6
[2] Final project report "KleVer", contact no. 0325833B, Fraunhofer ISE, 2019
[3] J. Weber *et al.*, Electrically Conductive Adhesive-Free Interconnection of Shingle Solar Cells, this conference

Low-temperature metallization & interconnection

Challenges for industrial application



Through-put

Resources

- Ag & Cu criticality
- Toxicity of Pb
- Commercial availability of products

Perfor-mance

- Electr. conductivity of LT paste, ECA, solder (R_{LINE}, ρ_c)
- Mechanical stability of joints (adhesion *F*)

Costs

- Power consumption due to low-temperature soldering
- Ag reduction in LT pastes & ECAs

Performance of LT materials

Mechanical stability

Peel force after interconnection

- Stable soldered & glued joints on SHJ solar cells
  - Peel forces in range 0.4 N/mm – 1.2 N/mm [1,2]
- Several soldered SHJ modules on the market passing TC [3]

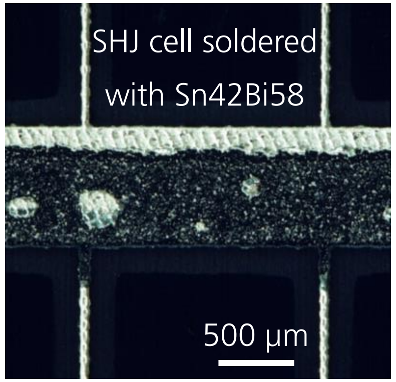
Challenges for LT soldering

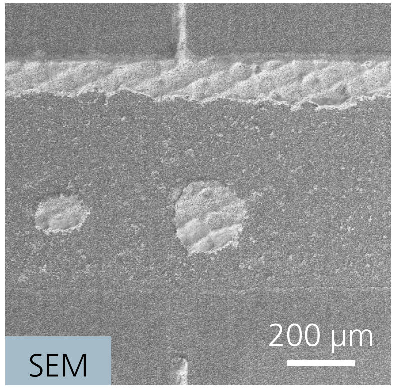
- Wetting of busbar/pad
- Interface between LT paste and wafer
  - Limits adhesion after soldering, dep. on LT paste [1,4]

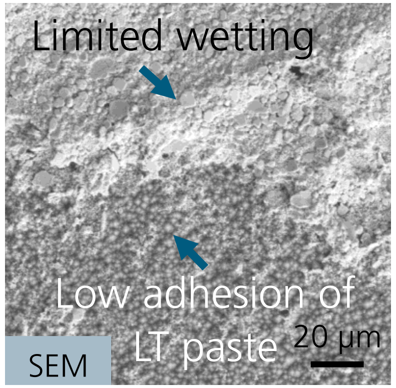
Challenges for gluing

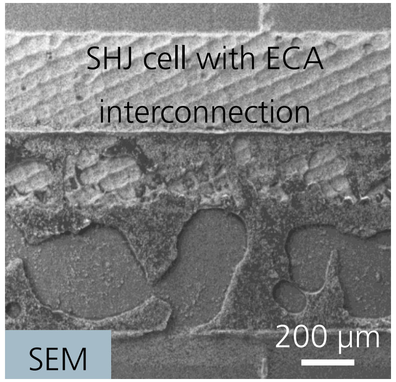
- Reduction of ECA amount w/o increase of R_s
- Stable joints for low curing temperatures
  - Epoxy-based ECAs available for processing < 150 °C for perovskite Si tandem solar cells

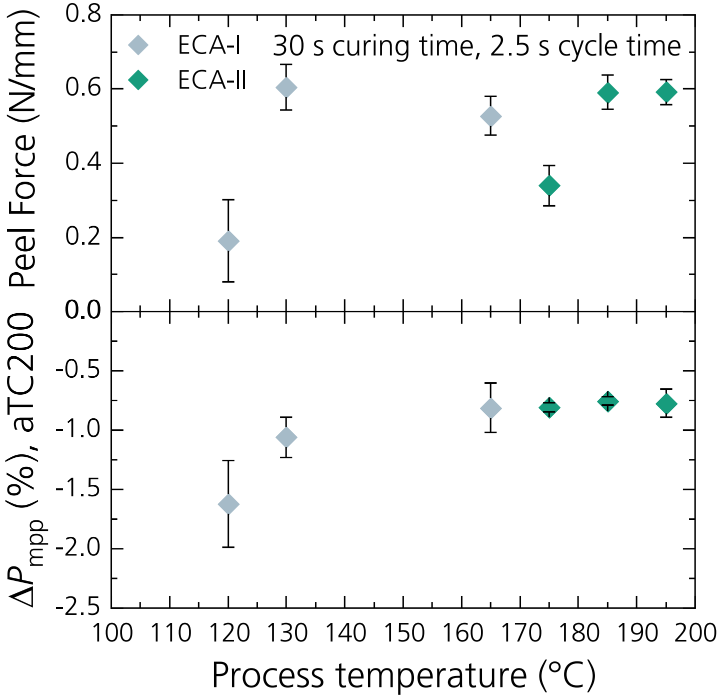
Top view microscopy











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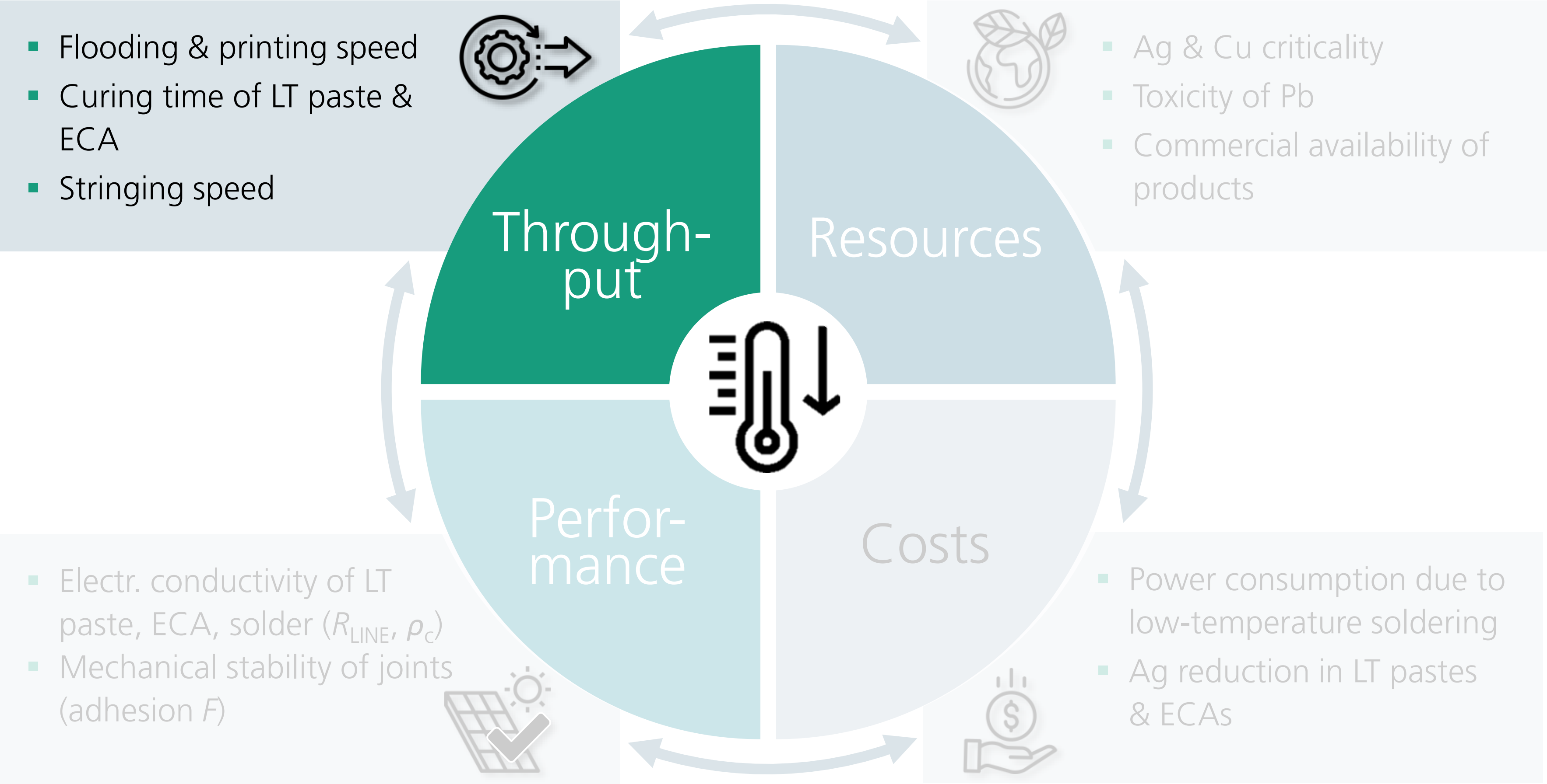
[1] A. De Rose *et al.*, Interconnection of SHJ solar cells by IR soldering, 36th EU PVSEC, 2019, DOI: 10.4229/EUPVSEC20192019-2CO.11.4
[2] C. Kaiser *et al.*, Reduction of ECA amount for the ribbon interconnection of heterojunction solar cells, 37th EU PVSEC, 2020, DOI: 10.4229/EUPVSEC20202020-4AV.2.6
[3] S. K. Chunduri, M. Schmela, Taiyang News - Heterojunction Solar Technology, 2019 Edition
[4] D. Güldali *et al.*, Material Joint Analysis of Pb-free Interconnection Technologies for Si PV, 2022, DOI: 10.1109/ISSE54558.2022.9812798

Low-temperature metallization & interconnection

Challenges for industrial application



- Flooding & printing speed
- Curing time of LT paste & ECA
- Stringing speed

- Ag & Cu criticality
- Toxicity of Pb
- Commercial availability of products

- Electr. conductivity of LT paste, ECA, solder (R_{LINE}, ρ_c)
- Mechanical stability of joints (adhesion F)

- Power consumption due to low-temperature soldering
- Ag reduction in LT pastes & ECAs

Throughput during LT processing

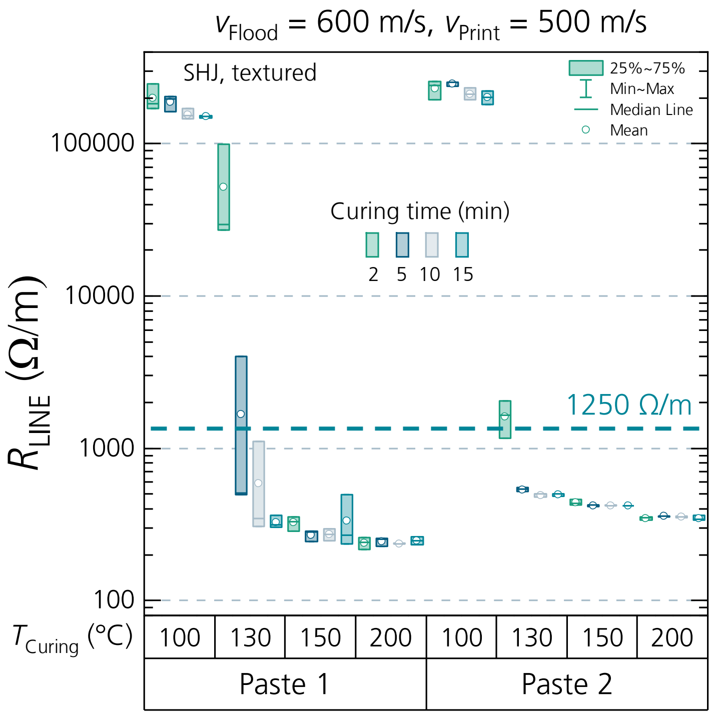
Industrially feasible processes

Fast processing of LT pastes

- Increased flooding & printing speed ensuring high conductivity of fingers [1]
- Fast curing of LT pastes resulting in good conductivity
  - $R_{\mathrm{LINE,max}}$ for perovskite Si tandem: 1250 Ω/m [2]
  - Paste 2: good conductivity for $T_{\mathrm{Curing}} < 150$ °C, fine line printability and fast curing $t_{\mathrm{Curing}} = 2$ min

High throughput LT interconnection

- Industrially feasible processes on stringer possible
  - Cycle time < 2 s per solar cell
- Transfer to full-size perovskite Si tandem cells
  - Successful fabrication of soldered full-format tandem modules; adhesion LT paste/wafer remains challenging
  - Numerous perovskite silicon tandem modules (~1.8 m²) manufactured with ECAs, achieving $P_{\mathrm{mpp}} > 400$ W [3]



Screen-printing of LT pastes on SHJ bottom cells

3BB perovskite silicon tandem module with ECA interconnection[3]

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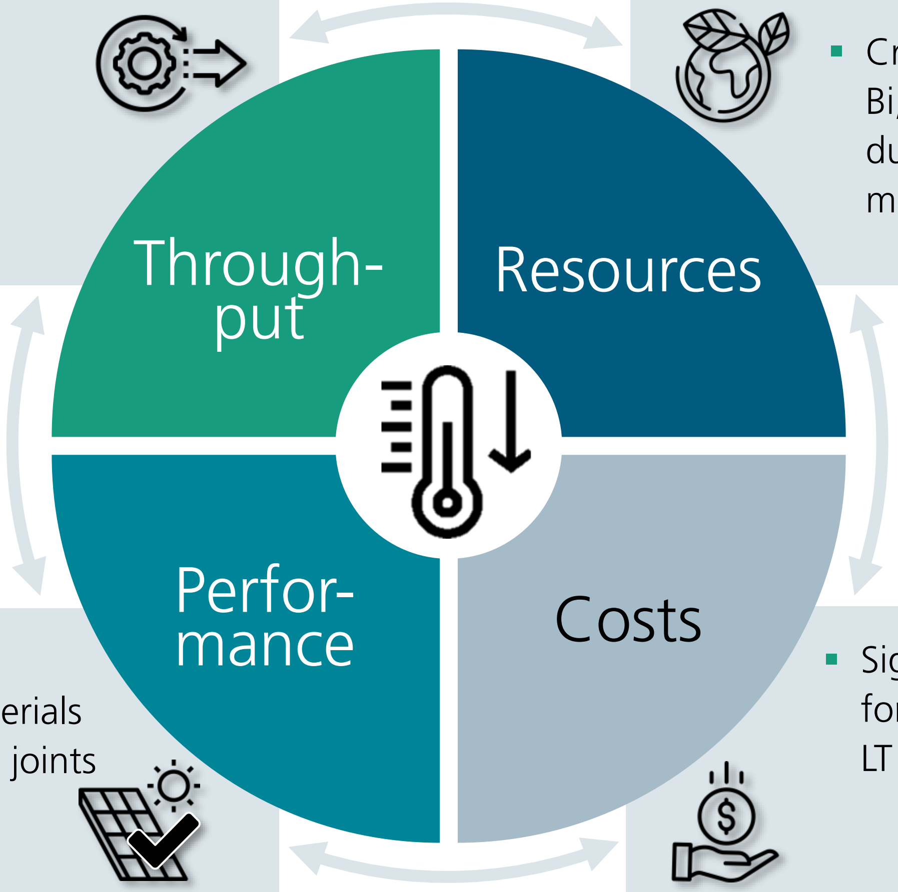
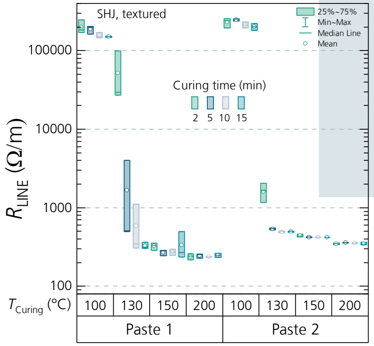
[1] S. Pingel *et al.*, Reduction of Scarce Materials in SHJ Cells and Implication son the Performance in Field, Silicon PV, 2023, to be published
[2] C. Messmer *et al.*, Optimized front TCO and metal grid electrode for module-integrated perovskite-silicon tandem solar cells, 2021, DOI: 10.1002/pip.3491
[3] T. Rößler *et al.*, Production of Full-Size Perovskite SHJ Tandem PV Modules, Talk at 2nd TandemPV Intern. Workshop, 2022

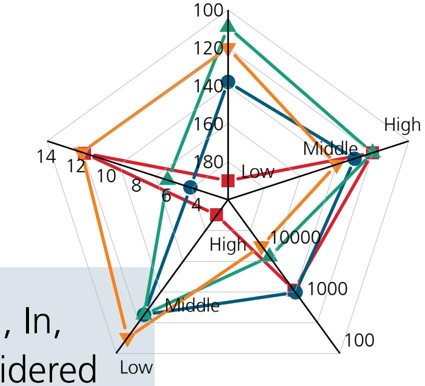
Low-temperature metallization & interconnection

Take-away messages

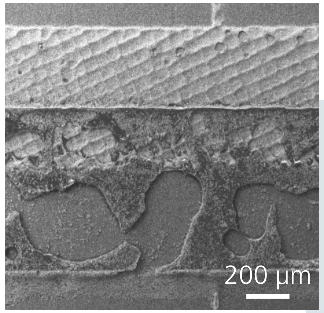




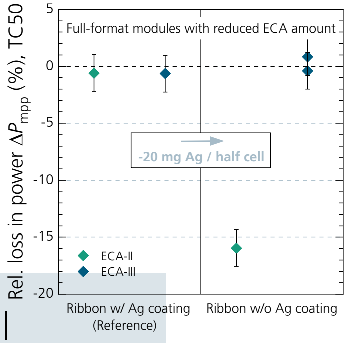
- Fast curing (~2 min), soldering and gluing (< 2 s / cell) with LT materials

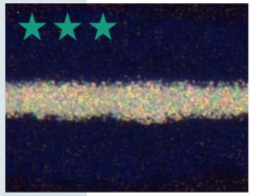


- Criticality of esp. Ag, In, Bi, Cu must be considered during replacement of materials; products available



- Suitable choice of LT interconnection materials for mechanically stable joints





- Significant potential for Ag reduction in LT pastes & ECAs

Thank you for your attention!

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