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A Techno-Economic Perspective on Perovskite Solar Modules

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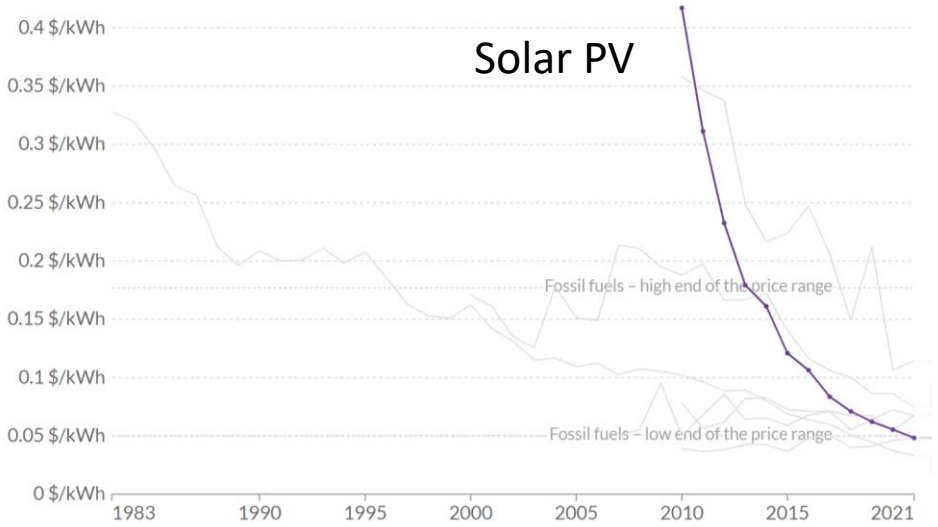
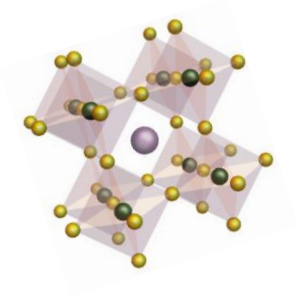
Under the supervision of Prof. Bob van der Zwaan

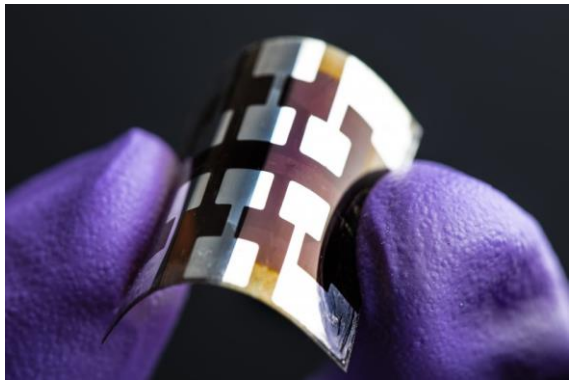
Introduction



Today 95% market c-Si

How can we further push PV growth?





Perovskite modules in PV

Low cost
High efficiency
Flexible & light-weight

But still many unknowns…

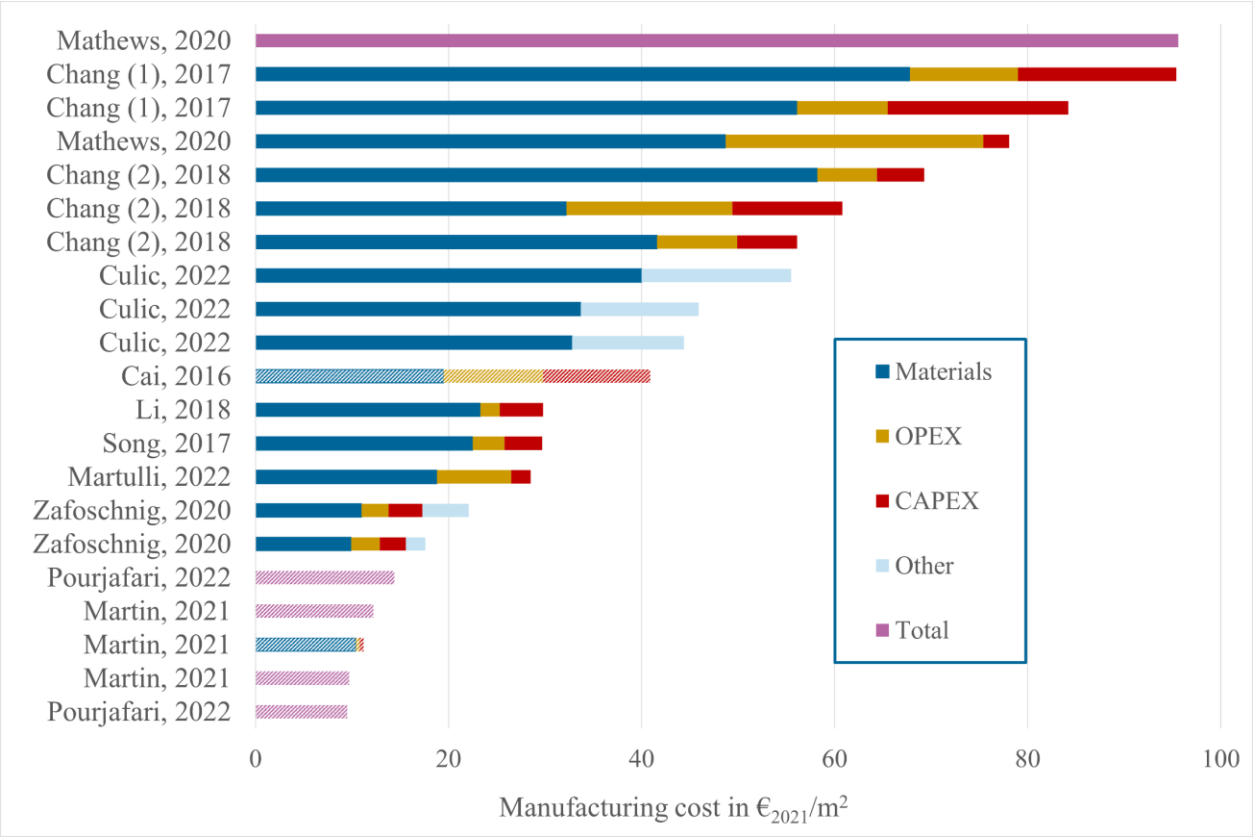
Conditions for competition with silicon? Future cost reductions?
→ Techno-economic analysis of perovskite PV

1) Module cost analysis
2) LCOE map
3) Future cost scenario

Our program for today

1) Manufacturing cost for perovskite modules

- Data extracted for **manufacturing cost**
- Data in €/W reconverted to €/m^2 with assumption of 18-20% PCE for module (flexible and rigid)
- Inflation-corrected and converted to EUR

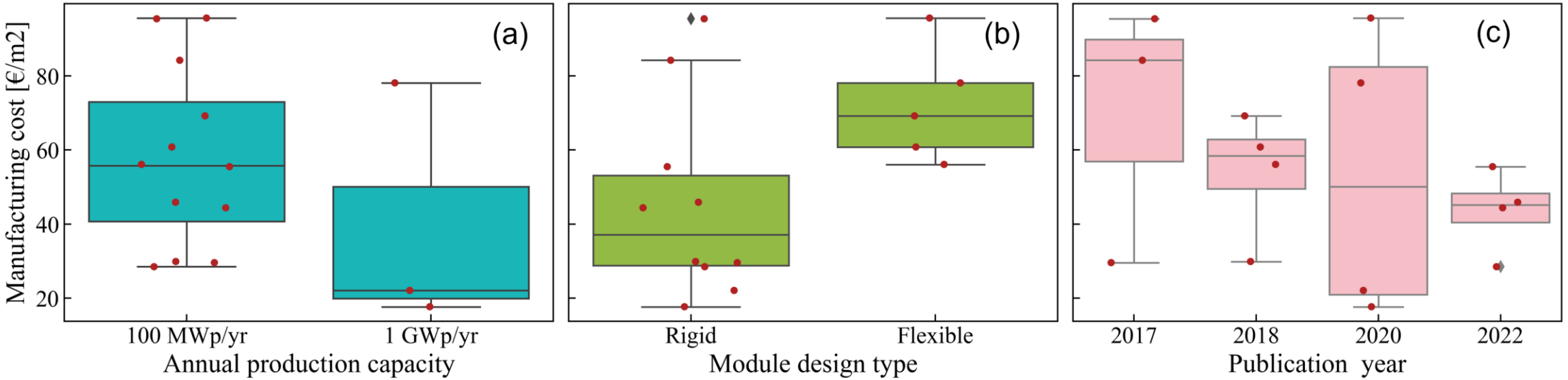


→ Large difference in cost estimates
→ Material costs at least 50%
→ Different assumptions

L McGovern, EC Garnett, S Veenstra, and B van der Zwaan, A techno-economic perspective on rigid and flexible perovskite solar modules, Sustainable Energy & Fuels, 2023.

1) Levers on the manufacturing cost

Various assumptions can influence manufacturing cost



→ Cost **depends** on **annual production capacity** & **design type**
→ Recent estimates are lower than initial estimates

L McGovern, EC Garnett, S Veenstra, and B van der Zwaan, A techno-economic perspective on rigid and flexible perovskite solar modules, Sustainable Energy & Fuels, 2023.

2) Calculation of LCOE

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{T} \frac{\mathrm{OPEX}}{(1+\delta)^{t-1}}}{\sum_{t=1}^{T} \frac{E_t}{(1+\delta)^{t-1}}}$$

$$\mathrm{CAPEX} = \mathrm{CAPEX}_{\mathrm{module}} + \mathrm{CAPEX}_{\mathrm{BOS}}$$

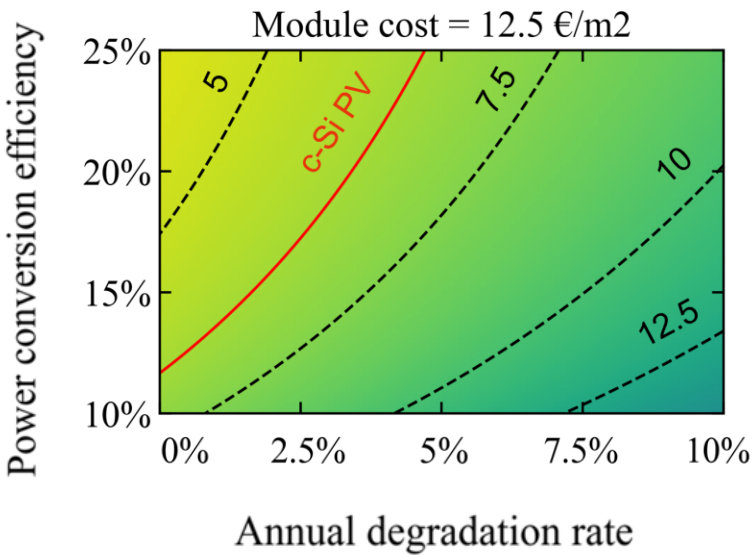
$$E_t = \mathrm{PR} \times \mathrm{Irr} \times (1 - ADR)^{t-1}$$

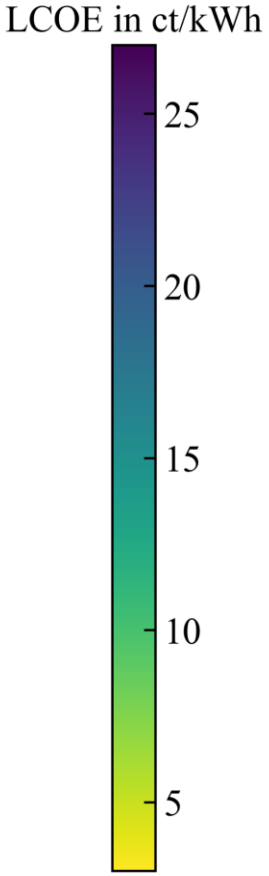
<u>European conditions (utility-scale)</u>

- CAPEX BOS = 400 $€_{2021}$/kWp*
- OPEX = 15 $€_{2021}$/kW/yr*
- DR = 5%*
- T = 25 years solar power plant
- PR = 85 % performance ratio
- Irr = 1200 kWh/m^{2}**

Datasource: *IRENA **Solaris

2) LCOE maps for perovskite modules





Comparison Perovskite and c-Si

1-to-1 Comparison in utility sector

Varying efficiency & stability of pk modules (fixed efficiency & stability for c-Si)

For **one** module cost

For **multiple** module costs

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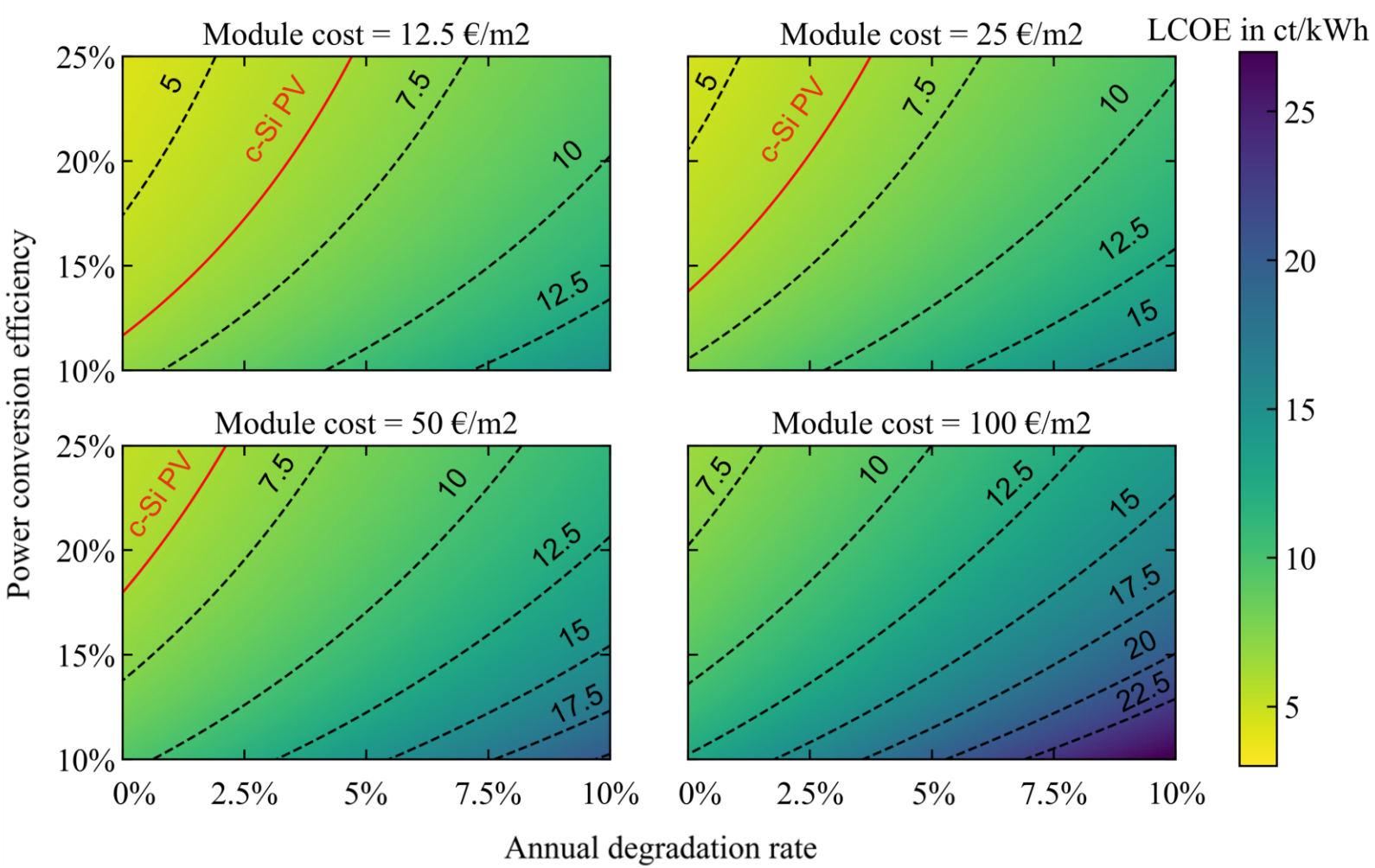
2) LCOE maps for perovskite modules



Comparison Perovskite and c-Si

1-to-1 Comparison in utility sector

→ Dependent on **all 3** parameters
→ Hard to compete with c-Si PV
→ 4.3 to 25.5 ct/kWh

New roll-to-roll modules?
Flexible & low-weight

L McGovern, EC Garnett, S Veenstra, and B van der Zwaan, A techno-economic perspective on rigid and flexible perovskite solar modules, Sustainable Energy & Fuels, 2023.

3) Future cost scenarios for perovskite modules

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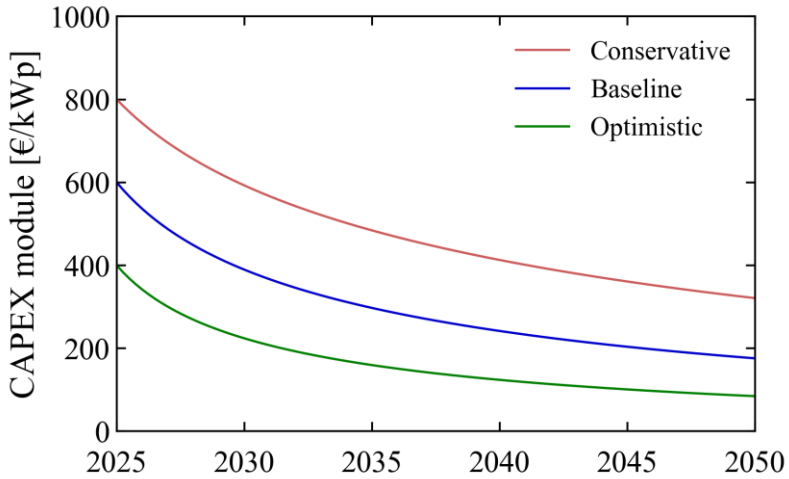
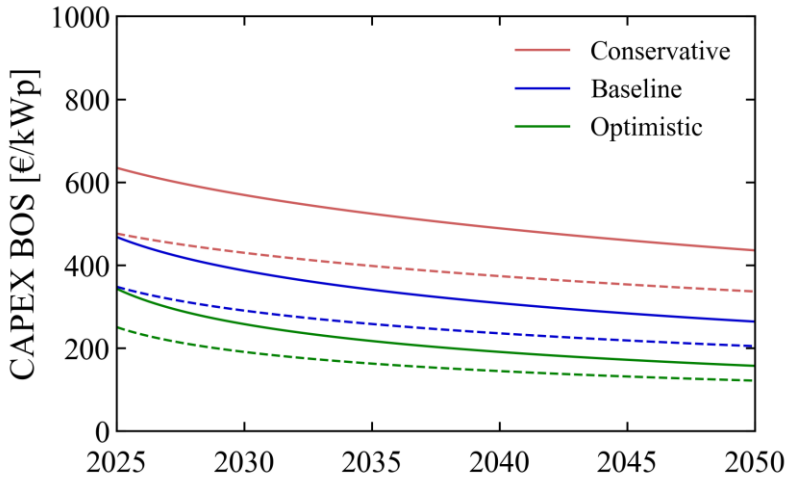
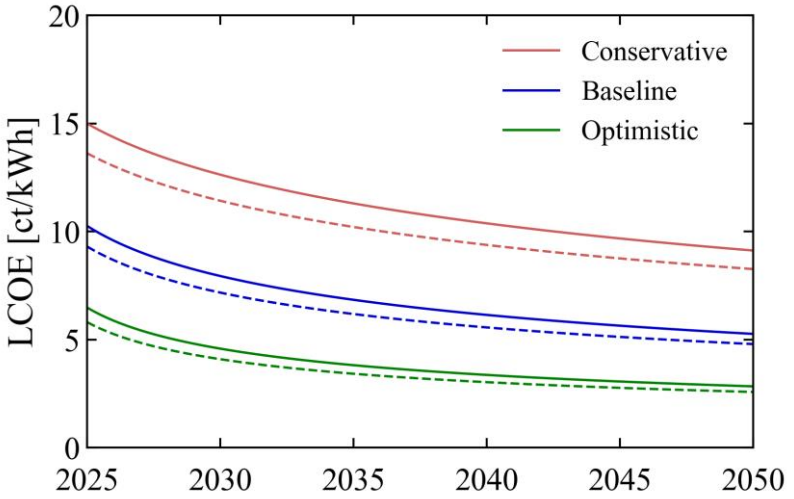
2 ingredients
- learning curve analysis (module & BOS)
- PCE enhancement

25 ± 5% and 10 ± 5%
0.2 to 0.4%/yr







3 scenarios

LR module > LR BOS

In 2050 2.8, 5.3, 9.1 ct/kWh

→ Below 6.3 ct/kWh of Si PV

Competitive with Si PV by 2026/2039, if LCOE Si PV remains fixed

L McGovern, EC Garnett, S Veenstra, and B van der Zwaan, A techno-economic perspective on rigid and flexible perovskite solar modules, Sustainable Energy & Fuels, 2023.

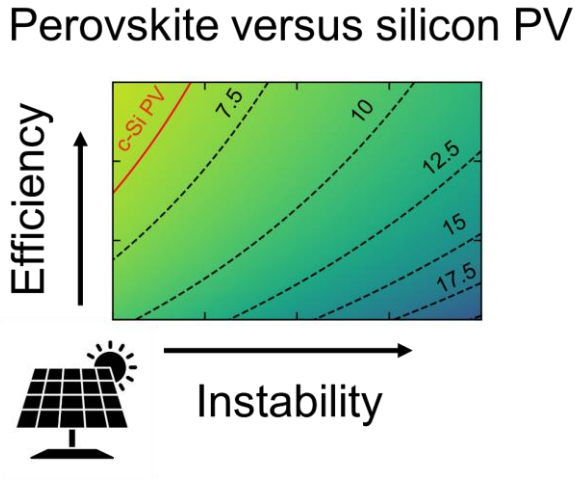
Conclusion

- Module manufacturing cost between 10 and 100 €/m^2
- Dependent on both design (rigid / flexible) and annual production capacity

- LCOE maps for perovskite modules
- Show **all parameters matter** = module cost, stability and efficiency
- **Competition with c-Si PV in utility sector hard** on LCOE basis alone

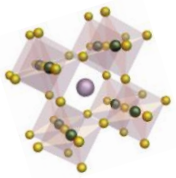
- But **flexibility & low-weight advantage** for residential + commercial sectors

- Cost reduction scenarios allow for a minimum of 2.8 ct/kWh of LCOE in 2050
- Competitive with silicon PV in 2039 in baseline scenario



- L McGovern, EC Garnett, S Veenstra, and B van der Zwaan, *A techno-economic perspective on rigid and flexible perovskite solar modules*, Sustainable Energy & Fuels, **2023**.
- L McGovern, E Alarcón-Lladó, EC Garnett, B Ehrler, and B van der Zwaan, *Perovskite Solar Modules for the Residential Sector*, ACS Energy Letters, **2023**.

Thank you for your attention!



2) The advantage of low-weight modules

$$\mathrm{CAPEX_{BOS}} = \mathrm{CAPEX_{BOS}(a)\ [€/m^2]} + \mathrm{CAPEX_{BOS}(c)[€/Wp]}$$

Area-dependent costs	Capacity-dependent costs
- Electrical installation - Mechanical installation - Mounting/racking - DC cabling / wiring - Soft costs	- Inverter - Grid connection - Soft costs

2) The advantage of low-weight modules

$$CAPEX_{BOS} = CAPEX_{BOS}(a)\ [€/m^2] + CAPEX_{BOS}(c)[€/Wp]$$

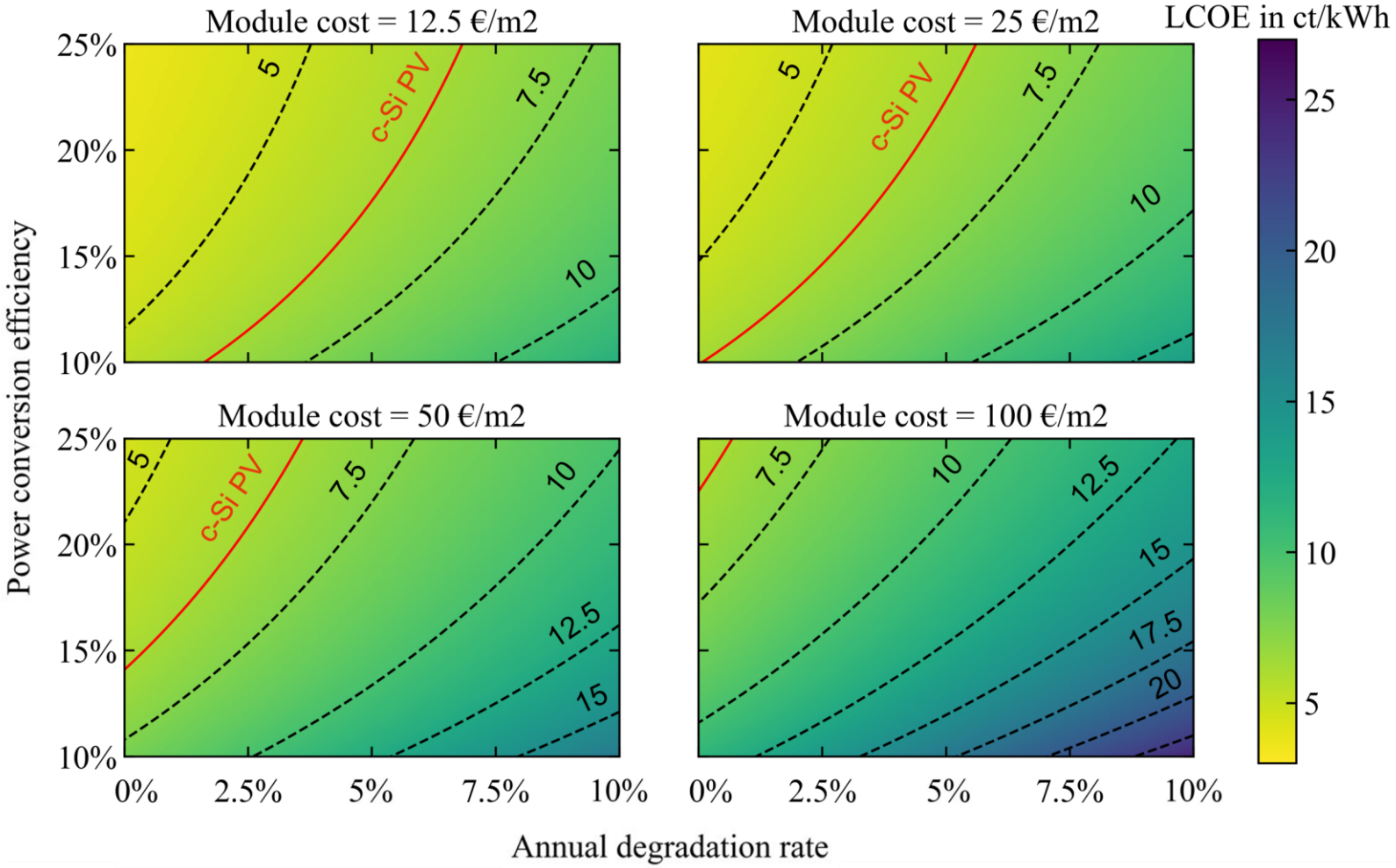
	Area-dependent costs	Capacity-dependent costs
Not impacted by weight	- Electrical installation - DC cabling / wiring - Soft costs	- Inverter - Grid connection - Soft costs
Impacted by weight	- Mounting /racking - Mechanical installation	

→ Extension of LCOE analysis with 10-times decrease in weight-dependent $CAPEX_{BOS}(a)$

CAPEX BOS = 400 $€_{2021}$/kWp*
Including - CAPEX BOS (c) = 130 $€_{2021}$/kWp
- CAPEX BOS (a) = (150 + 120) $€_{2021}$/kWp (nw & w)

Datasource: *IRENA

2) LCOE maps for low-weight perovskite modules



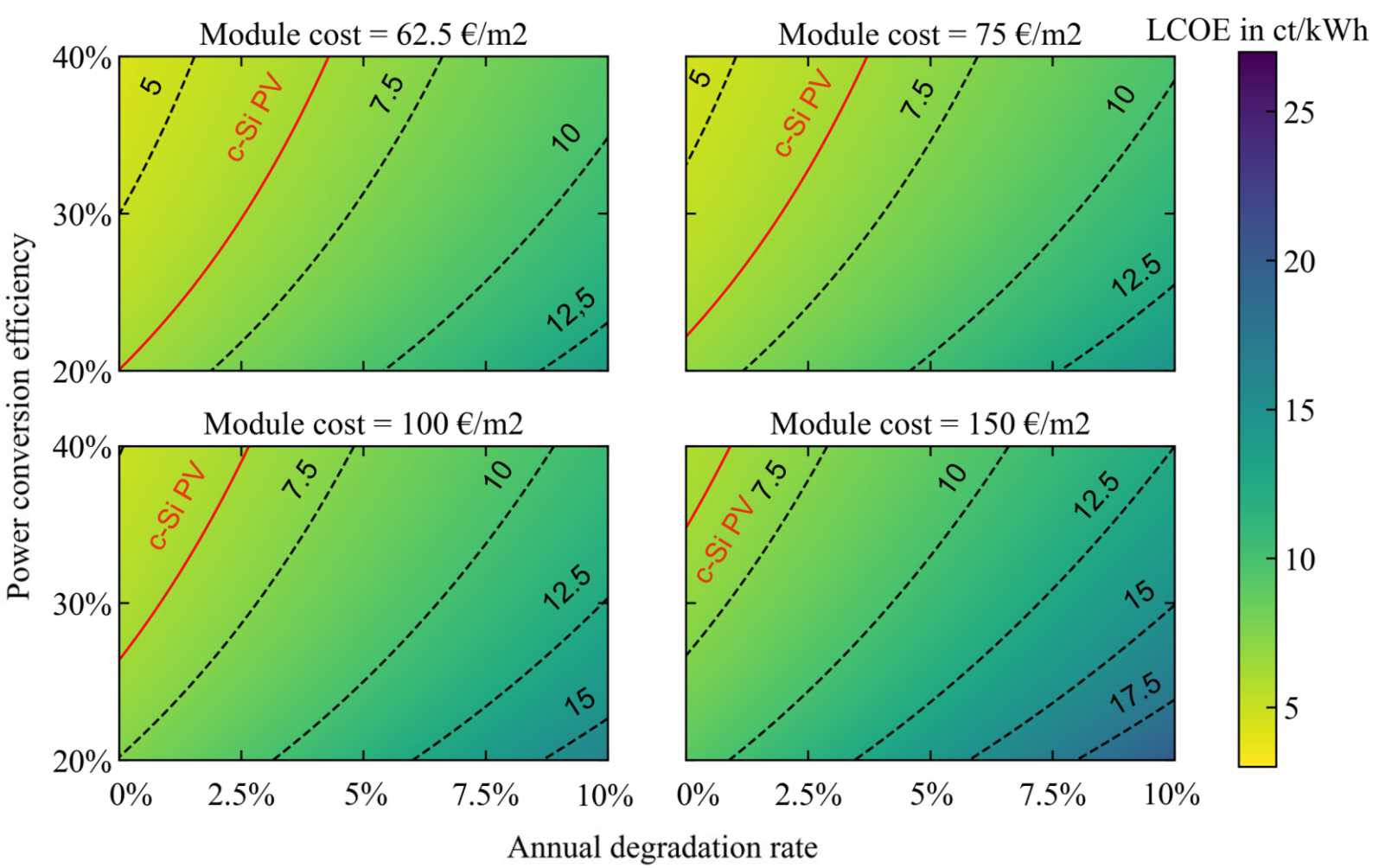
Light-weight modules

10-times decrease weight-dep $CAPEX_{BOS}(a)$

→ Dependent on **all 3** parameters
→ ± Easier to compete with c-Si PV
→ 3.7 to 23 ct/kWh

→ But 2 ct/kWh difference at best

Combining perovskite with silicon : the tandem case



Tandem modules

higher efficiency range (up to 40%)
& larger cost (+ 50 €/m^2)

→ 4.4 to 18 ct/kWh
→ Dependent on **all 3** parameters
→ ± Easier to compete with c-Si PV

Cost scenarios for tandem modules

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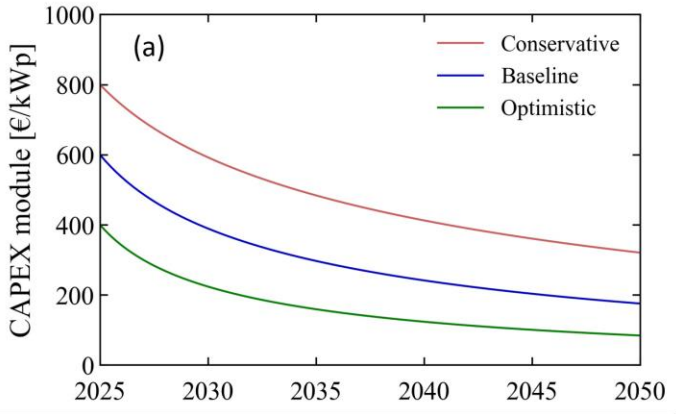
2 ingredients
- learning curve analysis (module & BOS)
- PCE enhancement

Evolution of $CAPEX_{module}$ and $CAPEX_{BOS}$
LR module > LR BOS
Lower $CAPEX_{BOS}$ than for SJ

LCOE with input from $CAPEX_{module}$ and $CAPEX_{BOS}$
→ 2.8, 5, 8.5 ct/kWh in 2050
Better than SJ in baseline & conservative

Lowest is same as SJ modules



	Conservative	Baseline	Optimistic
LR CAPEX module [%]	20	25	30
LR CAPEX BOS [%]	5	10	15
PCE module [%]	20	22,5	25
APR PCE module [%/yr]	0,2	0,3	0,4
CAGR [%]	20	25	30
Initial CIC [GW]	1	1	1
Initial CAPEX module [€/m²]	150	125	100
Initial CAPEX BOS (a) [€/m²]	60	50	40
Initial CAPEX BOS (c) [€/kW]	155	135	115
ADR [%/yr]	3	2	1