19. Nationale Photovoltaik-Tagung 2021, Bern
19e Congrès photovoltaïque national 2021

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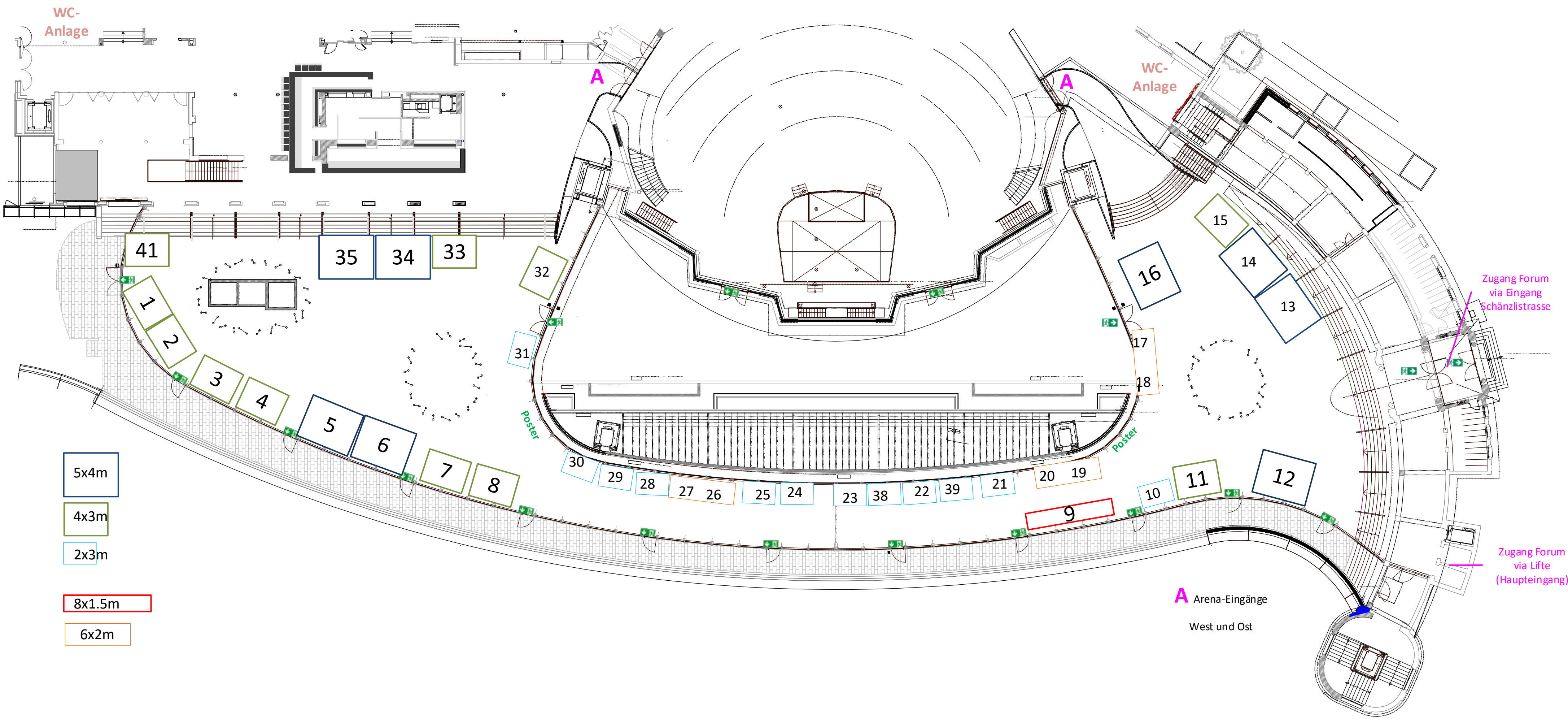
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A Arena-Eingänge
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Posterbeiträge Photovoltaik-Tagung 2021, Bern
Poster contribution congrès photovoltaïque national 2021

No.	Cat.	Titel	Institution	Contact	E-Mail	Authors
1	A	**SHAMAN: Shadow mask localization of thin films for back-contacted crystalline silicon solar cells & energy harvesters**	**CSEM SA Rue Jaquet-Droz 1 CH - 2002 Neuchâtel**	Gizem Nogay	gizem.nogay@csem.ch	G. Nogay,J. Zhao, J. Geissbuhler, N. Badel, L.-L. Senaud, P. Wyss, C. Allebe, G. Christmann, M. Despeisse, B. Paviet-Salomon, C. Ballif
2	A	**Localisation of front side passivating contacts for direct metallisation of high-efficiency c-Si solar cells**	**Ecole Polytechnique Fédérale de Lausanne (EPFL) IMT PV-Lab Rue de la Maladière 71b CH 2002 Neuchâtel**	Franz-Josef Haug	franz-josef.haug@epfl.ch	F. Meyer, A. Ingenito, J. J. Diaz Leon, X. Niquillea, C. Allebé, S. Nicolay, F.-J. Haug, C. Ballif
3	A	**POWER: High-performance tandem solar cells with improved stability and cost-competitive manufacturing**	**CSEM SA Rue Jaquet-Droz 1 CH - 2002 Neuchâtel**	Arnaud Walter	arnaud.walter@csem.ch	A. Walter, B. A. Kamino, S. Rafizadeh, T.Moser, Y. Jiang, F. Sahli, F. Fu, Q. Jeangros, M. Despeisse, S. Nicolay
4	A	**Replacement of Silver by Copper for Metallization of Heterojunction Solar Cells**	**CSEM SA Rue Jaquet-Droz 1 CH - 2002 Neuchâtel**	Agata Lachowicz	agata.lachowicz@csem.ch	A. Lachowicz, N. Blondiaux, G. Andreatta, N. Badel, A. Faes, A. Descoeudres, C. Ballif
5	A	**The Tunnel-IBC Technology: A Cost-Effective Approach for Back-Contacted Silicon Heterojunction Solar Cells & Modules**	**CSEM SA Rue Jaquet-Droz 1 CH - 2002 Neuchâtel**	Bertrand Paviet-Salomo	bps@csem.ch	J. Zhao, G. Nogay, L.-L. Senaud, N. Badel, J. Champliaud, P. Papet, B. Legradic, R. Kramer, T. Kössler, L. Vuithier, L. Barraud, N. Holm, W. Frammelsberger, D. L. Baetzner, N. Bassi, C. Ballif, M. Despeisse, A. Faes, D. Lachenal and B. Paviet-Salomon1
6	A	**Perovskite thin film tandem solar cell research at Empa**	**EMPA Überlandstrasse 129 CH - 8600 Dübendorf**	Severin Siegrist	severin.siegrist@empa.ch	S. Siegrist, H. Lai, Y. Zwirner, T. Moser, R. K. Kothandaraman, X. Sun, A. N. Tiwari and F. Fu
7	A	**Thin-film Cu(In,Ga)Se2 for flexible, lightweight photovoltaic applications**	**EMPA Überlandstrasse 129 CH - 8600 Dübendorf**	Romain Carron	romain.carron@empa.ch	R. Carron, S.-C. Yang, S. Nishiwaki, A. N. Tiwari
8	B	**A Radically Simpler Way to Manufacture Thin-Film Solar Panels, On the Scale-Up to Meet Future Photovoltaic Goals**	**Solaronix SA Rue de l'Ouriette 129 CH - 1170 Obonne**	David Martineau	david.martineau@solaronix.com	D. Martineau, S. Narbey, A. Verma, T. Meyer, R.Schneider, J. Hier, F. Nüesch
9	C	**Betreten von PV Modulen**	**SPF Institut für Solartechnik, OST Ostschweizer - Fachhochschule Oberseestrasse 10 CH - 8640 Rapperswil**	Evelyn Bamberger	evelyn.bamberger@spf.ch	E. Bamberger, A. Jeanjaquet
10	C	**Operating Temperature of Modules in Open-Rack and BIPV Mounting Configurations**	**SUPSI-DACD-ISAAC Via Francesco Catenazzi 23 CH-6850 Mendrisio**	Ebrar Özkalay	Ebrar.Ozkalay@supsi.ch	E. Özkalay, G. Friesen
11	D	**Utilisation of solar hydrogen for mobility**	**HES-SO Valais-Wallis Route de Rawil 47 CH - 1950 Sion**	Julien Udry	Jjulien.udry@gmail.com	J. Udry, F. Savy, M. Schopfer, D. Martinet, C. Ellert
12	D	**Green hydrogen lab with photovoltaic supply**	**HES-SO Valais-Wallis Route de Rawil 47 CH - 1950 Sion**	Felix Savy	felix.savy@hevs.ch	F. Savy, J. Udry, D. Martinet, P. Barrade, A. Germanier, A. Carrupt, C. Ellert

	Cat.	Titel	Institution	Contact	E-Mail	Authors
13	D	**Heimspeicher Systemtest: Batteriesysteme auf dem Prüfstand**	**SPF Institut für Solartechnik, OST Ostschweizer - Fachhochschule Oberseestrasse 10 CH - 8640 Rapperswil**	Evelyn Bamberger	evelyn.bamberger@spf.ch	E. Bamberger, R. Haberl, A. Reber, C. Biba
14	E	**Versatile Lightweight Photovoltaic Module Line at CSEM with Customized Module Stacks to Meet Application Oriented Reliability and Aesthetic Targets**	**CSEM SA Rue Jaquet-Droz 1 CH - 2002 Neuchâtel**	Matthieu Despeisse	matthieu.despeisse@csem.ch	M. Despeisse, P. Duvoisin, C. Charrière, S. Prabhudesai, X. Bulliard, G. Nogay, A. Faes, H. Li, P. Merme, G. Cattaneo, J. Escarre, R. Loos, R. Domjan, C. Ballif
15	E	**Photovoltaik-Freiflächen-Anlagen in Wintersportorten**	**ZHAW Wädenswil Campus Grüntal CH-8840 Wädenswil**	Jürg Rohrer	rohu@zhaw.ch	A. Beerli, R. Rupf, B. Salak, J. Rohrer
16	F	**Ist eine Batterie für mehr PV-Integration ins Netz eine Alternative zu Netzausbau?**	**OST - Ostschweizer Fachhochschule Werdenbergstrasse 4 CH - 9471 Buchs**	Markus Markstalder	markus.markstalder@ost.ch	M. Markstalder
17	G	**Accredited Swiss Energy Testing Laboratories**	**Berner Fachhochschule (BFH) Technik und Informatik, Photovoltaiklabor Jlcoweg 1, CH-3400 Burgdorf**	Christof Bucher	christof.bucher@bfh.ch	A. Bohren, C. Bucher, M. Caccivio, M. Eschmann, H. Huber, T. Strebel
18	G	**Blendung an PV-Anlagen**	**Berner Fachhochschule (BFH) Technik und Informatik, Photovoltaiklabor Jlcoweg 1, CH-3400 Burgdorf**	Christof Bucher	christof.bucher@bfh.ch	C. Bucher, P. Wüthrich, S. Danaci
19	G	**PV Brandprävention und Brandbekämpfung - GVB Projekt**	**Ingenieurbüro Muntwyler/ Dr. SchüpbachMuntwyler GmbH i.Gr. Hopfenrain 7 CH - 3007 Bern**	Urs Muntwyler	urs_muntwyler@gmx.ch	U. Muntwyler, E. Schüpbach
20	K	**Distributed Intelligent Micro Storage (OFEN MSID)**	**HES-SO Valais-Wallis Route de Rawil 47 CH - 1950 Sion**	David Wannier	david.wannier@hevs.ch	D. Wannier, V. Mitrovic, J. Vianin, J-M. Alder, H. Pereira
21	K	**SCCER FURIES Digitilization - simplyfying exchange of photovoltaic kWh between electric vehicles charging stations**	**HES-SO Valais-Wallis Route de Rawil 47 CH - 1950 Sion**	David Wannier	david.wannier@hevs.ch	A. Weibel, N. Jordan, H. Pereira, J-M. Alder, J. Vianin, D. Wannier
22	L	**Solar technology for architects and planners. A Swiss website for solar architecture**	**SUPSI-DACD-ISAAC Via Francesco Catenazzi 23 CH-6850 Mendrisio**	Francesco Frontini	francesco.frontini@supsi.ch	I.Zanetti, P. Bonomo, F. Frontini, A. Hekler, D. Studer
24	L	**Ausbau von EE und Energieeffizienz: Treiber der CO2-Emissionsreduktion, der Wirtschaftlichkeit, der inländischen Wertschöpfung und von Arbeitsplätzen**	**ZHAW Wädenswil Campus Grüntal CH-8840 Wädenswil**	Jürg Rohrer	rohu@zhaw.ch	L. Hälg, M. Siegwart, D. Sauter, G. Battista Cavadini, J. Rohrer
25	F	**Assesing the benefits of using distributed PV flexibility over grid reinforcement**	**Ecole Polytechnique Fédérale de Lausanne (EPFL) IMT PV-Lab Rue de la Maladière 71b CH 2002 Neuchâtel**	Jordan Holweger	jordan.holweger@epfl.ch	J. Holweger, L. Bloch, C. Ballif. N. Wyrsch
26	D	**A heuristic indicator-based heat pump control algorithm**	**Ecole Polytechnique Fédérale de Lausanne (EPFL) IMT PV-Lab Rue de la Maladière 71b CH 2002 Neuchâtel**	Jordan Holweger	jordan.holweger@epfl.ch	J. Holweger, L. Bloch, C. Ballif. N. Wyrsch

SHAMAN: Shadow mask localization of thin films for back-contacted crystalline silicon solar cells & energy harvesters

G. Nogay, J. Zhao, J. Geissbühler, N. Badel, G. Christmann, L.-L. Senaud, P. Wyss, C. Allebé, M. Despeisse, B. Paviet-Salomon, & C. Ballif

PV-Center, Centre Suisse d'Électronique et de Microtechnique (CSEM), Rue Jaquet-Droz 1, CH-2002 Neuchâtel, Switzerland

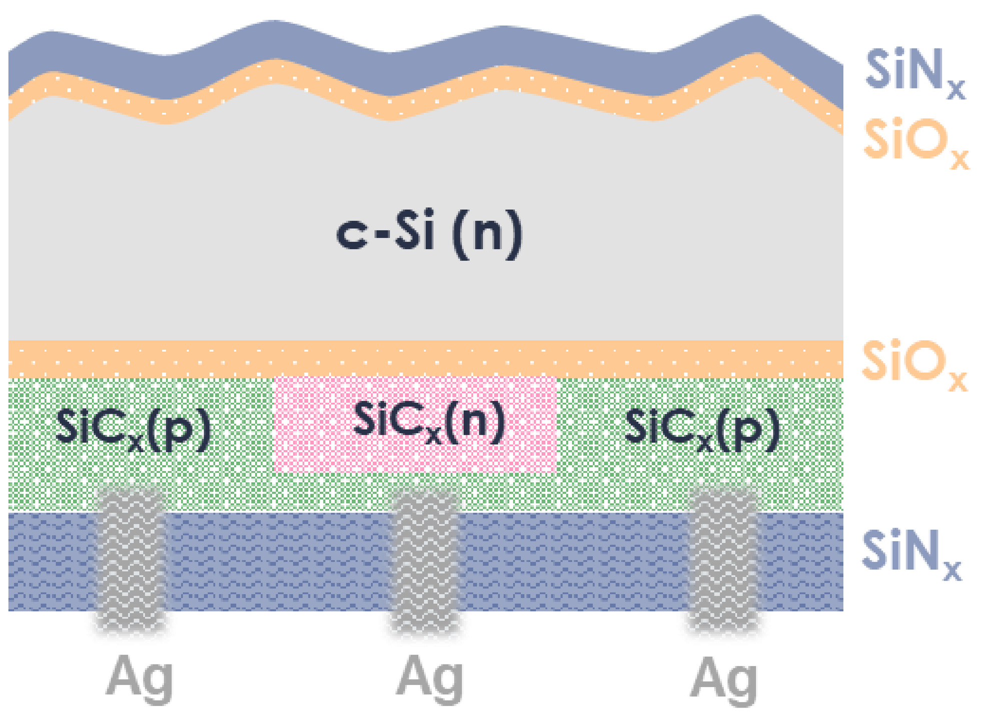
Interdigitated Back-Contacted c-Si Solar Cell Concept with High Temperature Stable Passivating Contacts

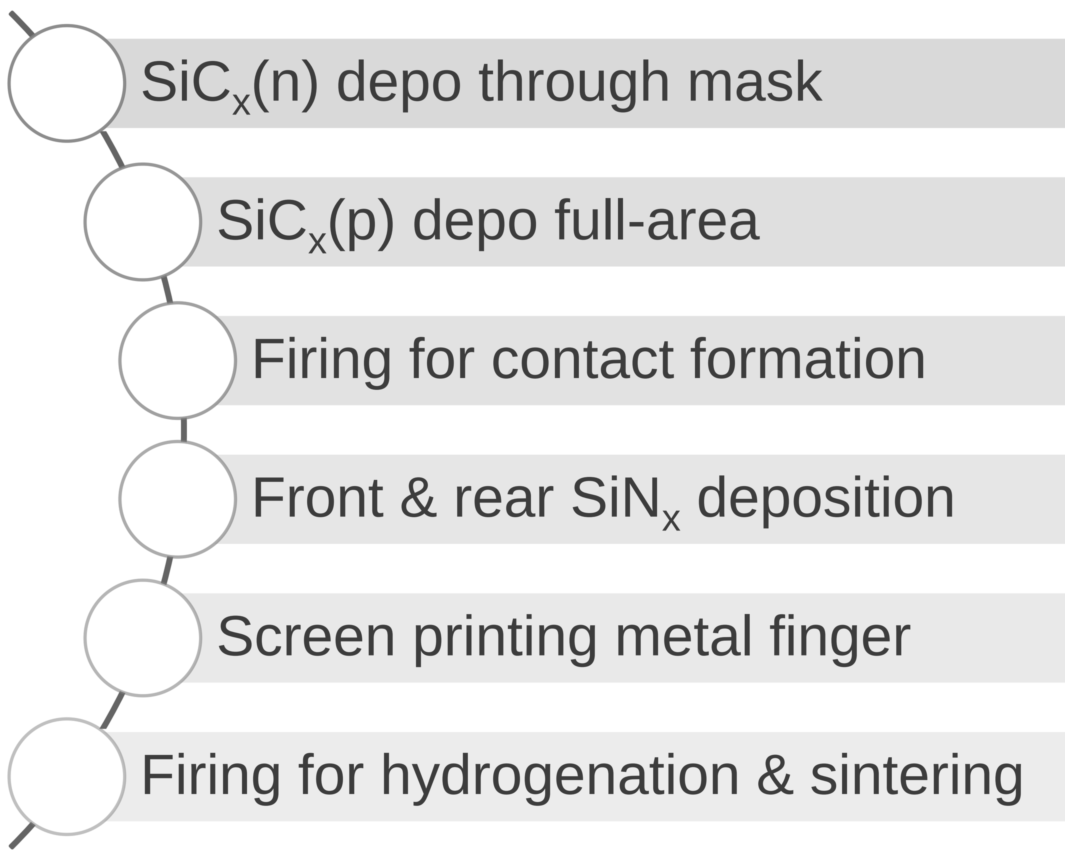
Motivation:

High efficiency potential of IBC cells with passivating contact has been demonstrated with efficiencies up to 26.1% using complex processing

→ Up to today there is no established simple way for fabrication of such solar cells

Target back contacted solar cell design and process flow:





Advantages:

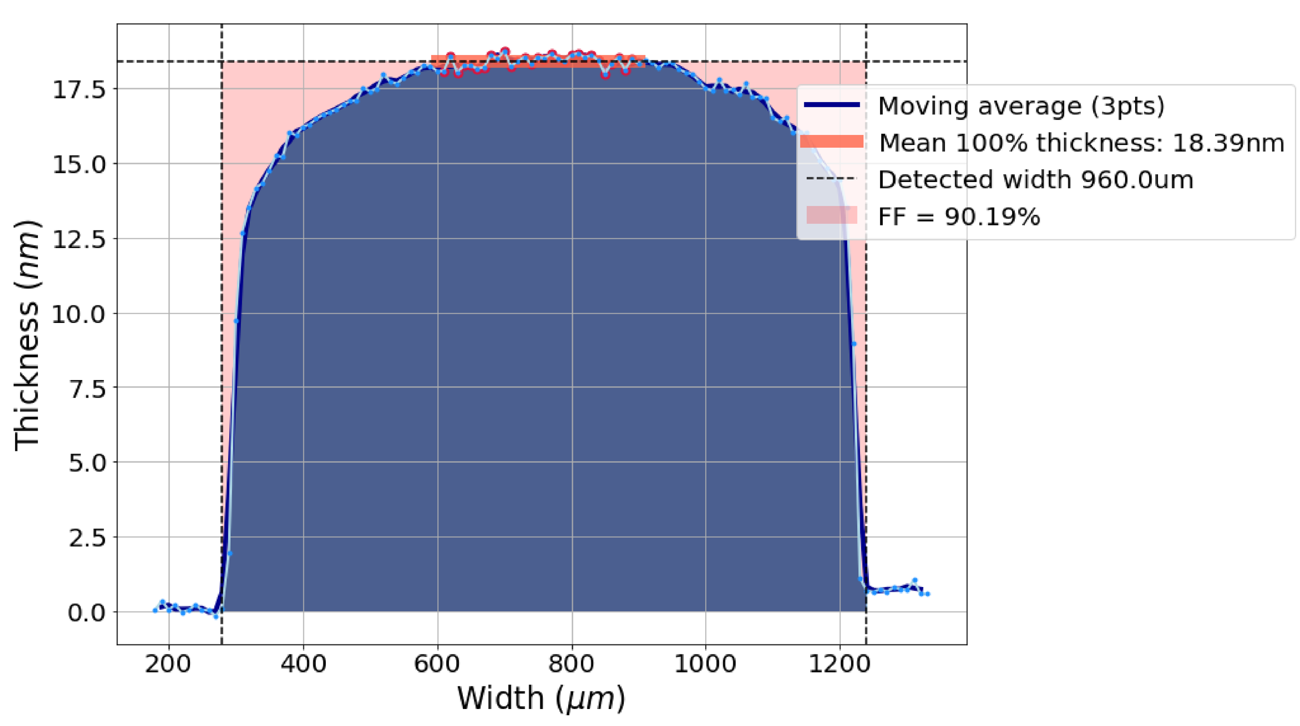
- Flexibility in material choice: Possibility to use low-cost base material thanks to high temperature treatment
  - Impurity gathering
  - Thermal donor killing
- Possibility to avoid TCO and compatibility with industrial firing-through direct metallization processes
- Potentially better compatibility for tandem application with perovskite top cell for 2TT applications

Challenges:

I. Optimizing p&n contact for the same thermal treatment conditions
II. Designing a front side compatible with the rear side
III. Optimizing n/p interface not to have shunt but good charge carrier extraction

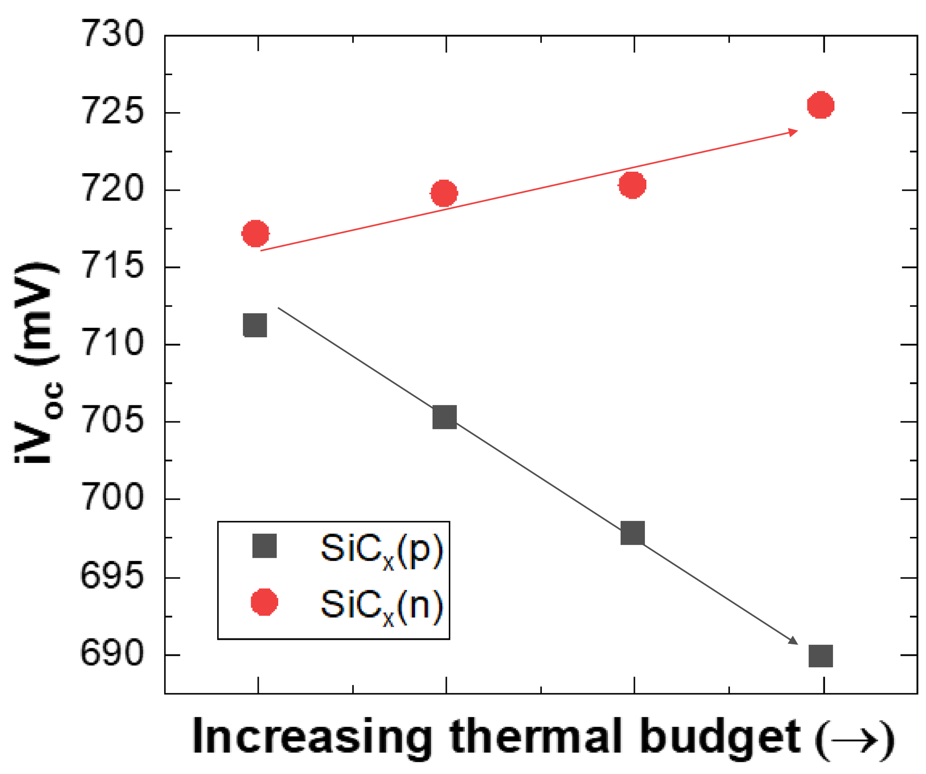
Localization

- Thickness profile of the localized SiC_x(n) shows a good step coverage with filling factor above 90% and no tapering



Surface passivation

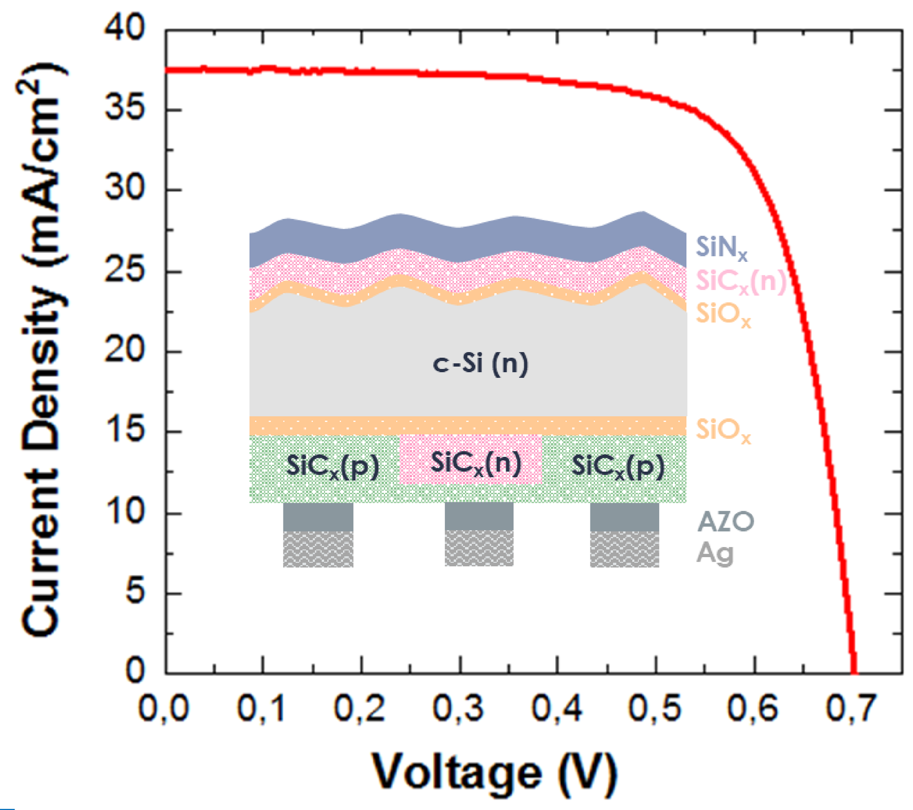
- SiC_x(p) & SiC_x(n) react differently to increase thermal budget and they do not have the same optimum



Device Integration

- Proof-of-concept solar cell integration with low-T metallization

Eff [%]	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]
19,2	703,6	37,5	72,6



Conclusions & Outlook

- Proof of concept cell with efficiency up to 19.2% has been demonstrated with single shadow masking and firing process for contact formation of both polarities
- Next steps are (i) high temperature metallization development, (ii) further interface & layer optimization to improve V_{oc} and FF, testing different designs with various pitches

This work receives funding from the Swiss National Science Foundation under grant agreement 200021_192310/1 "SHAMAN"

Localisation of front side passivating contacts for direct metallisation of high-efficiency c-Si solar cells

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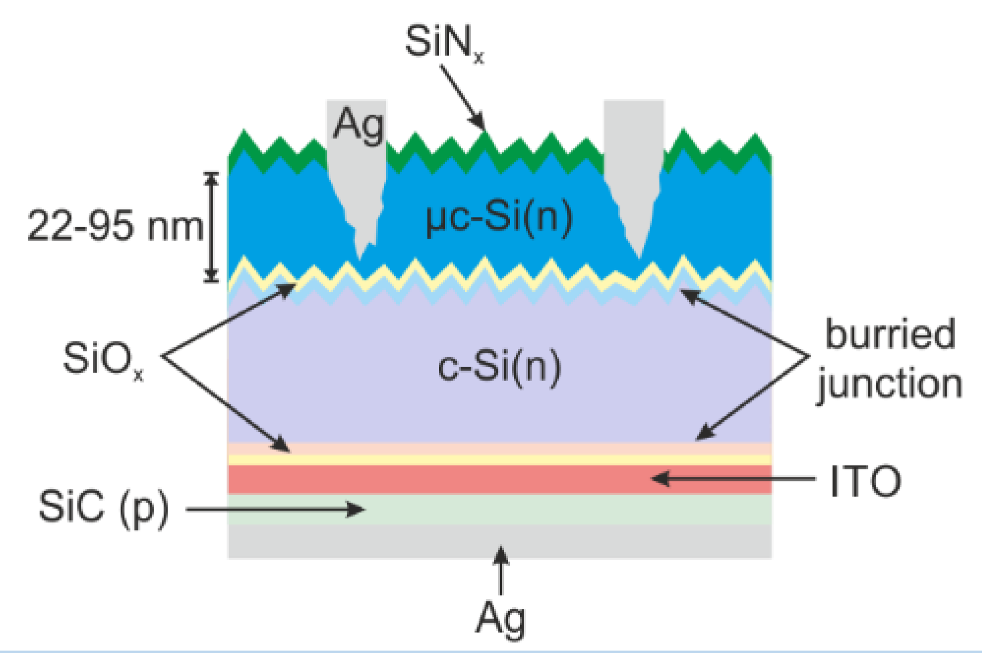
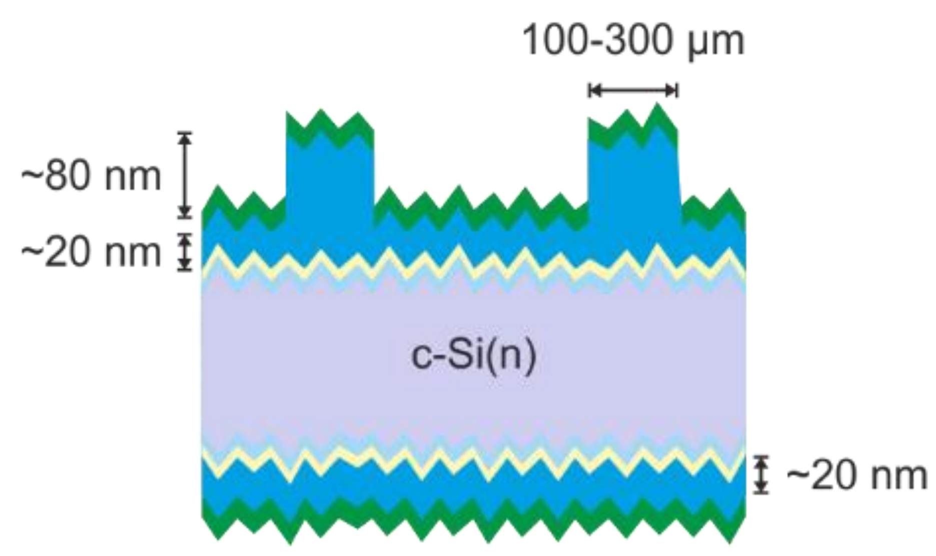
Firing Through Process: PVLAB strategies

Passivating contacts are keys to enable conversion efficiency ≥26%[1,2,3] and are compatible with firing through process. To ensure high V_{OC}, thick passivating contacts must be integrated at the front without compromising photo-generation of carriers.

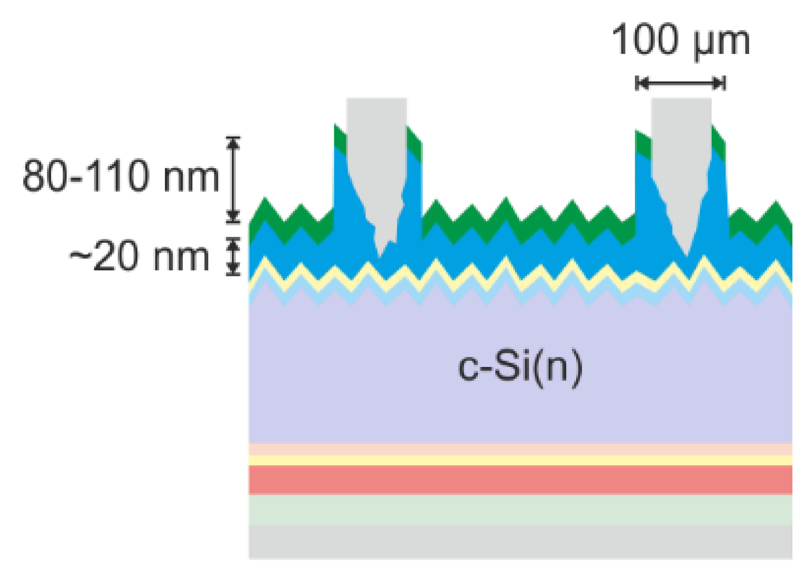
Non-patterned cells
Record efficiency of 19.4 %



Symmetrical structure to proof the localisation feasibility



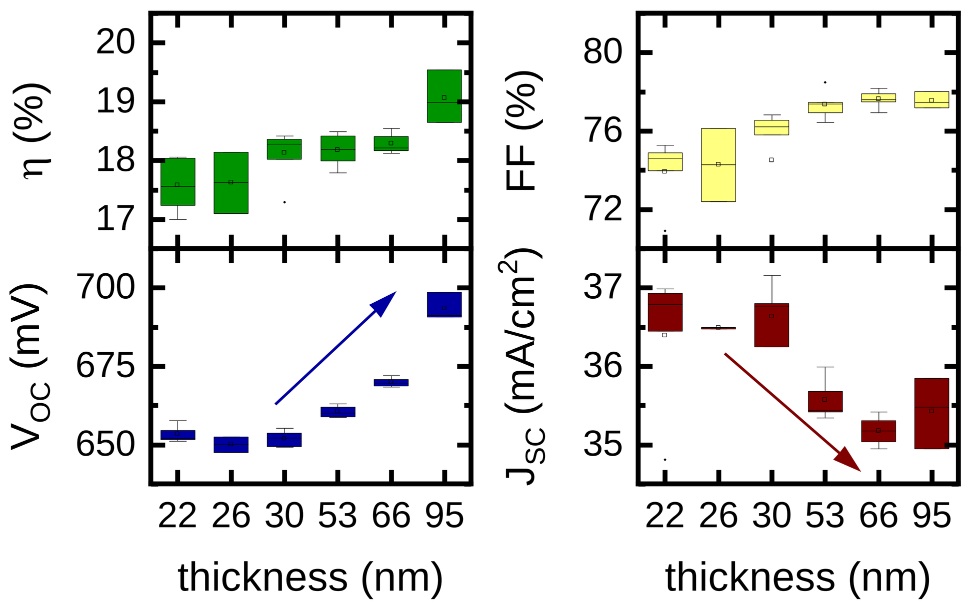
Patterned cells
Record efficiency of 21.72 %



Non-Patterned Solar Cells

Cell demonstrator:

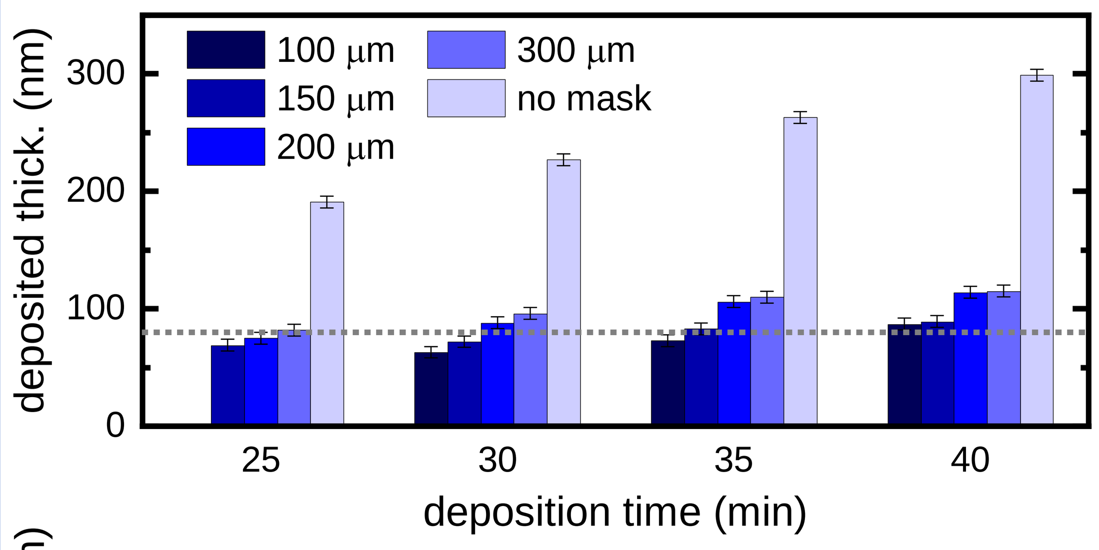
- PECVD deposition of various µc-Si(n) thickness (front) and SiC(p) (rear)
- Co-annealing at 850°C
- SiN_X deposition and Ag paste printing (front)
- Firing (hydrogenation and contacting of the Ag paste)
- metallization with sputtered ITO/Ag stack at the rear

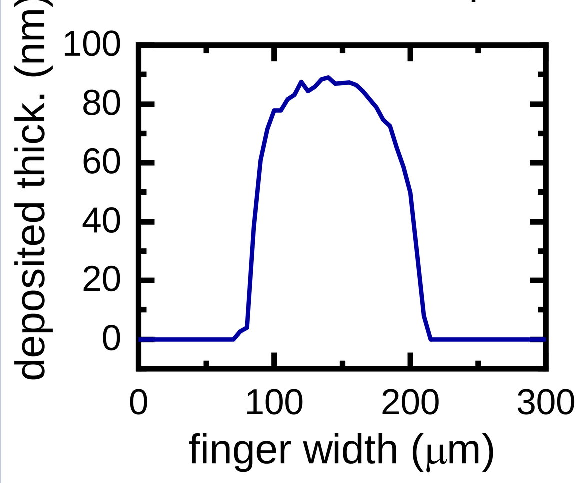


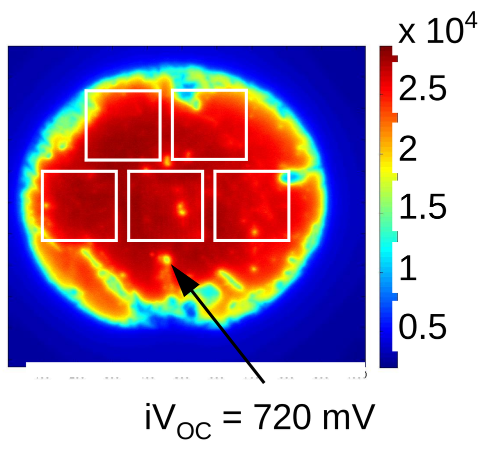
✓ Ag paste can be confined in the passivating contacts at 95 nm (V_{OC} up to 700 mV)

× Thick passivating contacts are responsible of large parasitic absorptions (low J_{SC})

Localization of Passivating Contacts







- Localised contacts deposited through hard mask during PECVD
- Localisation can reduce the parasitic absorptions
- Tested on symmetrical structure
- Profile made with Raman spectroscopy[4]

✓ Feasibility demonstrated up to 100 µm

✓ Low fingers tapering

✓ Homogeneous passivation

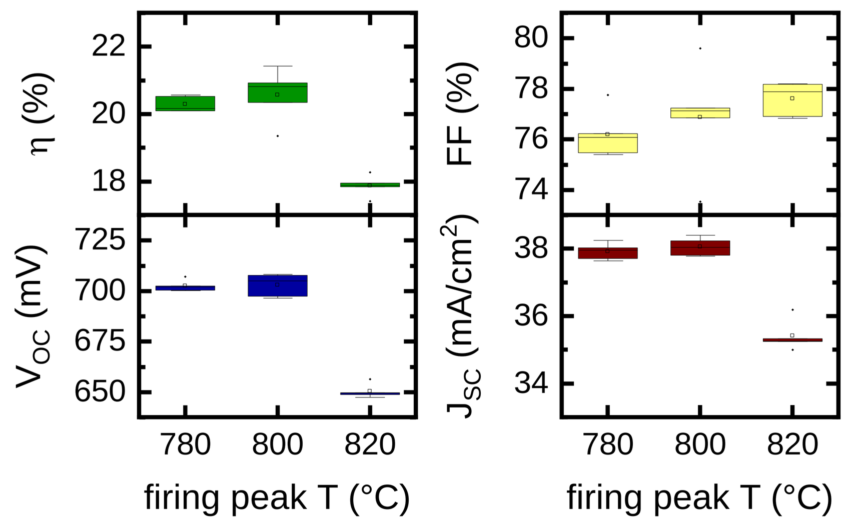
× Large increase of the deposition time

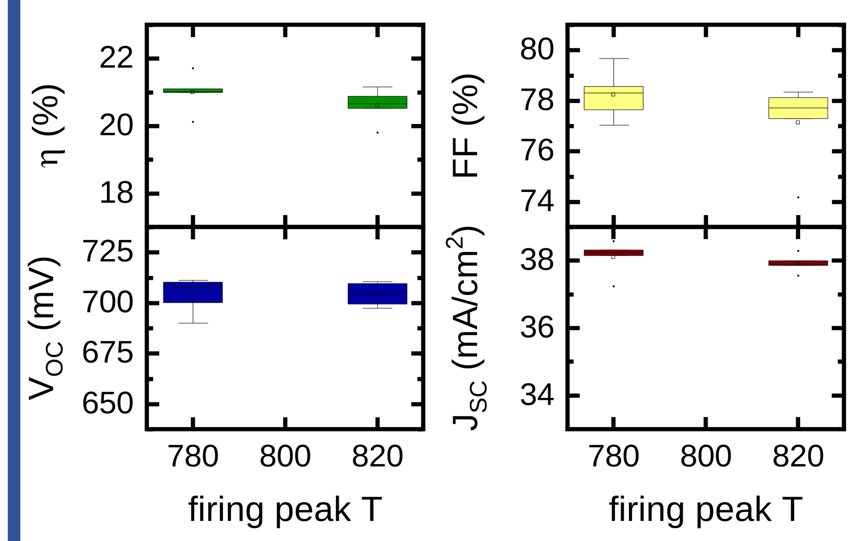
Solar Cells with Localized Front Passivating Contacts

Cell demonstrator:

- PECVD deposition of various localized µc-Si(n) thickness, addition of full-area thin µc-Si(n) (front) and SiC(p) (rear)
- Co-annealing at 850°C
- SiN_X deposition and Ag paste printing (front)
- Firing (hydrogenation and contacting of the Ag paste)
- metallization with sputtered ITO/Ag stack at the rear

Thick. (nm)	Eff. (%)	FF (%)	V_{OC} (mV)	J_{SC} (mA/cm²)
~100	19.06	79.5	658.6	36.40
~115	21.43	79.6	707.7	38.04
~130	21.72	79.7	711.2	38.32





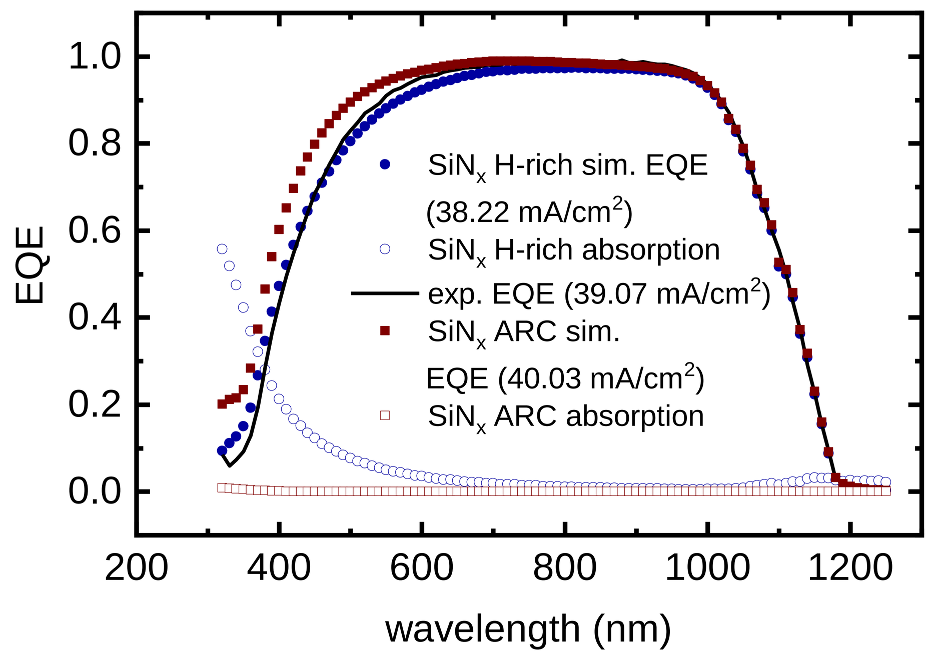
✓ Ag paste can be confined in the passivating contacts even at a firing peak T of 820°C

✓ V_{OC} up to 711 mV for the best cell

✓ High FF of almost 80 %

× Final cell efficiency mostly limited by the J_{SC}

- Simulated EQE are compiled with CROWM[5] to understand SiN_x impact on J_{SC}
- Simulation are in close agreement with reality within a minor error of 2% relative
- SiN_x optimized for hydrogenation induces large parasitic absorption
- More stoichiometric nitride optimized for ARC could push forward cell eff. over 22.3%



Conclusion

Non-Patterned Solar Cells

- Demonstration of thick blistering-free passivating contacts adapted for firing through process
- V_{OC} up to 700 mV
- Thick passivating contacts are responsible of large parasitic absorption → need of patterning for front side application

Localization of Passivating Contacts

- Demonstration of localization process through hard mask during PECVD
- Low finger tapering and homogenous passivation
- Increase drastically the deposition time → need a better solution to be integrated to industry process

Solar Cells with Localized Front Passivating Contacts

- Demonstration of high efficiency solar cells >21.7% with high V_{OC} >710 mV and high FF >79.5%
- Final cell efficiency limited by J_{SC} → can be easily improved by using a SiN_x optimized for ARC
- Long term objective: contact also the rear during firing through process

References

[1] A. Richter *et al.*, Solmat, 2017
[2] F. Haase *et al.*, Jpn. J. Appl. Phys., 2017
[3] A. Richter *et al.*, Nat Energy 6, 2021
[4] M. Ledinský *et al.*, Nat. Publ. Gr., 2016
[5] B. Lipovšek *et al.* Inf. MIDEM. 41, 2011

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CSEM

EPFL PV-lab IMT NEUCHATEL

Empa

POWER: High-performance tandem solar cells with improved stability and cost-competitive manufacturing

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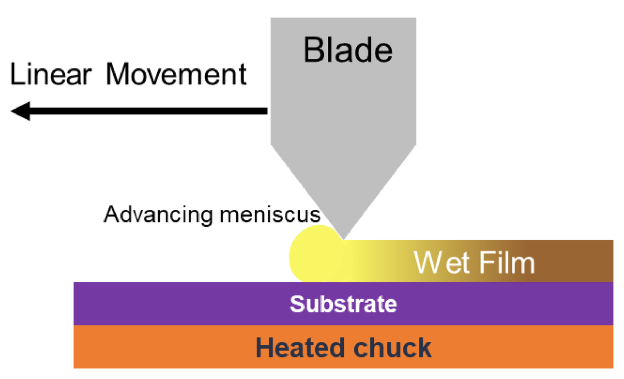
[1]*CSEM SA, PV-center* [2]*EPFL, PV-lab* [3]*Empa, Thin Films and Photovoltaics*

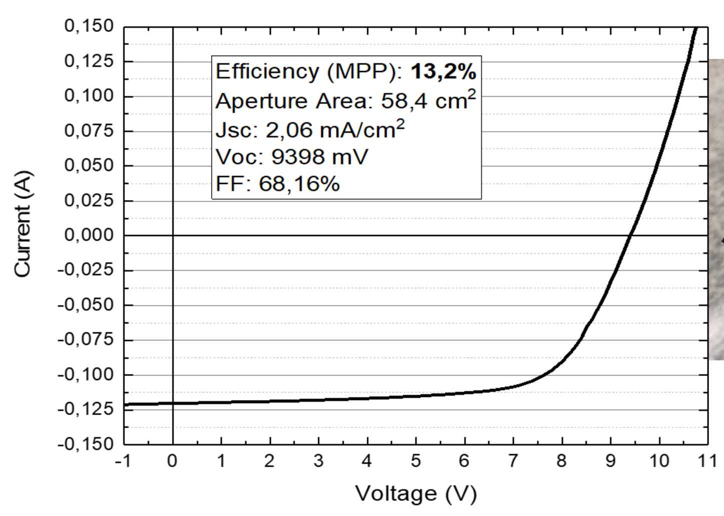
BRIDGE

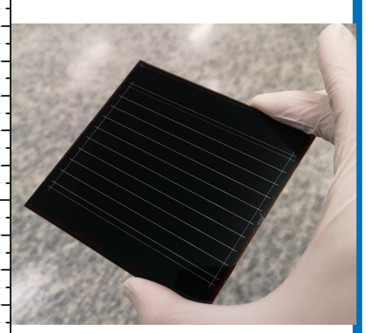
The POWER Project aims to develop a new generation of solar cells by combining emerging perovskite cells with market-proven CIGS and crystalline silicon cells. By combining scientific excellence with innovation and production oriented development, the project will pave the way towards the realization of low cost solar cells with >30% performance, surpassing 25 years lifetime.

Scalable deposition techniques

- Spin coating is the technique of choice for deposition of small scall PK devices
- We demonstrate that this can be successfully applied to coating of up to 4" wafer size with no loss of uniformity
- To achieve high throughput, high uniformity on large area substrates, meniscus (blade) coating was applied

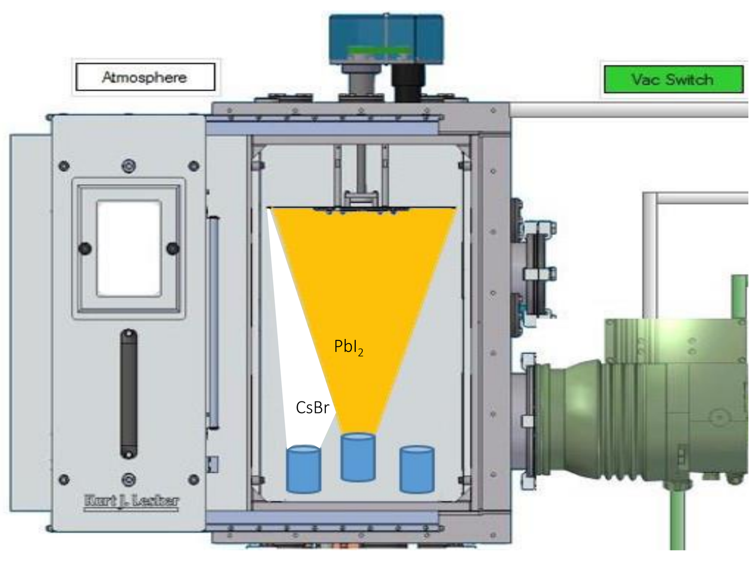


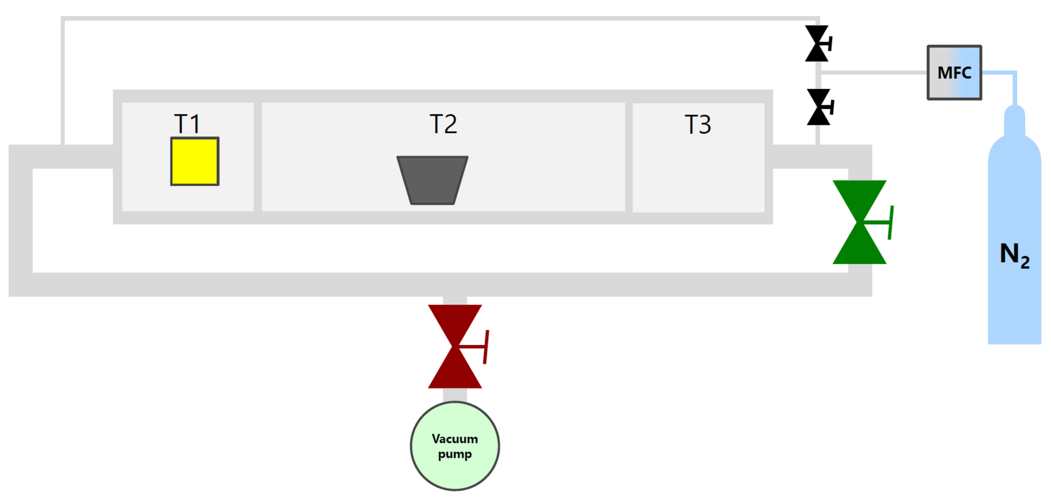




Fully laser interconnection, single junction mini-module on 10x10 cm² substrate by blade coating

- A scalable hybrid evaporation-CVD technique has been developed
- First a CsPb(I,Br) template is evaporated under high vacuum
- An organo-halide component (e.g. FAI) has then to be incorporated to form the photoactive perovskite
- This can be done by either spin-coating from a solution or a CVD-like technique

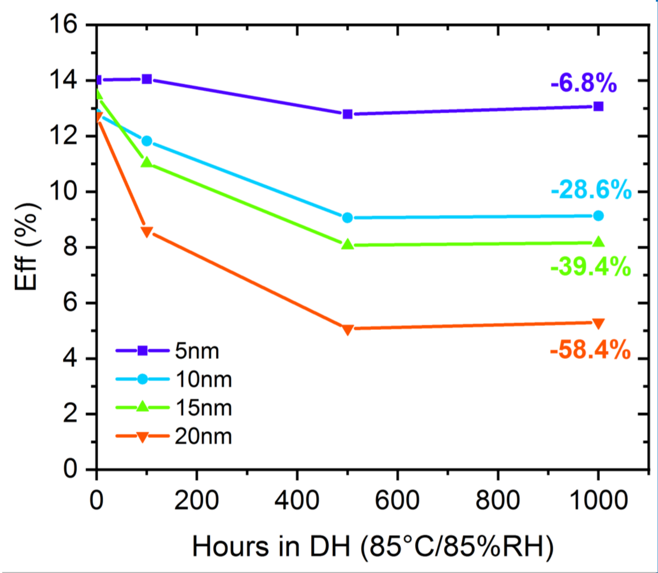


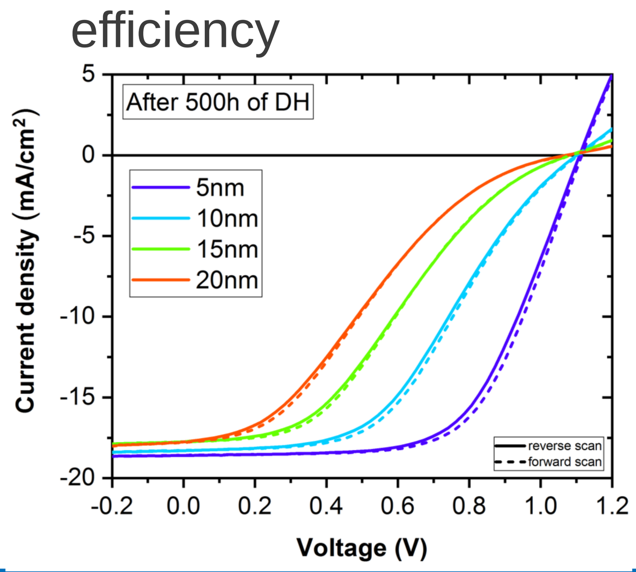


- A custom CVD reactor was developed in the form of a multizone tube furnace with reversible carrier gas flow for a fine control of the heating and deposition steps (see also Poster 6 by S. Siegrist *et al.*)

Accelerated aging of PK cells

- Charge extracting layers are found to play a crucial role in the long-term stability of PK cells
- Here we vary the thickness of the NiO hole transporting layer
- The encapsulated devices are subjected to accelerated aging for 1000h
- A clear trend is observed, with the thinner NiO device losing less than 10% relative efficiency

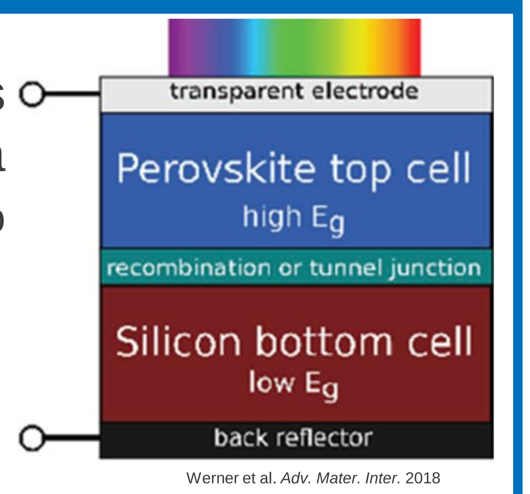


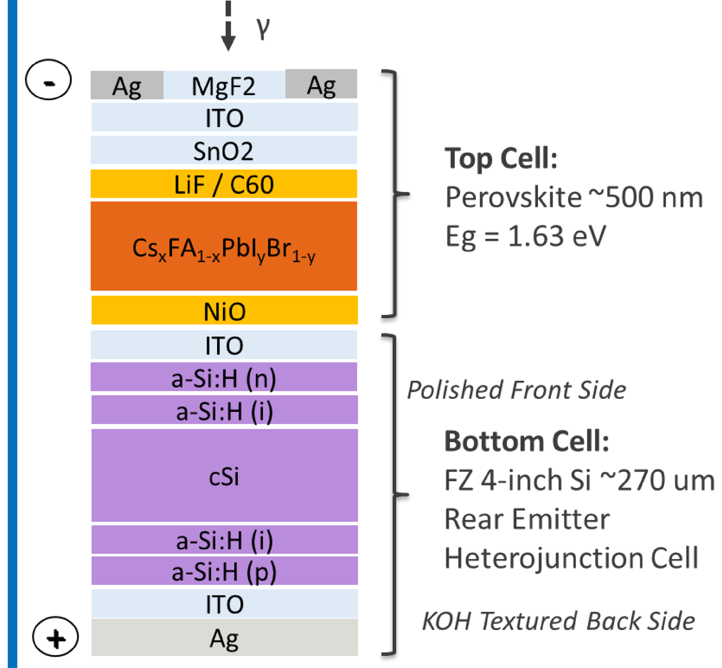


- An extraction barrier is building at the interface between PK and NiO due to a band misalignment, creating an s-shape
- M. Dussouillez *et al.*, Manuscript in preparation

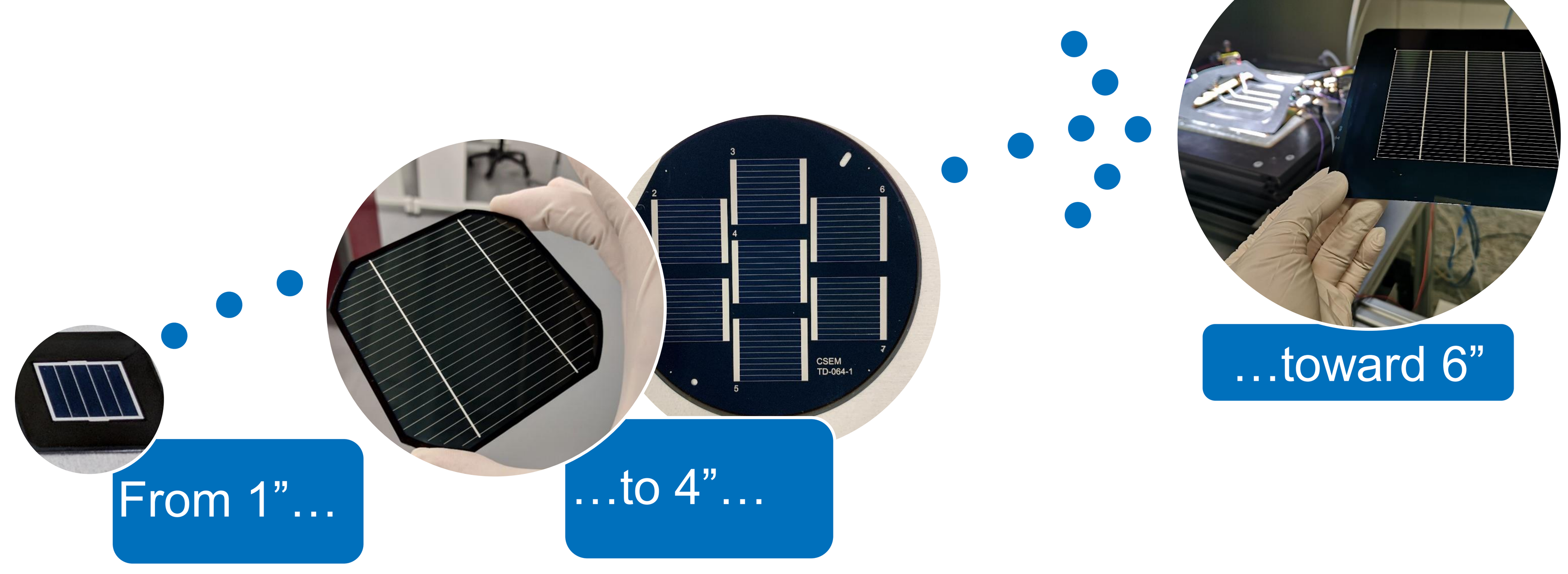
PK/Si tandems: towards industrialization

- Perovskite on low-bandgap absorbers (such as CIGS and Si) tandem devices are seen as a promising way of bringing PV across the 30% PCE limit by limiting thermalization losses

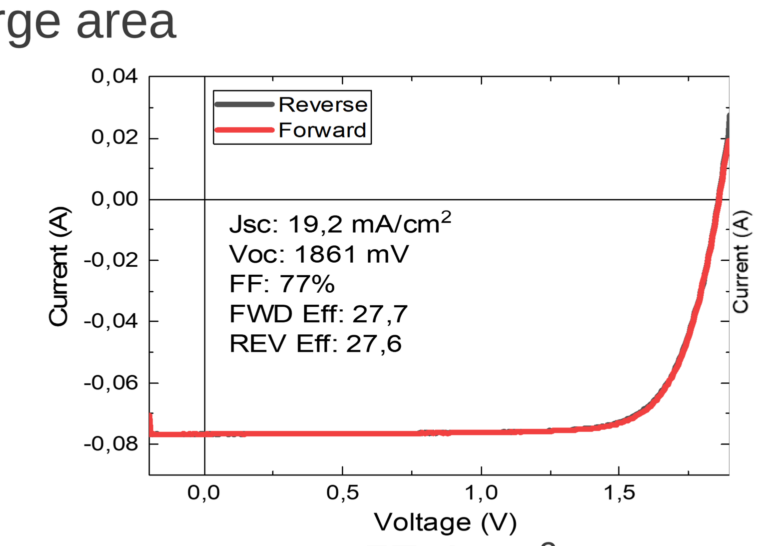




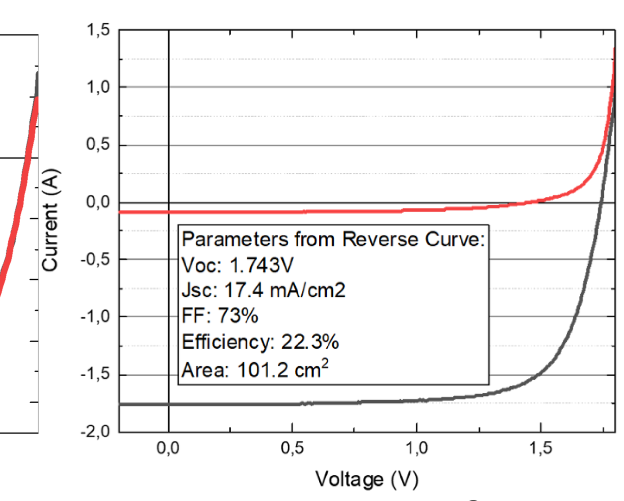
- Si Heterojunction is used as bottom cell
- Excellent passivation of bottom cell provides high V_{OC} and good NIR response
- Top cell absorber is deposited by solution processing (spin-coating or blade coating) or hybrid evaporation + solution



- POWER provides a platform for the development of industry relevant processes for the contacting of tandem devices
- Screen printing of industrial low-temperature silver paste was demonstrated to achieve very high efficiency on record breaking large area

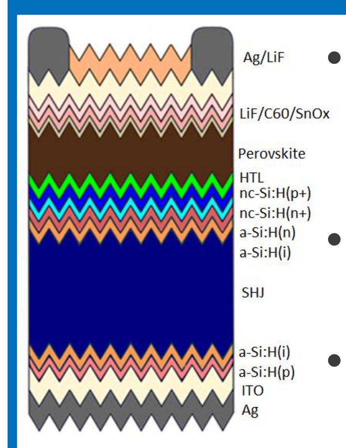


57.4 cm²

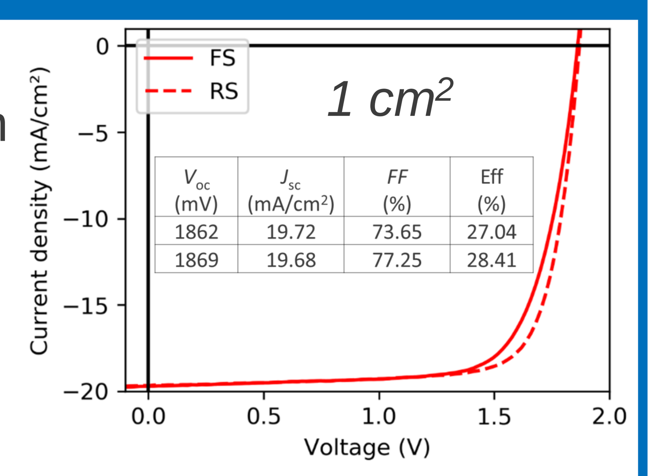


101.2 cm²

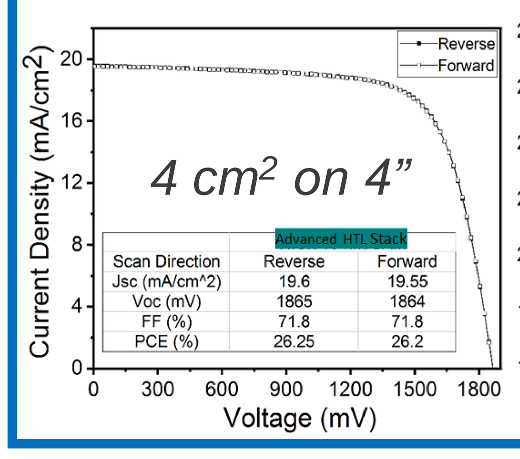
Textured tandems: potential unlocked



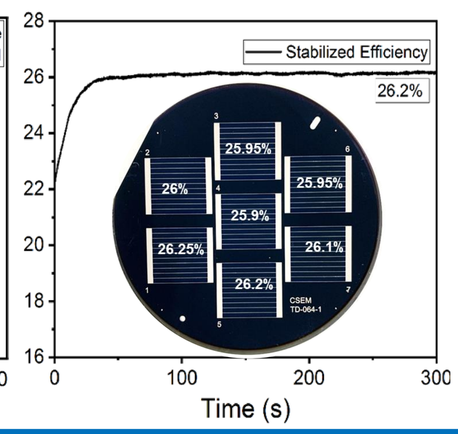
- To unlock the true potential of tandems, a fully textured bottom cell should be used
- Only a process based on vapor deposition is suitable
- With optimized contacts: record efficiency!



V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)	Eff (%)
1862	19.72	73.65	27.04
1869	19.68	77.25	28.41



Scan Direction	Reverse	Forward
Jsc (mA/cm^2)	19.6	19.55
Voc (mV)	1865	1864
FF (%)	71.8	71.8
PCE (%)	26.25	26.2



- Ready for scaling: 4 cm² cells show minor efficiency loss
- Outstanding homogeneity over full 4" wafer

This work has received funding from SNF Bridge project POWER (No. 20B2-1_176552)

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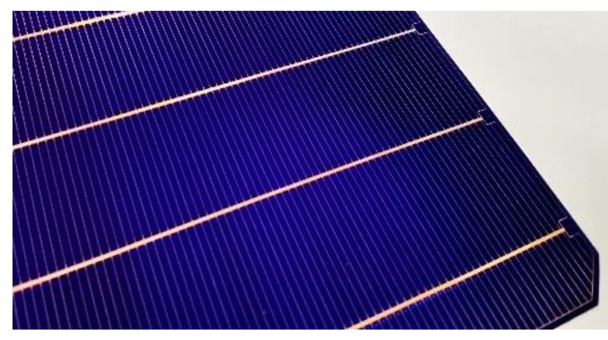
FNSNF

ANR

REPLACEMENT OF SILVER BY COPPER

FOR METALLIZATION OF HETEROJUNCTION SOLAR CELLS



A. Lachowicz, G. Andreatta, N. Blondiaux, J. Gay, N. Badel, A. Faes, C. Allebé, A. Descoeudres, B. Paviet-Salomon, S. Nicolay and C. Ballif
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Too Much Silver Needed for All the PV to Come

Only a small amount of silver is required for one solar cell, around 80 mg. But for the current global solar cell production of 150 GW this adds up to more than 2000 tons per year, more than 10% of the entire annual silver supply.[1]
And the production grows rapidly. Terawatt scale volumes are postulated already for 2030! [2]

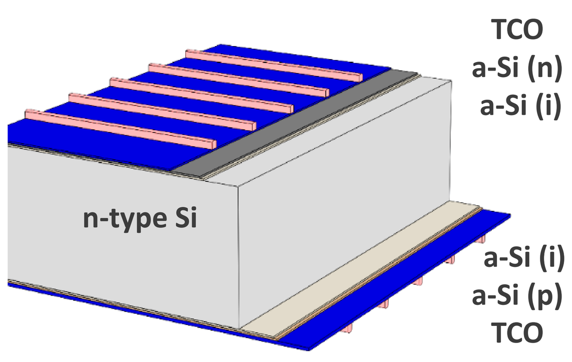
Even with strongly reduced silver consumption per cell, thousands of tons of silver would be needed for PV production in the terawatt range.
10 000 tons of silver will be required for annual production of **1.5 Terawatt** (calculated with 50 mg silver and with 7 W per cell).

2000 TONS of SILVER for 150 GW annual production

The global cumulative PV capacity has reached 600 GW. In order to reach zero CO2 emissions in 2050 altogether 70 TW solar capacity need to be installed worldwide.[3] This is about 100 times more than available now!

The silver price has increased by 50% last year. Replacement of rare and expensive materials will be mandatory to avoid material shortage and to ensure fast growing PV production at continuously decreasing cost.

Heterojunction Cells

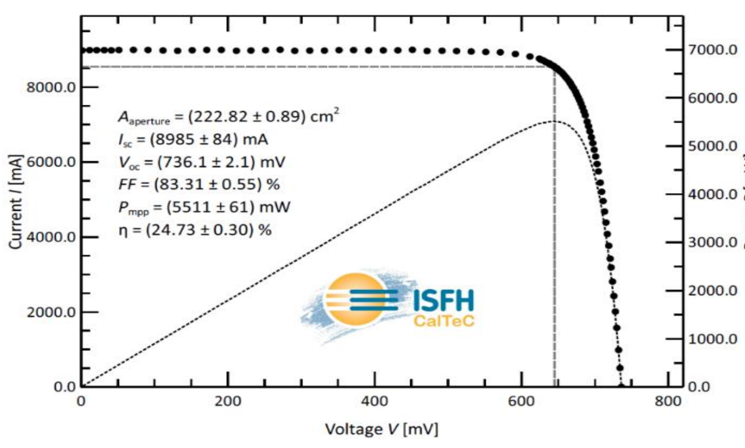


Heterojunction cells are symmetrical and intrinsically bifacial, with layers of amorphous Si and a TCO – thin conductive oxide on both sides. Beside high efficiency and a simple processing sequence, with all processes at low temperature, the structure offers an important advantage for copper metallization: TCOs are excellent barriers against copper diffusion.[4] This makes heterojunction cells resistant against copper ingress and the perfect structures for copper metallization.

Heterojunction and cells with tunnel oxide and polysilicon passivation are considered the next mainstream technologies. Since replacement of silver by copper will be crucial for growing PV production, the particular suitability of heterojunction cells for copper metallization could be an important point for the choice of the future cell technology.

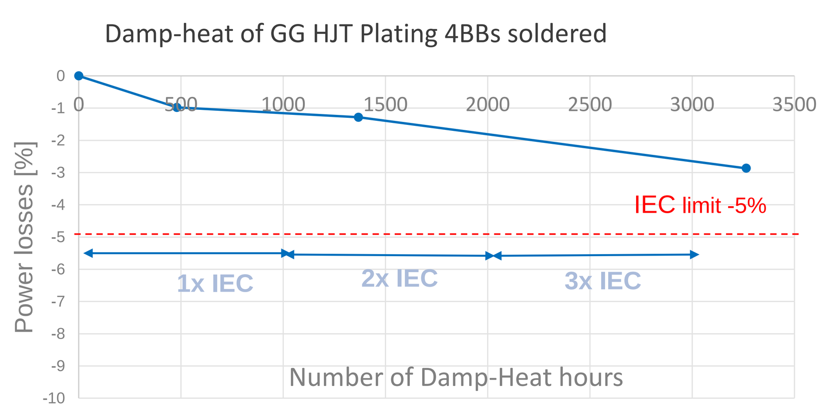
Reference Copper Plating Process at CSEM

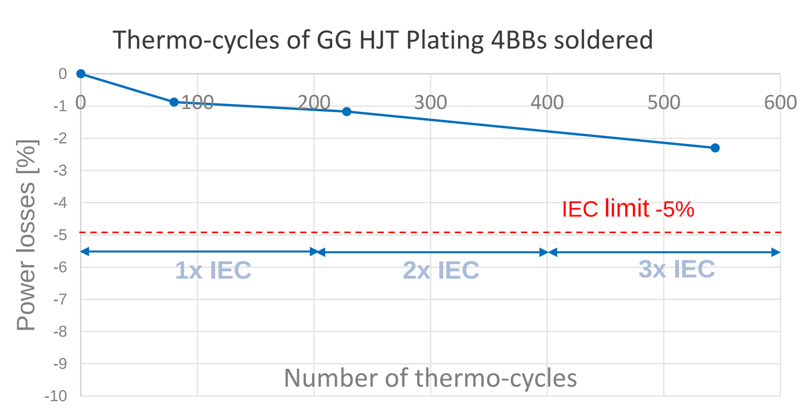
Process with a sputtered metal seed layer and patterning by inkjet printing of an organic mask. High efficiency >24.7% achieved on industrial heterojunction cell precursors.
The process offers cost advantage over silver screen printing and has been tested on industrial equipment for implementation in production by a cell manufacturer.



EXCELLENT MODULE STABILITY > 3x IEC NORM

1-cell modules tested with SmartWire Interconnection and cells with pure copper seed layer, sputtered directly on TCO. The excellent module stability confirms the resistance of heterojunction cells against copper ingress. For interconnection with soldered ribbons cells with an additional adhesion layer have been used, because of higher requirements on adhesion.

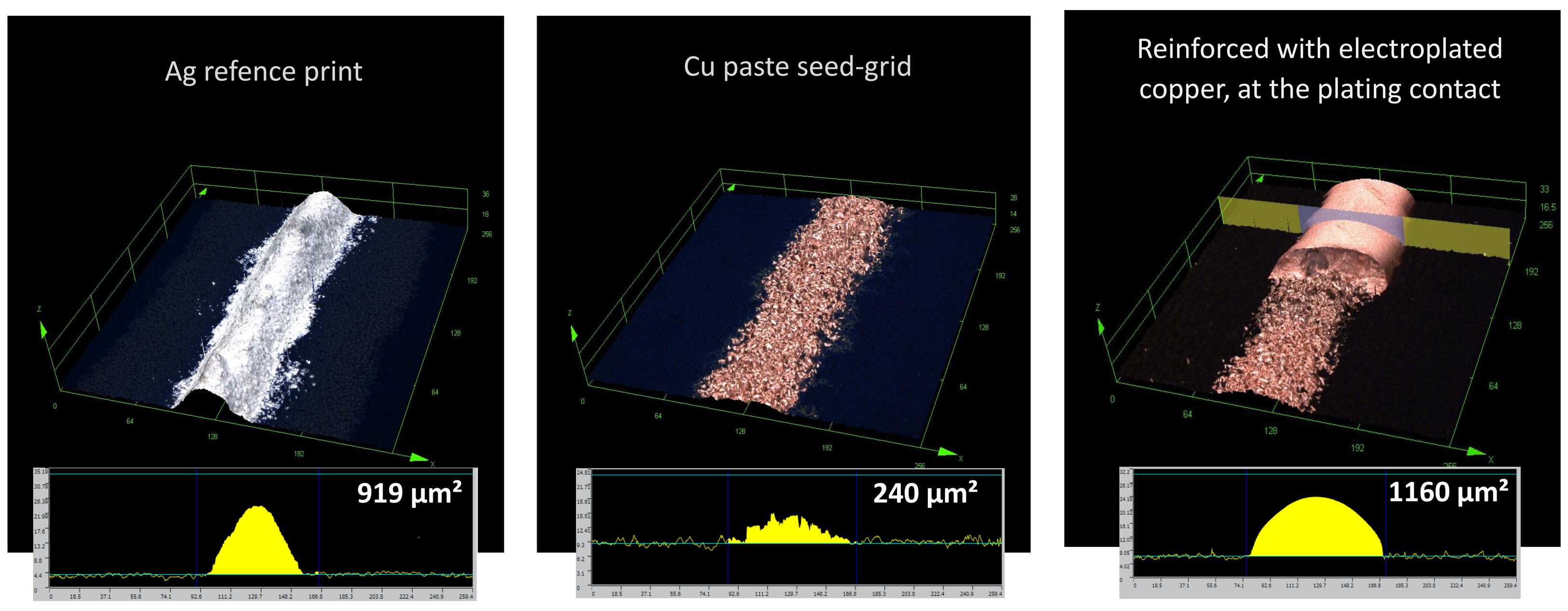




Replacing Silver by Copper

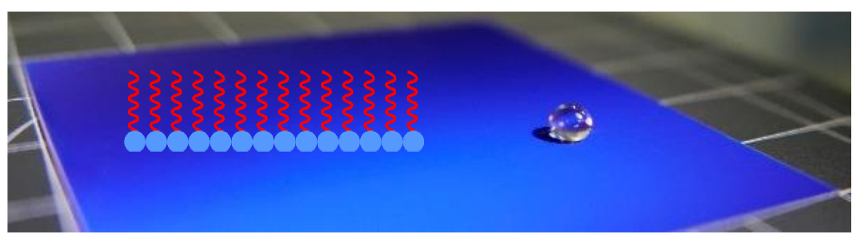
The standard method for the formation of metallization grid lines on crystalline silicon solar cells is screen printing of a silver particle paste.

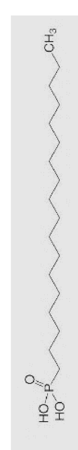
Simply replacing the silver paste by copper paste leads to low cell efficiency. The resistivity of printed copper paste is too high. The lines are therefore reinforced with an electrodeposited copper layer.



	Ag paste	Cu paste	Cu plated	
Specific resistivity	5.3	**27**	**2.0**	**[µΩ·cm]**
Line resistance per length unit (40 µm screen opening)	1.5	**95**	**0.3**	**[Ω/cm]**

The surface of heterojunction cells is conductive and after seed-grid printing an insulating plating mask is deposited. It is either an inorganic dielectric layer, like Al_2O_3 or SiO_xN_y, or so called self-assembling molecules (SAMs). The mask enables copper deposition selectively only on grid positions.





C18-PA

Phosphonic acids like octadecyl phosphonic acid (C18-PA) form a covalent bond to ITO and the hydrocarbon chains form a well-ordered monolayer. This monolayer is highly hydrophobic and protects the wafer surface against strongly acidic copper electrolyte solutions.

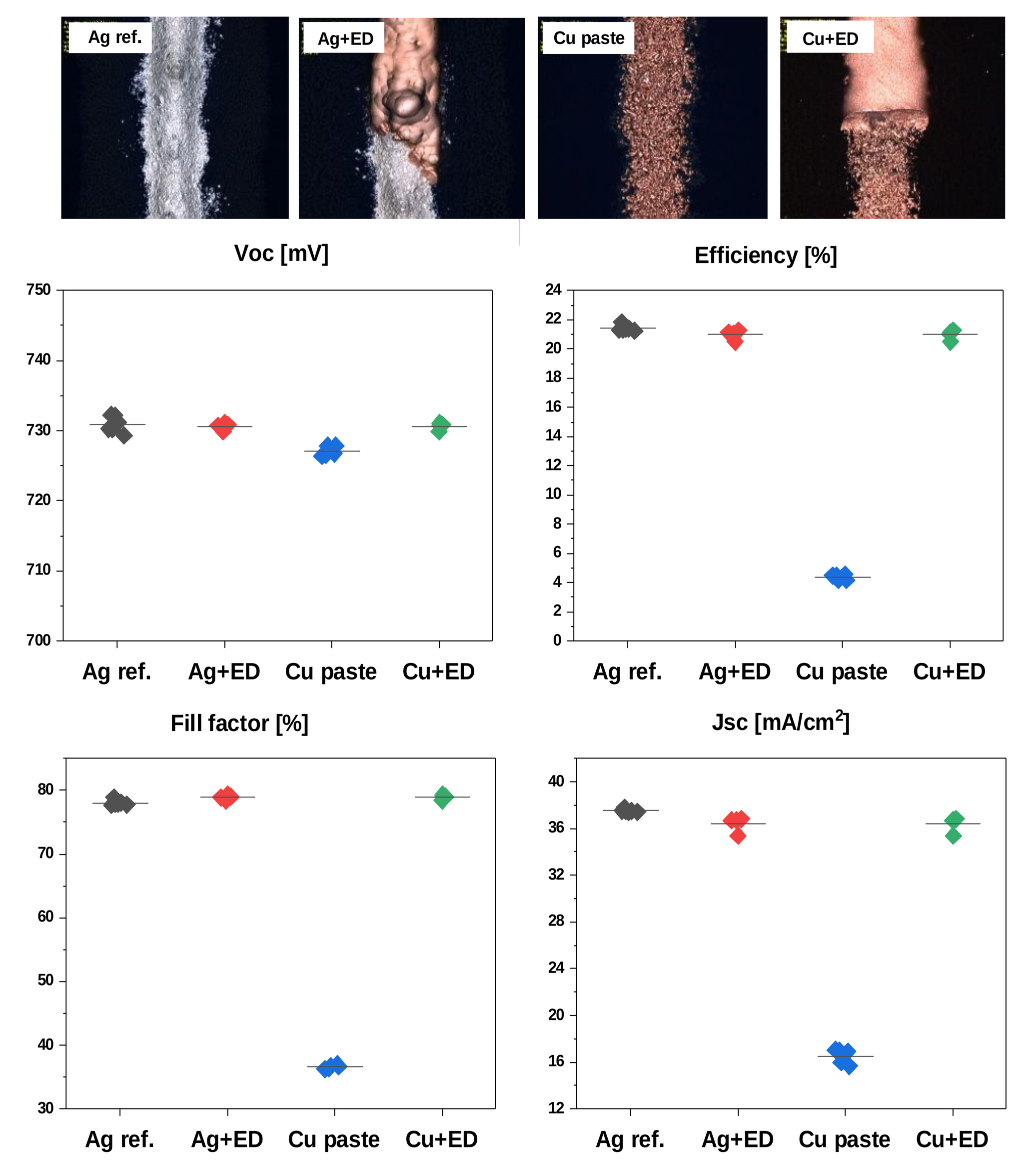
Inorganic dielectric layers are 10-100 nm thick, a SAM layer is only 2 nm thick. The SAM consumption per wafer is ~5 mg. These layers enable enormous material savings for high volume production compared to standard technology: a standard organic mask is 20-25 µm thick and the consumption per wafer is in the range of 1 g.

CELL EFFICIENCY COMPARISON

With copper paste alone the efficiency drops to below 5% (4-busbar-layout on M2 wafers). But after reinforcement with electrodeposited copper all cell parameters reach the same level as the silver reference.

Printing and annealing of copper paste directly on TCO (ITO) does not impair the cell performance.

The process is short and simple: screen printing, mask depositon and electroplating. Additional equipment would be necessary only for mask deposition and for plating. Beside the lower material consumption also the upfront investment is lower compared to the reference process.



ED = electrodeposited copper

WE THANK THE SWISS NATIONAL SCIENCE FOUNDATION SNF AND THE FRENCH NATIONAL RESEARCH AGENCY ANR FOR FUNDING THE AMELIZ PROJECT

GRANT AGREEMENT NUMBER 200021L_182101

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[1] The Silver Institute, "World Silver Survey 2020"; https://www.silverinstitute.org/wp-content/uploads/2020/04/World-Silver-Survey-2020.pdf
[2] P. Verlinden, "Future challenges for photovoltaic manufacturing at the terawatt level", J. Renewable Sustainable Energy, 2020
[3] Energy Watch Group and Lappeenranta University, "Global Energy System Based on 100% Renewable Energy", 2019; http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf
[4] C. Liu et al., «ITO as diffusion barrier between Si and Cu», Journal of the Electrochemical Society, 2005
[5] A. Lachowicz et al., «Project Ameliz: Patterning Techniques for Copper Plating»; http://www.metallizationworkshop.info/fileadmin/metallizationworkshop/metallization2020/presentations/4.1_MIW2020_Lachowicz_CopperPlatingHJT.pdf

Perovskite solar cell research at the Laboratory for Thin Films and Photovoltaics

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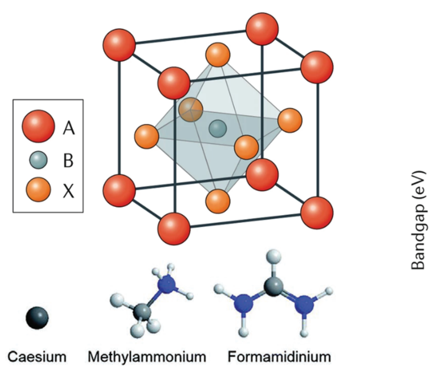
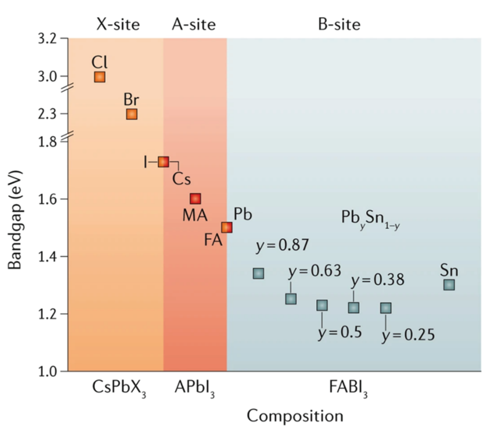
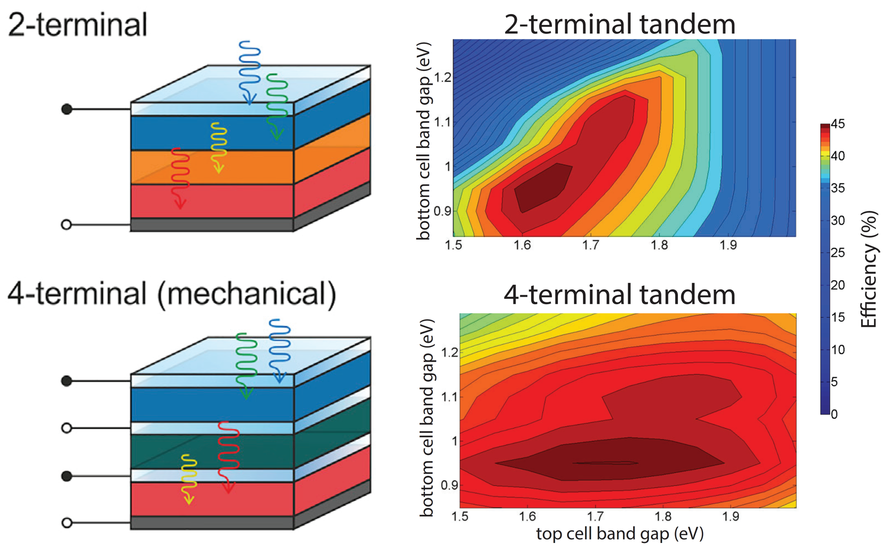
Empa
Materials Science and Technology

Perovskite research focus

Organic-inorganic metal halide perovskites







What are perovskites?

- Perovskite refers to ABX_3 crystal structure.
- It is a class of semiconductor materials with excellent opto-electronic properties for photo-voltaic applications, etc.

What is the uniqueness of perovskites?

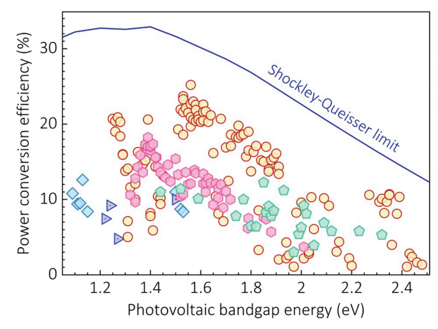
- High efficiency of 25.5 %[1]
- Broad bandgap tunability
- Solution-based fabrication, e.g. blade coating, dip coating or spin coating.

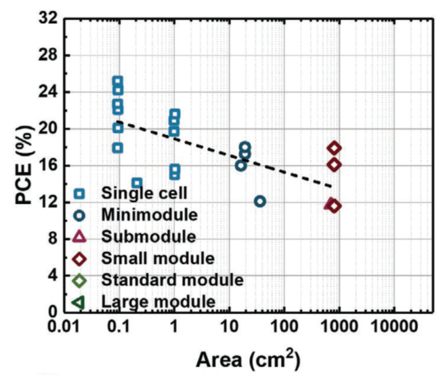
Why are we interested in perovskite?

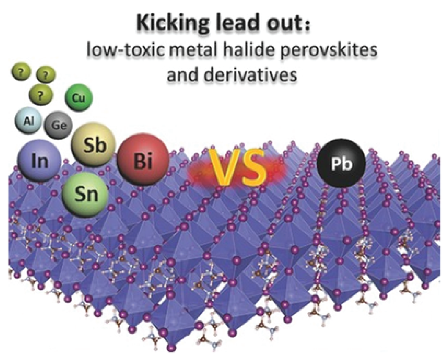
- Suitable for perovskite/silicon, perovskite/-CI(G)S or all-perovskite tandem solar cells (2-terminal, 4-terminal configuration) to break the Shockley-Queisser limit of single junction solar cells.

[1] www.nrel.gov/pv/cell-efficiency
[2] Anaya, M. et al. (2017), Joule, 1(4), pp. 769–793.
[3] Eperon, G. E. et al. (2017), Nature Reviews Chemistry, 1(12).

Challenges of perovskite solar cells







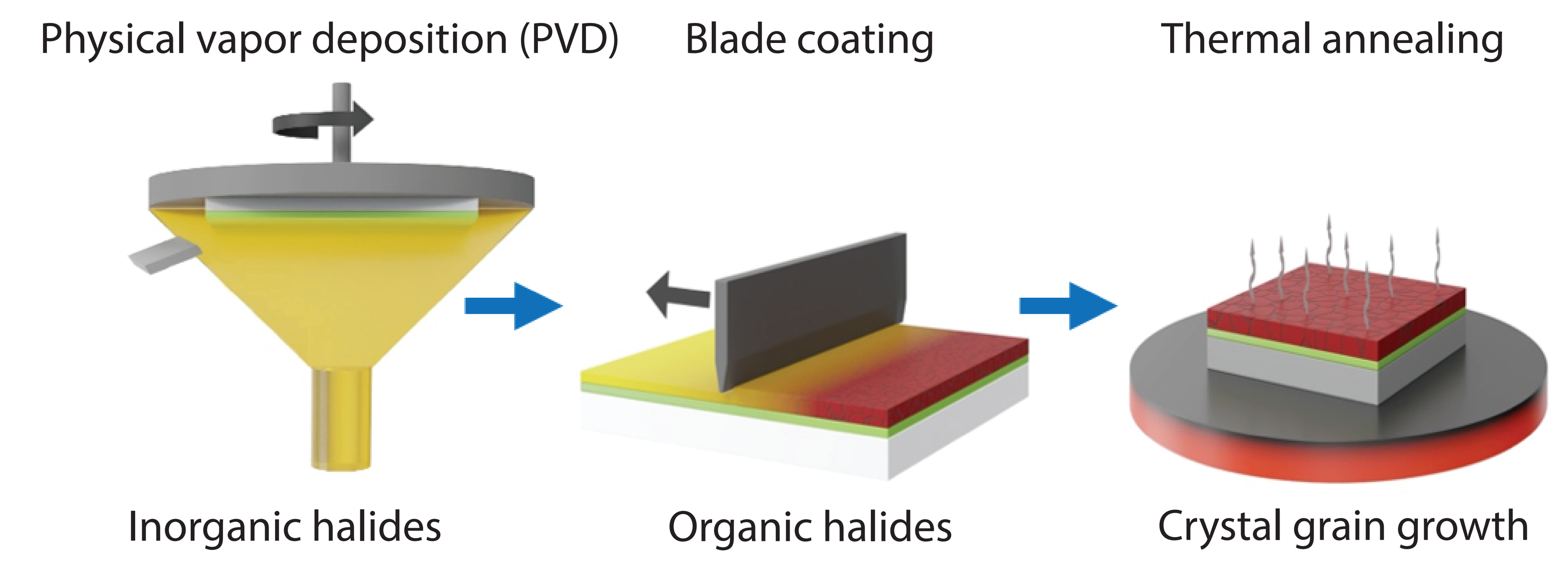
What are the challenges for commercialization of perovskite solar cells ?

- Efficiency: Our aim is to develop highly efficient near-infrared-transparent wide bandgap perovskite top cells and narrow bandgap perovskite bottom cells for all-thin film tandem solar cells.
- Upscalability: We work on scalable deposition processes to fabricate high quality and uniform perovskite absorbers with green solvents.
- Stability: Advanced characterization techniques are used to understand the mechanisms which influence the stability of perovskite solar cells.
- Lead toxicity: Lead-free perovskite solar cells are developed for flexible all-perovskite tandem solar cell applications.

[1] www.emerging-pv.org
[2] Lee, S. W. et al. (2020), Advanced Materials, 32(51), pp. 1–25.
[3] Lyu, M. et al. (2017), Advanced Energy Materials, 7(15).

Perovskite results

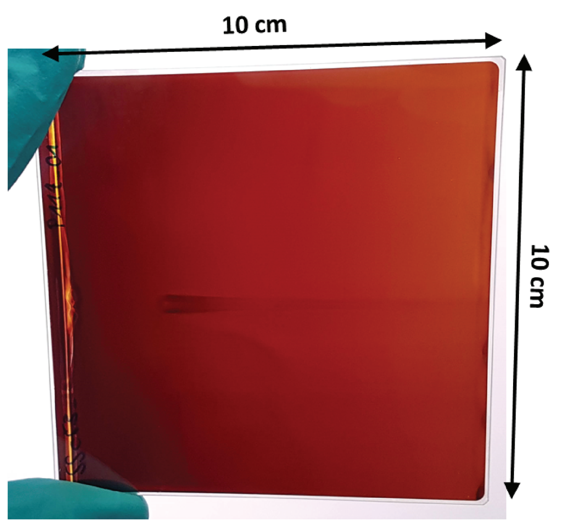
Physical vapor deposition and blade coating

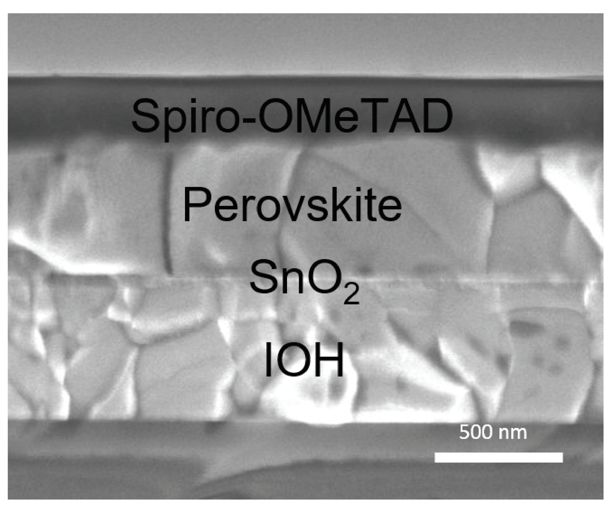


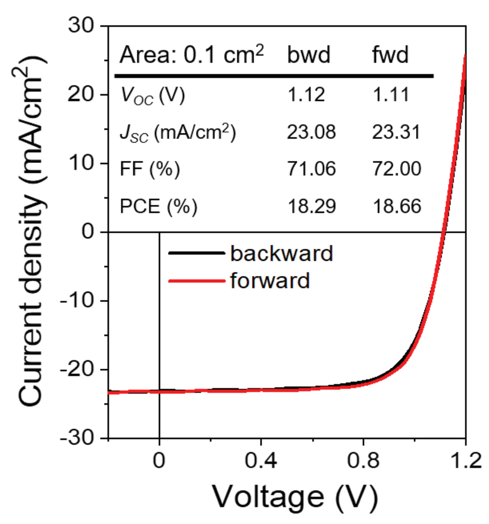
Advantages:

- Perovskite absorber fabricated by industrial-scalable depositions only
- Only green solvents are needed (2-propanol)
- Uniform deposition on large-area substrates
- Suitable to conformally coat rough surfaces, e.g. textured silicon or CI(G)S solar cells

Scalabe perovskite solar cells with green solvents



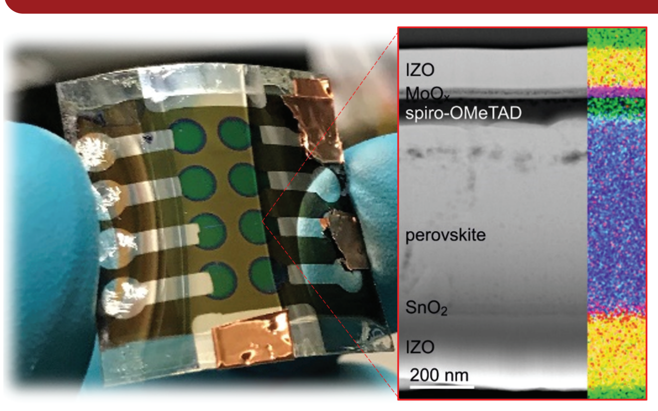


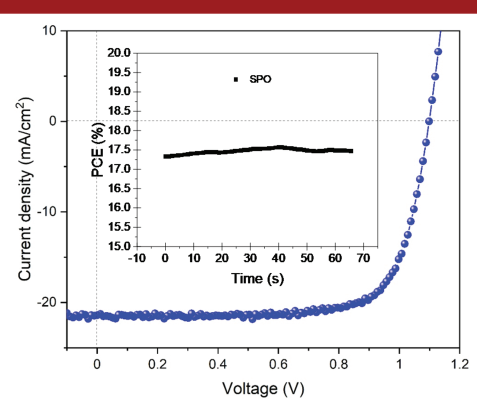


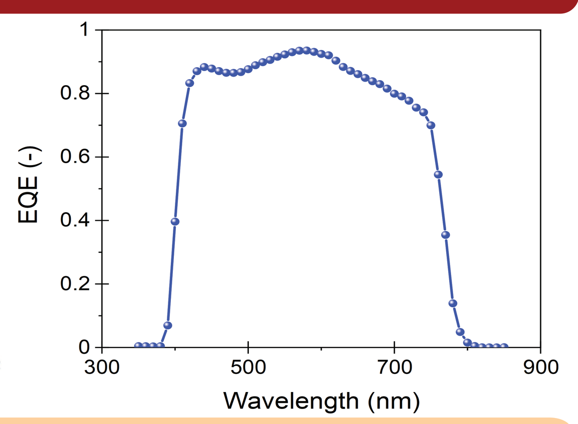
Main achievements:

- Efficiency > 18 % for perovskite solar cell on 5 x 5 cm² substrates
- Perovskite absorber fabricated by PVD and Blade coating
- Both charge transporting layers are blade coated
- Green solvents used: 2-propanol (perovskite), p-Xylene (Spiro-OMeTAD), water (SnO_2)

Flexible semi-transparent perovskite solar cells

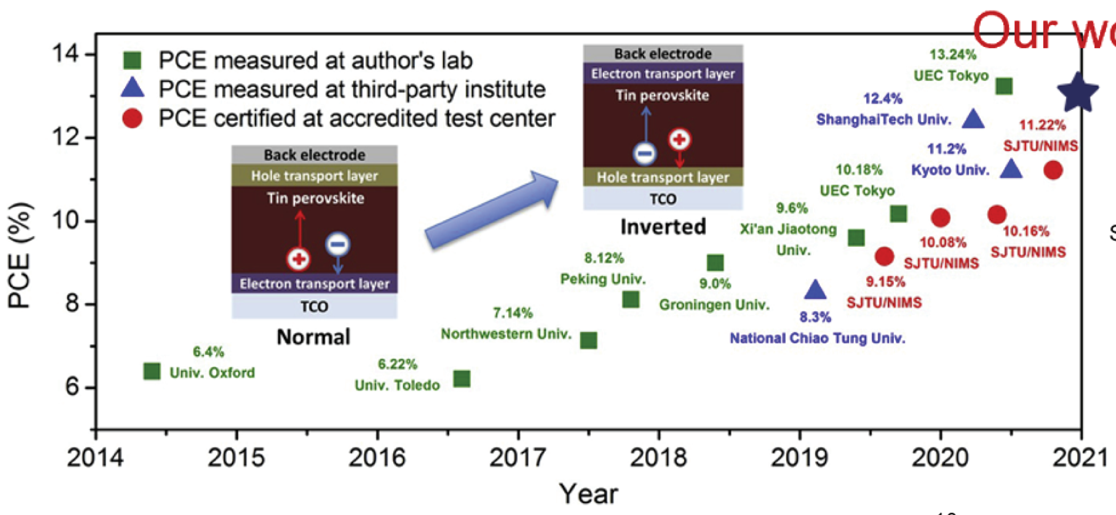


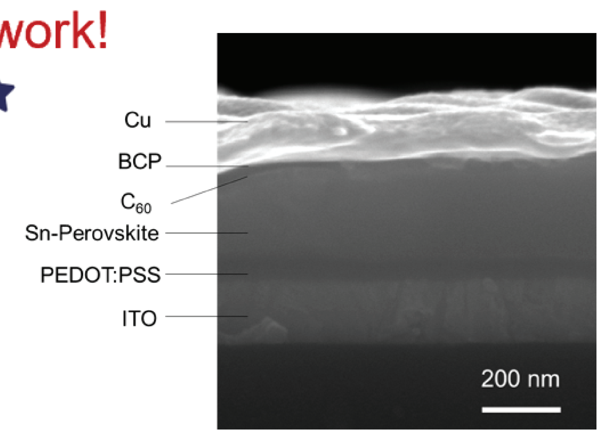


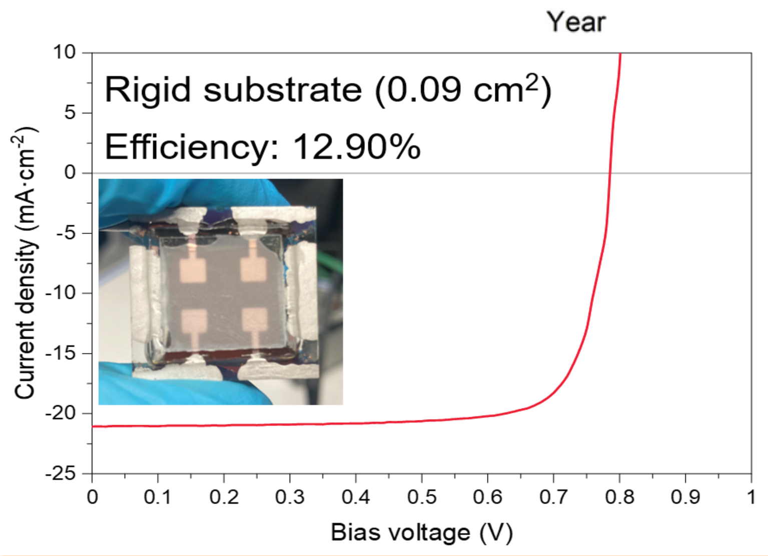


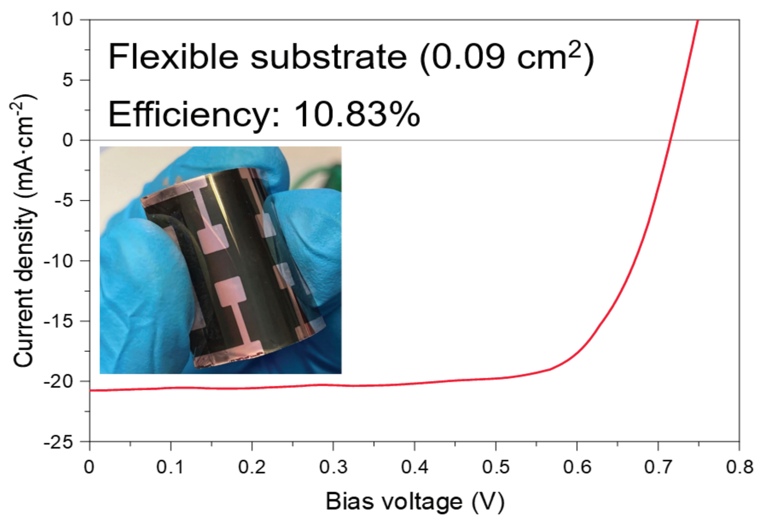
- Flexible near-infrared-transparent PSC with stabilized 17.5 % efficiency on CIGS frontsheet.
- Can be used for perovskite/CIGS tandem solar cells.

Lead-free perovskite solar cells





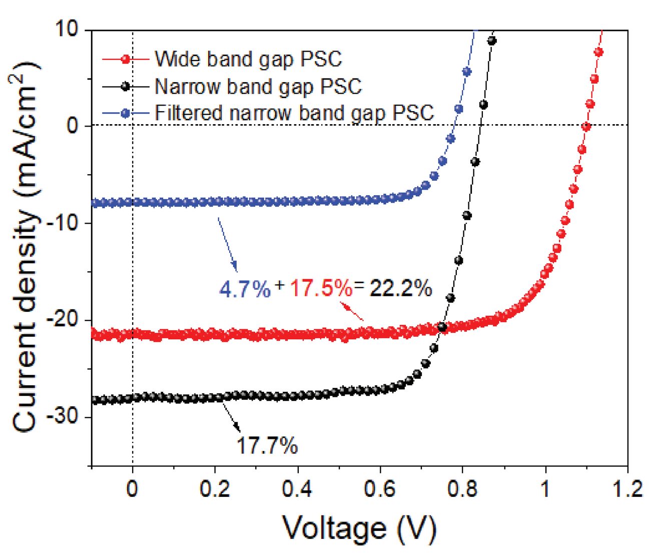


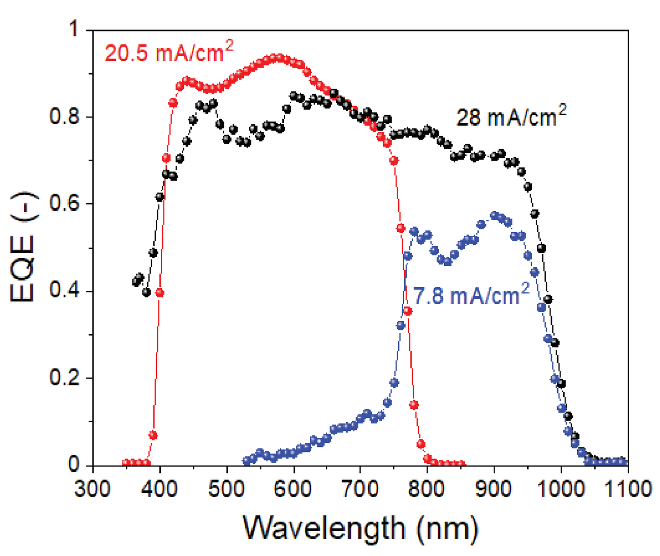


- One of the best efficiencies (12.90 %) realized for Sn-based PSCs on rigid substrates.

Pb-Sn perovskite for flexible all-perovskite tandems

- Efficiency: 18.75 %
- Cell area: 0.09 cm²





- Best cell efficiency: 18.75 % for 1.24 eV bandgap perovskite solar cell.
- Flexible 4-terminal all-perovskite tandem solar cell with 22.2 % efficiency.

Summary

- PVD and Blade coating is an industrial-scalable perovskite fabrication process without toxic solvents.
- 18.6 % efficient perovskite solar cell by fully scalable deposition methods and green solvents.
- Lead-free pervskite solar cell with 12.9 % efficiency on rigid and 10.8 % on flexible substrates.
- Narrow band gap perovskite solar cell on flexible substrates with 17.7 % efficiency.
- Flexible, near-infrared-transparent wide band gap perovskite solar cell with 17.5 % efficiency
- 22.2 % efficient 4-terminal all-perovskite tandem solar cell on flexible susbstrate.

Acknowledgement

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Contact

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Thin-film Cu(In,Ga)Se₂ for flexible and lightweight photovoltaic applications

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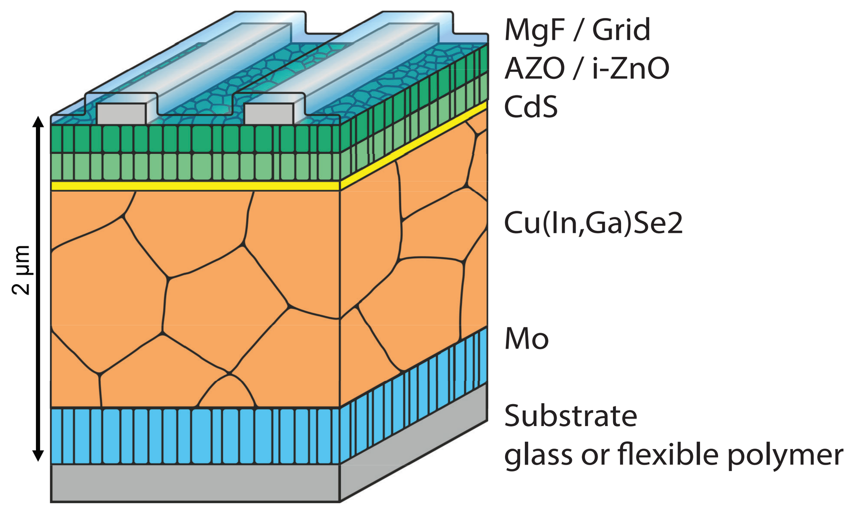
Empa
Materials Science and Technology

Research Focus

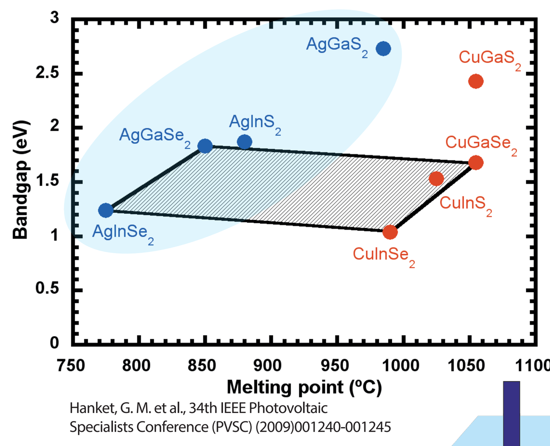
High performance $Cu(In,Ga)Se_2$ (CIGS) solar cells on flexible substrates

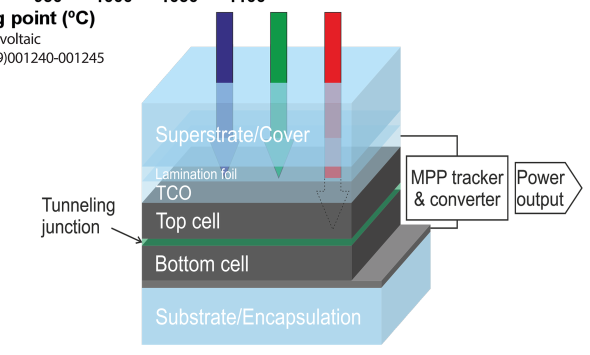


Advantages:
- Flexible, light weight (<2 kg/m² commercially available)
- Roll-to-roll processing
- Uniform appearance
- BIPV, mobility applications

Selected research activities

- High performance single junction devices
  - Process tailoring: composition, gradients, interfaces, doping
  - Flexible substrates
- Robust manufacturing processes
  - Relaxed processing requirements
    Thermal budget, process control, etc.
  - Simplified manufacturing processes
    Co-evaporation, doping, etc.
- Bottom cell for tandem devices
  - Low bandgap (1.0 eV for current matching)
  - Reduced surface roughness

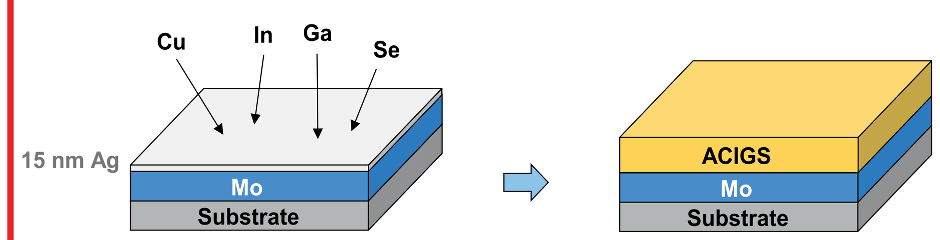




Results

Lower deposition temperatures

Modified deposition process:
Precursor layer before coevaporation



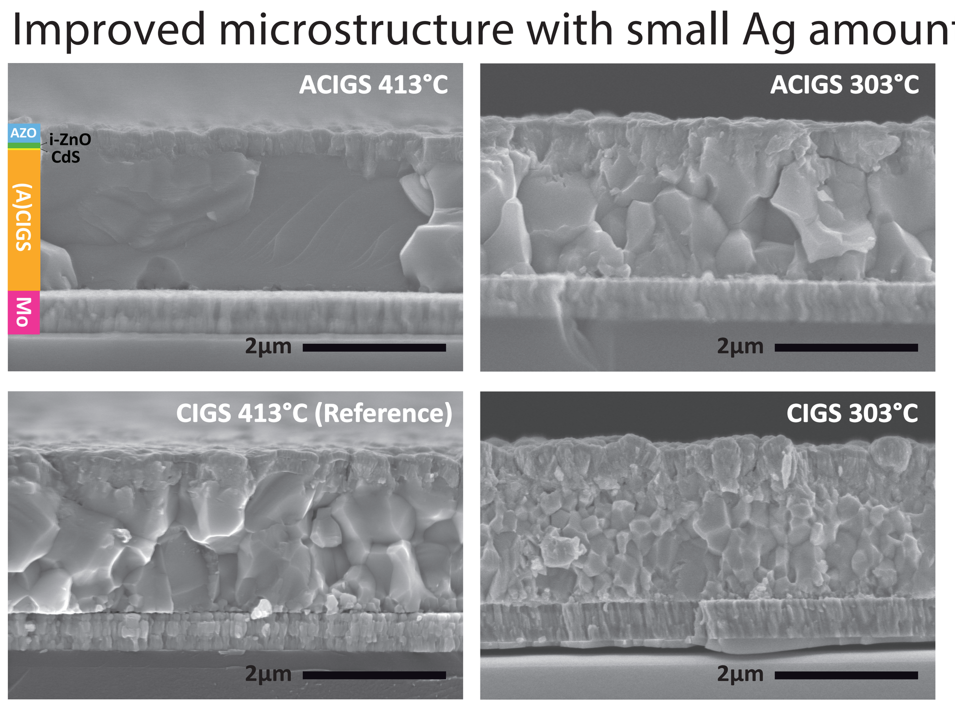
WHAT ARE WE INTERESTED IN ?

Robust processes, drastically reduced deposition temperatures

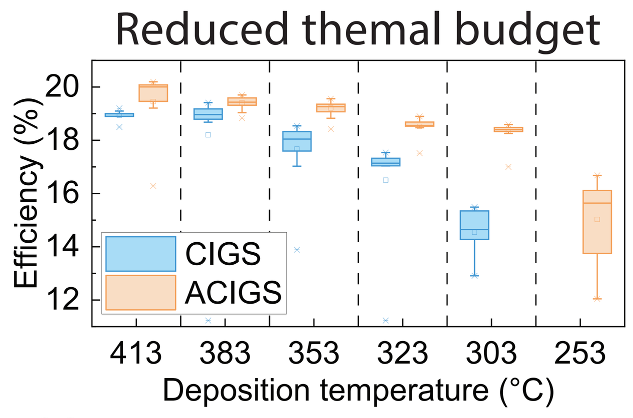
High performing devices

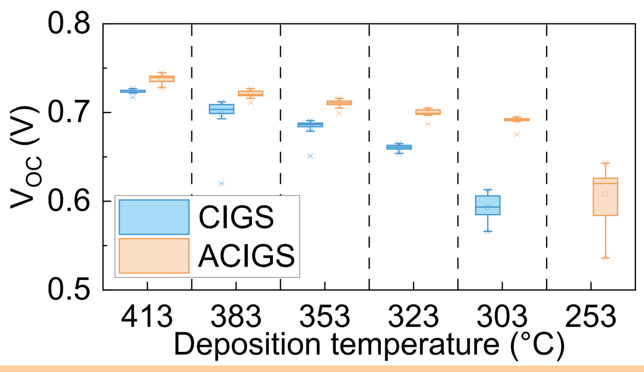
Possible new devices architectures

Improved microstructure with small Ag amount



Wider processing window
Reduced themal budget





- Improved morphology, larger grain size, increased efficiency
- Reduced thermal budget, wider process tolerances (T, dopants)
- Minimal requirements on hardware change

New efficiency record on flexible solar cells

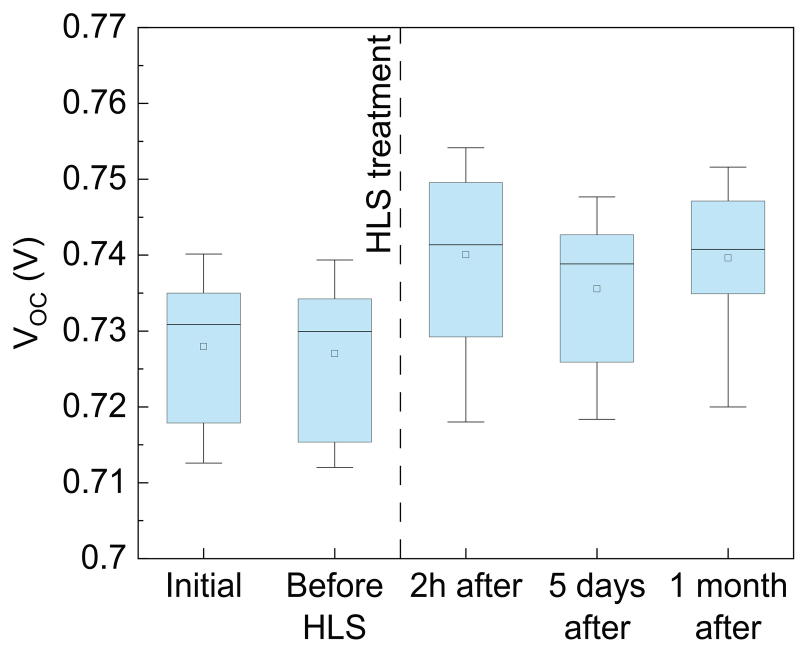
Thermal treatment on finished devices (heat light soaking)

- Improvements stable for months
- Evaluating industrialisation of findings

WHAT ARE WE INTERESTED IN ?

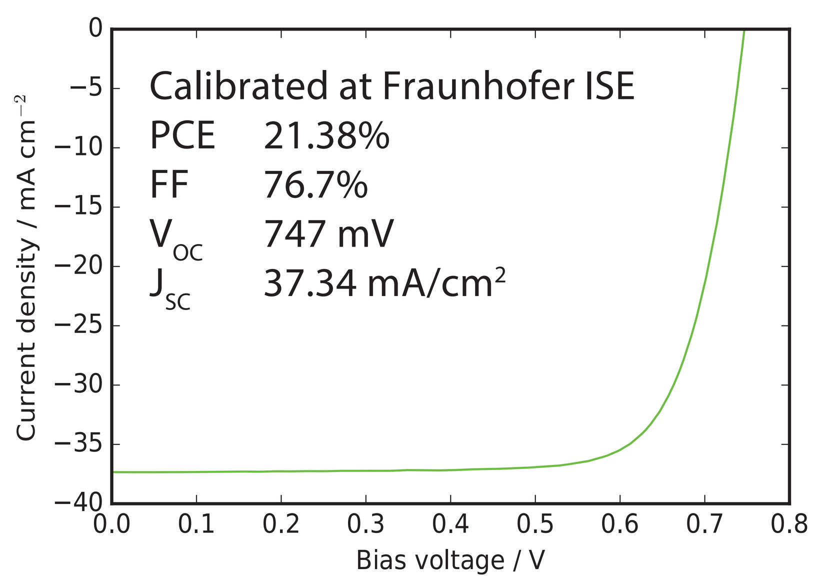
High power conversion efficiency for
- Increased energy production
- More profitable PV installations

Demonstrate technology potential



Increased device efficiency
- Increase in V_{OC} (higher doping density)
- Stable or slight improvement in FF, J_{SC}
- Slight negative impact on non-rad. recomb.

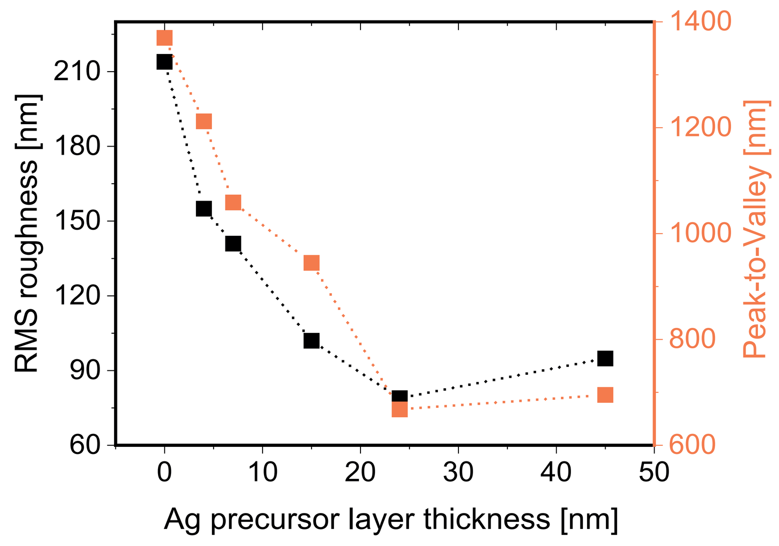
New record flexible CIGS solar cells



- New record efficiency: 21.4% for CIGS on flexible substrate
- Thermal treatment for :
  - improved V_{OC}
  - increased doping density

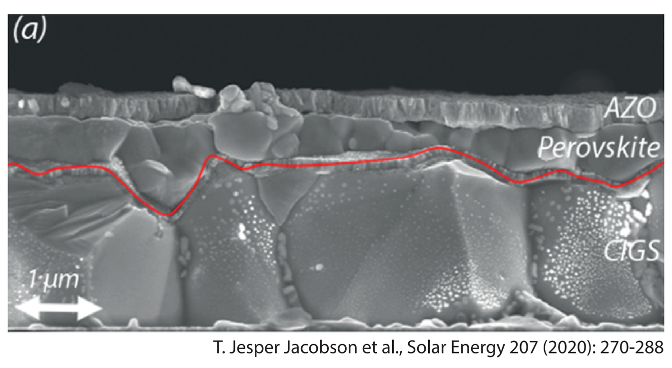
Roughness reduction for tandem device applications

Reduced surface roughness



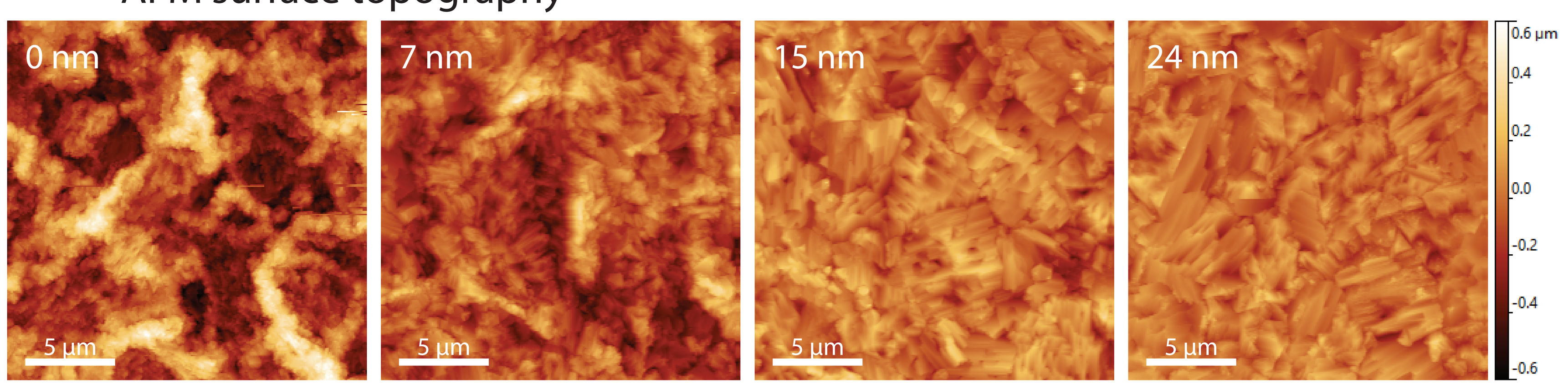
WHAT ARE WE INTERESTED IN ?

Reducing the surface roughness for 2-terminal perovskite-CIS tandem applications



T. Jesper Jacobson et al., Solar Energy 207 (2020): 270-288

AFM surface topography



- Better suitability for two-terminal tandem devices
- Facilitated conformal coverage for thinner buffer layers

Summary

- New record efficiency: 21.4% on CIGS solar cell on flexible substrate
- Modified CIGS absorbers with small Ag amount
  - Improved morphology, larger grain size for higher efficiency
  - High efficiencies retained at 100°C lower temperature than state-of-the-art (413°C to 303°C)
  - Wider processing windows (temperature, alkali)
  - Precursor layer method: minimal hardware and process modification
- Reduced surface roughness, in view of monolithic tandem devices

Acknowledgement

This work received funding from the Swiss Federal Office of Energy (SFOE) under ImproCIS project (Contract no.: SI/501614-01), the Swiss State Secretary for Education, Research and Innovation (SERI) under contract number 17.00105 (EMPIR project HyMet) and the European Union's Horizon 2020 research and innovation programme under grant agreement No 850937.

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A RADICALLY SIMPLER WAY TO MANUFACTURE THIN-FILM SOLAR PANELS ON THE SCALE-UP TO MEET FUTURE PHOTOVOLTAIC GOALS

In partnership with: Empa Materials Science and Technology

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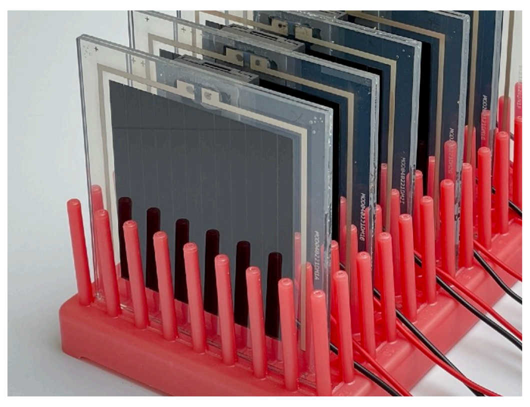
[•] Solaronix SA, Rue de l'Ouriette 129, CH-1170 Aubonne, Switzerland [*] EMPA, Überlandstrasse 129, 8600 Dübendorf, Switzerland

With the support of: Schweizerische Eidgenossenschaft, Confédération suisse, Confederazione Svizzera, Confederaziun svizra, Swiss Federal Office of Energy SFOE

WHY OUR PEROVSKITE THIN-FILM PANELS?

Photovoltaics are undeniably playing an increasing role in the transition to renewable energy sources. Consequently, solar installations are poised to grow at a staggering rate.

Solar panel manufacturing is particularly under pressure to scale up production in order to match even the most conservative photovoltaic deployment scenarios. Mainstream solar panels have seen impressive improvements in efficiency, though with increased manufacturing complexity.



Affordable solar energy for all

While cost per panel has gradually decreased, the initial investments to build production facilities remains all-time high.

Herein, we demonstrate a radically simpler way to produce stable perovskite thin-film solar panels with extremely low material usage, and industry-proven high throughput techniques.

As a result, we project that such panels will require much lower capital expenditure and achieve unrivaled production cost.

This also represents an opportunity to localize photovoltaic panel production, and hereby further reduce environmental impact.

A TECHNOLOGY THAT SCALES UP

STABLE

The solar architecture presented here rely on a ceramic-like scaffold that's hosting a perovskite absorber. This especially skips the use of the fragile organic compounds commonly employed in other perovskite solar cells, making our technology inherently stable.

Best, we have proven stability of over 11'000 hours under continuous simulated solar sunlight[1]. That is already the equivalent of over 11 years in real daylight cycles!

SCALABLE

Perovskite solar cells are certainly all the rage in scientific research, but very few could actually scale up to any meaningful device area.

Winning technologies can scale up big

Our modules are capable of retaining the same efficiency as obtained with small R&D cells. This is notably thanks to our module design that is already on par with state-of-the-art thin-film panel geometrical fill factor (>93%).

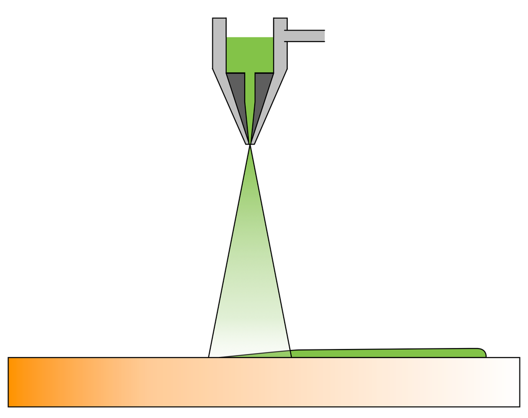
NIMBLE

Ingredients are used in very small amounts: the active component is as thin as a fifth of a human hair.

More importantly, they are only made of low-cost, abundant materials that do not threat of any supply shortage. Our devices don't employ precious metal back-contact but simply rely on a carbon layer instead.

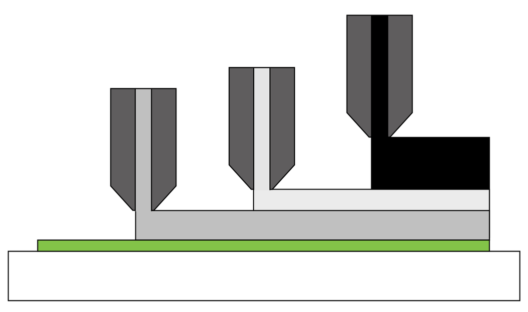
Our wet coating fabrication methods are relying on own-developed functional inks that we formulated with green solvents in the perspective of mass manufacturing.

UNRIVALED EASE OF FABRICATION



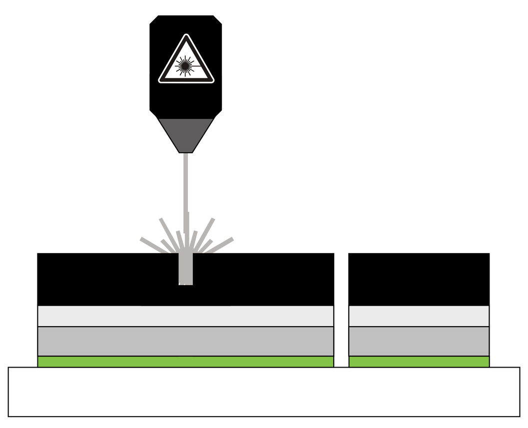
❶ *Spray coating of conductive and underlayer on float glass.*

Likewise any thin-film solar panel, the fabrication starts with a float glass that is coated with a transparent and conductive layer. In the present case, the substrate also takes an underlayer similarly to existing self-cleaning glasses.



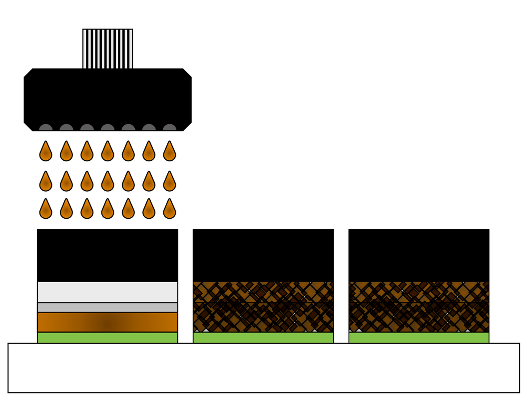
❷ *Slot-die coating of anode, spacer, and cathode layers.*

Next, the layered metal-oxide and carbon structure is deposited by means of slot-die coating[3,4], undeniably the fastest deposition method found in the industry. This is also how electric car batteries are being produced.



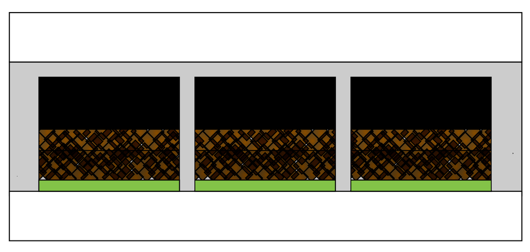
❸ *Selective laser ablation of interconnections.*

Solar cells are individualized and connected in series by selective laser ablation of the different layers. This layout commonly found in thin-film solar panels greatly reduces resistive losses and maximizes power output.



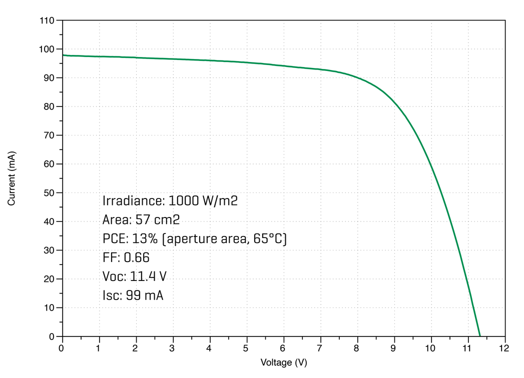
❹ *Deposition and annealing of the perovskite absorber.*

The perovskite absorber is introduced last, via inkjet deposition of a precursor solution that crystallizes upon drying. We found this digital coating method extremely clean and precise, while offering excellent device performance.



❺ *Lamination and connection with existing methods.*

Finally, the solar module is laminated with a back glass to protect it from the environment, and receives junction box and wiring just like any other solar panel technology.

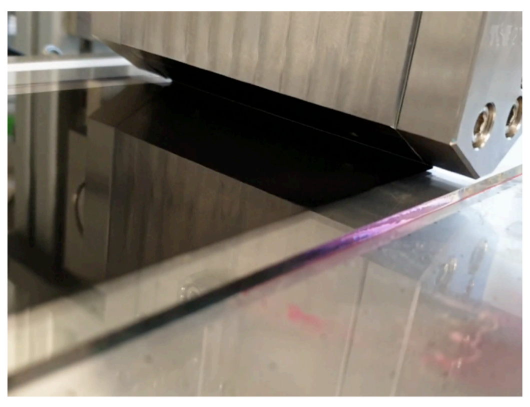


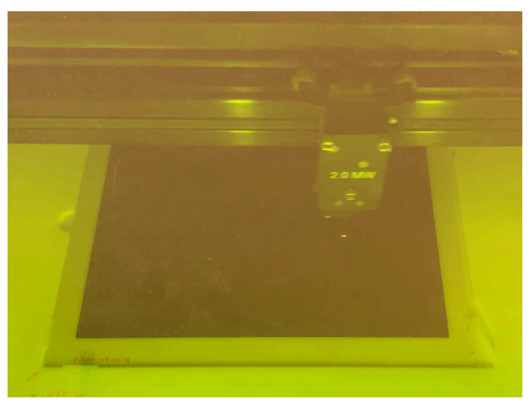
Typical current-voltage plot of a module prototype.

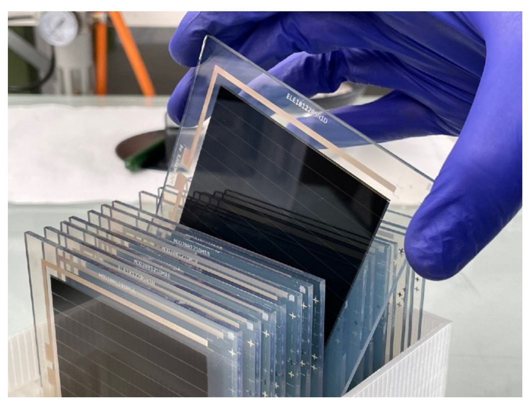
This entire fabrication relies on extremely simple manufacturing processes already being employed in other high volume industries.

A paradigm shift in PV manufacturing

All is realized in ambiant air, and does not require ingot growth nor vacuum deposition. As a result, such photovoltaic panels feature a reduced embodied energy, and a lower carbon footprint than incumbent technologies.





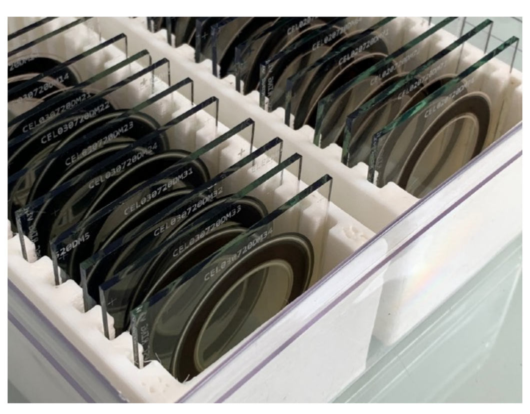


A VERSATILE TECHNOLOGY

In addition to the above fabrication path, we actually developed a host of alternative methods to choose from, depending on targeted application.

Many more options

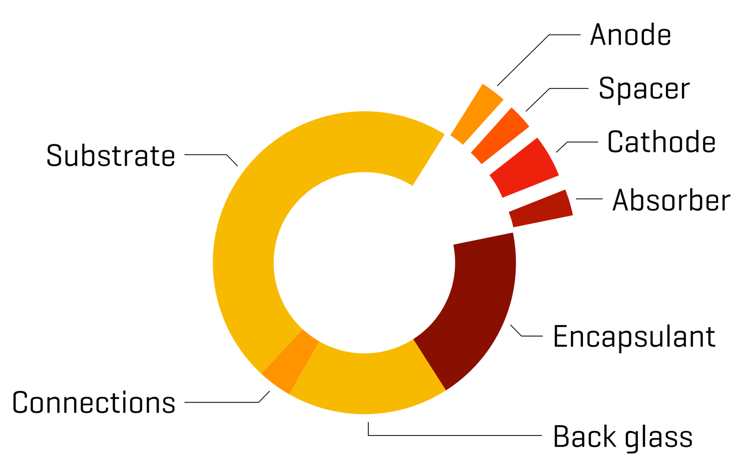
All of the ingredients could very well be casted by slot-die coating, screen-printing, or even inkjet[2].



While the first offers the highest throughput, the other two printing techniques bring interesting patterning methods, even able to replace laser interconnection patterning.

BILL OF MATERIALS

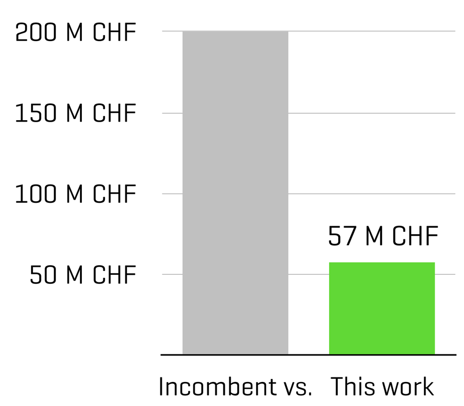
The active materials employed in our solar technology are so inexpensive that most of the bill of materials is constituted by ancillary items such as glass and encapsulant.



Total materials: 0.07 CHF/Wp

SETUP COSTS

The use of simple fabrication techniques really shines when it comes to capital expenditure. Initial investments are much reduced.

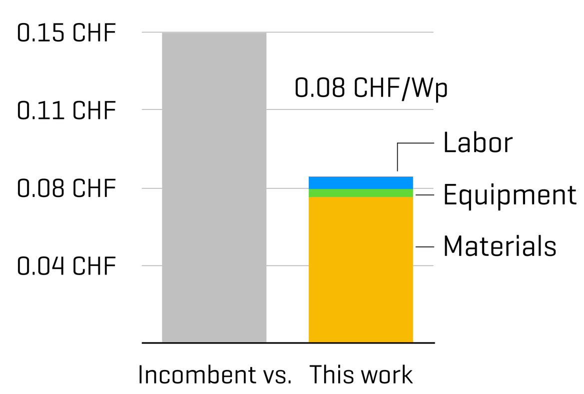


CAPEX for a 2 GWp/year facility

Slashed setup costs & halved production costs

PRODUCTION COSTS

By combining inexpensive materials and extraordinary simple fabrication techniques, we forecast production costs to almost half of incumbent technologies.



Production cost/Wp

Acknowledgment:

Specials thanks to all of the contributors to this endeavors at EMPA, and the Swiss Federal Office of Energy for their PeroPrint and UPero projects fundings.

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[1] One-Year stable perovskite solar cells by 2D/3D interface engineering, Nature Communications 2017, 8, 15684 (doi:10.1038/ncomms15684)
[2] Inkjet printed mesoscopic perovskite solar cells with custom design capability, Mater. Adv. 2020, 1, 153-160 (doi:10.1039/d0ma00077a)
[3] lNovel Electronic Device and Method for Slot-Die Depositing Layers of the Same, Patent WO2019219952A1
[4] lNovel electronic device and method for producing layers of the same, Patent WO2019219951A1

This poster in PDF at solx.ch/19epv

Betreten von PV-Modulen

Evelyn Bamberger, Aymeric Jeanjaquet

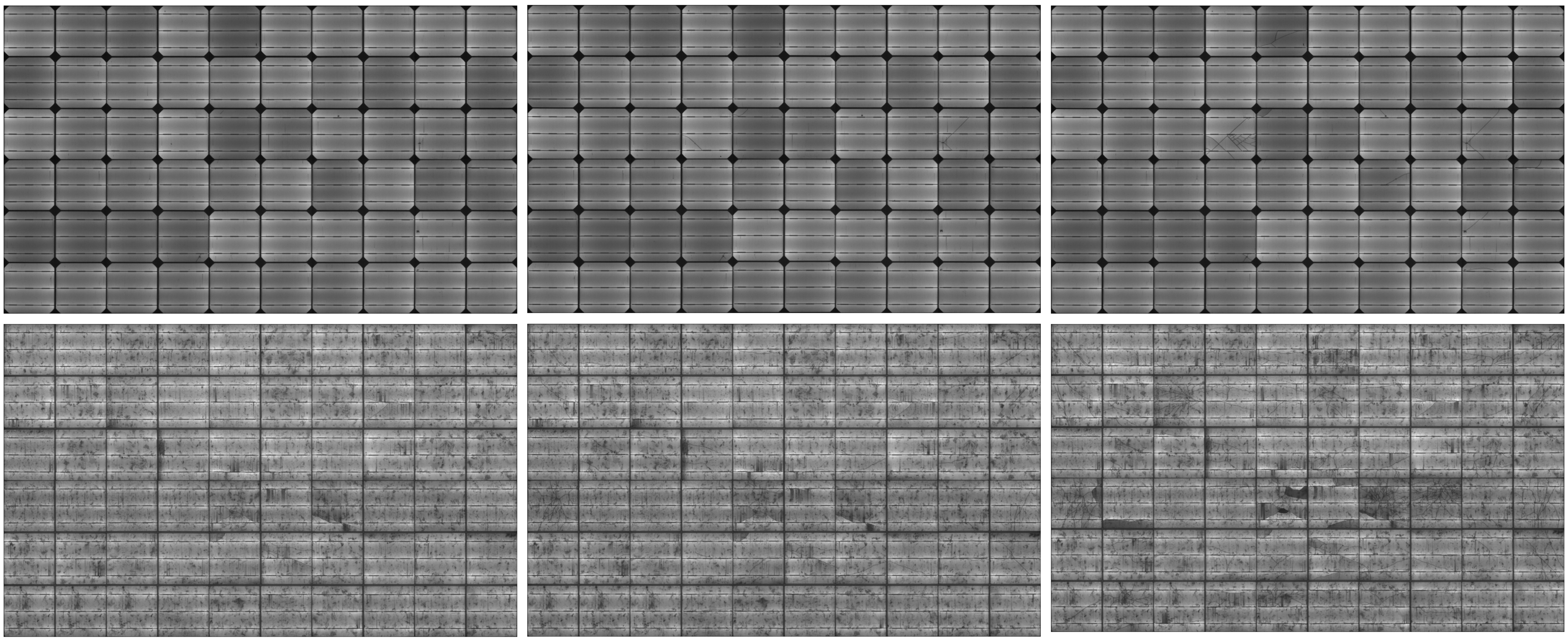
Problemstellung

PV-Anlagen auf Schrägdächern werden meist als grössere, zusammenhängende Modulfelder installiert. Um bei der Installation oder späteren Wartung des PV-Generators Module im Inneren des Feldes zu erreichen, kommt es häufig vor, dass das Modulfeld betreten wird. Durch die hohe punktuelle Belastung können Schäden an den Modulen entstehen, die Auswirkungen auf die Leistung und Sicherheit der Module haben können. Die Schäden können direkt oder erst mit der Zeit auftreten und sind mit blossem Auge meistens nicht sichtbar.

Versuchsdurchführung

Montagesystem und Modul wurden flach am Boden liegend montiert. Die Begehung erfolgte jeweils an definierten Stellen am Rand und in der Mitte des Moduls durch die gleiche Person mit ihrem Eigengewicht sowie zusätzlichen Gewichten. Das Vorgehen wurde mit unterschiedlichen Modulen und Montagesystemen wiederholt. Vor und nach jedem Versuch wurden Leistungsmessungen und Elektrolumineszenzaufnahmen durchgeführt.

Ergebnisse



EL-Aufnahmen (links) vor der Belastung, (Mitte) mit 55 kg, (rechts) mit 105 kg von jeweils (oben) einem neuen, rahmenlosen Glas-Folienmodul mit Indach-Montagesystem sowie (unten) einem ca. 5 Jahre alten gerahmten Glas-Folienmodul mit Aufdach-Montagesystem mit 4 Klemmen

Schlussfolgerungen & Ausblick

Die wichtigsten Erkenntnisse aus den Versuchen:

- Glas-Folienmodule weisen bereits bei geringer Belastung erste Mikrorisse auf, die mit höheren Gewichten zunehmen, während es bei Glas-Glas Modulen selbst bei hoher Belastung nur sehr wenige sind.
- Neue Module werden durch die Begehung wesentlich weniger geschädigt als bereits gealterte Module. Ein Betreten während der Installation ist daher weniger kritisch als bei einer späteren Wartung.
- Mikrorisse treten vermehrt in der Mitte des Moduls und an Stellen mit Vorschädigungen auf.

Die Aussagen sollten mit weiteren Modulen, Montagesystemen und Aufbauten verifiziert werden. Bisher nicht untersucht wurde der Einfluss der Aussen- und Modultemperatur.

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SUPSI

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

19. Nationale Photovoltaik-Tagung 2021

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Swiss Federal Office of Energy SFOE

Institute for Applied Sustainability to the Built Environment

Operating Temperatures of Modules in Open-Rack and BIPV Configurations

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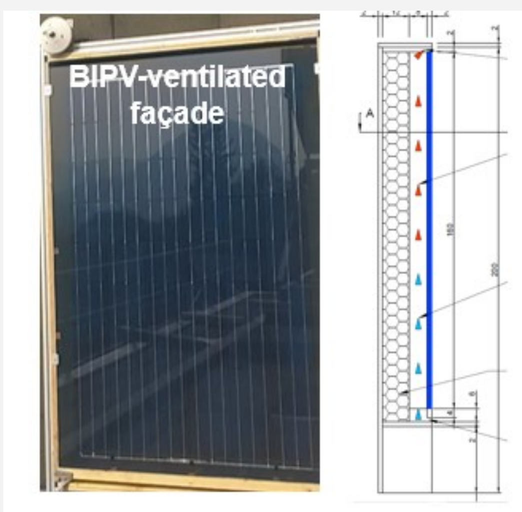
ABSTRACT

Elevated operating temperatures are expected in BIPV systems due to restricted or reduced rear-side ventilation, which impacts their performance and reliability. This work reports operating temperatures of the modules in open-rack and BIPV mounting configurations (BIPV-ventilated and BIPV-insulated) monitored over a period of 2-5 years in southern Switzerland. The modules in BIPV configurations operated at 20-30˚C higher temperatures than the same modules in open-rack. The suitability of the indoor qualification and safety tests in IEC 61215 and IEC 61730 series were evaluated according to the 98th percentile real-life operating module temperature (T_{98}) as defined in IEC TS 63126 guideline for qualifying PV modules operating at elevated temperatures. This work shows that according to IEC TS 63126, BIPV modules on a tilted surface in southern Switzerland may need to be tested at harsher conditions (e.g. higher temperatures) in a selection of indoor qualification and safety tests.

Test Stands

Solarbrick project, SUPSI

© SUPSI (stands built in the framework of ConstructPV project)

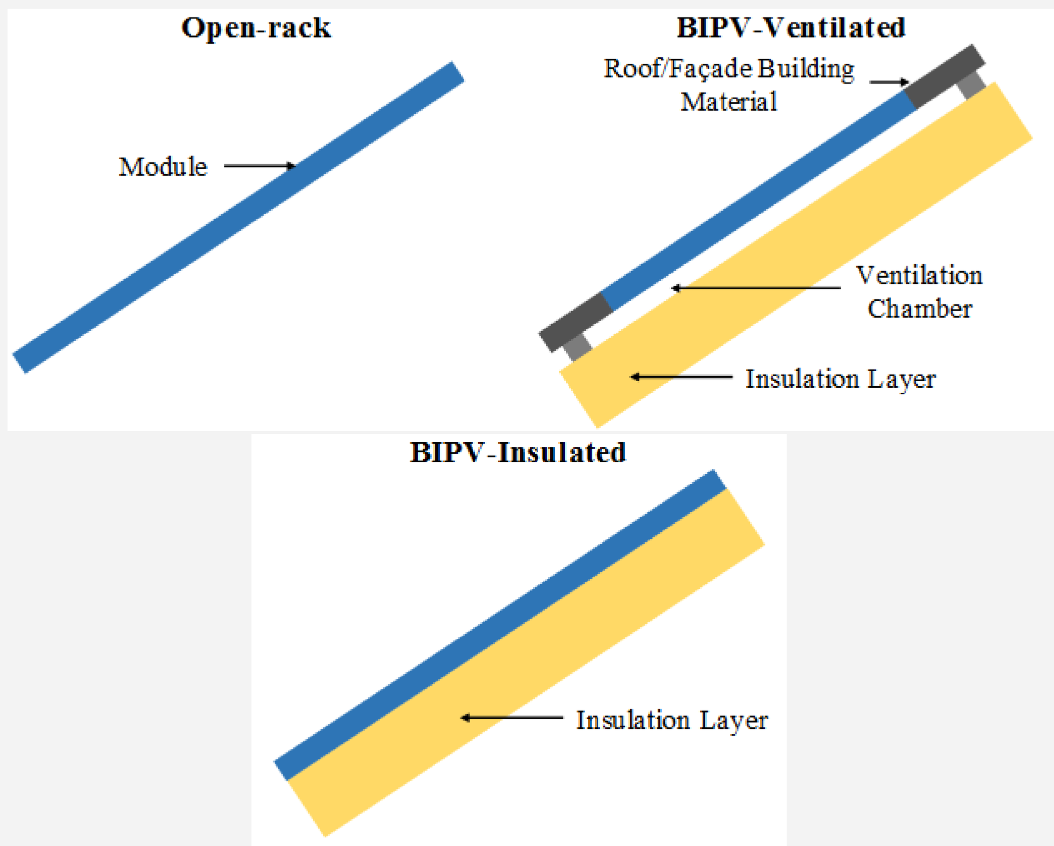


© SUPSI (stands built in the framework of IEA PVPS T15 project)

Test Stand	Cell and Module Technologies	Installation Configuration	Azimuth (South = 0˚) / Tilt Angles	Duration	Monitored Parameters
1	Al-BSF - G/EVA/BS Commercial module	• Open-rack • BIPV-Insulated	-4˚/ 6˚ (Roof)	51 Months	• G_{POA} (every 1 minute) • Module Temperature (Pt100 on rear-side of the modules) (every 1 minute) • Electrical performance using MPP tracker (every 1 minute)
	Al-BSF - G/PVB/G Commercial module				
2	HJT - G/G Prototype module	• Open-rack • BIPV-Ventilated (6 cm)	-4˚/ 20˚ (Roof)	53 Months	
	PERC - G/EVA/BS Commercial module	• BIPV-Ventilated (12 cm)			
3	PERC - G/PVB/G Commercial module	• BIPV-Ventilated (8 cm)	-4˚/ 90˚ (Façade)	27 Months	

Al-BSF: Aluminum back surface field, HJT: Heterojunction Technology, PERC: Passivated Emitter and Rear Contact, G: Glass, BS: Backsheet, EVA: Ethylene-vinyl acetate, PVB: Polyvinyl-butyral, G_{POA}: Plane of array irradiance and MPP: Maximum power point.

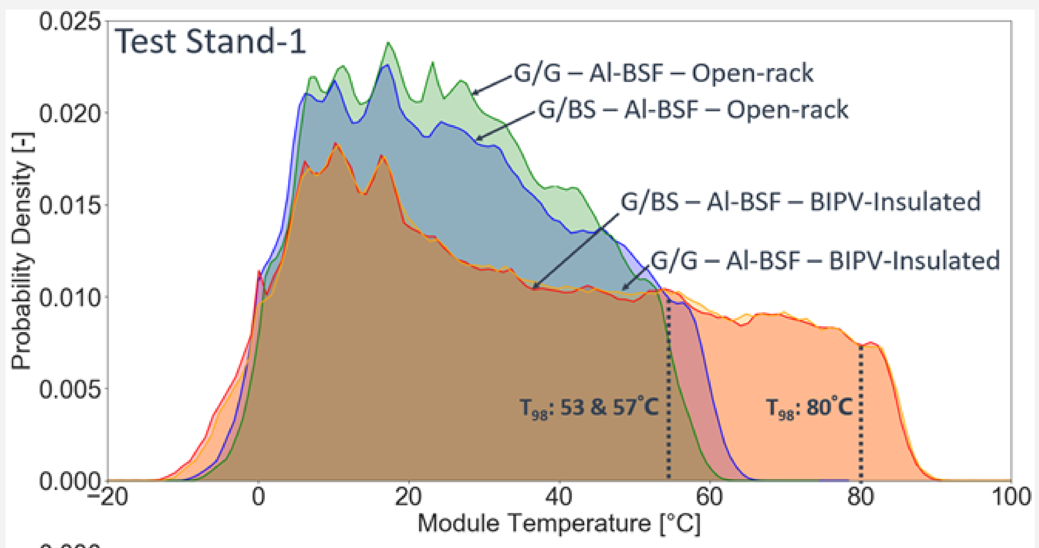
Mounting Configurations

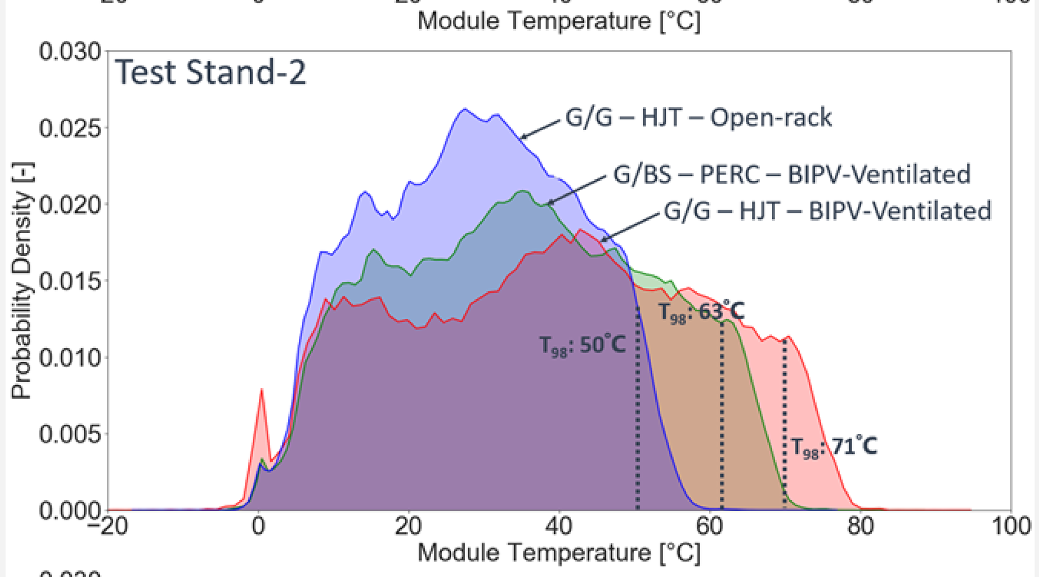


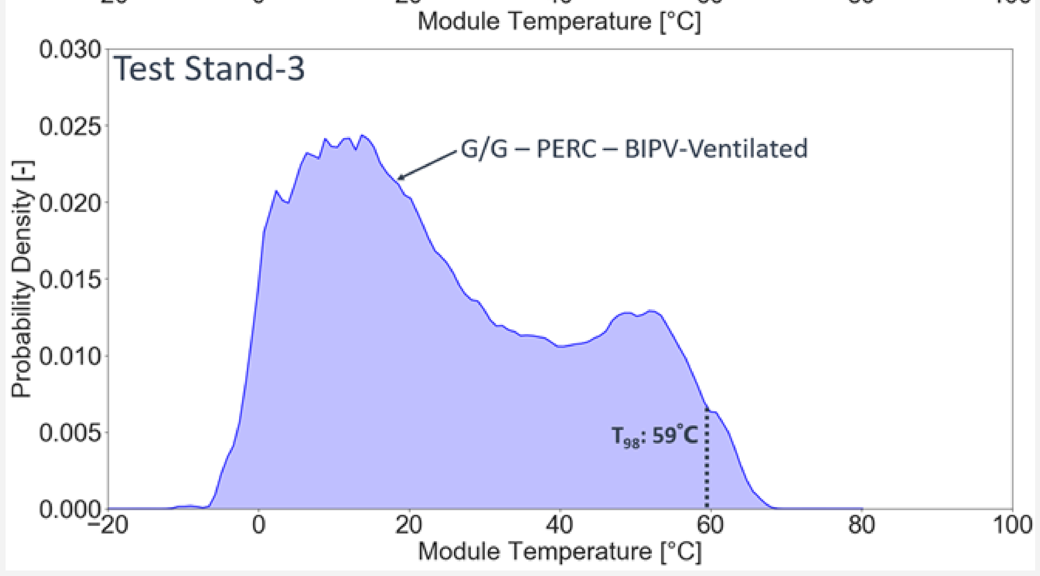
Operating Temperature Distributions and T_{98} (IEC TS 63126)

- The insulated modules in **Test Stand-1** operated at higher temperatures due to restricted rear-side ventilation. While the open-rack modules reached a maximum of 62˚C and 66˚C, respectively, the insulated modules exhibited a larger distribution, reaching temperatures slightly above 90˚C in southern Switzerland.
- T_{98} of the insulated modules in **Test Stand-1** are 80˚C, while T_{98} of the open-rack G/BS and G/G modules are 57˚C and 53˚C, respectively .
- The insulated modules are exposed to lower temperatures (even below 0˚C) with respect to modules in open-rack conditions due to the stronger radiative cooling at night.
- In **Test Stand-2**, the ventilated HJT module reached higher operating temperatures than the same module type in open-rack configuration due to limited rear-side ventilation. T_{98} of the open-rack and the ventilated HJT modules are 50˚C and 71˚C, respectively. The ventilated PERC module has a T_{98} of 63˚C (maximum of 77˚C).
- The ventilated G/G PERC BIPV module, installed as a façade module on **Test Stand-3**, operated at lower temperatures relative to the other modules in BIPV configurations. As expected, this is because there is usually a lower amount of irradiance on the vertical surface compared to the sloped surfaces, especially when solar altitude is high (e.g. in summer).
- **T_{98}** of the **two insulated BIPV modules** on **Test Stand-1** and **the ventilated HJT module** on **Test Stand-2** are all higher than 70˚C. According to the **IEC TS 63126**, these modules should be tested at **harsher testing conditions** (Level 1 Test Condition) in a selection of **indoor module qualification and safety tests defined in IEC 61215 and IEC 61730 series**.
- **BIPV modules** installed in a mid-latitude country (Switzerland) with a reduced or restricted rear-side ventilation **operated at temperatures 20-30˚C higher than the same modules installed in an open-rack** configuration. Exposure of the modules to **elevated operating temperatures (larger thermal stresses)** may lead to **higher degradation rates** (e.g. higher rate of encapsulant discoloration, damaged interconnections and solder joints, etc.) and a faster occurrence of **wear-out-failures** that shorten the lifetime of a PV module.

Test Stand	Cell and Module Technologies	Tilt Angles	Open-Rack		BIPV-Ventilated		BIPV-Insulated		Temperature Difference	
			T_{98} [˚C]	T_{max} [˚C]	T_{98} [˚C]	T_{max} [˚C]	T_{98} [˚C]	T_{max} [˚C]	T_{98} [˚C]	T_{max} [˚C]
1	Al-BSF - G/EVA/BS	6˚	57	66	-	-	**80**	92	23	26
	Al-BSF - G/PVB/G	6˚	53	62	-	-	**80**	91	27	29
2	HJT - G/G	20˚	50	64	**71**	83	-	-	21	19
	PERC - G/EVA/BS	20˚	-	-	63	77	-	-	-	-
3	PERC - G/PVB/G	90˚	-	-	59	68	-	-	-	-







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Utilisation of solar hydrogen for mobility

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GREEN HYDROGEN FOR CARBON NEUTRALITY

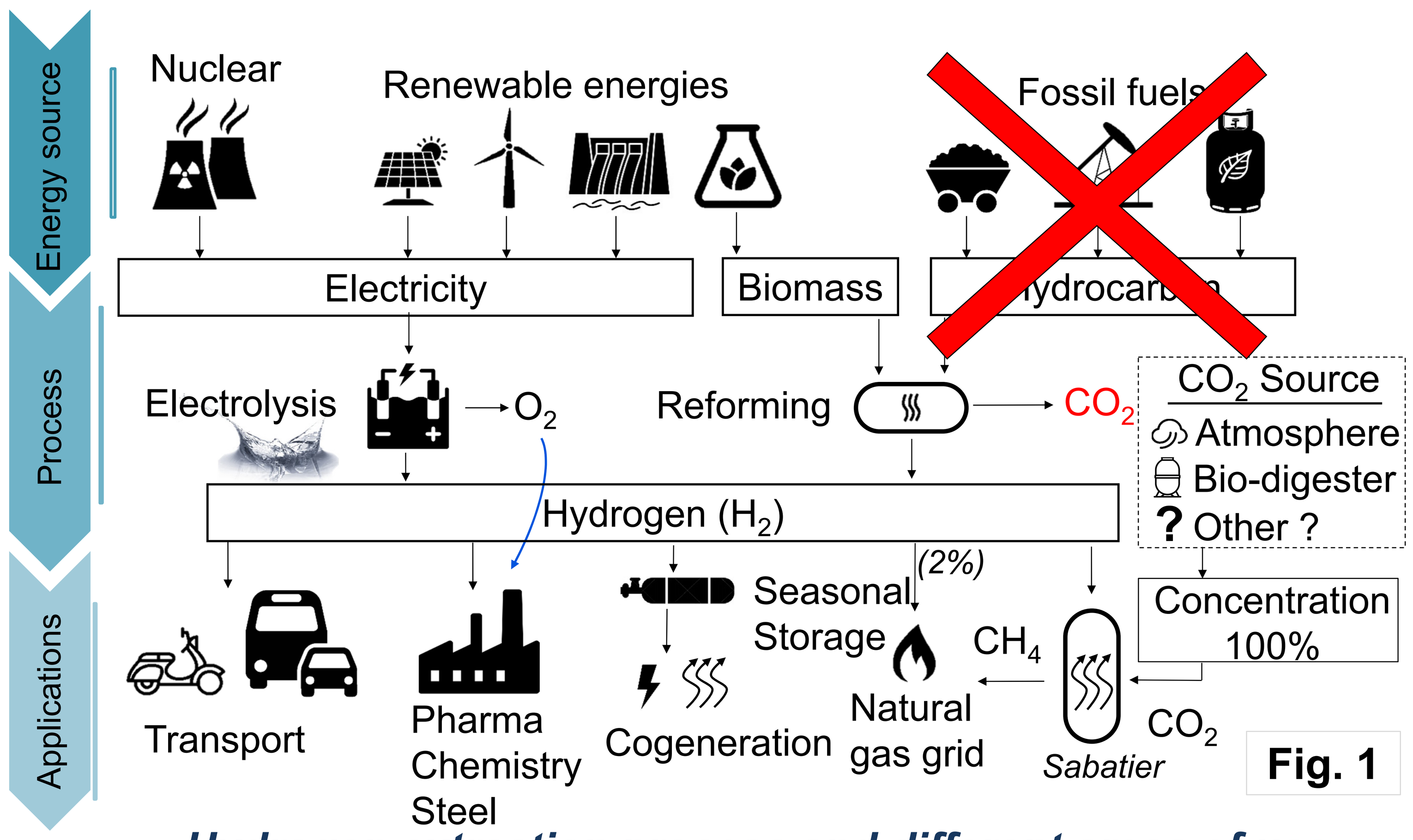


Fig. 1

Hydrogen extraction process and different areas of use

Small scale mobility application :

- **Green** hydrogen produced by PV power
- Store **green** hydrogen at low pressure (~10 bar) with metal hydrides
- Convert a gasoline vehicule (scooter) to run on **green** hydrogen

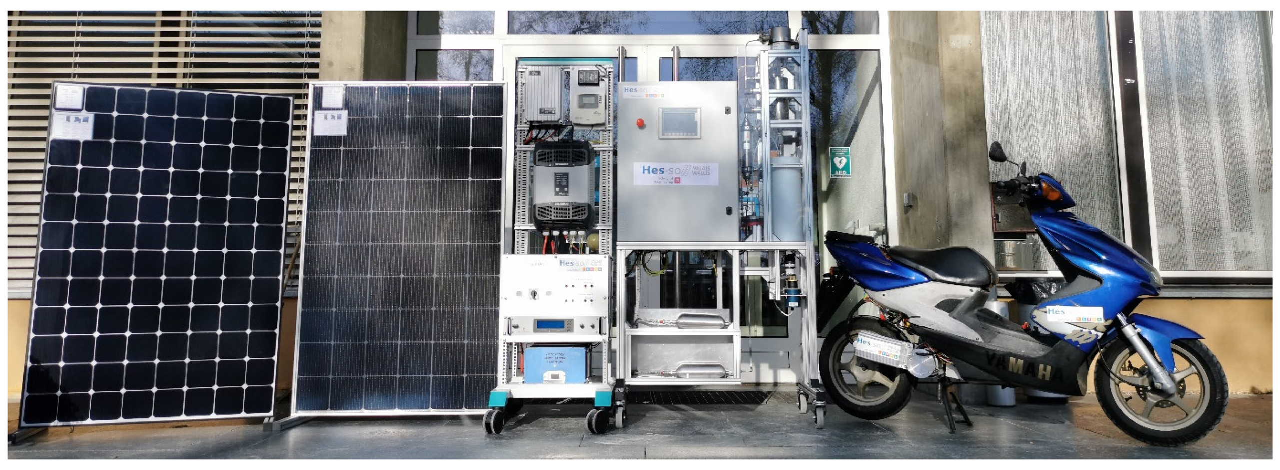


Fig. 2

Using hydrogen to transmit solar energy to the wheels of a converted scooter

H_2 FROM THE SUN TO WHEELS

Detailed components in refill station

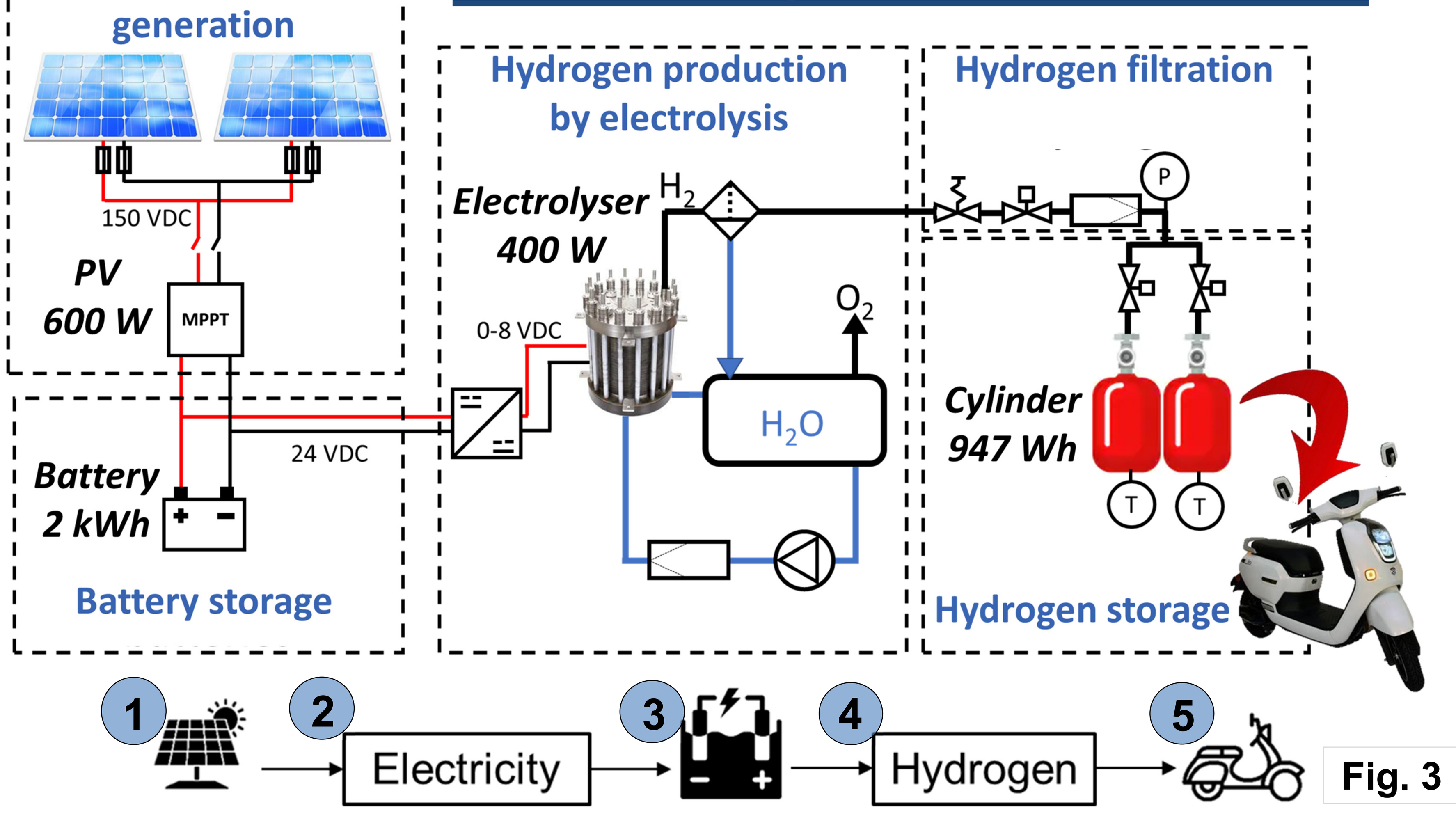


Fig. 3

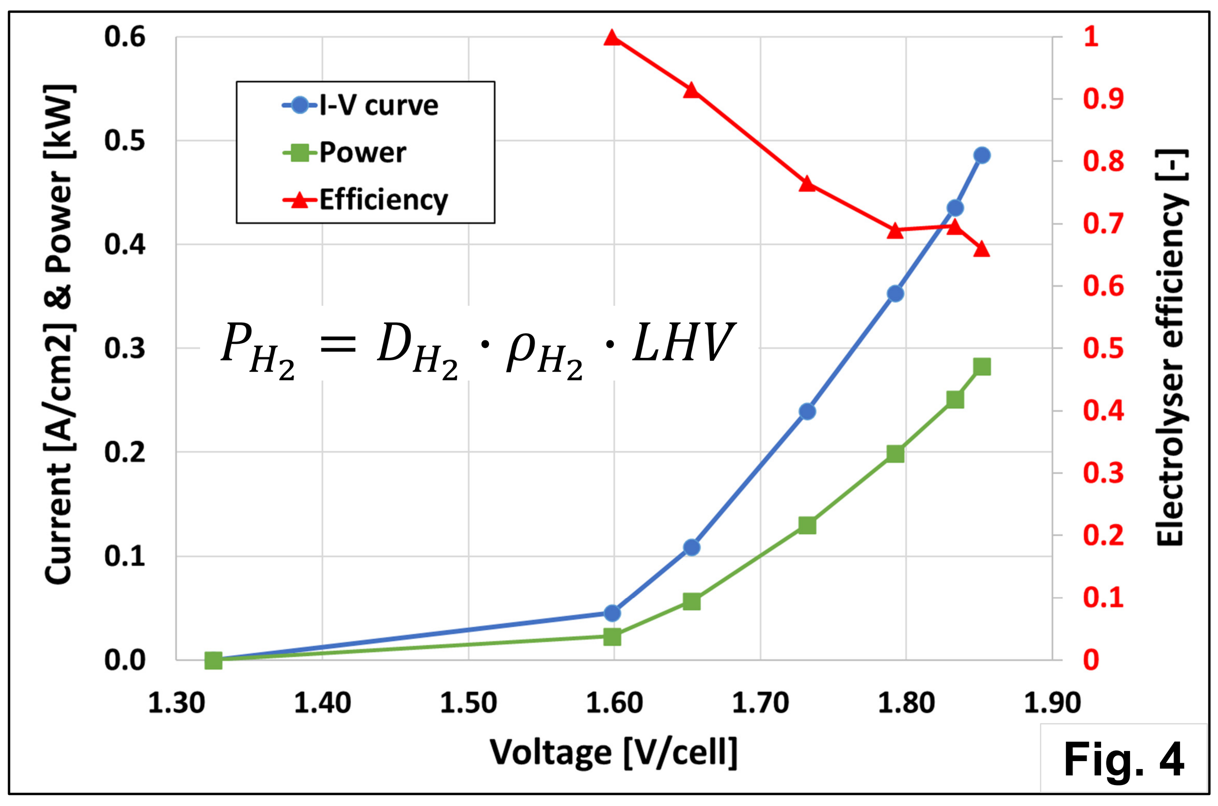


Fig. 4

Main components in the scooter

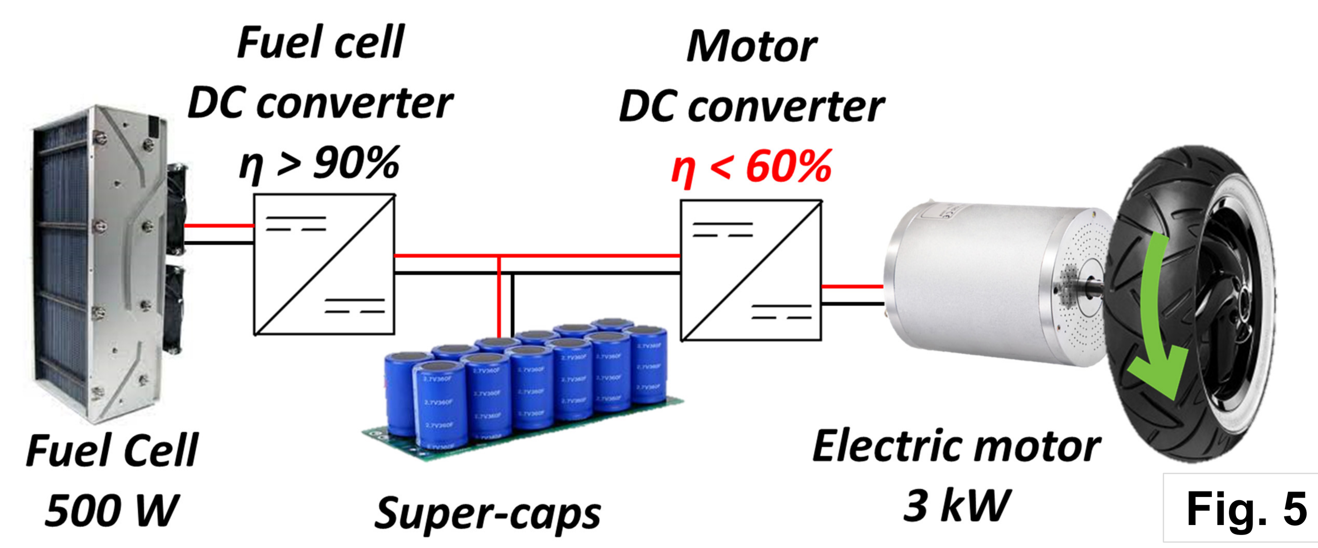


Fig. 5

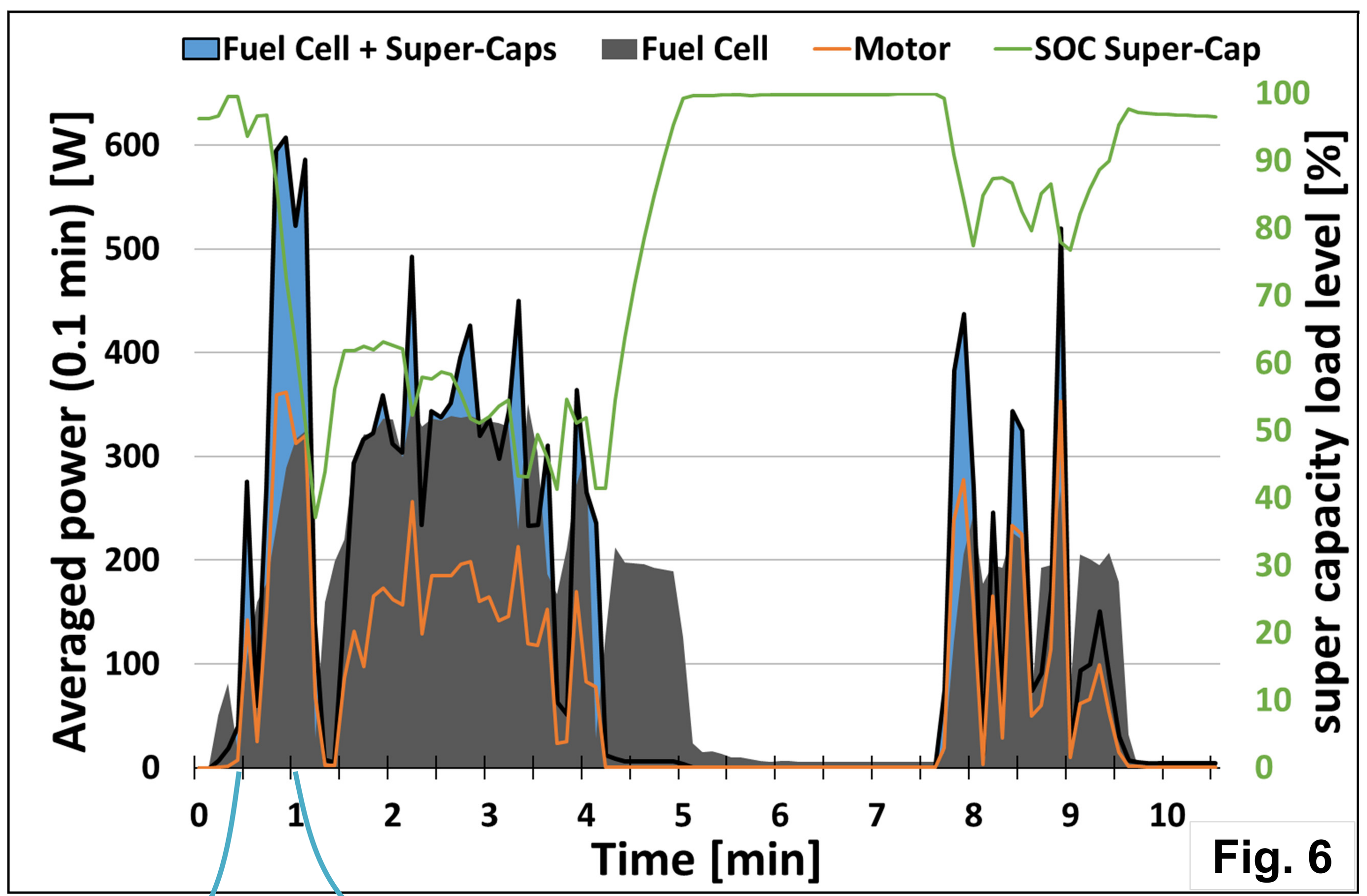


Fig. 6

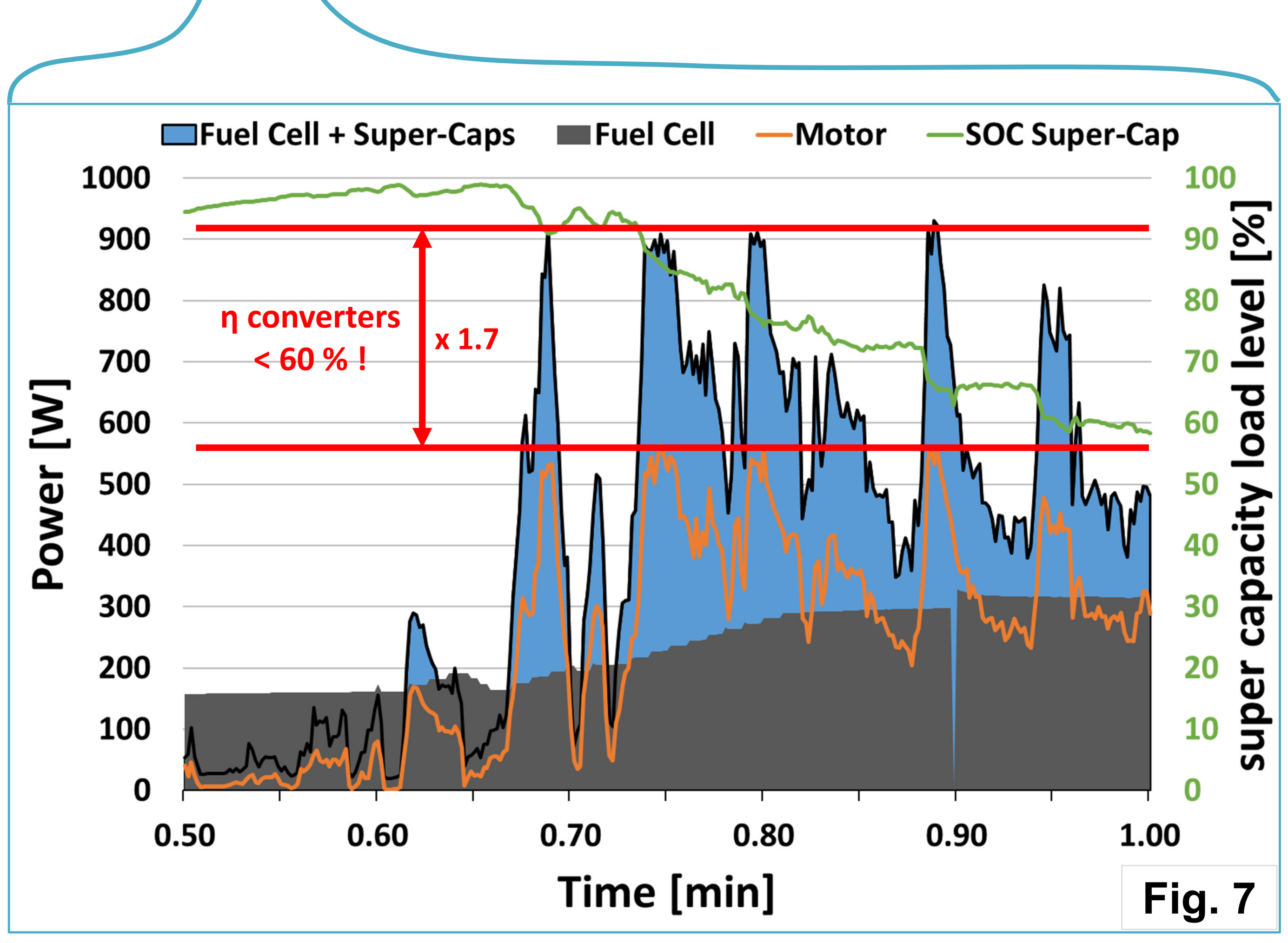


Fig. 7

RESULTS

- H_2 refill time :
  Estimated : 3h
  Measured : 5h
- Range with 2 bottles : 22 km
- Max speed : 25 km/h
- Cost : 15-20 kCHF
- Time to exchange 2 cylinders in scooter : 5 min

Measured efficiency :

Electrolyser (refill station)	:	67 %
Fuel cell DC converter (scooter)	:	> 90 %
Motor DC converter (scooter)	:	< 60 %

CONCLUSION

1. Real H_2 refill time is limited by the metal hydrides.
2. At present, motor converter is the weakest element of energy chain.
3. Averaged over 0.1 minutes, the fuel cell appears to be sufficient to power the engine. (figure 6)
4. Super-caps are essential to provide the power peaks. (figure 7)

PROSPECTIVE DEVELOPMENTS

1. Replace motor DC converter for better efficiency.
2. Use high-pressure storage to avoid dependence on limiting metal hydride flows.
3. Increase the power of the fuel cell (0.5 -> 3kW) to improve the speed and acceleration of the scooter.
4. More measure : power, range, T-behaviour.

Hes·so VALAIS WALLIS School of Engineering

01.07.2021

Green hydrogen lab with photovoltaic supply

F. Savy, J. Udry, D. Martinet, P. Barrade, A. Germanier, A. Carrupt, C. Ellert

School of engineering HES-SO Valais-Wallis, The Institute of Sustainable Energy, Route du Rawil 47, 1950 Sion, Switzerland

System setup

- Homemade direct current **(DC) micro-grid** : interconnect a PV field and consumers.
- **Energy Management System (EMS)** : solar power predictions and storage management.
- Homemade **DC/DC converter** → supply PEM electrolyser with the DC bus.
- Experiments with **green hydrogen (H_2)** : H_2 production → storage → electricity production.
- **Mobility** development : use our **green hydrogen** to supply electrical vehicles.
- **Methanation** experiments : convert CO_2 sources into methane with our **green H_2**.

22 kWc photovoltaic

11 kWe cars charging station

Public grid

AC / DC

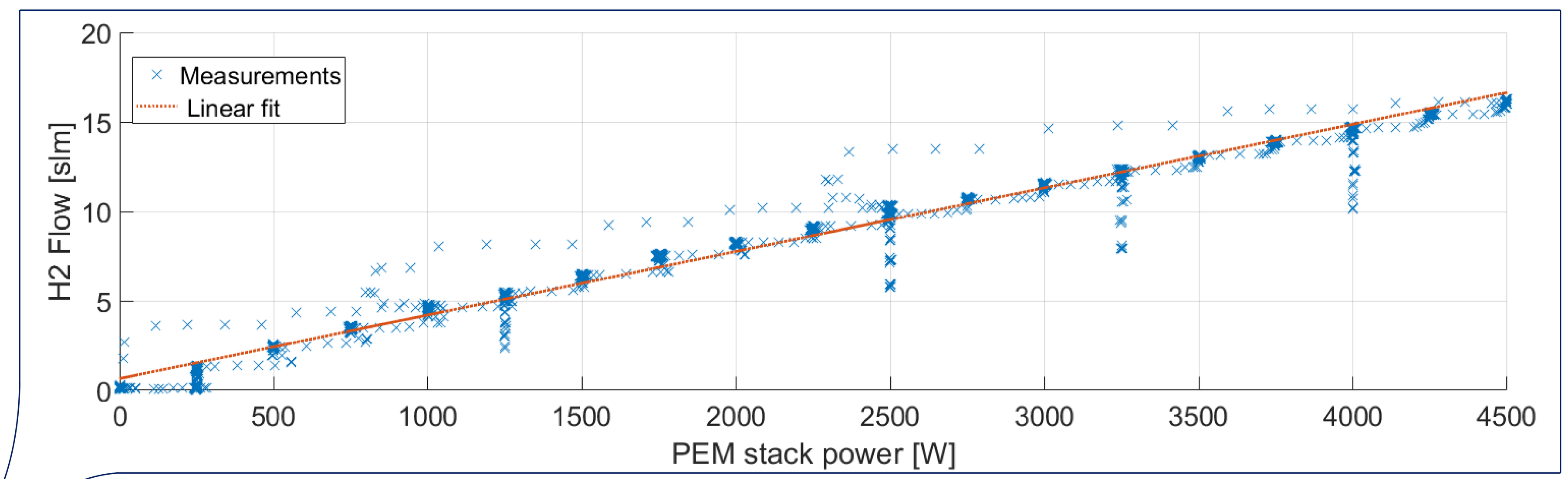
700 Vdc micro-grid (future 760 Vdc)

DC / DC

50 kWh Li batteries

2 kWe Heat pumps

DC / DC



H_2 production : linear function of electrical power

5.5 kWe electrolyser

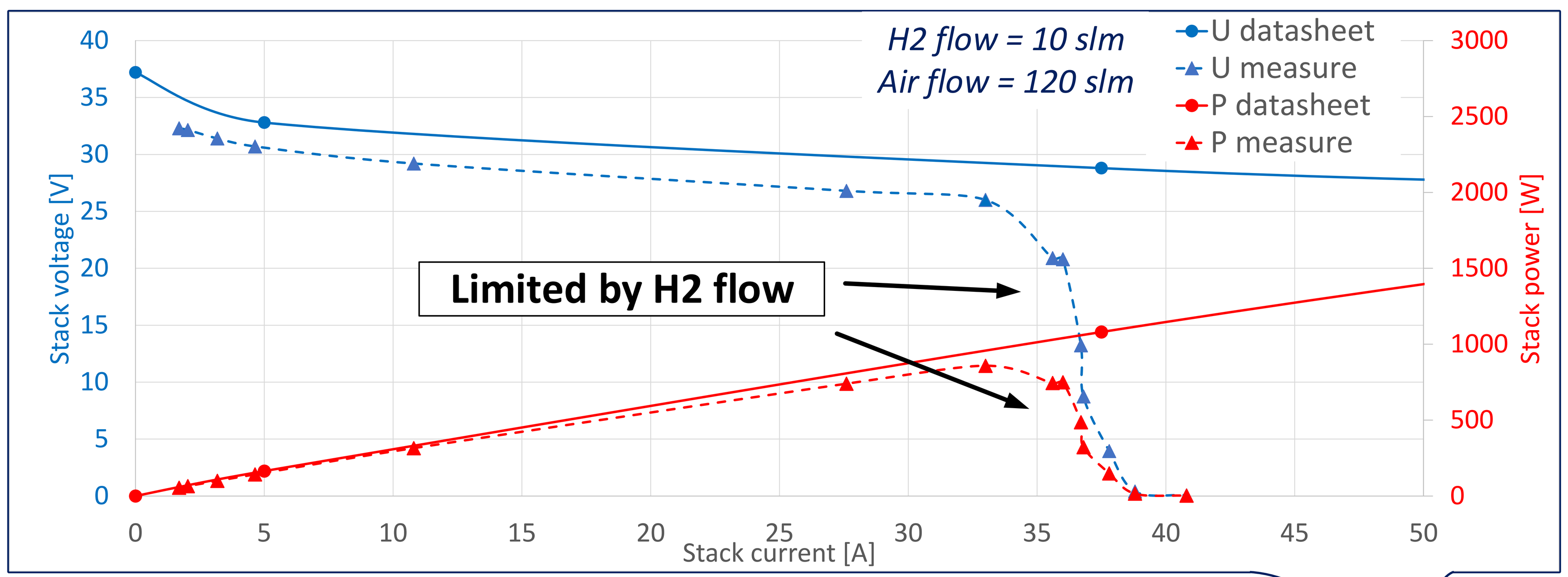
H_2 < 20 slpm

O_2 < 10 slm

Available (not used yet)

H2 mobility

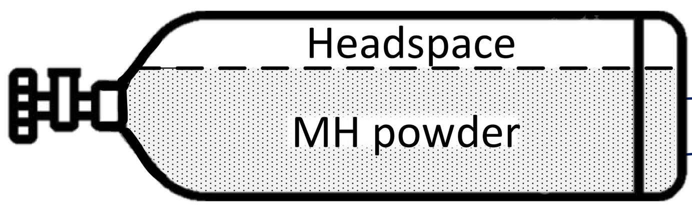
(Poster J. Udry)



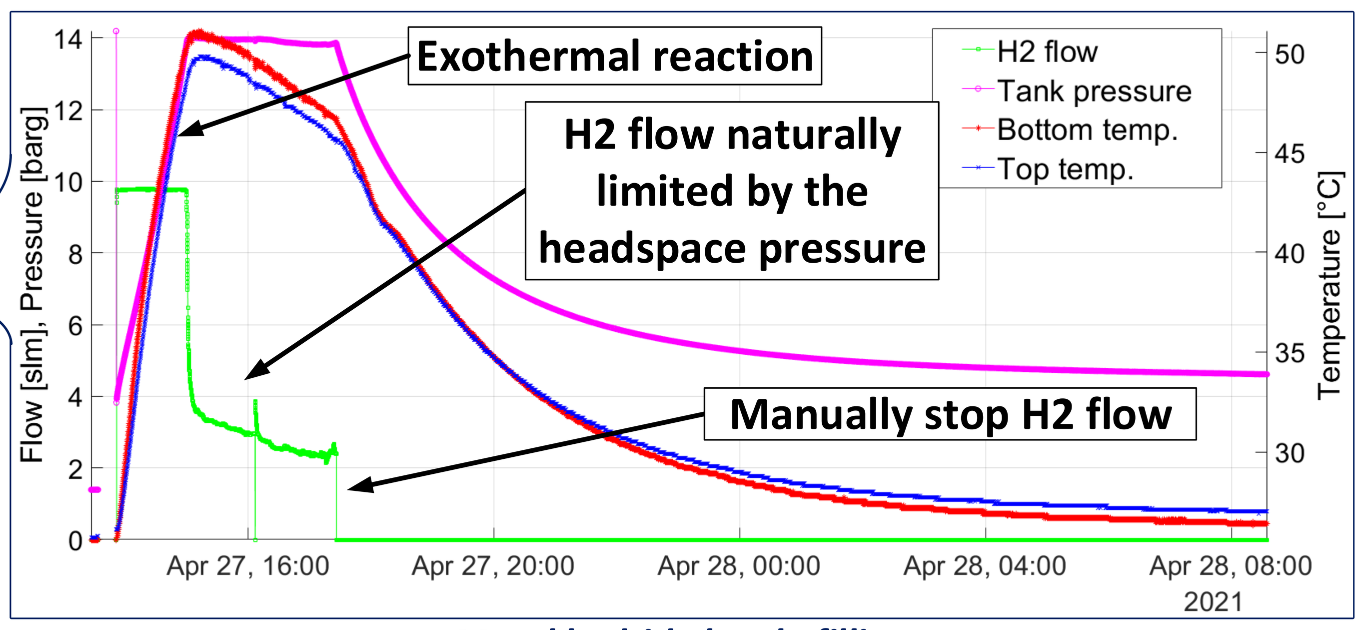
Comparison of I-V curve with datasheet : same behaviour at low current

Green hydrogen

2.4 kWe Fuel Cell



10L MH bottle (< 13.5 kWh)



Metal hydride bottle filling

Cogeneration Fuel Cell 2.5 kWe / 2.5 kWth

Heat (~70°C)

Bio-digester 20L

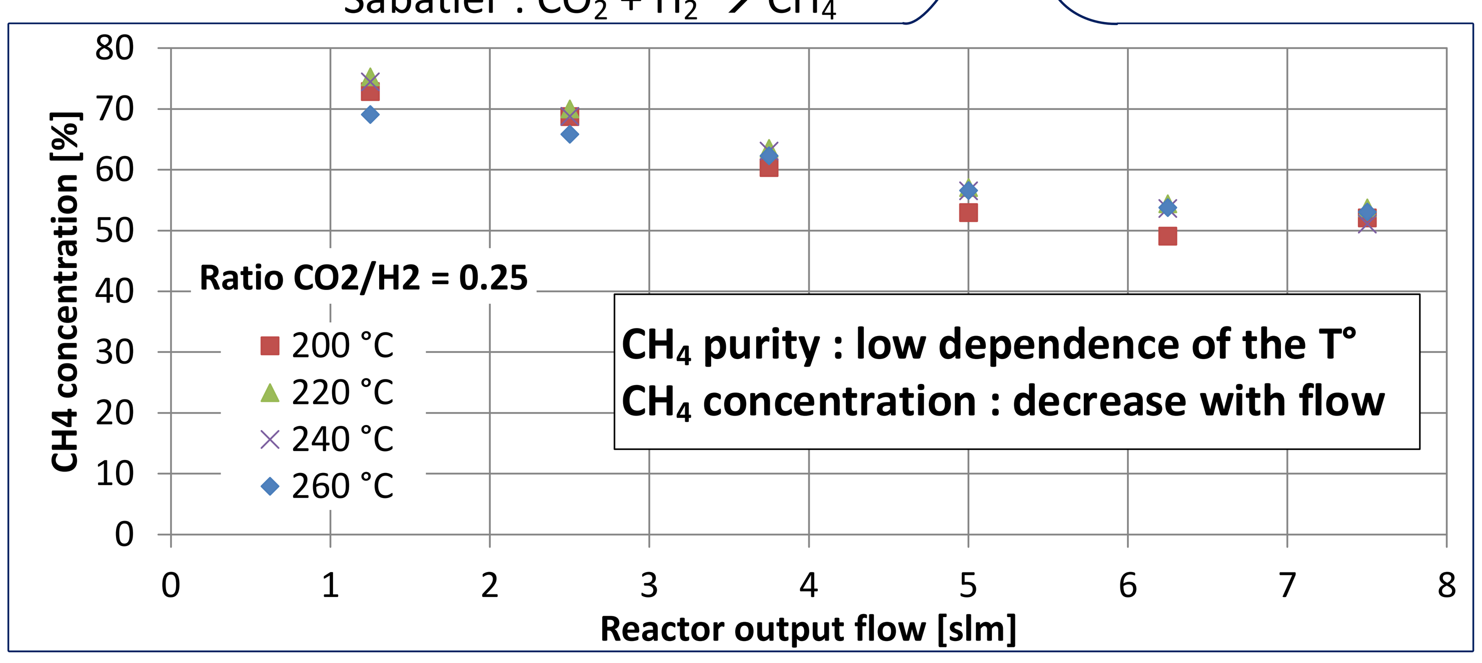
Methanation reactor

Biogas ($CH_4 + CO_2$)

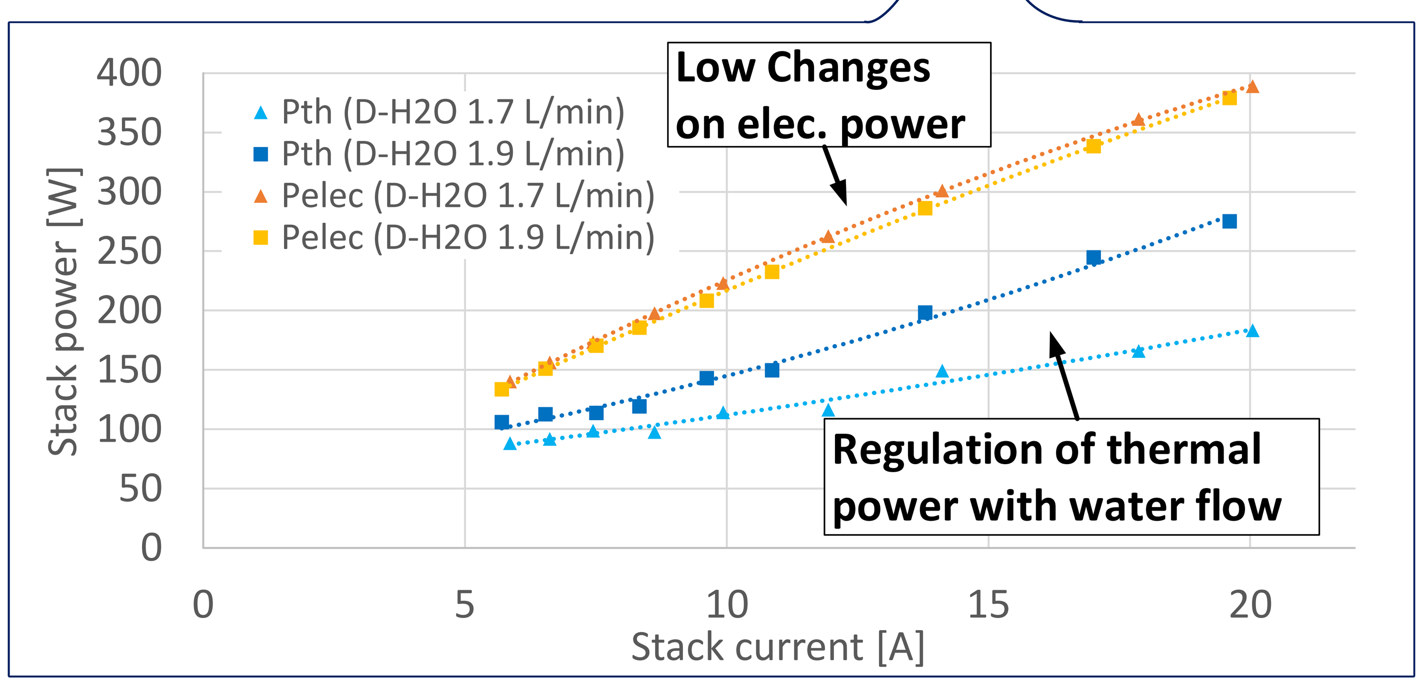
Methane (CH_4)

Public gas grid

Sabatier : $CO_2 + H_2 \rightarrow CH_4$



fully filled nickel catalyst (CO₂ and H₂ from bottles)



Impact of the water flow on the stack power and current

Conclusions

- H_2 equipments are functional : electrolyser, fuel cells, storage, methanation, scooter.
- Fuel cell operation is more delicate than electrolyser operation due to severe regulation constraints.
- Power range designed for 5 kW (electrolyser), sufficient for about 100 kW installed PV power.
- Metal hydride storage is preferable at this power range, compared to high pressure.

Outlook

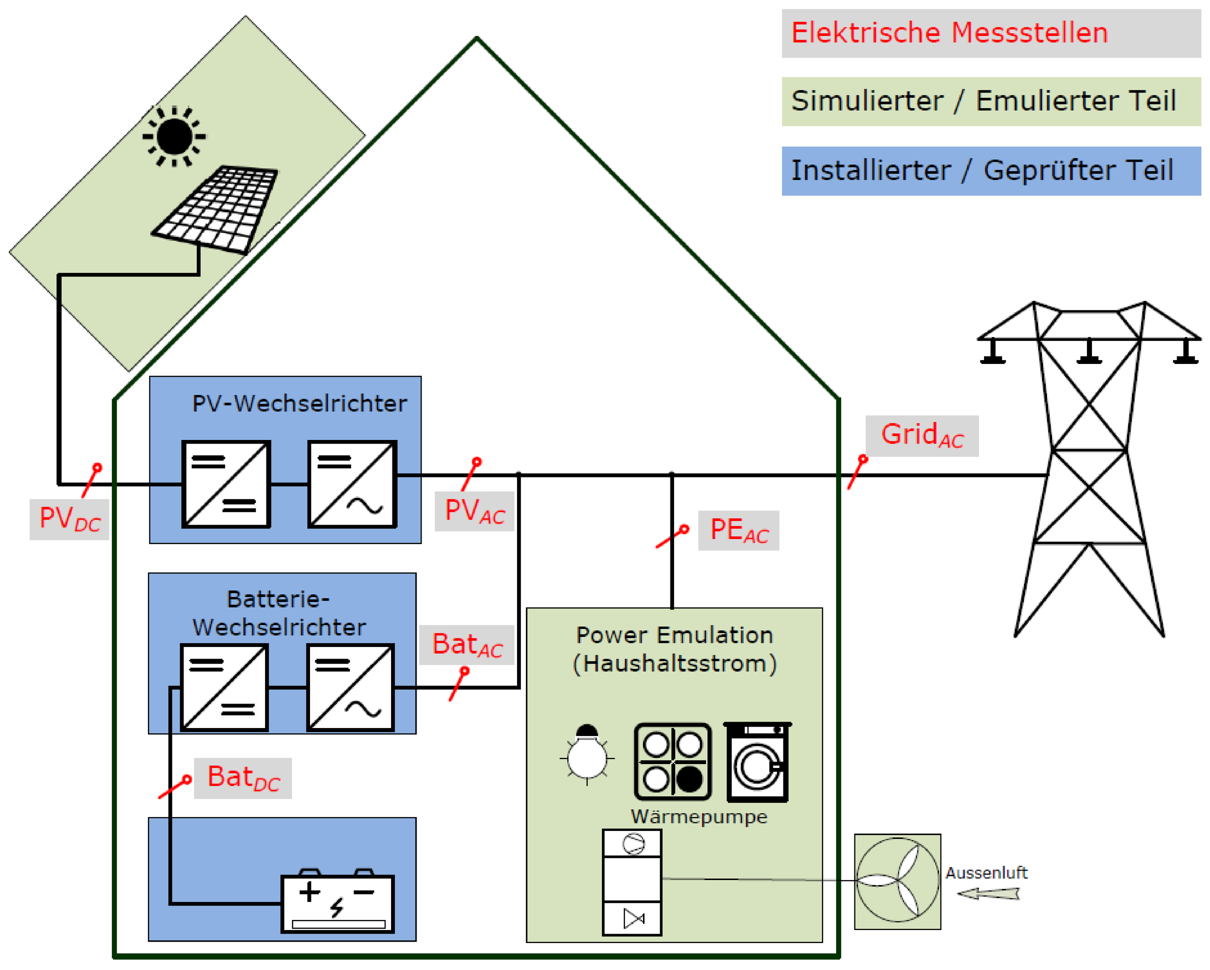
- Integrate whole H_2 chain into EMS/micro-grid.
- Implement DC/DC converter for fuel cells.
- Install the bio-digester.
- Test the methanation with biogas.

Heimspeicher-Systemtest: Batteriesysteme auf dem Prüfstand

Evelyn Bamberger, Robert Haberl, Andreas Reber, Christof Biba

Testverfahren

Mit dem Heimspeicher-Systemtest (CCT-Bat) können im Prüflabor im Hardware-in-the-Loop Prinzip innerhalb von drei Prüftagen alle relevanten Betriebsbedingungen von Batteriesystemen getestet und Jahreskennwerte extrapoliert werden. Dies erlaubt sehr genaue Analysen der Effizienz des Batteriesystems oder von Regelstrategien für Eigenverbrauch, Netznutzen oder zeitvariable Stromtarife. Alle im dynamischen Betrieb auftretenden Eigenschaften werden gemessen, eine nachträgliche Simulation entfällt. Ein weiterer Vorteil ist, dass auch neue Technologien oder Konzepte geprüft werden können.



Testaufbau eines AC-gekoppelten Systems

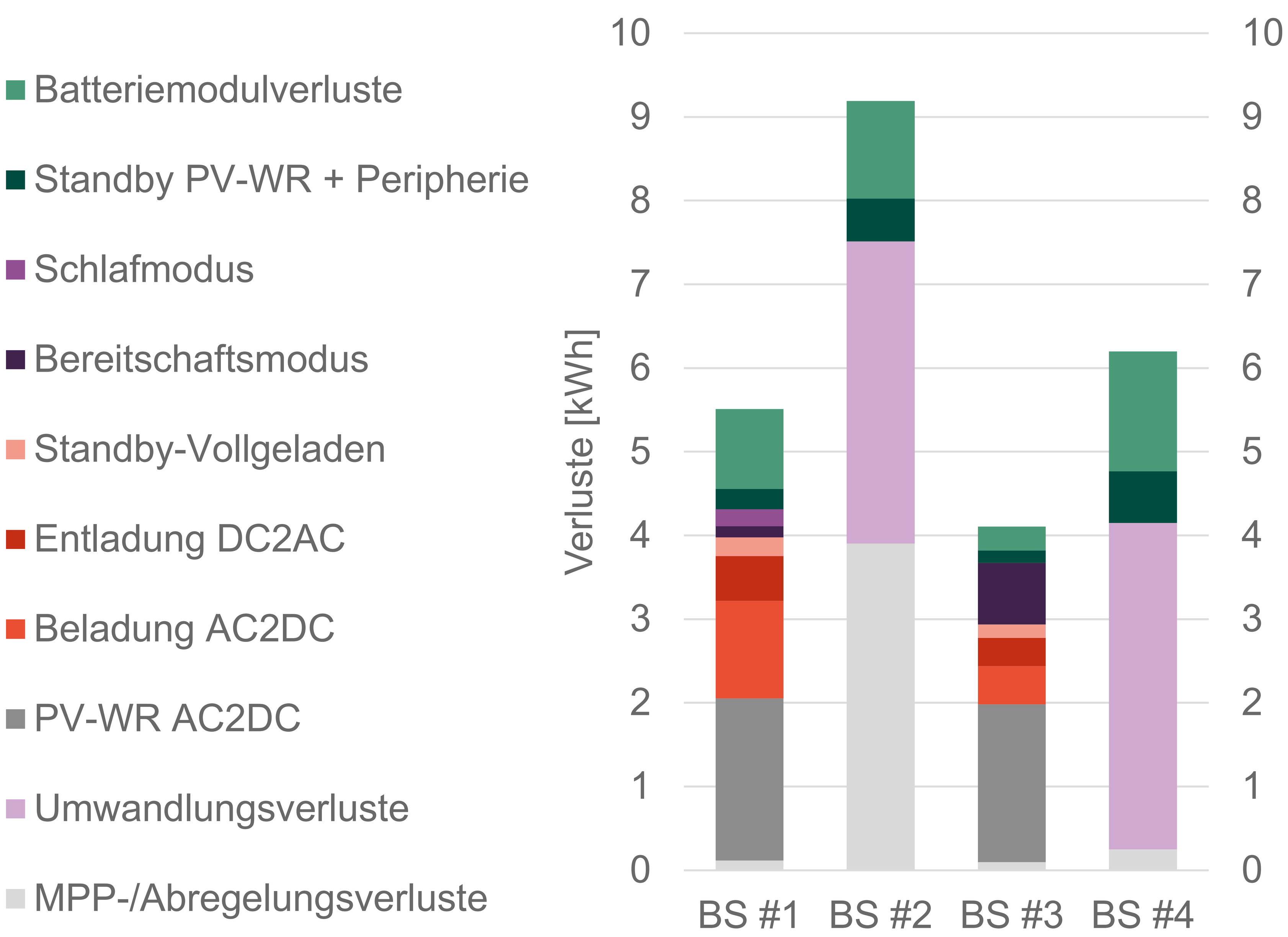
Standardsteuerung: Eigenverbrauchserhöhung

Voraussetzungen für eine hohe Effizienz sind die Vermeidung von Abregelungsverlusten sowie geringe Umwandlungs- und Standby-Verluste. Die getesteten Lithium-Ionen Batteriemodule weisen sehr ähnliche DC-Zykleneffizienzen auf, während es bei den Batteriewechselrichtern und der Steuerung grössere Unterschiede gibt, die auch entscheidender sind als die Systemtopologie.

Geprüfte Systeme mit Jahreskennwerten

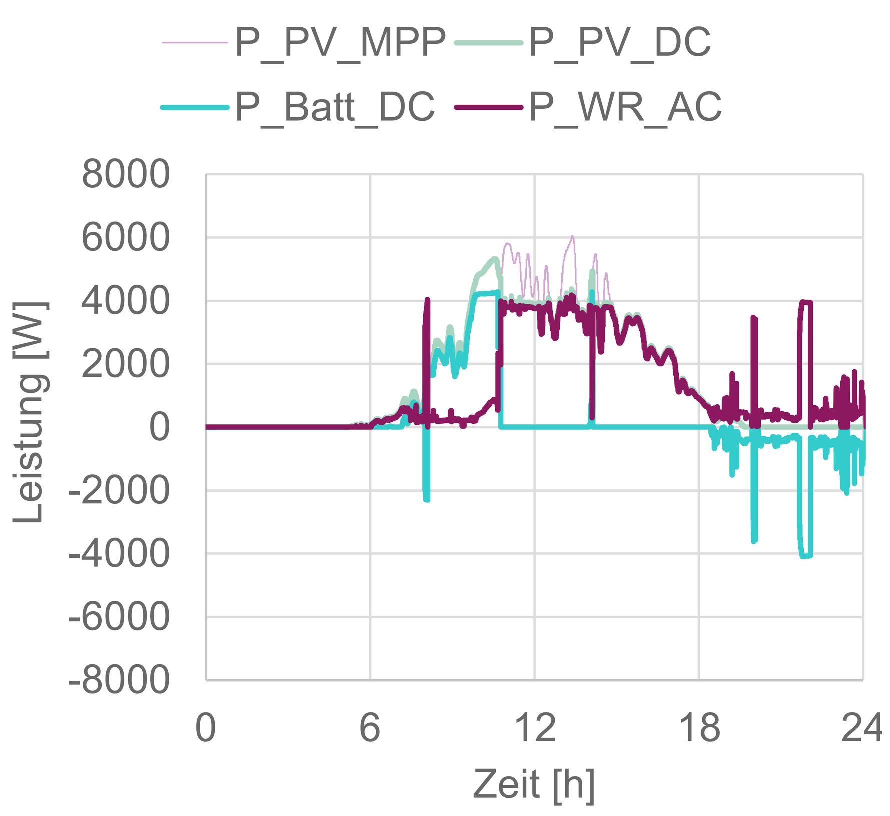
Batteriesystem (BS)	BS #1	BS #2	BS #3	BS #4
Systemtopologie	AC	DC	AC	DC
Nutzbare Kapazität [kWh]	6.5	6.4	2.25	7.7
DC-Zykleneffizienz	91.4%	91.4%	93.8%	91.5%
AC-Zykleneffizienz	74.8%	-	68.4%	-
Gesamtsystemeffizienz	92.4%	87.7%	94.7%	91.7%
Autarkiegrad	41.8%	42.6%	35.4%	47.4%

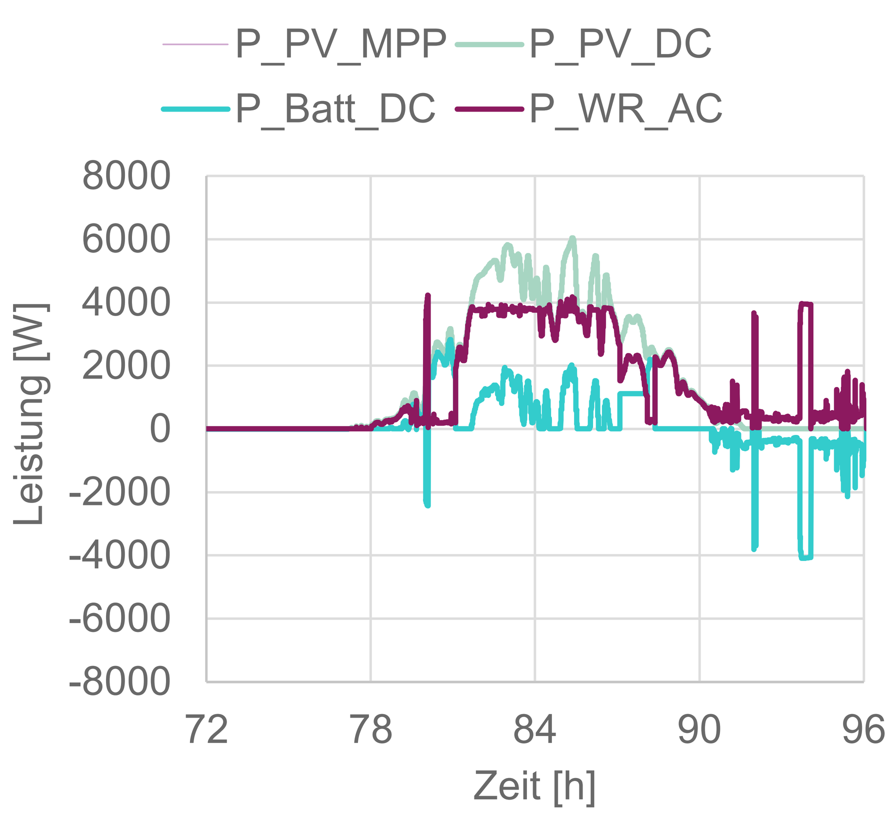
Rechts: Verluste aus dem 3-Tage Prüfzyklus



Reduzierung der Einspeiseleistung

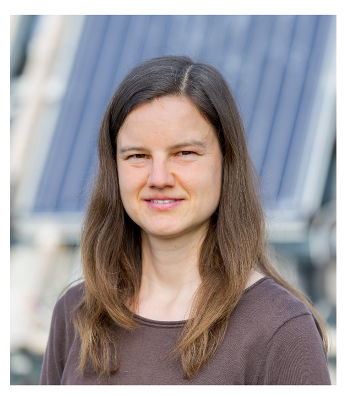
Mit Standardsteuerung zeigen alle Systeme eine frühzeitige Batterieladung. Ein System wurde zusätzlich mit einer Begrenzung der Einspeiseleistung und prognosebasierter Steuerung getestet. Nach einer Lernphase können Abregelungsverluste zwar teilweise, aber nicht vollständig vermieden werden. Die Gesamtsystemeffizienz sinkt bei einer Begrenzung auf 50% um ca. 3 Prozentpunkte während der Autarkiegrad gleich hoch bleibt.





BS#4: Systemverhalten am gleichen Testtag vor (links) und nach (rechts) der Lernphase

Kontakt



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Das Projekt *CCT-Bat Heimspeicher-Systemtest* wird vom *Schweizer Bundesamt für Energie* gefördert.

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Federal Office of Energy SFOE

Versatile Lightweight Photovoltaic Module Line with Customized Module Stacks to Meet Application Oriented Reliability and Aesthetic Targets

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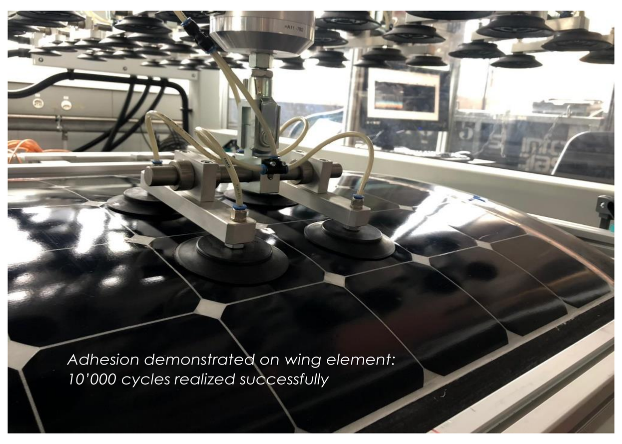
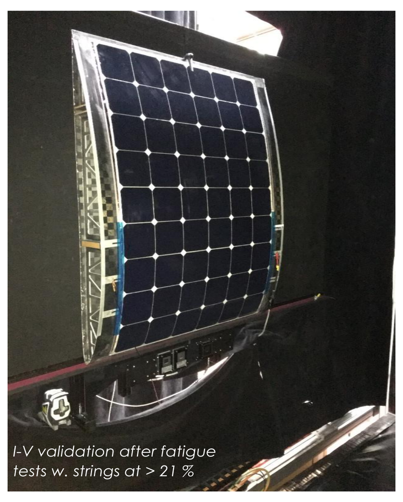
PV-Center, Centre Suisse d'Électronique et de Microtechnique (CSEM), Rue Jaquet-Droz 1,2002 Neuchâtel
SolarXplorers SA, Rue Galilée 7, 1400 Yverdon

Introduction

The photovoltaic market is rapidly diversifying from mainstream modules and entering the application-integrated domain. Each targeted application, such as vehicle-integration or building-integration, comes with its own set of requirements for optimum weight, aesthetics, color, mechanical strength, and structure in addition to its photovoltaic performance and reliability. A strong emphasis is set in CSEM on development of materials, processes, concepts and cost-effective production means for the realization of such lightweight photovoltaic modules.

SolarStratos plane demonstrator: Ultra light-weight down to 700 g/m^2





PERFORMANCE & RELIABILITY

CSEM developed new generations of special adhesives and encapsulant materials, as well as Pb-free interconnect, together with advanced module design and lay-up,enabling to demonstrate:

High performance with **>21% efficiency, ultralight weight of 700g/m^2**

High durability with all accelerated aging tests passed with modules implemented on wing element: mechanical stability & performance conserved after **10'000 cycles at 25 N/cell peel force,** after **200 thermal cycles between –40 °C and +80 °C, after bending fatigue tests simulating a maximum bending of the full wing of 3 meters, high UV resistance, ready for stratosphere.**

High integration quality on wing**, surface roughness < 0.2 mm** enabling for no impact on flight conditions, durable fixation technology and innovative inter-module connections.

RESULTS

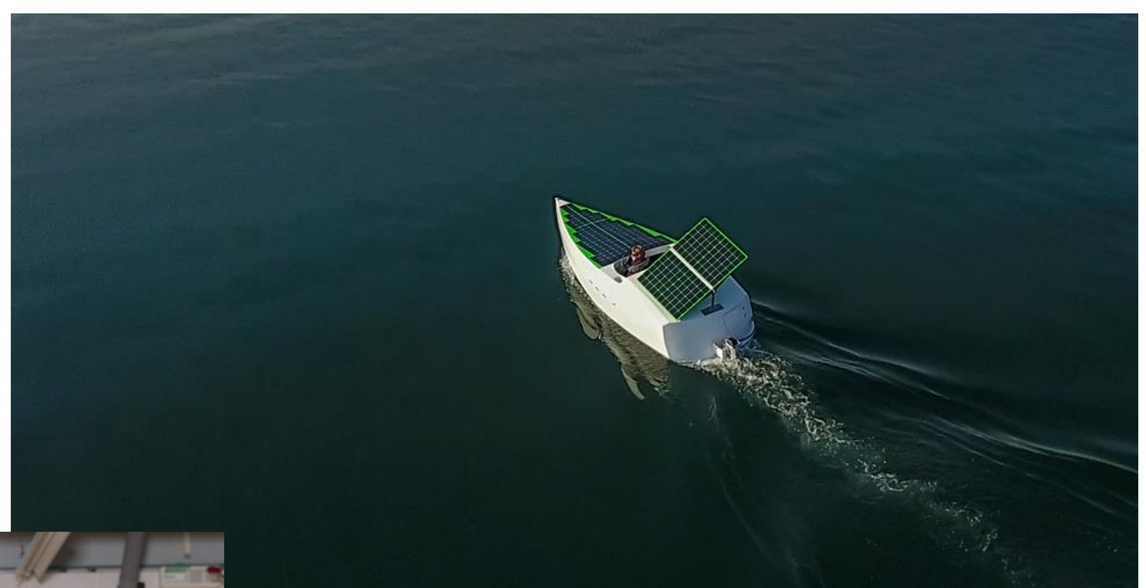
Successful integration of CSEM PV on the 2 wings of Solartratos completed in 2020, qualification of performance of installed PV system.

Successful flights in 2020 with two world records set: First solar free-fall without any CO_2 emissions, First jump in history from an electric plane

Qualified for extreme environments

Lightweight PV modules stacks developed for varying backsheets providing adapted mechanical rigidity depending on PV module dimensions and application. Self-standing modules with 2 to 4 kg/m^2.

CSEM nautic solutions with 2-3 kg/m3 were qualified in arctic extreme conditions /offshore corrosive environment / project Arctic Solar



Ultralightweight modules developed to power 40 stratospheric balloons for a meteorological expedition in the Indian Ocean as part of International Project Strateole-2 project with CNES, France.

CSEM lightweight PV Modules were qualified according to stratosphere required standards, and successfully validated in test flights in 2020

Custom-made for optimum integration

New possibilities developed: integration of CSEM colouring technologies, curved devices, large area systems

Conclusions

This work demonstrates the implementation of new materials and processes developed in CSEM for the realization of lightweight photovoltaic modules. In contrast to typical glass-based PV modules which exhibit a weight superior to 15 kg/m^2, the products developed can go from **as low as 700 g/m^2 for a module integrated** into an existing structure to **4 kg/m^2 for a self-standing module**. The exact module weight and stack depend on the mechanical rigidity the PV module must provide. In addition to high performance and reliability, CSEM solutions demonstrate high level of adaptation to custom-demand, including colouring technologies.

Ground-mounted photovoltaic power plants in Alpine winter sports destinations: Guest, resident and non-visitor preferences

Zürcher Hochschule für Angewandte Wissenschaften
zh aw Life Sciences und Facility Management
IUNR Institut für Umwelt und Natürliche Ressourcen

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How are ground-mounted PV systems perceived in alpine winter sports destinations? Our results show that in order for the energetic development of a destination to be well-balanced, various project attributes need to be evaluated. These attributes include factors such as how the landscape will be affected, if the project will use 100% renewable energy, whether a comprehensive climate action programme will be implemented and if a local stakeholder will operate the solar power plants. We identified five interest groups that differ significantly in terms of their preferences for how to develop ground-mounted PV plants: Residents, non-visitors and three contrasting groups of visitors.

Introduction

PV panels in the Swiss Alps achieve 1.5 to 2 times higher annual yields than elsewhere and a winter electricity share of up to 56%. Due to this potential, ground-mounted PV systems in Alpine areas will be able to meet a large proportion of the increased renewable energy demand in future, especially during the winter season. However, renewable energy systems can impact the aesthetics of a landscape and therefore face challenges in terms of social acceptance.

Method

In this study, we conducted an online discrete choice experiment, surveying a representative panel of 1,228 German-speaking Swiss to measure their preferences for hypothetical renewable energy production scenarios using ground-mounted PV systems near ski slopes in a winter sports destination.

A discrete choice experiment is a quantitative method used to elicit preferences from participants without directly asking them to state their preferred options. Participants were presented with a series of alternative hypothetical scenarios, each of which consisted of a combination of varying attributes (attribute-levels).

A sample scenario from the present study is illustrated in Figure 1. In total, participants were presented with six of these scenarios.

		Scenario A	Scenario B
			
Info on the solar systems in the picture	Advocacy organizations	• Mixed opinions in all bodies	• Municipal council • Second homes association • Business & Tourism • Nature conservation organizations
	Operator	• Local power company	• Region's lift operator
Climate protection measures		• Winter sports destination does not publish any information on climate	• 100% regional renewable energy • Comprehensive environmental program

I choose ○ Scenario A ○ Scenario B ○ None of the above scenarios

Figure 1: Example of a set of choices in the discrete choice experiment.

How did the attributes contribute to the survey respondents' choice of scenario?

The "**climate protection measures**" attribute (the extent to which the winter sports destination is committed to climate protection) had the greatest effect on respondents' decision to choose a particular scenario. The majority preferred scenarios with 100% regional renewable energy and a comprehensive environmental programme.

The „**opinion leaders**" attribute (organisations advocating for ground-mounted PV systems in the destination) and "**area**" attribute (area occupied by ground-mounted PV panels) influenced the decision to choose a particular scenario equally, while the **panellists disagreed most on the "area" and "climate protection measures" attributes**.

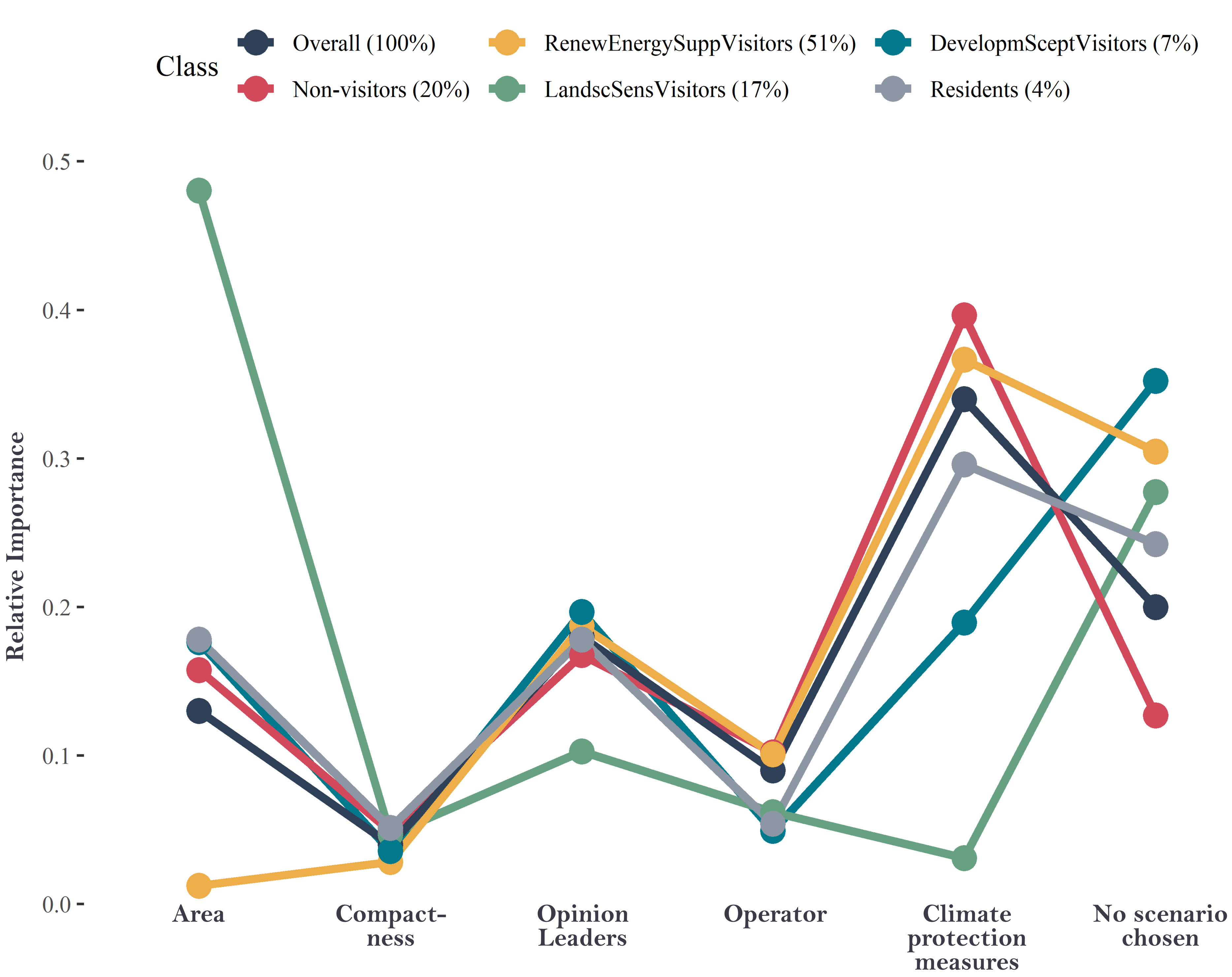

Figure 2: Relative importance of the evaluated attributes. Class size (%) in relation to the overall sample.

The panellists agreed on the „**operator**" attribute (who would profit financially from these PV systems, bear the risks and feed the renewable energy into the power grid?). Furthermore, the majority preferred scenarios where **a regional player, such as the local power company or the region's lift operator, would be in charge of operating the PV systems.**

There were no significant differences revealed in the effect of the "**compactness**" attribute (how densely the panels would be arranged).

Interest groups differed significantly in their preferences for the development of ground-mounted PV in winter sports destinations

Figure 2 presents the relative importance of the attributes in the choice model for each interest group.

Renewable energy supporting visitors based their decisions on climate protection measures. They represented the largest group in our panel and mostly preferred scenarios with 100% regional renewable energy. The proportion of women was higher in this group than in the landscape sensitive visitors group.

Landscape sensitive visitors based their decisions on the appearance of the landscape, preferring landscapes with fewer ground-mounted PV installations.

Development sceptical visitors tended not to select scenarios at all. This group represents the smallest visitor group, but visits winter sports destinations most often.

Residents live in winter sports destinations. The most decisive factor for them was climate protection measures, however, they also tended to assess landscape impact more critically than renewable energy supporting visitors.

Non-visitors almost never go to winter sports destinations in winter and differ significantly from the other groups in terms of age, income, and educational level. The most decisive factor for them was climate protection measures.

With the support of energieschweiz EWD

OST – Ostschweizer Fachhochschule

Institut für Energiesysteme, Werdenbergstrasse 4, Buchs/SG

Batterie als Alternative zum Netzausbau

Ausgangspunkt ist die Einspeisung einer 54 kWp-Photovoltaik-Anlage (PV) in ein schwaches Verteilnetz (36 kW Rückspeisung) eines landwirtschaftlichen Betriebs ausserhalb des Siedlungsraums. Als Alternative zur Verstärkung der 335m langen Leitung wurde ein Batteriesystem mit 54 kWh installiert.

Energiebilanzierung

Für eine Abschätzung des Speicherbedarf wurden die Daten des Solarmessstands der OST Campus Buchs verwendet mit 35° Neigung, -13.2° Ost-Ausrichtung mit 1130 kWh pro kWp und ohne Berücksichtigung von Eigenverbrauch.

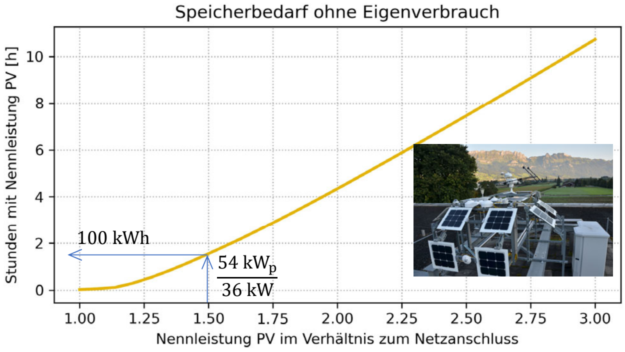

Abbildung 1 Stellt den Speicherbedarf dar in Abhängigkeit vom Verhältnis PV-Leistung zu Netzanschlussleistung. Speicherbedarf ist die Energie aus Zeit in Stunden mit der PV-Nennleistung.

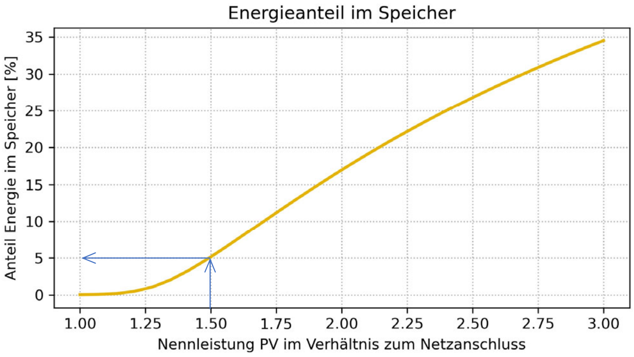

Abbildung 2. Anteil der Energie im Speicher zur gesamtproduzierten Energie über ein Jahr, dargestellt über dem Verhältnis PV-Nennleistung zu Netzanschlussleistung.

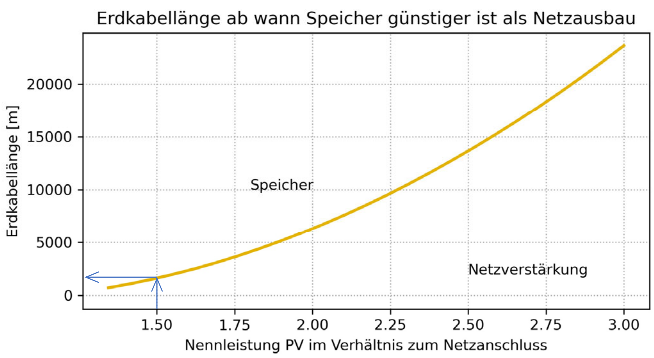

Abbildung 3 Länge des Erdkabels ab welchem ein Batteriesystem gleich oder günstiger ist, als eine Netzverstärkung, basierend den Kosten für das Batteriesystem inklusiv baulicher Massnahmen gegenüber offerierten Kosten für Netzverstärkung grösstenteils über Landwirtschaftsfläche

Monitoring Batteriespeichersystem

Nach Inbetriebnahme 2019 wurde das Batteriesystem über ein Jahr (15.03.2020 – 15.03.2021) messtechnisch begleitet. Aufgrund des konstanten Verbrauchs wurde die Eigenverbrauchsbetriebsart gewählt.

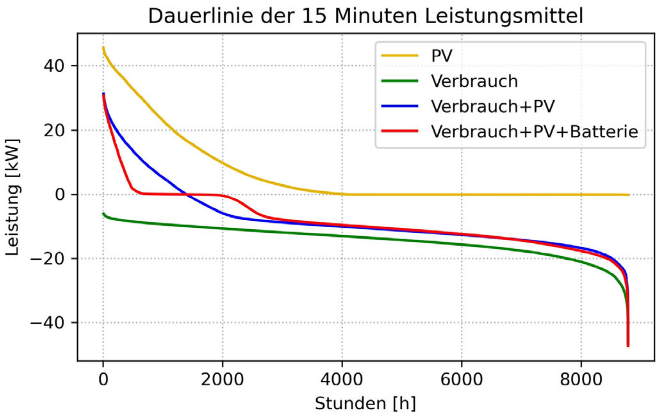

Abbildung 4 zeigt gelb die Dauerlinie der PV-Anlage. Blau die Dauerlinie der PV-Anlage reduziert um den Verbrauch. Der Verbrauch ist grün dargestellt. Rot die Dauerlinie am Netzanschlusspunkt mit Batteriesystems, PV-Anlage und Verbrauch.

Fazit

- Es ist eine grosse Speicherkapazität notwendig um die Einspeisespitze einer PV-Anlage aufnehmen zu können.
- Verbrauch dominiert das System.
- Ist die PV-Anlage weniger als 1.5-mal grösser als der Netzanschluss, so führt ein Abregeln zu weniger als 5% nicht einspeisbarer Energie.

Projektobjekt in Balzers
OST – Ostschweizer Fachhochschule, Campus Buchs
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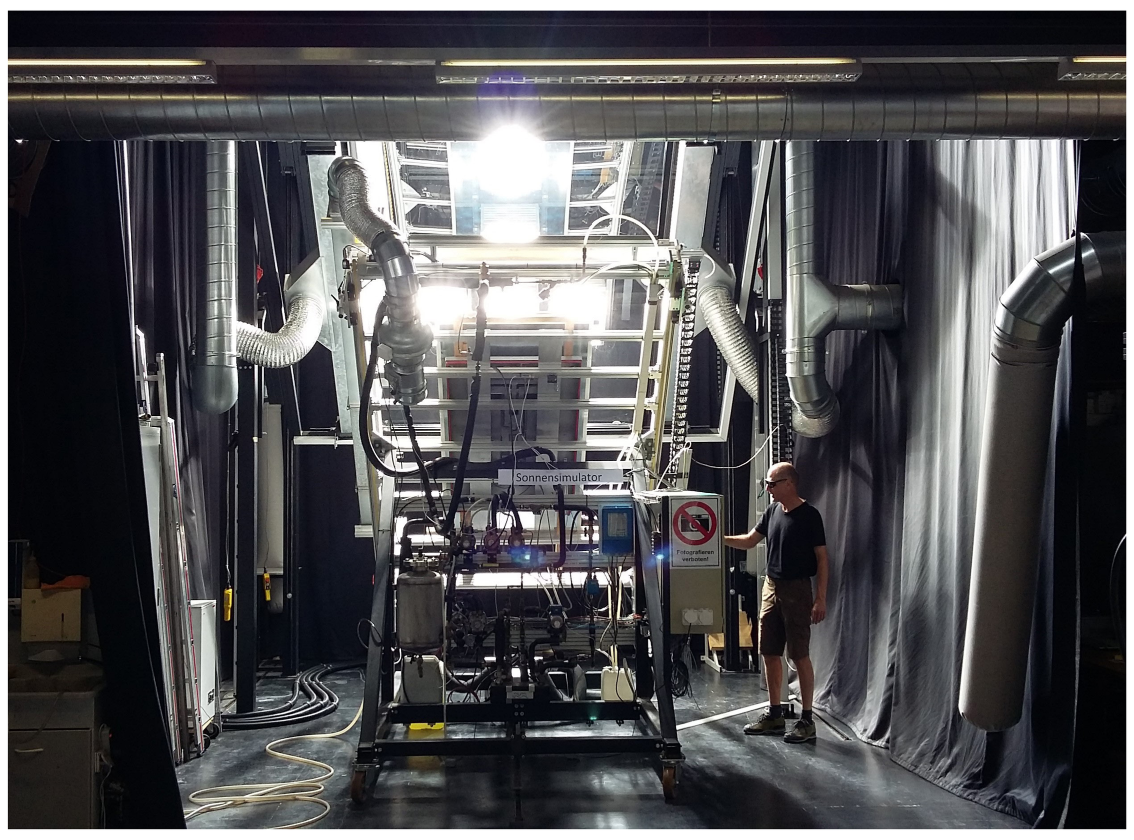
Accredited Swiss Energy Testing Laboratories

Die Vereinigung der akkreditierten Schweizerischen Energieprüflaboratorien ASETlabs (www.ASETlabs.ch) unterstützt die Energiewende. Die hochwertigen Prüfeinrichtungen werden für die Zertifizierung von Produkten eingesetzt, sie stehen aber auch für die Unterstützung von F&E-, P&D- und aR-Projekten zur Verfügung. Jedes der beteiligten Labore verfügt in seinem Bereich über höchste Fachkompetenz, die international anerkannt ist und durch die Schweizerische Akkreditierungsstelle gemäss SN EN ISO/IEC 17025 regelmässig bestätigt wird.

Das Zusammenspiel verschiedener Technologien ist ein wichtiger Treiber für die erfolgreiche Energiewende. Die Vernetzung der Laboratorien ermöglicht es, auf diese Herausforderungen einzugehen: Unterstützung von der Idee bis zum zertifizierten Produkt.

SPF Institut für Solartechnik



Das Institut für Solartechnik SPF ist Teil der Ostschweizer Fachhochschule in Rapperswil. In unserem international tätigen Prüflabor SPF Testing beurteilen und zertifizieren wir Komponenten und Systeme aus dem Umfeld der Solartechnologie sowie Anlagen zur Bereitstellung von Wärme im Gebäude. Zum Angebot gehören auch verschiedene Materialprüfungen und Messungen der thermischen und optischen Eigenschaften der Gebäudehülle.

SPF INSTITUT FÜR SOLARTECHNIK

Kontakt:
Andreas Bohren
testing@spf.ch

Prüfstelle Gebäudetechnik (HSLU)

Die Prüfstelle Gebäudetechnik der Hochschule Luzern führt thermische, strömungstechnische und akustische Untersuchungen von Komponenten und Apparaten der Gebäudetechnik durch. Die Lüftungstechnik bildet dabei den Schwerpunkt. So sind wir eines der international führenden Prüflabors im Bereich Wärmerückgewinnung.

Lucerne University of Applied Sciences and Arts
HOCHSCHULE LUZERN
Technik & Architektur
FH Zentralschweiz

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Prüfstelle für Holzfeuerungen

Die Prüfstelle für Holzfeuerungen ist Teil der Fachhochschule Nordwestschweiz in Brugg-Windisch, angegliedert an das Institut für Biomasse und Ressourceneffizienz.

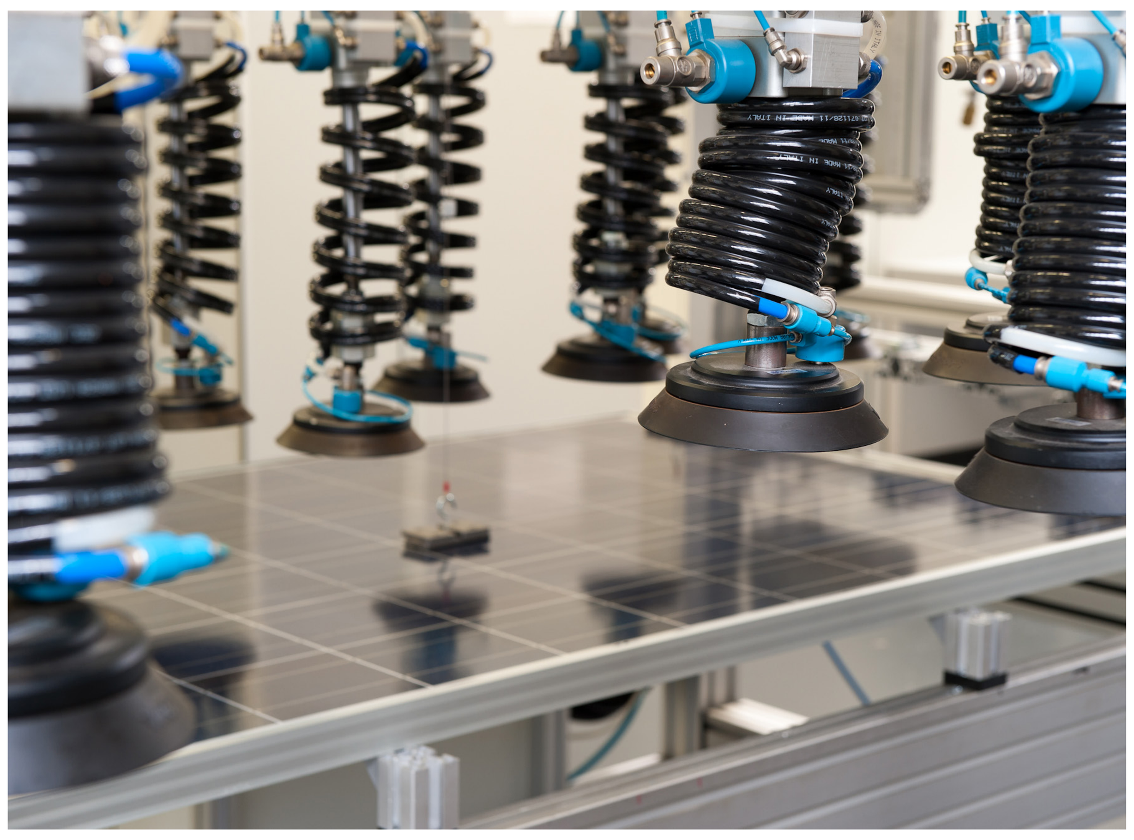
Unser Labor führt Typprüfungen durch von:
- Wohnraumfeuerungen (inkl. Kochherde)
- Heizkesseln bis 500 kW

Zudem Prüfen wir die Brandschutzanforderungen für Heizkessel grösser 500 kW.

n|w Fachhochschule Nordwestschweiz

Kontakt:
Tom Strebel
holzfeuerungen.technik@fhnw.ch

SUPSI PVLab



Das SUPSI PVLab bietet Prüf- und Messdienstleistungen für elektrische Charakterisierung im Labor und im Freien, Klima- und mechanische Überprüfung, sowie Sicherheitstests für PV-Module an.

Werkinspektionen und Bewertungen der Finanzierbarkeit werden durch externe Experten durchgeführt.

SUPSI

Kontakt:
Mauro Caccivio
mauro.caccivio@supsi.ch

Labor für Photovoltaiksysteme

An der Prüfstelle für PV-Wechselrichter des PV-Labors der Berner Fachhochschule können 1-String-Wechselrichter von 200 W bis 100 kW, sowie Multistring-Wechselrichter (1 bis 3 Strings) von 200 W bis 3 * 11.5 kW getestet werden. Das Prüfangebot umfasst den gesamten und dynamischen Wirkungsgrad, Oberschwingungsströme und EMV leitungsgebundene Funkstörungen.

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Christof Bucher
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Wärmepumpen-Testzentrum WPZ

Das Wärmpumpen-Testzentrum WPZ in Buchs SG ist ein international etabliertes Prüfzentrum für Wärmepumpen. Es ist in der Hochschule Ost (vormals NTB) eingegliedert. Das Labor führt diverse Zertifizierungsmessungen für den Europäischen Markt durch und leistet damit einen grossen Beitrag zur Qualitätssteigerung der Wärmepumpe in Punkto Effizienz und Schall.

WPZ Wärmepumpen-Testzentrum

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Blendung an Photovoltaik-Anlagen

19. Nationale Photovoltaik-Tagung, Juli 2021, Bern
Von Prof. Dr. Christof Bucher, Peter Wüthrich, Sirin Danaci, Berner Fachhochschule, PV-Labor

Reflexionen der Sonnenstrahlung an Glasoberflächen können zu störenden Blendwirkungen führen, wenn zwei Voraussetzungen gegeben sind: Die geometrischen Verhältnisse müssen eine Blendung ermöglichen und die Reflexion an der Glasoberfläche muss gerichtet, das heisst gebündelt sein. In diesem Poster wird gezeigt, wie neuartige Glasoberflächen die Bündelaufweitung erhöhen und damit eine Blendung wirkungsvoll reduzieren oder verhindern. Exemplarisch wird die Sanierung einer PV-Anlage zur Reduktion der Blendung beschrieben und ausgewertet. Aus dem Beobachtungswinkel eines Anwohners wird dabei die Leuchtdichte der PV-Module während des Blendereignisses um rund drei Grössenordnungen reduziert.

Einleitung

Praktisch alle heute im Handel erhältlichen Photovoltaik-Module (PV-Module) sind nach dem Stand der Technik reflexionsarm ausgeführt und genügen damit grundsätzlich den Anforderungen der Raumplanungsverordnung (RPV Art. 32a) [1]. Die Praxis zeigt jedoch, dass gerade bei gut einsehbaren Norddächern eine störende Blendung der Nachbarschaft nicht immer ausgeschlossen werden kann. Bei ungünstigen geometrischen Verhältnissen können auch an reflexionsarmen PV-Modulen Reflexionen mit Leuchtdichten oberhalb von 1'000'000 cd/m2 auftreten. Sie werden bei längerer Einwirkdauer auf einen Beobachter oft als störende Blendungen wahrgenommen.

Leuchtdichte und Blendung

Die Leuchtdichte in cd/m² ist das Mass der Helligkeit einer Oberfläche aus einer bestimmten Beobachtungsrichtung. Sie ist damit das relevante Mass zur Beurteilung einer möglichen Blendung [2]. Anders als oft angenommen führt die Reduktion der Reflexion (d. h. ein geringerer Anteil des einfallenden Lichts wird zurückgeworfen) meist nicht zu einer relevanten Reduktion der Leuchtdichte.

Die Leuchtdichte wird primär dann signifikant reduziert, wenn das reflektierte Licht stärker gestreut wird (Bündelaufweitung). Abbildung 1 zeigt die Leuchtdichten verschiedener Glasoberflächen. Typischerweise werden Leuchtdichten oberhalb von 100'000 cd/m² als blendend wahrgenommen, während sich das menschliche Auge gut an Leuchtdichten unterhalb von ca. 25'000 cd/m² (entspricht einer weissen Fassade bei direkter Sonneneinstrahlung) anpassen kann. Leuchtdichten unterhalb von 25'000 cd/m² können bei Glasoberflächen praktisch nur dann erreicht werden, wenn die Bündelaufweitung grösser als bei einem reflexionsarmen Standard-PV-Modul ist.

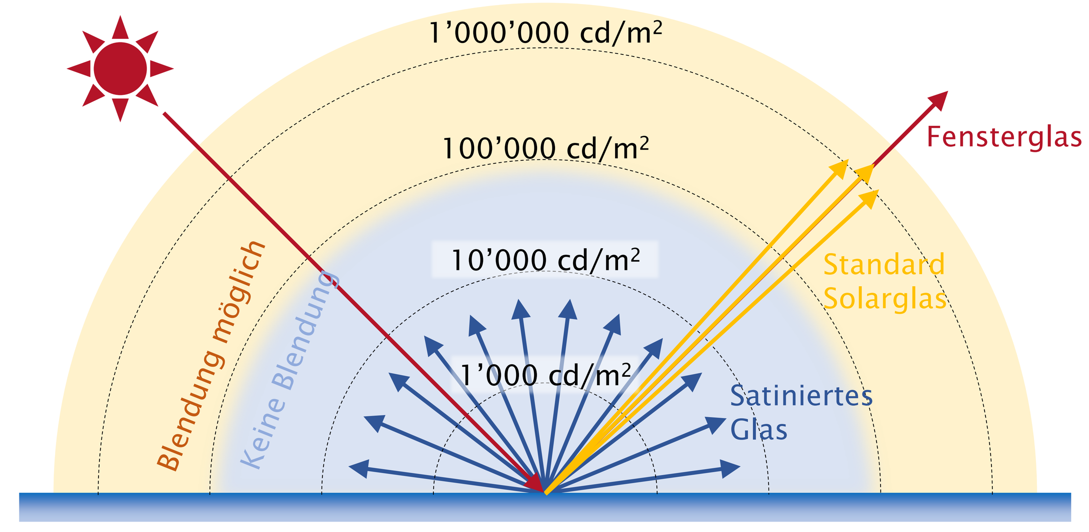

Abbildung 1: Leuchtdichte an verschiedenen Oberflächen

Die Leuchtdichte ist winkelabhängig. Je flacher die Sonneneinstrahlung auf eine Glasoberfläche trifft, desto höher ist bei allen für dieses Poster untersuchten Glastypen die Leuchtdichte (Abbildung 2). Bei sehr flachen Einstrahlungswinkeln (Winkel zwischen Flächennormale und Reflexionsstrahl >80°) wird diese jedoch nicht mehr als relevant betrachtet, da Sonnen- und Blendstrahl aus einer ähnlichen Richtung auf den Beobachtungspunkt treffen.

Neue Glasoberflächen

Satinierte (chemisch geätzte) Glasoberflächen wirken optisch matt. Sie reflektieren zwar nicht weniger als Standard-Solargläser, verteilen die Reflektion aber nahezu homogen in der Hemisphäre. Gemäss den Messungen des PV-Labors der BFH bleibt damit die Leuchtdichte aus praktisch allen relevanten Beobachtungspunkten deutlich unterhalb einer möglichen kritischen Grenze (Abbildung 2). Insbesondere ist die Leuchtdichte jeweils tiefer als diejenige eines weissen Blattes Papier oder einer weissen Fassade.

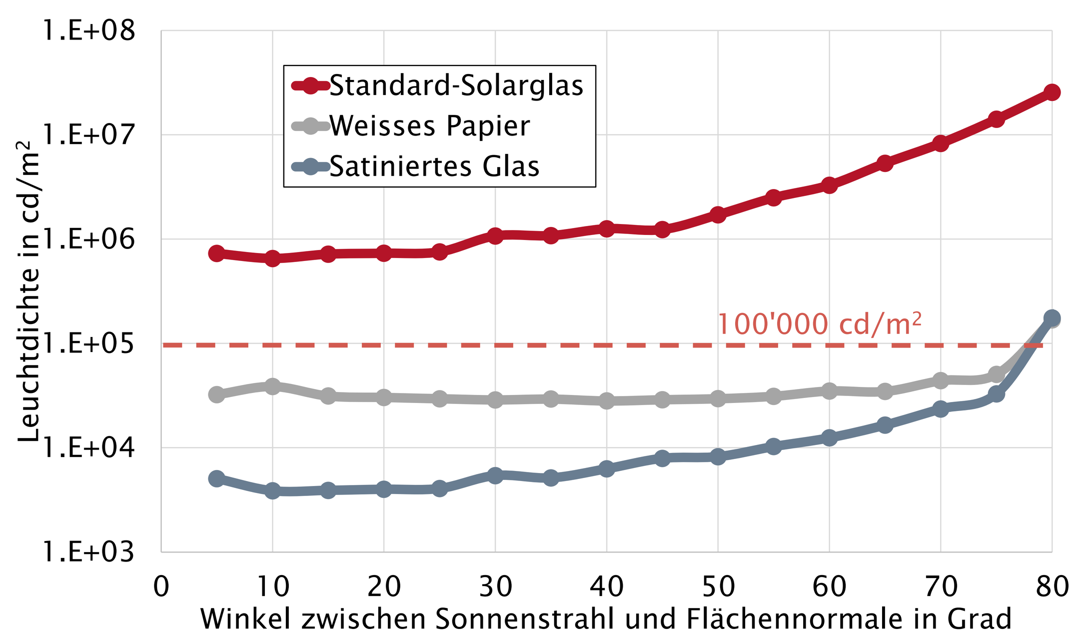

Abbildung 2: Winkelabhängigkeit der Leuchtdichten von Reflexionen an verschiedenen Oberflächen.

Pilotprojekt: Blendsanierung

Das um 45° geneigte Norddach eines Einfamilienhauses im Kanton Zürich ist vom direkt nördlich angrenzenden und einige Meter höher gelegenen Nachbarn sehr gut einsehbar. Er macht jeweils in den Sommermonaten am Nachmittag eine Blendwirkung geltend. Dieser Befund wird von einem Reflexionsgutachten der Basler & Hofmann AG gestützt und mit bis zu 2.5 Stunden je Beobachtungspunkt quantifiziert.

Die Leuchtdichte der im Jahr 2016 verbauten PV-Module vom Typ MegaSlate der Firma 3S Solar Plus wird im Juni 2021 vom PV-Labor der BFH vor Ort an einem wolkenlosen Tag gemessen. In einem Testaufbau werden anschliessend vier der Module mit gleichformatigen Modulen mit satinierten Gläsern ersetzt (MegaSlate Satinato). Die gemessenen Leuchtdichten werden um rund Faktor 1000 reduziert und liegen damit deutlich unterhalb der einleitend genannten Grenze von 25'000 cd/m² (Abbildung 3). Je nach Blickwinkel verändern die neuen PV-Module ihr Erscheinungsbild. Über das Langzeitverhalten liegen erst wenige Informationen vor.

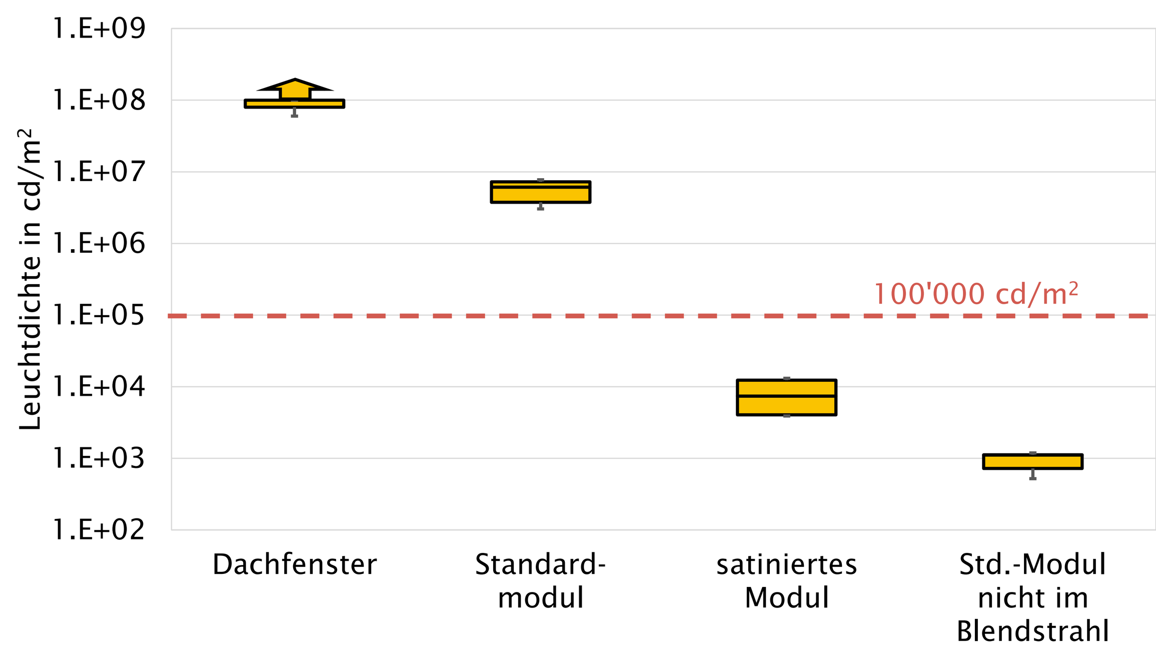

Abbildung 3: Leuchtdichten aus der Feldmessung des Pilotprojekts.

Fazit und Ausblick

Satinierte Gläser können die Blendwirkung von PV-Modulen stark reduzieren oder verhindern. Über ihre Langzeitstabilität wie beispielsweise das Derating der Glasoberfläche ist erst wenig bekannt. Weitere Langzeituntersuchungen sind notwendig. Aufgrund der geringen Verfügbarkeit, der aufwändigeren Herstellung sowie der noch offenen technischen Fragen sollen satinierte Module heute nur in besonderen Ausnahmefällen eingesetzt werden.

Referenzen

[1] D. Stickelberger et al., Leitfaden zum Melde- und Bewilligungsverfahren für Solaranlagen, Swissolar, Februar 2021.
[2] F. Ruesch et al., Methode zur Quantifizierung der Blendung durch Solaranlagen- Vergleich mit anderen Materialien der Gebäudehülle, SPF, 26. OTTI Symposium Thermische Solarenergie, 2016.

Abbildung 4: Dachfläche vor der Sanierung

Abbildung 5: Bemusterung 4 blendfreie PV-Module

Abbildung 6: Dachfläche nach der Sanierung

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Neue Strategien in der PV Brandbekämpfung

19. PV Konferenz Bern, 2021
Professor Urs Muntwyler, Ingenieurbüro Muntwyler, 3007 Bern, urs_muntwyler@gmx.ch
PD Dr. Eva Schüpbach, CEO Dr. Schüpbach Muntwyler Consulting GmbH, Bern+Unterseen
Poster: Prof. Urs Muntwyler (Berner Fachhochschule BFH, Burgdorf)

Partner:
GVB
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Einleitung

PV Anlagen haben ein geringes Risiko, Bränden zum Opfer zu fallen. Die Fälle, bei denen PV Anlagen die Ursache sind oder die von einem Brand betroffen sind, hängen mit der Anzahl der Anlagen und technischen Mängeln aller Art zusammen. Prof. Urs Muntwyler und das PV Labor der BFH in Burgdorf beschäftigen sich seit über 30 Jahren mit der Prävention von Bränden bei PV Anlagen. In den letzten Jahren konnten die Arbeiten des PV Labors BFH im Bereich der PV Brandprävention durch die Unterstützung der Berner Gebäudeversicherung GVB intensiviert werden.

Unpräzise Brandursachen

In einer grossen Studie (2014) zu Bränden von PV Anlagen (TÜV Deutschland und PV Labor der BFH) wurden 1,3 Millionen PV Anlagen (30 GWp) mit 400 Vorfällen erfasst.
Bei 180 Anlagen war die PV Anlage der Grund. PV Indach-Anlagen hatten ein 20x höheres Brandrisiko als PV Aufdachanlagen (IEC TR63226).
Die Brandursachen "technische Ursache" wurden nicht im Detail ermittelt und dürften oft nicht präzise angegeben sein.

Der häufigste Fall in der Schweiz: Ein Hausbrand zerstört eine PV Anlage. Foto: GVB 2021 / Wolfisberg.

Brand einer PV Indach-Anlage bei Thun im Sommer 2021. Foto: Urs Muntwyler.

Neue Indach Brandbekämpfungs-strategie "Fognail"-Einsatz

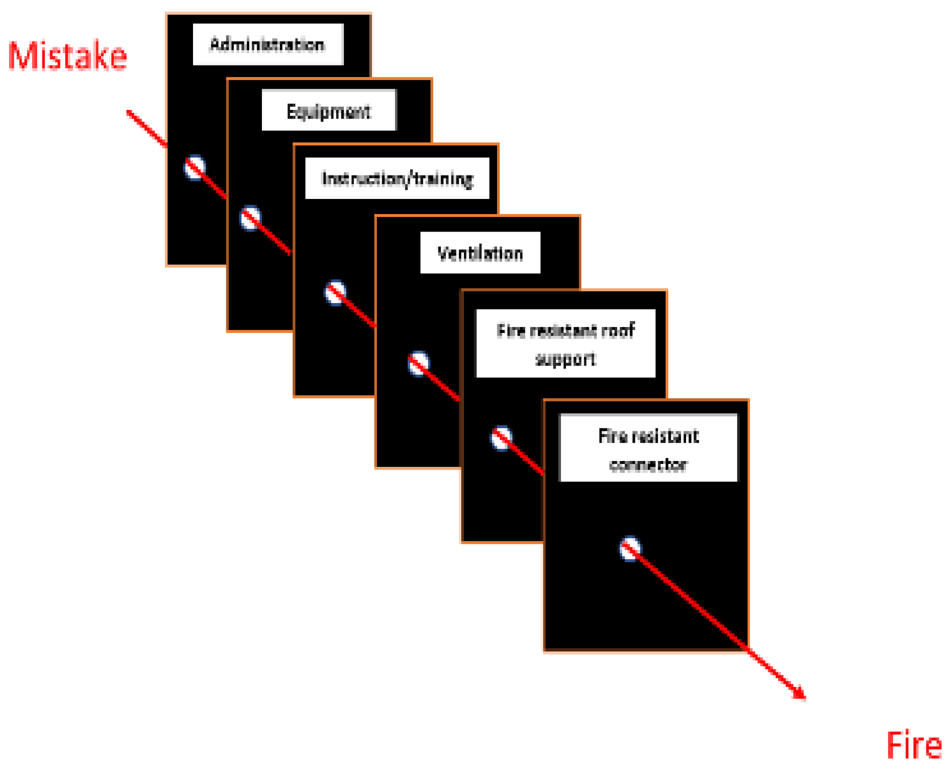
Die Thuner Feuerwehr hat im Juli 2020 erfolgreich die «Fognail» Technik zur Bekämpfung des Brandes in einer PV Indach-Anlage eingesetzt. Diese Methode ist sehr effektiv und hat einen minimalen Wasserschaden zur Folge.
Details zum Brandeinsatz sind im «Swissfire 118» (Ausgabe 05/2021) beschrieben.
Die Thuner Feuerwehr hat nun die «Fognail» fix im Einsatzfahrzeug (ADL).

Der Thuner Feuerwehrkommandant Roland Gfeller mit der verlängerten "Fognail" zur Bekämpfung von PV Indach-Anlagebränden (Foto: Urs Muntwyler).

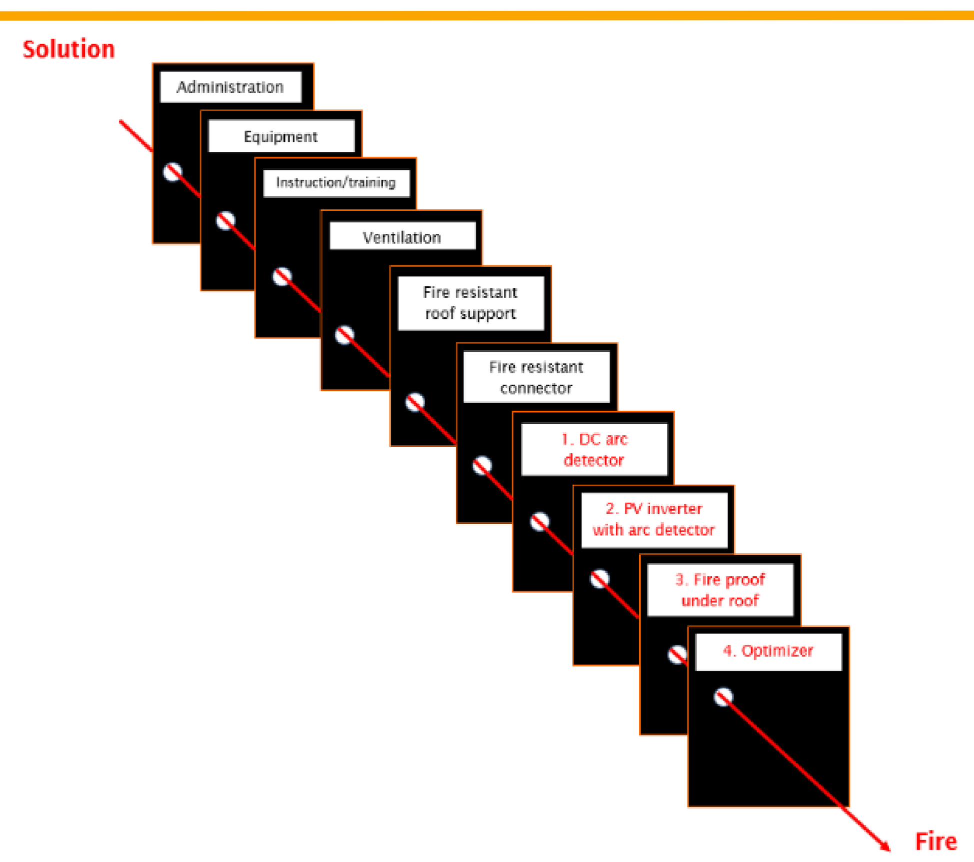
Das Einsatzfahrzeug ADL der Thuner Feuerwehr mit der "Fognail". Foto: Urs Muntwyler.

Neue Brandpräventions-Strategie

Analysierte die TÜV Studie (2014) eine Vielzahl technischer Mängel, die zum Brandausbruch führen konnten, so wird heute meistens die Kreuzverbindung von PV Steckern als Ursache angegeben (TNO Studie 2019).
Wir haben aber verschiedene Fälle von brennenden PV Modulen gefunden, bei denen Bypass-Dioden versagten. Dies hat zur Zerstörung der PV Anlage oder gar zum Brand geführt, was in Zukunft berücksichtigt werden muss.



PV Indach-Anlagen können zu wenig Sicherheits-Layer haben, was einen Brand-Ausbruch möglich machen kann.



Wir schlagen daher zusätzliche Sicherheits-ebenen für Indach-Anlagen vor, die einen Brand-Ausbruch unmöglicher machen.

Berner Fachhochschule

Verdankungen: Wir schätzen die Zusammenarbeit mit der Feuerwehr Thun und der Berner Gebäudeversicherung GVB und weisen in verdankenswerter Weise hin auf das Feuerwehrmagazin "Swissfire 118" (Ausgabe 05/2021), Artikel über PV Brandbekämpfung mit der «Fognail» (von Prof. Urs Muntwyler).

Kontakt bis Ende 2021: Prof. Urs Muntwyler, Jlcoweg 1, 3400 Burgdorf / www.pvtest.ch / urs.muntwyler@bfh.ch

Kontakt ab sofort und per 1.1.2022: Prof. Urs Muntwyler, c/o Dr. Schüpbach Muntwyler Consulting GmbH, Hopfenrain 7, 3007 Bern / urs_muntwyler@gmx.ch

Micro Stockage Intelligent Distribué (OFEN MSID)

A. Weibel, Prof N. Jordan, H. Pereira, J.-M. Alder, J. Vianin, Prof. D. Wannier
HES-SO Valais-Wallis, Institute of Sustainable Energy, Technopole 3, 3960 Sierre, Suisse

Summary

The OFEN MSID is a 3 years project that brings together the interests of 4 distribution service operators (DSO). Their objectives include remote network stabilization (use cases 1 and 2), optimization of self-consumption and co-creation of new business models to make photovoltaic storage profitable (use cases 3 and 4). This project aims to aggregate micro-storage systems (electric vehicles, batteries, heat-pumps) and develop associated business models. The FMA (Gryon/Vaud) and OIKEN (Sierre/Valais) pilot sites both have grid voltage challenges. The FMA site is located at an altitude of 1'114 meters. The micro-grid include a farm equipped with 30 kW photovoltaic panels (PV) as well as a mountain cafe. The OIKEN site is a tennis hall with 120kWp PV and a small consumption.

Introduction

One of the work package dedicated to FMA and OIKEN aims to optimally size and control an energy storage system taking into consideration voltage constraints.

Both use cases are encountering network overvoltage problems due to high PV feed-in coupled with their spatiotemporal characteristics (PV location in the grid topology and low consumption at specific date and time). To achieve our goal an inverse problem methodology has been developed and will be published at the 26th International Conference & Exhibition on Electricity Distribution (CIRED 2021).

Partners

Methods

There are two requirements for the methodology; First, one must provide network topology and elements characteristic. Secondly, one must collect data of voltages and power (at least two measurements on specific location on the studied network). Then the procedure is described as follow:

- Synthetic data generation
- Data-driven modelling
- Power flow boundaries estimation
- Optimal energy storage sizing and control

The details about the implementation will be revealed in the paper "Physic-guided machine learning for distribution network modelling: Application on optimal storage sizing and control" related to CIRED2021 event.

Results

We will present the result obtained for the OIKEN use case. After successfully training the data-driven power grid model, we applied a linear optimization algorithm to obtain the optimal energy storage sizing solutions. We studied power feed-in limitations also known as peak shaving by directly restricting/limiting the power injected by the inverters. The figure 1 demonstrated that the higher the desired voltage stability, the more storage is required. We analyse that peak shaving allows to optimise the storage size.

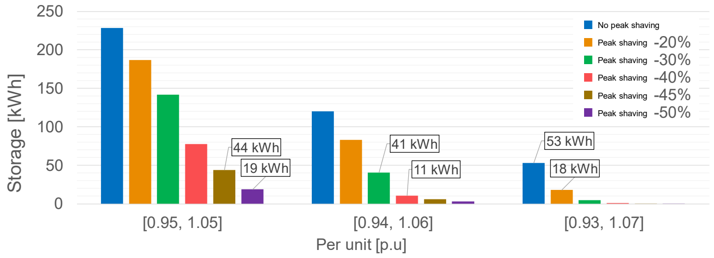


*Figure 1 : Results of **optimal sizing** using data-driven model*

The figure 2 illustrated the performance of using the data-driven based optimal control for voltage regulation.

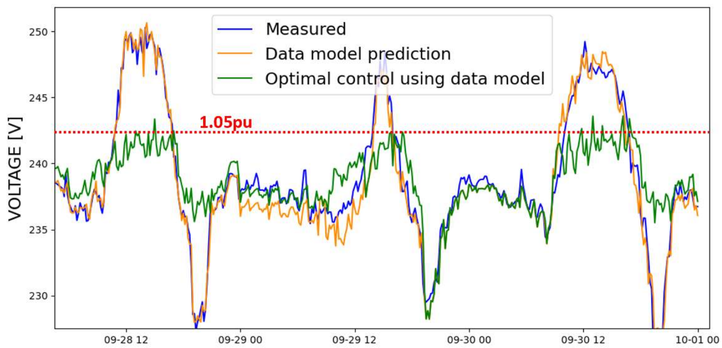


*Figure 2 : Results of **smart optimal control** using data-driven model*

Conclusions

In this applied research project, we successfully demonstrated the performance of combining physic modelling and data in order to achieve more accurate and computationally efficient result of energy storage sizing and control.

Contact and more information: david.wannier@hevs.ch, https://hevs.ch/en/minisites/projects-products/easilab/

SCCER - FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

Digitalization SCCER-FURIES Blockchain for EV Management

Prof. D. Wannier[1], N. da Conceição[1], J. Vianin[1], V. Mitrovic[1], Jean-Marie Alder[1], Helena Pereira[1], Marina Dorokhova[2]
[1] University of Applied Sciences Western Switzerland (HES-SO), Switzerland,
[2] EPFL / STI / IMT-NE / PV-LAB

Summary

Optimization of the management of charging stations for electric vehicles (EVs) within the network of Green Mobility hotels in Val d'Hérens (Figure 1) by exploiting the flexibility of EVs and simplify the exchange of energy between owners of the charging station using the blockchain technology.

Introduction

The project Digitalization SCCER-FURIES aims to simplify exchanges of photovoltaic kWh between electric vehicles (EV) charging stations. A first release is already implemented and will be deployed soon in our pilot environment.

Methods

The Two Tracks Unified Process (2TUP) methodology has been chosen for this project. This methodology merge the technical and functional branch before the development phase.

Technical branch

- The master thesis of Jérémie Vianin (2018) analysed of the technical possibility to link blockchain and a dynamic API request.
- Research analysis performed with our partners EPFL-PV-Lab and SUPSI during SCCER-FURIES project Digitalization (2019-2020) analysed and implemented a smart-contract with the framework AragonOS
- The master thesis of Nelson da Conceição (2020) described the blockchain's ecosystem for EV charging stations.
- EnergyWebFoundation proof of concept was implemented during the Bachelor thesis of Gabriel Riedo (2021)

Functional branch

After having analysed the business needs for our blockchain ecosystem, we studied private and public blockchain systems based on Ropsten testnet (Figure 1).

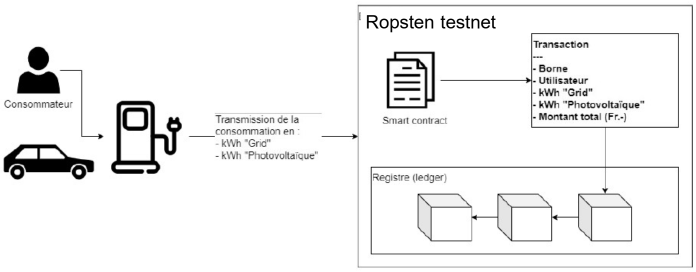


Figure 1 :Architecture of Ropsten testnet proof-of-concept

Development phase

We concluded that a simple smart-contract that contains three methods addHotel, AddEnergyTransaction and getBalance was needed to answer the business needs. This allows all hotel transactions and balances to be managed within the blockchain.

Results

Pilot infrastructure deployed to hotels member of the Green Mobility network and a test infrastructure at our campus Sierre.

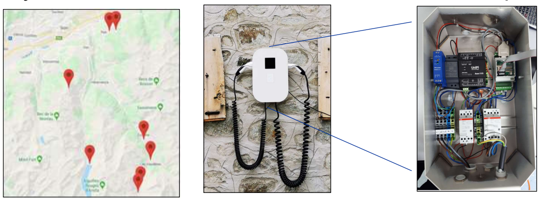


Figure 2 :pilot infrastructures deployed in the Val d'Hérens (Valais-Switzerland)

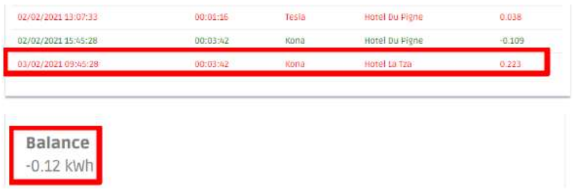


Figure 3 : Management interface to check Blockchain transactions and balance

After having implemented the solution, we analysed the real costs. The notion of gas refers to the fee, required to successfully conduct a transaction or execute a contract. The gas is linked with the requested time response and the consensus (figure 1). Ethereum use the proof of work that requires a lot of computational resources. When the test was done, the transaction price was around CHF 70.- on the main network (Figure 4). Ethereum has planned to migrate to hybrid proof of stake/work that will be lighter.

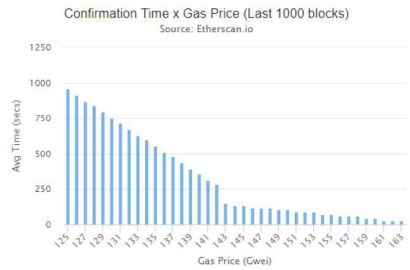


Figure 4 : Confirmation time (secs) and gas price (Gwei) for the last 1000 blocks

We are now studying another approach which combine private and public blockchain systems to reduce the cost by a factor 10 and reach about CHF 7.00 per transaction. We are looking forward to testing the lighter version of Ethereum's consensus.

Partners

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Innosuisse – Swiss Innovation Agency

ELECTRINFO
EPFL
OIKEN

Conclusions

- Our objective is to analyse the pertinence of blockchain ecosystems in the energy sector.
- The platform is fully functional, deployed on test infrastructure and ready to be deployed in a production environment

Contact and more information: david.wannier@hevs.ch, https://hevs.ch/en/minisites/projects-products/easilab/

SWISSOLAR ETH zürich SUPSI
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SOLARCHITECTURE
building solutions

A SWISS WEBSITE FOR SOLAR ARCHITECTURE

The interest in solar architecture is growing – and so is our platform.

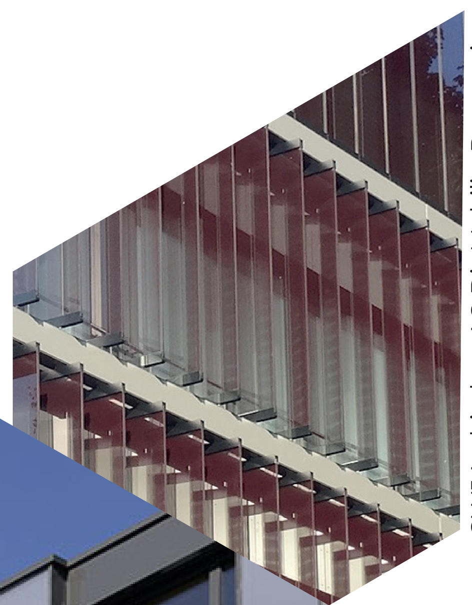
ABSTRACT

Our platform Solarchitecture.ch is all about knowledge and inspiration. It offers not only exciting new building concepts, but also detailed insights about already built objects, construction details, products and much more.
The structural set-up and development phase of our website was completed in 2019 and in 2020/2021 we are focusing on achieving competitiveness through the development and implementation of higher quality content, by achieving a more mature level of preparation in the many areas of the website and also by providing access to the three main national languages.

BECOME A PARTNER

If you would like to present yourself as a key player in the field of solar architecture contact us to find out about the different options of collaboration and sponsorship opportunities.

HMS Architekten AG, Kindergarten in Einigen, photo source: 3S Solar Plus AG

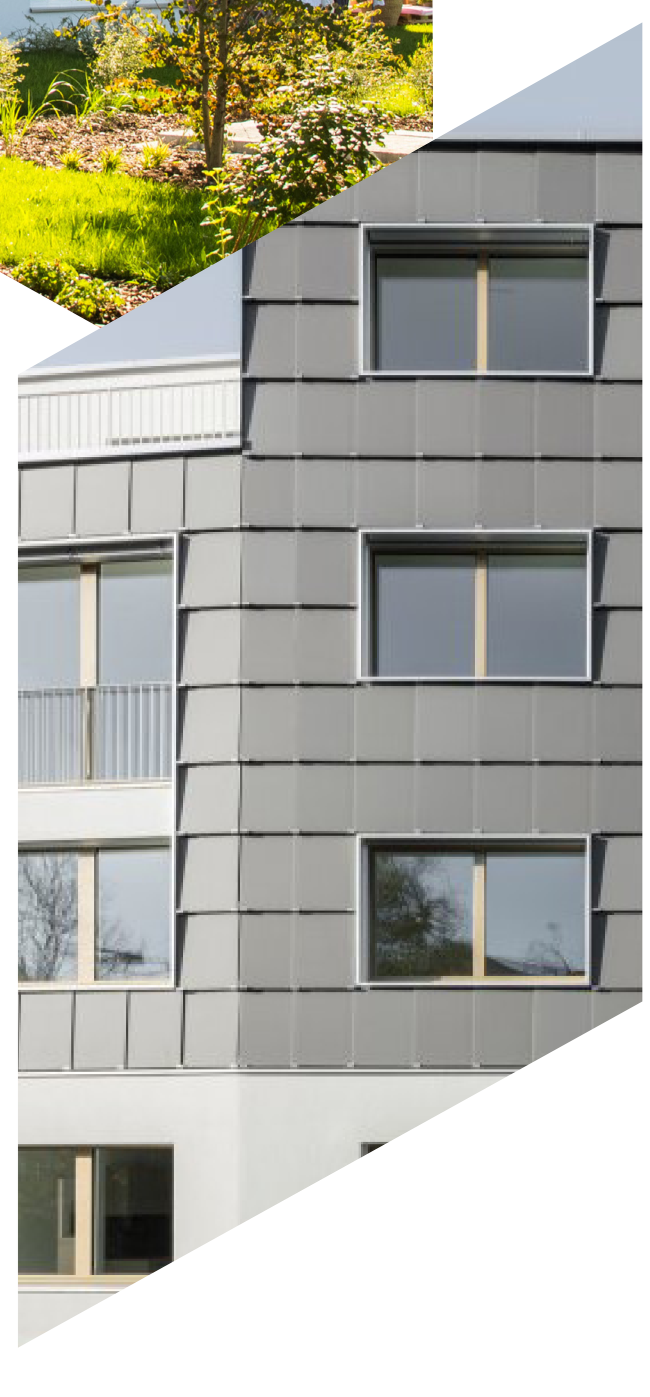


GWJ Architektur AG, Die Mobiliar Renovation, photo source: Kaspar Martig

Kämpfen Zinke + Partner AG, apartment building Zürich-Schwamendingen, photo source: Kämpfen Zinke+Partner AG

MFH in Mannedord, Switzerland, SOLAXESS

Viriden + Partner AG, MFH in Seewadelstrasse, photo source: Viriden + Partner AG



René Schmid Architekten AG, project in Zwirnerstrasse, photo source: René Schmid Architekten AG

solarchitecture.ch

This project, initiated by SUPSI (as Swiss BIPV competence centre) with the collaboration of Swissolar and ETHZ-BUK, wants to play a key-role in implementing specific measures related to the transfer of solar energy in the built environment. The support of SwissEnergy is essential to make the platform a reference place for all Swiss architects and solar architecture planners and to be able to guarantee the neutrality of the content implemented.

For more information contact us via info@solarchitecture.ch

SYNAGE 3S Solar Plus KIOTO SOLAR Kromatix ewz SEEN

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für Angewandte Wissenschaften

zh aw Life Sciences und Facility Management

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Das Potential und die Kosten von Dekarbonisierungsmassnahmen und deren Rolle als Treiber der inländischen Wertschöpfung und Arbeitsplätze

Le potentiel et les coûts de mesures de décarbonation et leurs rôle en tant que vecteur important de la création de valeur et d'emplois en Suisse

Ausgangslage

Dekarbonisierungsmassnahmen, wie der Ausbau der erneuerbaren Energien und der Energieeffizienz, leisten nicht nur einen wertvollen Beitrag zum Klimaschutz, indem sie die Energie zur Elektrifizierung von verschiedenen Sektoren liefern. Sie schaffen auch Wertschöpfung und Arbeitsplätze. Beide Effekte erzielen sie teilweise sogar billiger als ihre fossilen Alternativen und bringen so zusätzliche volkswirtschaftliche Einsparungen. Die Sonnenenergie spielt dabei eine entscheidende Rolle, da sie ein grosses Potential hat, schnell und modular einsetzbar ist und sowohl Strom als auch Wärme liefern kann.

Hier fassen wir die Ergebnisse aus mehreren Studien zusammen. Einerseits wurde analysiert, wie viele Treibhausgasemissionen verschiedene Dekarbonisierungsmassnahmen jährlich einsparen könnten und zu welchen Kosten (siehe rechts). Ausserdem wurde untersucht, wie viel inländische Wertschöpfung und wie viele Arbeitsplätze durch den Ausbau der Photovoltaik geschaffen würden (siehe unten). Die Studien kommen zum Schluss, dass Dekarbonisierungsmassnahmen und der Ausbau der erneuerbaren Energien neben der Reduktion von Treibhausgasemissionen auch erheblichen volkswirtschaftlichen Mehrwert schaffen.

1. Potential und Kosten von Dekarbonisierungsmassnahmen

In dieser Studie wurde analysiert, wie viel Treibhausgasemissionen verschiedene Dekarbonisierungsmassnahmen jährlich einsparen könnten und zu welchen volkswirtschaftlichen Kosten [1]. Die untersuchten Massnahmen beinhalten technische und Suffizienz-Massnahmen und decken die Kategorien Stromproduktion, Mobilität, Gebäude und Industrie ab. Die Resultate in Abbildung 1 zeigen, dass bei einer Umsetzung aller technischen Massnahmen jährlich rund 13.6 Millionen Tonnen CO_2-Äquivalente (CO_2eq) eingespart werden können. Mehr als 12 Millionen Tonnen CO_2eq können dabei für unter 200 Franken pro Tonne eingespart werden. Dieser Wert entspricht den Kosten, die eine ausgestossene Tonne CO_2eq an Klimaschäden verursacht. Ein erheblicher Teil der Treibhausgasemissionen kann zu negativen volkswirtschaftlichen Kosten reduziert werden. Sie sind also billiger als ihre fossilen Alternativen. Der Ausbau der Photovoltaik-Kapazitäten kann beispielsweise jährlich rund eine Million Tonnen CO_2eq vermeiden und gleichzeitig 39 Franken pro Tonne einsparen.

Abbildung 2 zeigt, dass verschiedene Suffizienz-Massnahmen zusätzlich jährlich 22.6 Millionen Tonnen CO_2eq einsparen können, wobei rund drei Viertel dieser Einsparungen im Ausland anfallen. Vor allem eine Reduktion der Flugreisen durch Schweizerinnen und Schweizer zeigt ein grosses Potential zu Emissionseinsparungen.

CO_2eq-Reduktionspotential und –Kosten der technischen Massnahmen im Jahr 2030

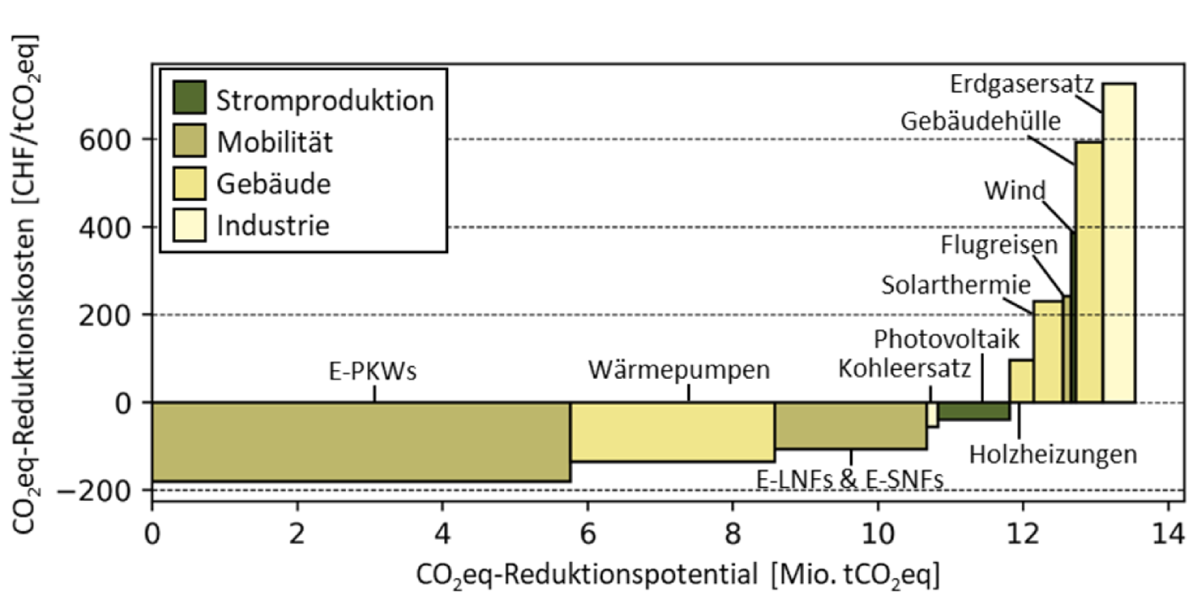

Abbildung 1. CO_2eq-Reduktionspotential und CO_2eq-Reduktionskosten im Jahr 2030 bei Umsetzung der Massnahmen ab 2021.

Dekarbonisierung durch Suffizienz

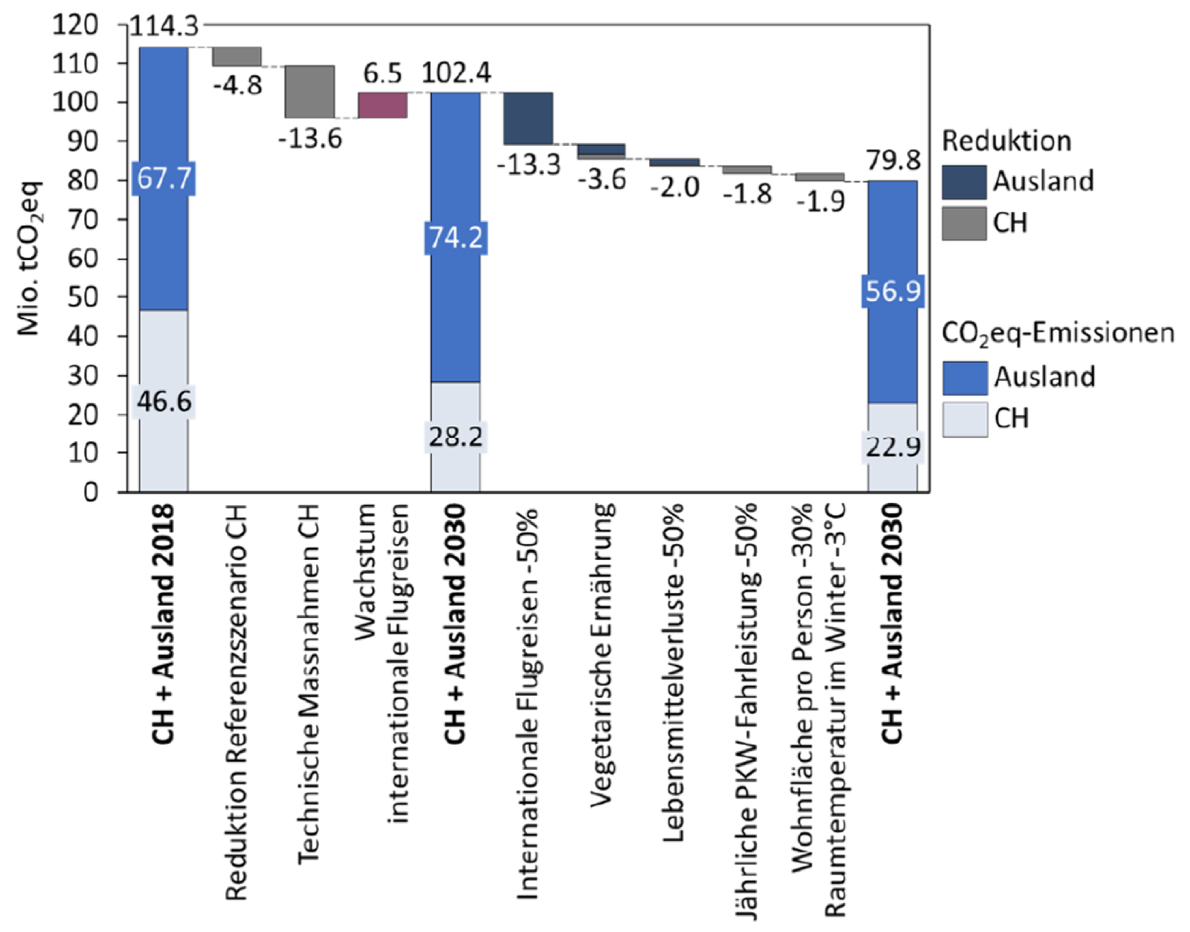

Abbildung 2. CO_2eq-Emissionen innerhalb der Schweizer Grenze (hellgrau) und durch SchweizerInnen im Ausland verursacht (hellblau) im Jahr 2030 im Vergleich zum Jahr 2018.

2. Inländische Wertschöpfung und Arbeitsplätze durch den Ausbau der erneuerbaren Energien und der Energieeffizienz

Arbeitsplätze in der PV-Branche

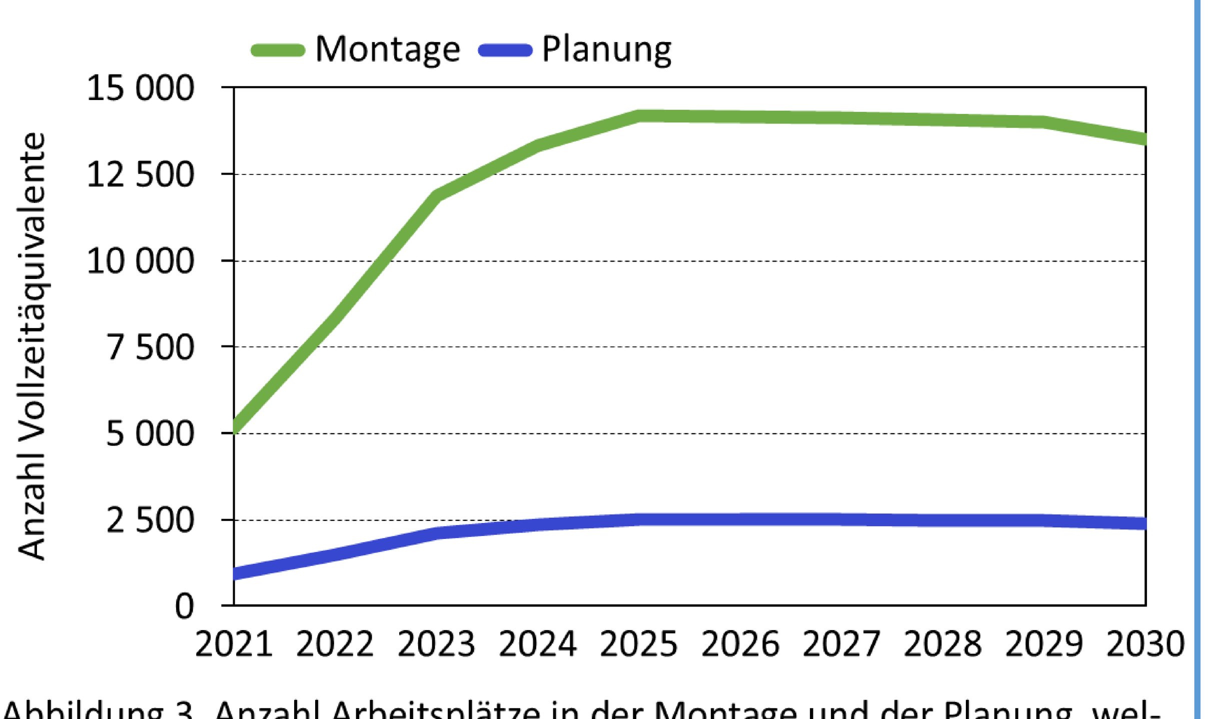

Abbildung 3. Anzahl Arbeitsplätze in der Montage und der Planung, welche durch den forcierten Ausbau der PV-Kapazitäten bis 2030 entstehen könnten.

Die Resultate in Abbildung 3 zeigen, dass der Ausbau der Photovoltaik bis 2030 rund 14'000 Arbeitsplätze schaffen könnte [2]. Ein Grossteil davon werden in der Montage geschaffen, aber auch in der Planung von PV-Anlagen würden rund 2'500 Arbeitsplätze entstehen. Es wurde dabei angenommen, dass die PV-Stromproduktion bis 2040 auf 50 Terawattstunden ansteigt, was für das Erreichen eines Netto-Null-Szenarios bis 2050 nötig sein wird. Weitere Berechnungen zeigen, dass eine solche Ausbaukurve bis 2030 ausserdem inländische Wertschöpfung von mehr als 14.3 Milliarden Franken schaffen könnte. Eine noch unveröffentlichte Studie zeigt, dass auch der forcierte Ausbau anderer erneuerbaren Energien und der Energieeffizienz ein grosses inländisches Wertschöpfungs- und Arbeitsplatzpotential hat [3]. Hier wurden neben der Photovoltaik auch der Ausbau der Windkapazitäten, Solarwärme, Holzheizungen und Wärmepumpen sowie die energetische Sanierung der Gebäudehülle untersucht.

Präsentierte Studien

[1] Siegwart, M., Hälg, L., Sauter, D., Rohrer, J. (2020). Technische und Suffizienz-Massnahmen zur Reduktion der schweizerischen Treibhausgasemissionen: Der Vermeidungskostenansatz. Wädenswil: Zürcher Hochschule für Angewandte Wissenschaften (ZHAW). (https://doi.org/10.21256/zhaw-2653)

[2] Rohrer, J. (2020). Ausbau der Stromproduktion aus Photovoltaik in der Schweiz: Bedarf, Potential und Umsetzung. Wädenswil: Zürcher Hochschule für Angewandte Wissenschaften (ZHAW). (https://doi.org/10.21256/zhaw-2654)

[3] Hälg, L., Cavadini, G. B., Rohrer, J. Arbeitsplätze und Wirtschaftlichkeit durch den Ausbau der erneuerbaren Energien und der Energieeffizienz in der Schweiz. Wädenswil: Zürcher Hochschule für Angewandte Wissenschaften (ZHAW). *In Bearbeitung.*

Wir bedanken uns für die Unterstützung

WWF SES energiestiftung.ch aee SUISSE Dachorganisation der Wirtschaft für erneuerbare Energien und Energieeffizienz WSS WERNER SIEMENS-STIFTUNG

Résumé

Des mesures de décarbonation, comme le développement des énergies renouvelables et de l'efficience énergétique, contribuent non seulement à la protection du climat en fournissant l'énergie nécessaire pour l'électrification de différents secteurs. Elles créent aussi de la valeur ajoutée et des emplois en Suisse. Souvent elles sont même moins chères que leurs alternatives fossiles et réalisent ainsi des économies supplémentaires au niveau national. L'énergie solaire joue un rôle capital puisque son potentiel est énorme, elle peut être développée de façon modulaire et rapide et produit de l'électricité ainsi que de la chaleur.

Ici nous résumons les résultats de plusieurs études indépendantes. D'une part, nous avons analysé le potentiel annuel de différentes mesures de décarbonation de réduire les émissions de gaz à effet de serre et les coûts associés à ces réductions (ci-dessus) [1]. D'autre part nous avons estimé la valeur ajoutée et le nombre d'emplois crées par le développement accéléré de l'énergie photovoltaïque en Suisse (à gauche) [2], [3]. Les études concluent que les mesures de décarbonation et le développement des énergies renouvelables ont le potentiel de non seulement réduire les émissions des gaz à effet de serre mais aussi de créer de la survaleur économique importante.

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A heuristic indicator-based heat pump control algorithm

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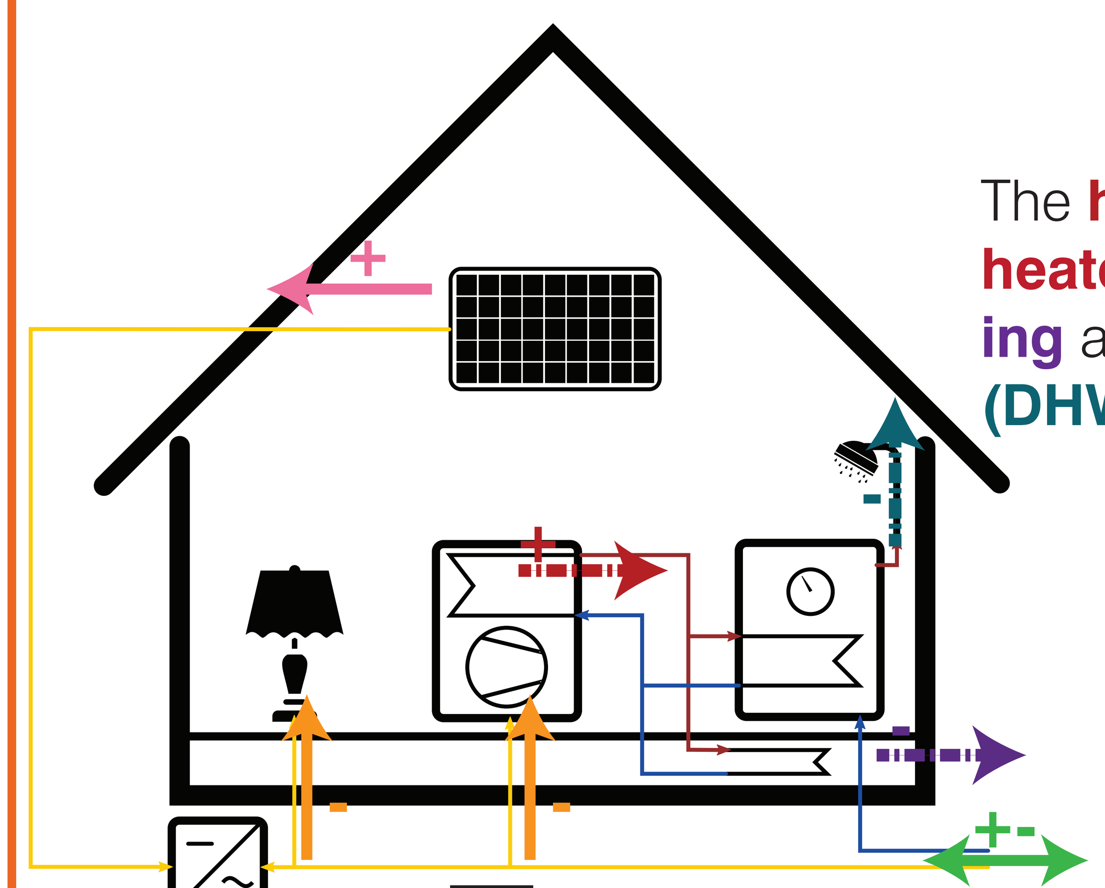
Motivation

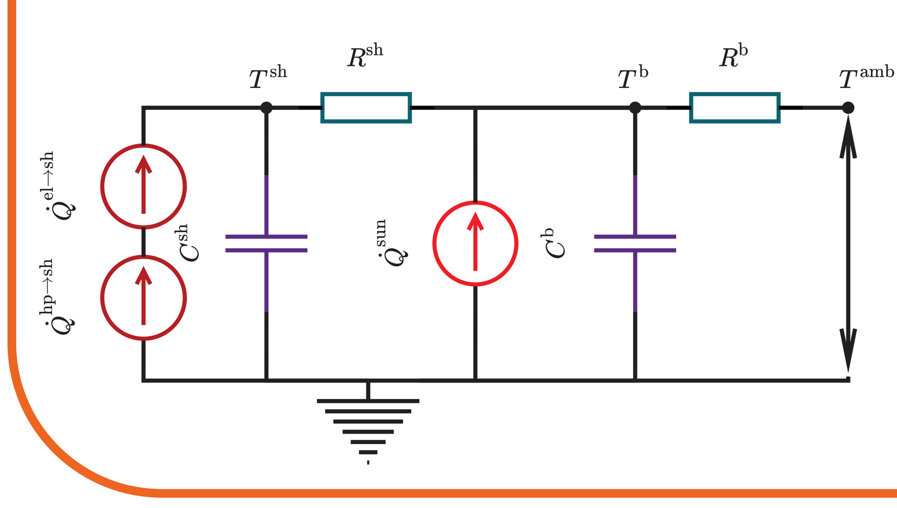
Simple and efficient control algorithms are required to enable the electrification of the building heating system and the integration of **photovoltaic (PV)**. The complexity of modern control algorithms for energy management applications might be detrimental to the rapid deployment of **smart heat pumps** and PV systems. Hence there is a need for **easily implementable** control algorithms. Our **heuristic control algorithm (HCA)** is a novel, simple and efficient heat pump control algorithm dedicated to optimizing the operating cost under PV generation. The algorithm aims to optimize an indicator that relates the variation of the operational cost due to a given action (like increasing the energy fed to a heat pump) and the heat production gain.

System modeling

The **PV array** and **grid** fulfill the **electric demand**.



The **heat pump** and **electric heater** fulfill the **space heating** and **domestic hot water (DHW)** demand.

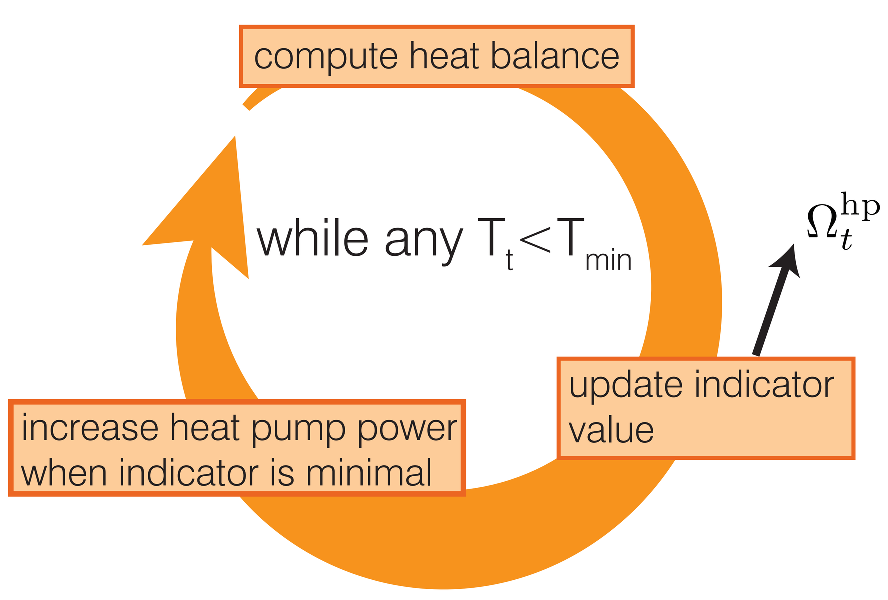


Thermal model as an electrically equivalent circuit, where the heat pump and electric heater are the **heat sources**, the **resistances** model the heat transfers and **capacitance** correspond to the thermal inertia. It also includes **solar gains**. A similar circuit is used for the DHW tank.

Algorithm

The HCA is a simple state machine performing three subsequent actions in a loop:

1) perform heat balance over the time horizon.
2) calculate the indicator values over the time horizon
3) choose the action that minimizes the indicator



If the heat pump is at max power, use electric heater.

$$OPEX_t = OPEX_t^{grid} + OPEX_t^{hp}$$

$$OPEX_t^{grid} = \left(P_t^{imp} \cdot c_t^{imp} - P_t^{exp} \cdot c_t^{texp}\right) \cdot TS_t$$

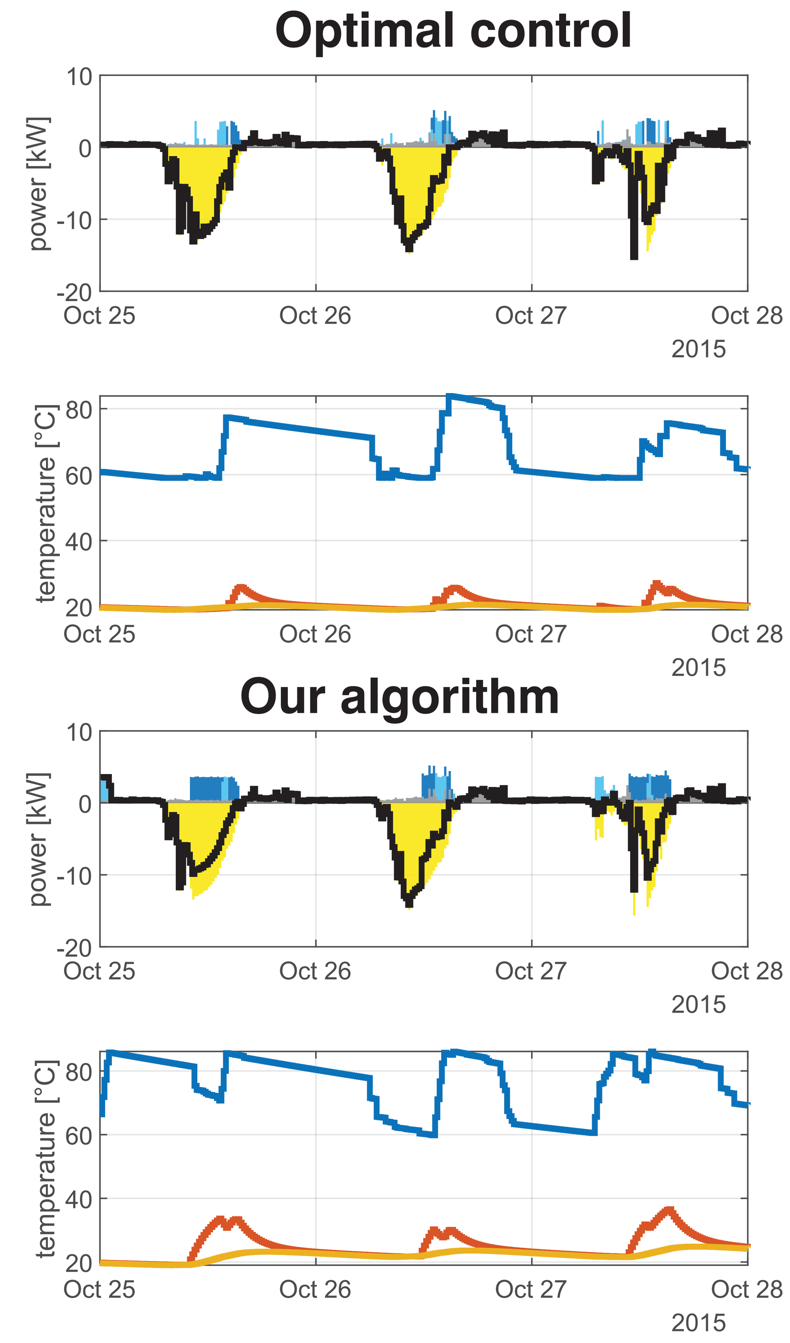
$$OPEX_t^{hp} = c^{start} \cdot S_t + c^{run} \cdot R_t \cdot \mathrm{TS}_t$$

$$\Omega_t^{hp} = \frac{\Delta OPEX_t}{\Delta Q_t}$$

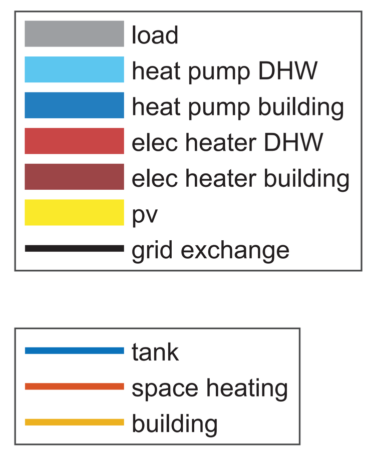
$$Q_t^{hp}(P_t^{hp}) = P_t^{hp} \cdot COP_t(P_t^{hp}) \cdot TS_t$$

The indicator relates the operating cost variation and the heat gain for a given increase of heat pump power

Qualitative comparison with optimal control



The benchmark consists of 15 representative buildings (split into three categories: single-family, multi-family, and non-residential buildings). For each building, the HCA is executed for 4 representative weeks (only 3 days are represented here as an example) and compared to optimal control.



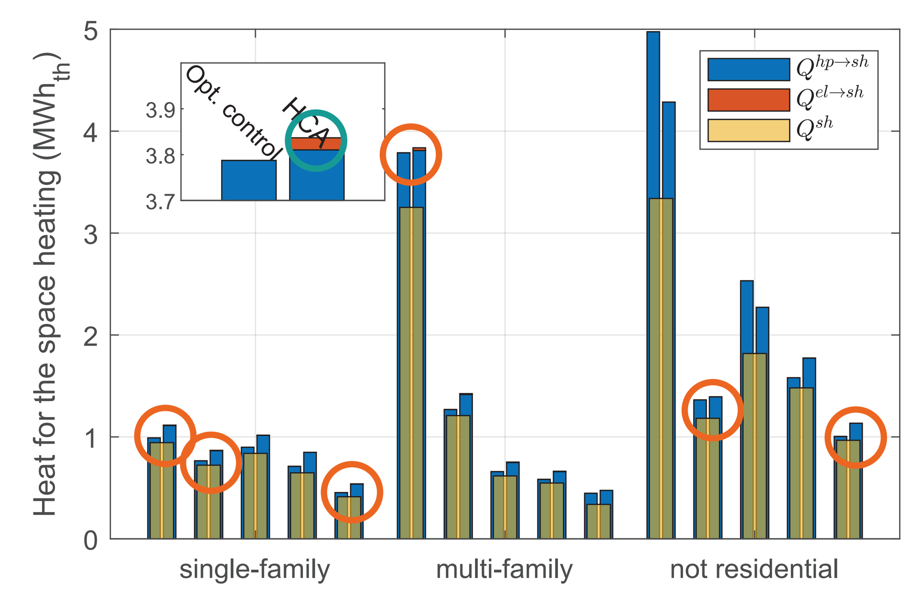
Compared to optimal control, the HCA follows a very close trajectory.

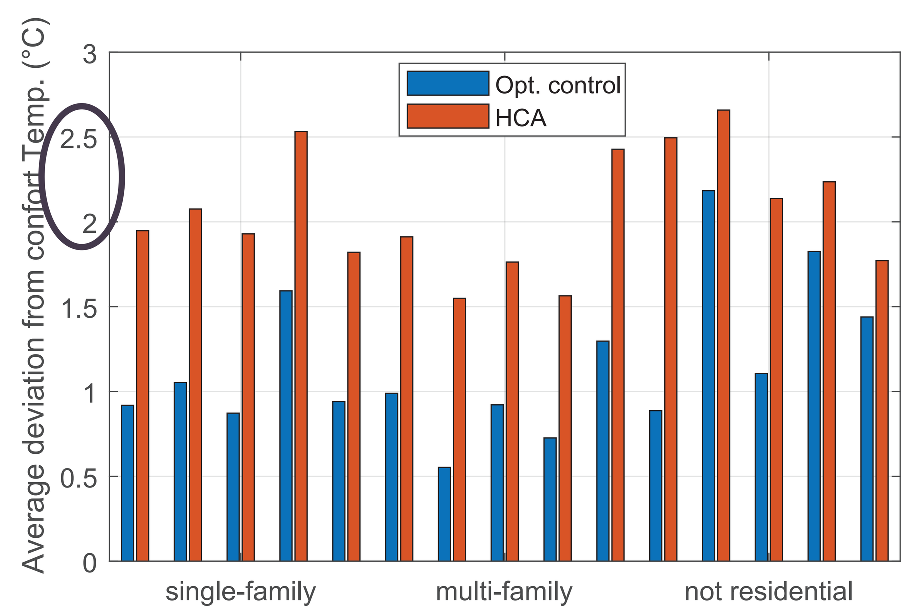
Quantitative comparison with optimal control

- **Heat generations** are very similar.
- The **electric heater** only generates a very insignificant fraction.
- **Temperature deviations** are significantly different but stay below 2.5°C.
- HCA achieves similar ***OPEX*** to optimal control.

average *OPEX* (CHF/day)

	MILP	HCA	Δ
single-family	-4.27	-4.06	0.21
multi-family	0.65	1.43	0.77
non-residential	-6.90	-6.79	0.11





Conclusion

Our heuristic control algorithm (HCA) for heat pump and PV system presents performance close to optimal control under a perfect forecast assumption. On average, the additional costs (with respect to optimal control) are below 1 CHF/day for single-family, multi-family, and non-residential buildings. The temperature deviations are mostly driven by the solar gain. Most differences between the optimal control and HCA are linked to the fact that the HCA considers the heat pump running and switching costs (which the MILP formulation of the optimal control does not).

In summary, this algorithm is efficient and simple enough to be implemented in any heat pump microcontroller.