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Australian Government
Australian Renewable Energy Agency

ACAP AUSIAPV

Australian Centre for Advanced Photovoltaics

Manufacturing Cost Analysis Method

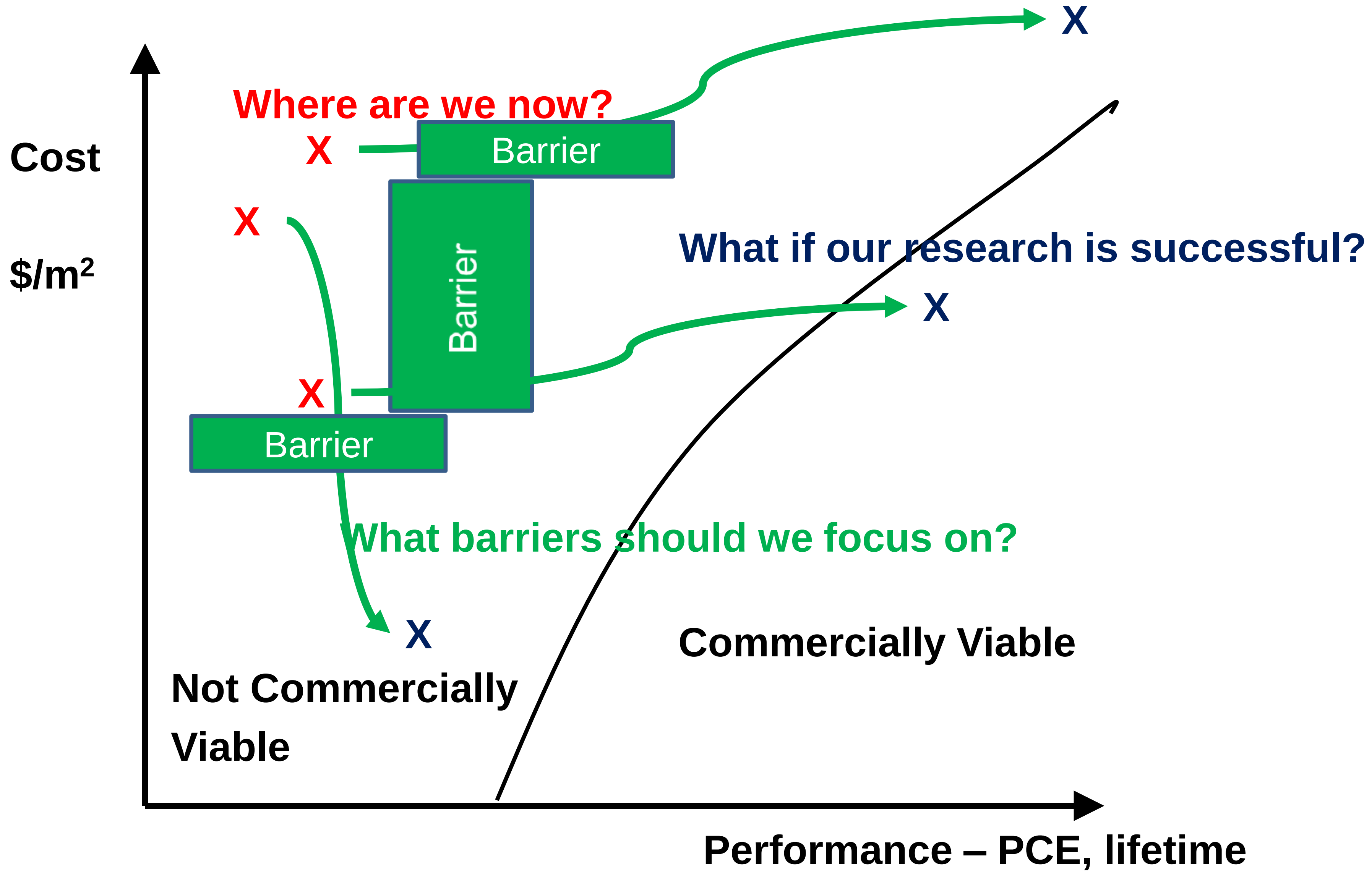
Perovskite and c-Si results

Nathan Chang

Cost Analysis Background

- > 15 years in Solar. R&D and Manufacturing - Pacific Solar / CSG Solar / Suntech R&D Australia
- Cost analysis of CSG Thin film silicon technology
  - 1999-2003 – Lab process - Guide research
  - 2004-2005 – Lab process - Justify Manufacturing
  - 2006–2008 – Lab/Manufacturing process - Analysing process changes

Motivation: Assess new technologies



Problem: Accurate Data

- Technical
  - Process sequence? What Equipment? Material utilization? Cell/Module efficiencies?
- Cost
  - Single tool cost? Multiple tool cost? High volume pricing of materials?
- Market
  - Selling price?
  - Special features?

Cost analysis method – Part 1

- Monte Carlo Analysis

Select Parameter Ranges

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	A	C	D	E	F	H	I	J	K
1	Iteration	Tool Cost (US$k)	Down time (%)	Thruput (m2/h)	Facility Capex (%)	Spare Parts (%)	Electrical Power (kW)	# Operators	# Maint
2	nom	1274	6	87	15	3	52	2	3
3	low	892	4	83	10	2	36	1	2
4	high	1656	8	92	20	5	67	3	4

Generate values for parameters

	A	C	D	E	F	H	I	J	K
1	Iteration	Tool Cost (US$k)	Down time (%)	Thruput (m2/h)	Facility Capex (%)	Spare Parts (%)	Electrical Power (kW)	# Operators	# Maint
2	nom	1274	6	87	15	3	52	2	3
3	low	892	4	83	10	2	36	1	2
4	high	1656	8	92	20	5	67	3	4
5	0	987.4							
6	1	1556.4							
7	2	951.1							
8	3	1122.7							
9	4	1366.3							
10	5	1044.4							
5004	4999	2071.6							

Two half log normal distribution where:

Median = Nominal

10th percentile = Low

90th percentile = High

$$\sigma_H = \ln(Y_{High}/Y_{Nom})/1.28$$

$$\sigma_L = \ln(Y_{Nom}/Y_{Low})/1.28$$

$$Y_i = \begin{cases} Y_{Nom} \cdot \exp(\sigma_H \cdot Z_i) & \text{if } Z_i > 0 \\ Y_{Nom} \cdot \exp(\sigma_L \cdot Z_i) & \text{if } Z_i < 0 \end{cases}$$

Z_i = a sample of the standard normal distribution

In Excel: Norm.S.Inv(rand())

Example Generated parameters

	A	C	D	E	F	H	I	J	K
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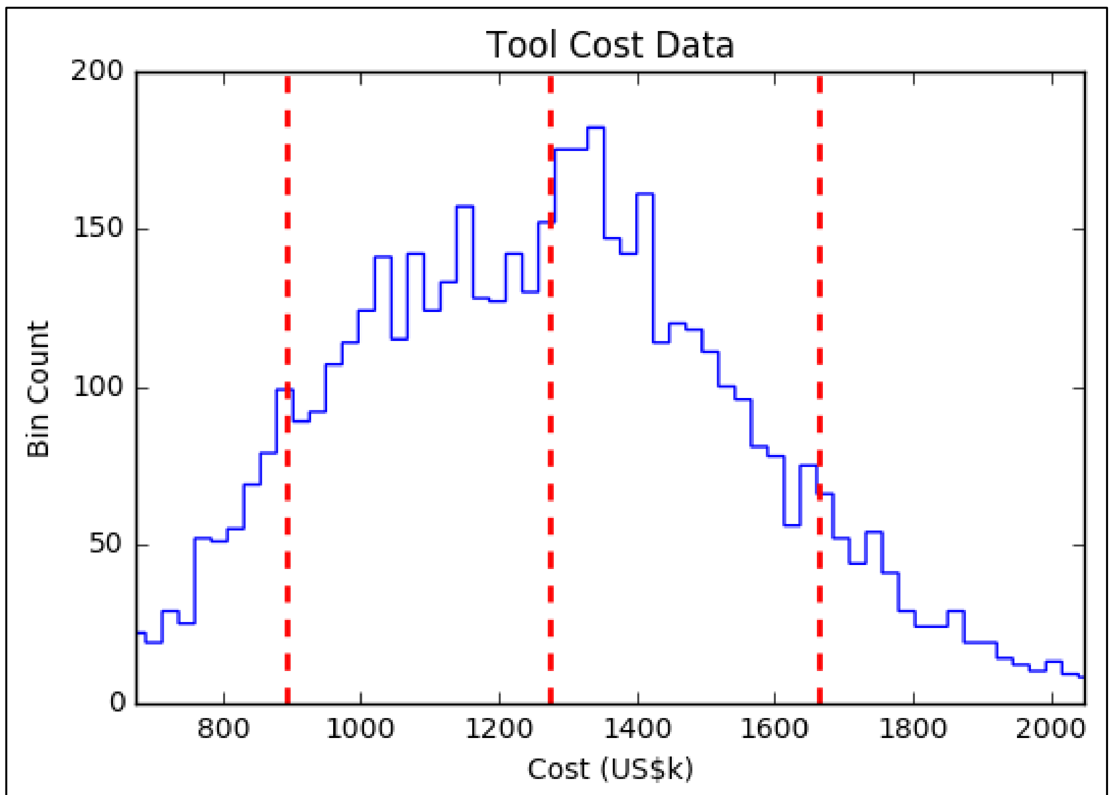

Repeat for each parameter

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	A	C	D	E	F	H	I	J	K
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5	0	987.4	6.77	82.27	21.03	3.57	55.00	2.53	2.05
6	1	1556.4	7.76	88.97	18.12	1.45	37.46	2.27	2.91
7	2	951.1	3.78	97.61	15.45	4.05	58.99	2.76	2.64
8	3	1122.7	3.30	82.56	16.58	4.27	40.81	2.10	3.06
9	4	1366.3	5.84	88.98	13.41	3.79	41.96	2.01	3.21
10	5	1044.4	5.61	82.22	10.27	3.38	46.63	1.55	3.37
5004	4999	2071.6	2.84	83.14	19.36	4.02	40.44	1.89	3.50

Calculate each iteration

	A	C	D	E	F	H	I	J	K
1	Iteration	Tool Cost (US$k)	Down time (%)	Thruput (m2/h)	Facility Capex (%)	Spare Parts (%)	Electrical Power (kW)	# Operators	# Maint
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6	1	1556.4	7.76	88.97	18.12	1.45	37.46	2.27	2.91
7	2	951.1	3.78	97.61	15.45	4.05	58.99		
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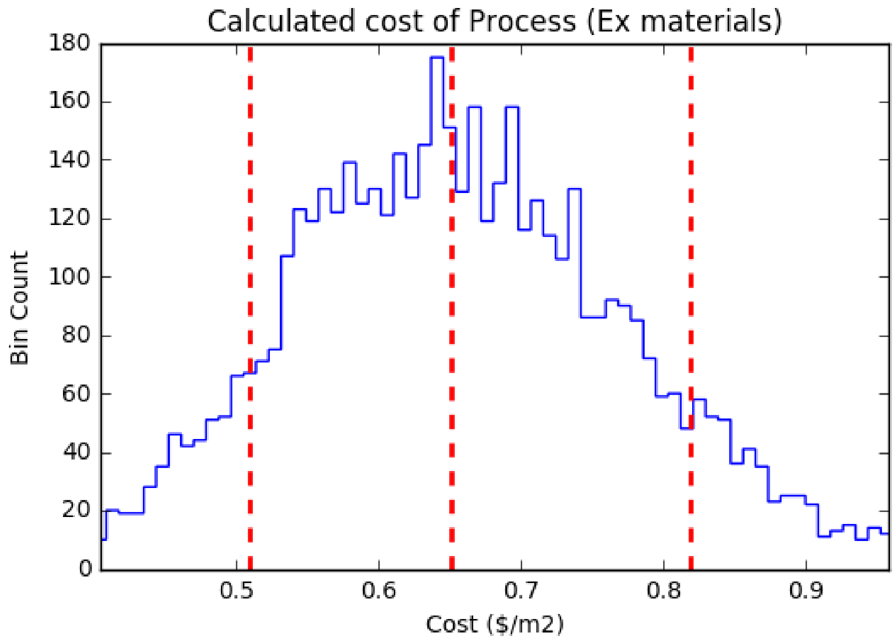
10	5	1044.4	5.61	82.22	10.27	3.38	46.63		
5004	4999	2071.6	2.84	83.14	19.36	4.02	40.44		

	A	AI
1	Iteration	Total Cost ($/m2)
5	0	0.68
6	1	0.70
7	2	0.56
8	3	0.62
9	4	0.65
10	5	0.56
5004	4999	0.89

Global assumptions, eg

- **Electricity cost ($/kWh)**
- **Labour cost ($/h)**
- **Depreciation time (years)**

Analyse Total Cost



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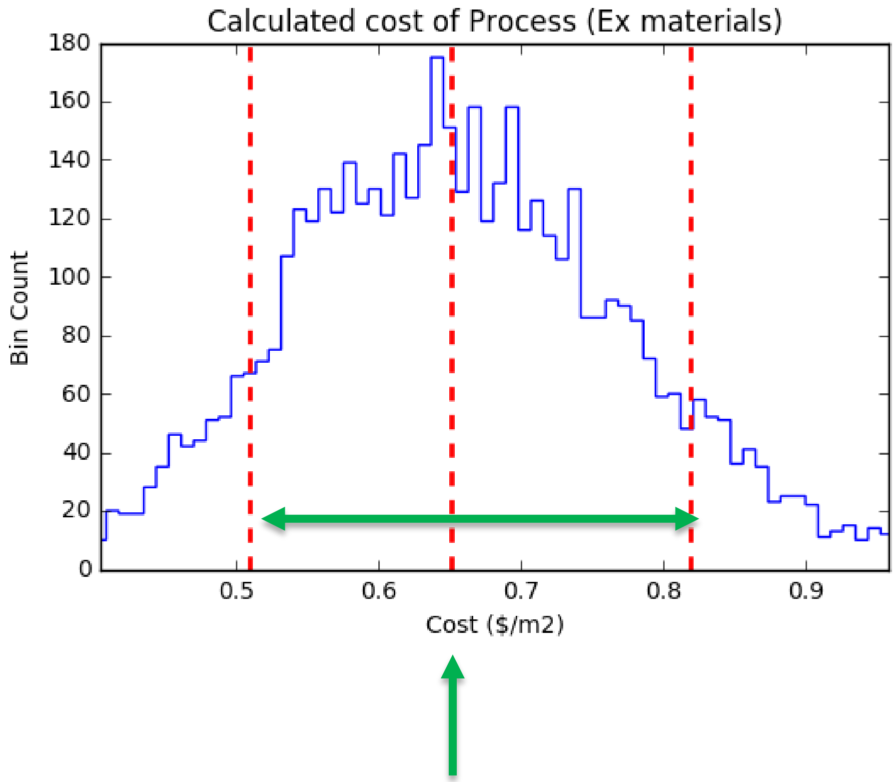

Normalised Uncertainty =
(90th – 10th) / Median

	A	AI
1	Iteration	Total Cost ($/m2)
5	0	0.68
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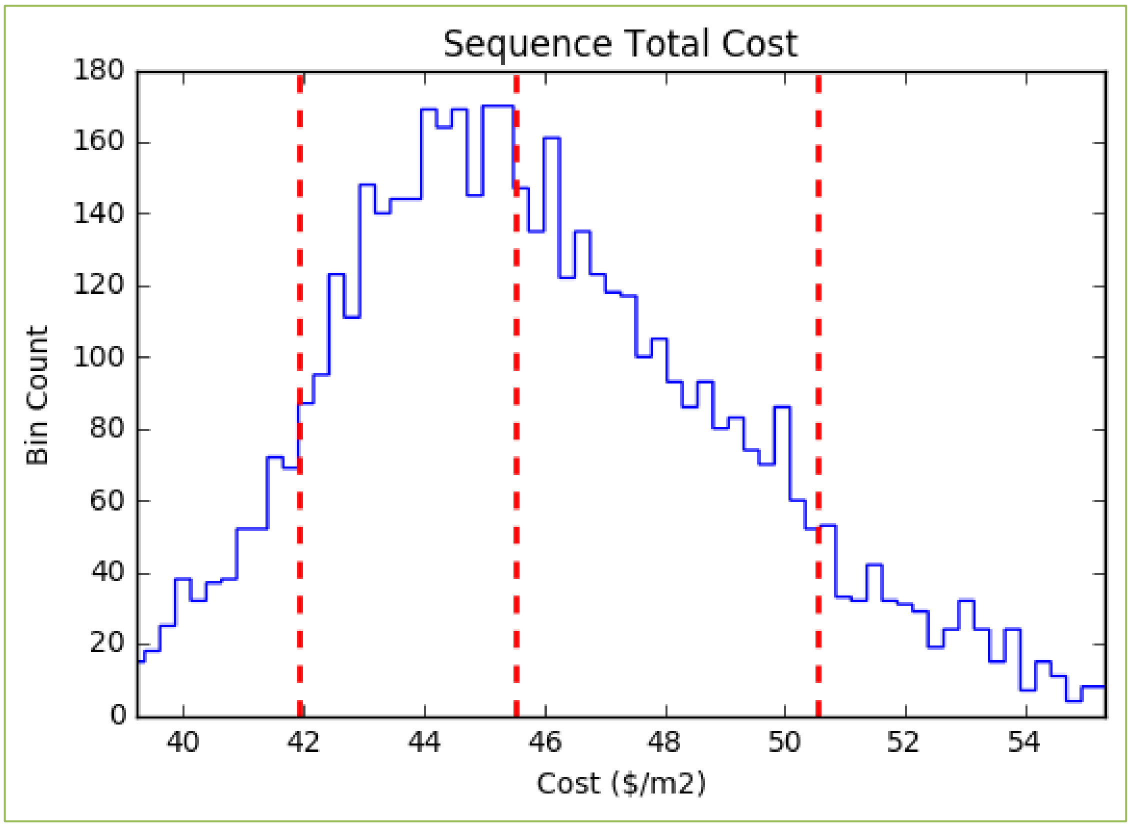
8	3	0.62
9	4	0.65
10	5	0.56
5004	4999	0.89
5005		
5006		
5007	Median	0.66
5008	10th %	0.51
5009	90th %	0.81
5010	Norm Uncert	0.46

All processes and materials

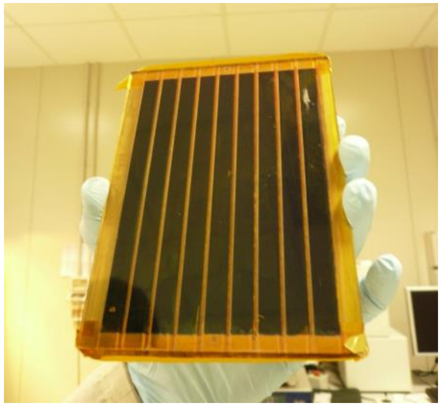
	A	B	C	D	E	F	H	I	K	I	M	N	O	P	Q	R	S	T	U
1	Seq									A									
2	Iter	Cell Test	Diffusion Furnace	Diffusion chems	Firing Furnace	Front Ag paste	PECVD SiN	PECVD chems	Rear Etch chems	Rear Pastes	Rear etch bath	Screen Print Screens	Screen Printer (rear)	Screen Printer (front)	Texture Etch chems	Wafer Etch Bath	Wafer Inspect	p-type wafer	**Total Cell cost $/m2**
3	0	0.71	0.98	2.24	0.42	1.24	0.59	0.52	1.31	1.96	0.62	0.03	0.54	0.15	0.45	0.53	0.61	29.39	**42.29**
4	1	0.65	0.65	1.77	0.50	1.47	0.53	0.60	1.06	1.24	0.47	0.06	0.39	0.18	0.64	0.39	0.63	32.19	**43.44**
5	2	0.66	1.11	2.14	0.40	1.67	0.68	1.02	2.19	1.10	1.04	0.04	0.38	0.18	1.02	0.46	0.72	30.91	**45.71**
6	3	0.55	1.18	1.97	0.35	1.75	0.63	1.02	1.13	1.44	0.94	0.05	0.31	0.15	0.74	0.39	0.86	30.85	**44.32**
7	4	0.50	0.91	1.37	0.33	1.56	0.79	0.95	1.04	1.53	0.71	0.05	0.52	0.14	0.58	0.43	0.62	32.91	**44.93**
8	5	0.63	0.96	2.00	0.32	1.45	0.74	0.80	1.43	1.44	0.85	0.05	0.55	0.21	0.60	0.52	0.69	31.07	**44.32**
9	6	0.89	0.95	1.59	0.44	1.72	0.54	0.82	0.98	1.73	0.66	0.04	0.62	0.19	0.53	0.58	0.46	37.26	**50.00**
5002	4999	0.61	1.34	2.70	0.30	0.95	0.69	0.57	1.36	1.61	0.69	0.05	0.39	0.15	0.55	0.75	0.49	32.40	**45.60**
5003																			
5004	Norm Uncer	0.39	0.50	0.59	0.44	0.60	0.47	0.59	0.60	0.60	0.50	0.62	0.50	0.62	0.60	0.47	0.39	0.26	0.19
5005	Med	0.66	0.92	1.94	0.40	1.69	0.65	0.75	1.30	1.70	0.71	0.04	0.45	0.16	0.67	0.49	0.62	32.26	45.53

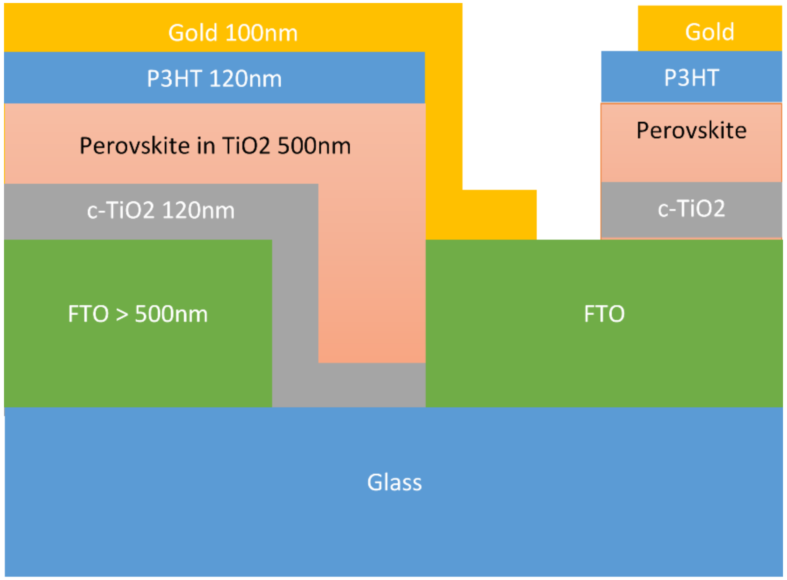
All processes and materials

	A	B	C	D	E	F	H	I	K	I	M	N	O	P	Q	R	S	T	U
1	Seq									A									
2	Iter	Cell Test	Diffusion Furnace	Diffusion chems	Firing Furnace	Front Ag paste	PECVD SiN	PECVD chems	Rear Etch chems	Rear Pastes	Rear etch bath	Screen Print Screens	Screen Printer (rear)	Screen Printer (front)	Texture Etch chems	Wafer Etch Bath	Wafer Inspect	p-type wafer	**Total Cell cost $/m2**
3	0	0.71																	**42.29**
4	1	0.65																	**43.44**
5	2	0.66																	**45.71**
6	3	0.55																	**44.32**
7	4	0.50																	**44.93**
8	5	0.63																	**44.32**
9	6	0.89																	**50.00**
5002	4999	0.61																	**45.60**



Application 1 – Perovskite on glass (CHOSE 100 cm^2 module*)



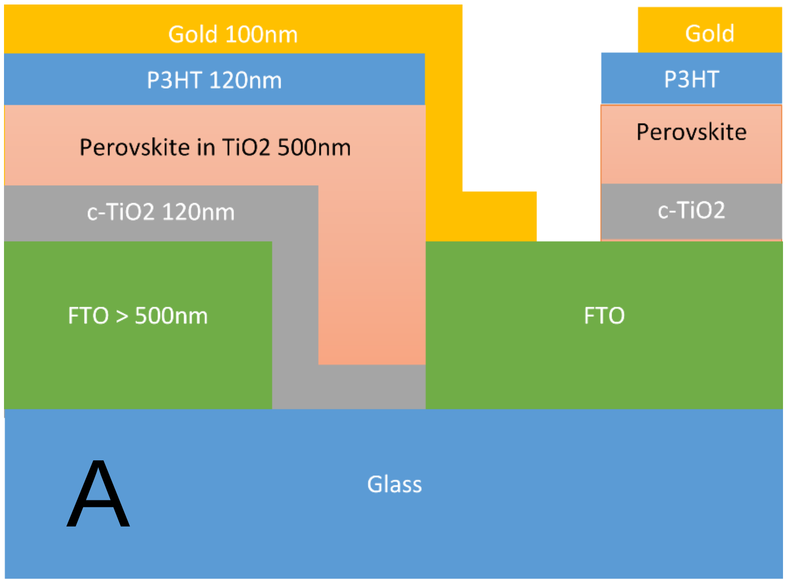


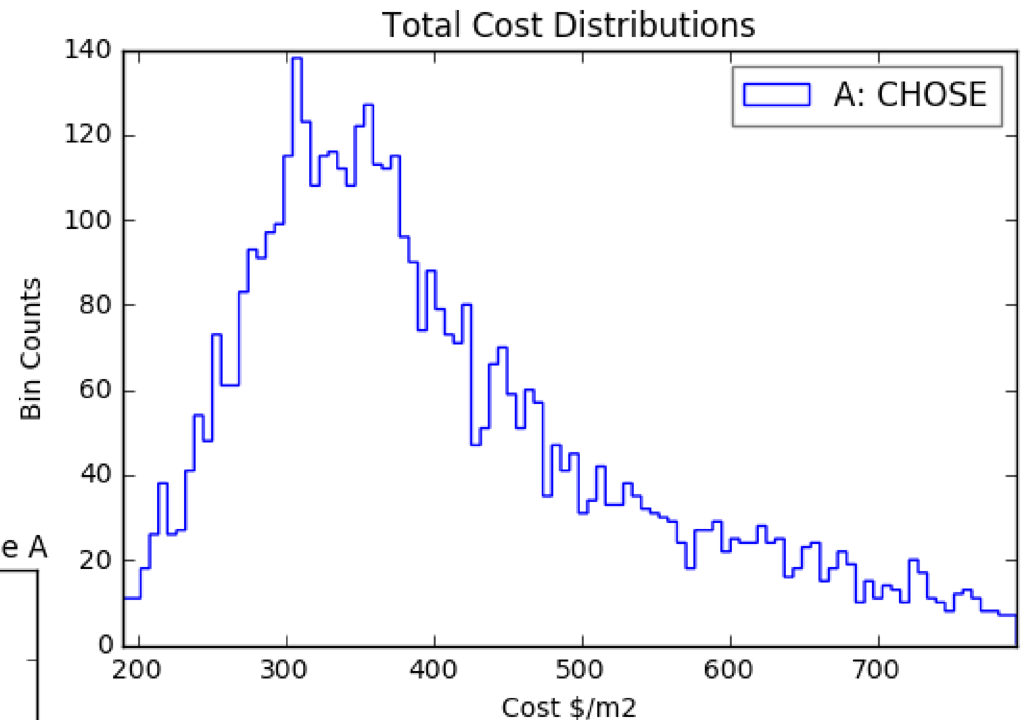
Layer	Formation Method	Pattern Method
FTO Glass	Purchased	Laser 1
C-TiO2	Spray Pyrolysis	Chemical lift off (Ag mask)
TiO2 Scaffold	Screen Print	Laser 2
Two-step perovskite	Blade Coat	Laser 2
P3HT (HTM)	Blade Coat	Laser 3
Metal (Gold)	Evaporation	Masked

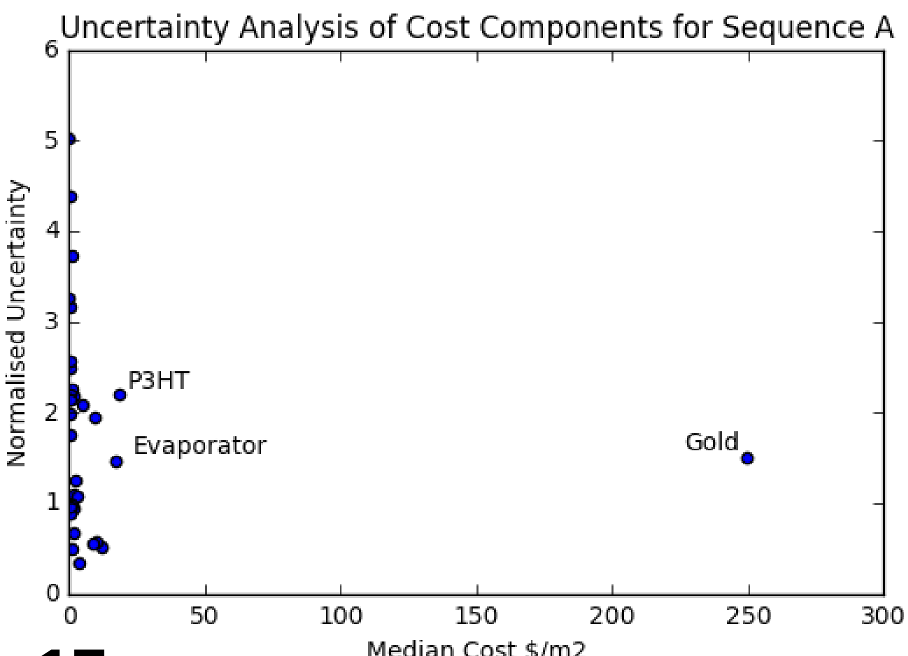
* Razza et al. Journal of Power Sources 2015; 277: 286–291.

Cost Data Sources

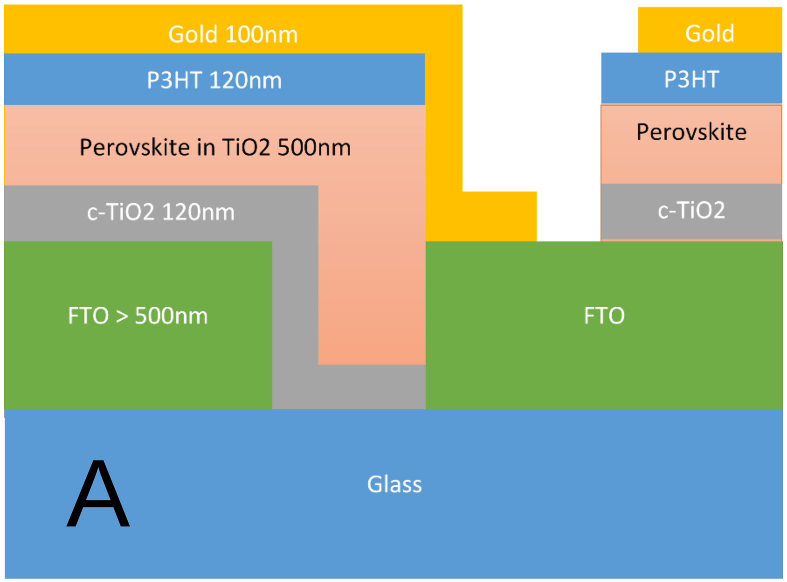
- Thin film silicon cost publications.
- c-Si cost publications
- OPV cost publications
- CdTe cost publications
- Materials suppliers (list prices)

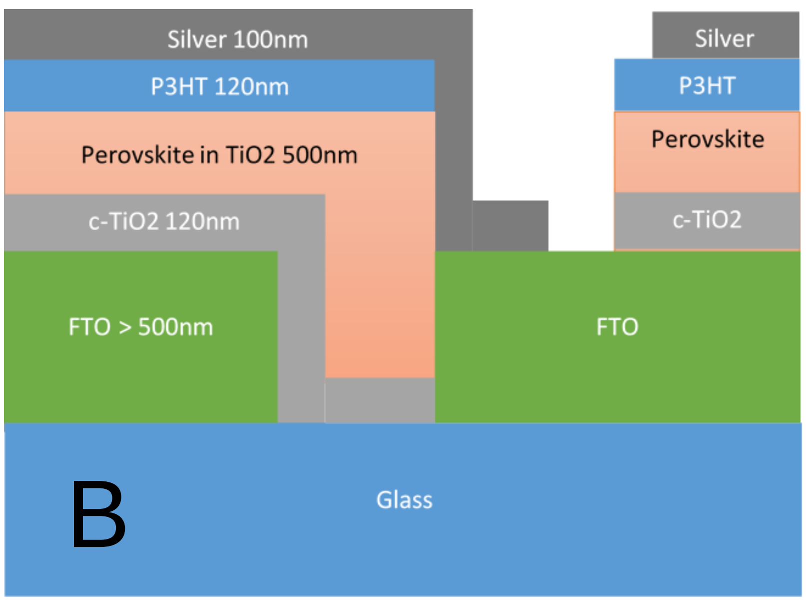


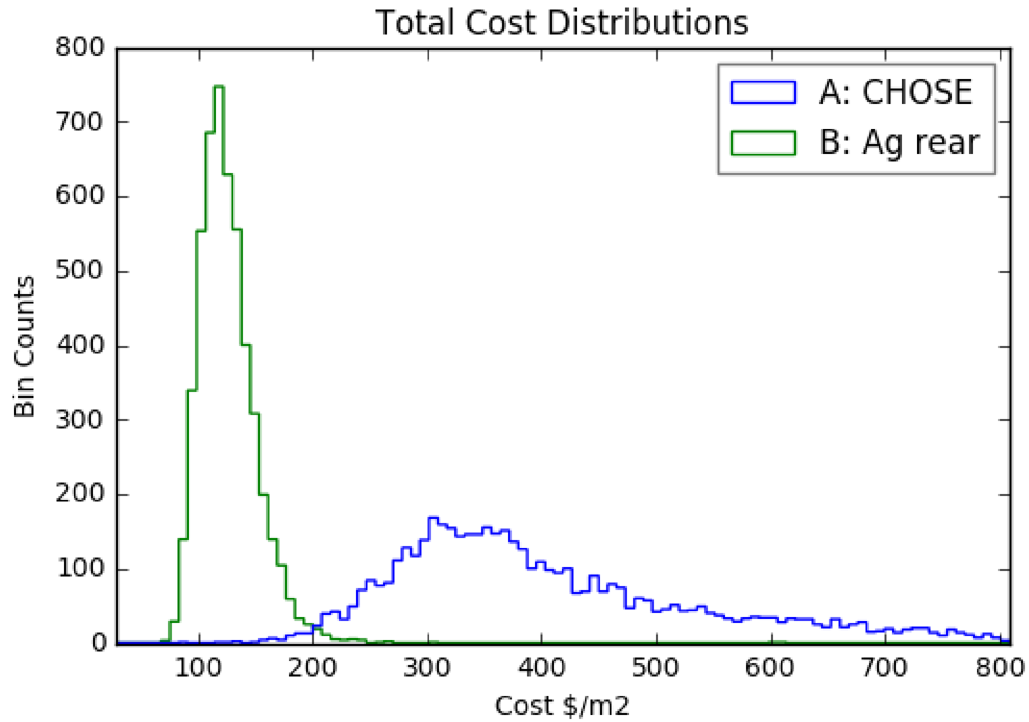




Note: c-Si module spot price ~ US$67/m2

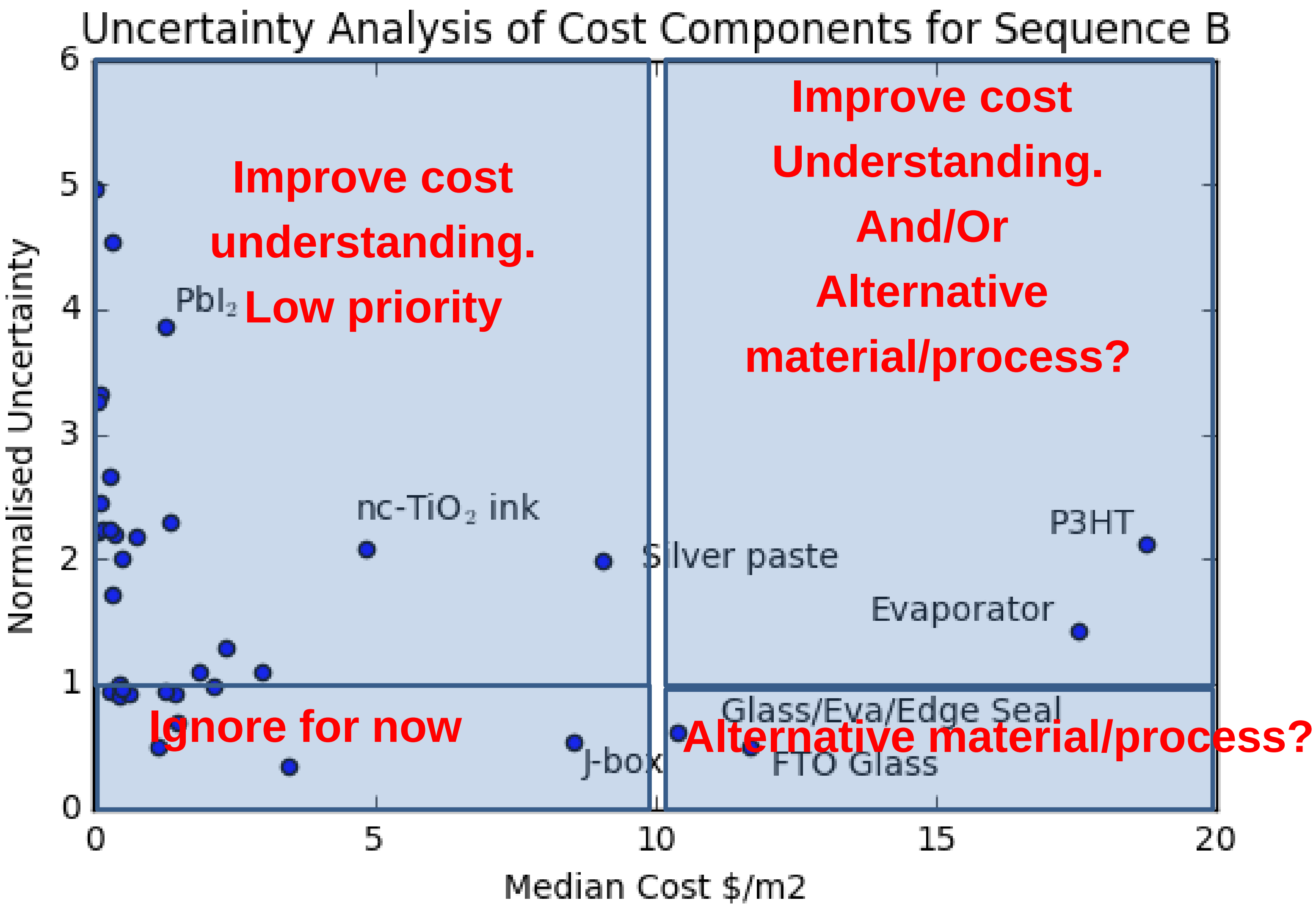






c-Si module spot price ~ US$67/m2

Normalised Cost Uncertainty = (90th – 10th)/ Median



Perovskite on Glass – Guidance to Researchers

- Gold as rear layer – prohibitive cost.
- P3HT material – can it be replaced? Cost study?
- Evaporated metal – can it be replaced? Cost study?

- More Details:

N. L. Chang, A. Y. Ho-Baillie, P. A. Basore, T. L. Young, R. Evans, R. J. Egan. **A manufacturing cost estimation method with uncertainty analysis and its application to perovskite on glass photovoltaic modules**, *Progress in Photovoltaics: Research and Applications* 25 (5) (2017) 390–405

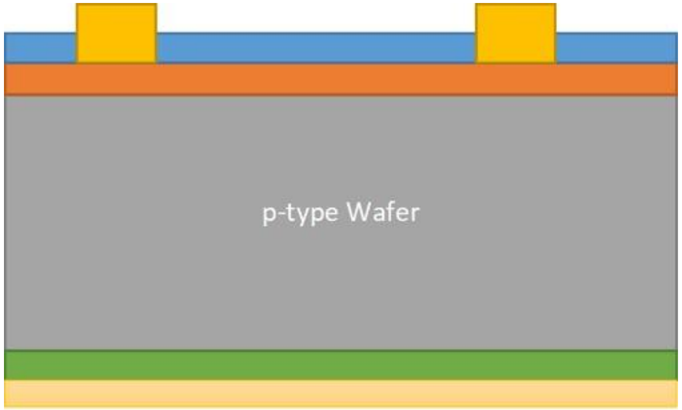
- Includes: Additional cost improvements, LCOE analysis, efficiency and lifetime targets.

Cost Analysis Method – Part 2

- What about:
  - Efficiency ($/m2 -> $/W)
  - Market value (selling price)
    - Premium for high efficiency (higher $/W price)
    - Impact of changed energy yield (eg temperature co-efficient, light induced degradation, lifetime)
    - Other features (light-weight, aesthetics).

Application 2 – Improvements to c-Si cells

A: Al-BSF

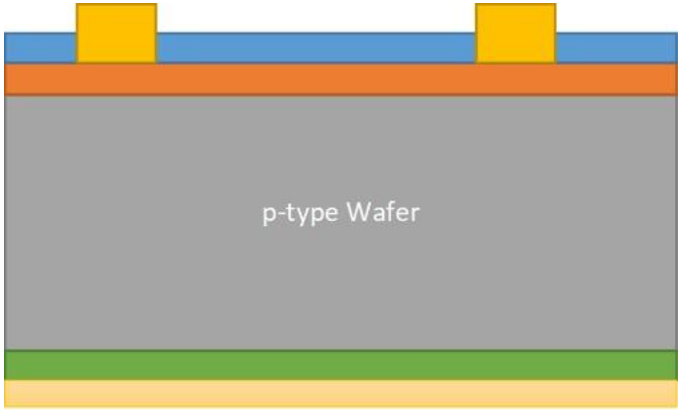


A: Al-BSF

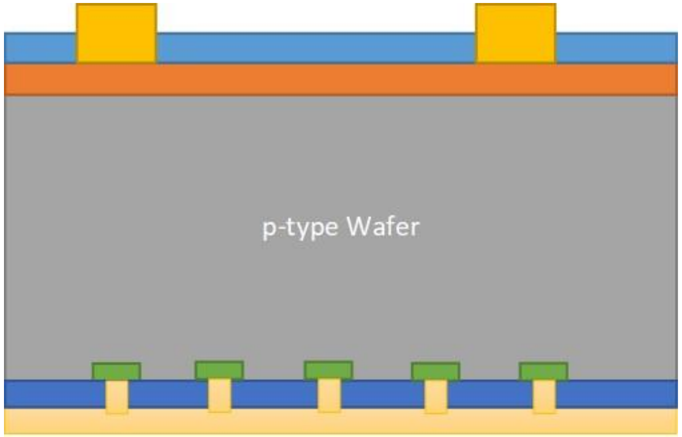
- Aluminium Back Surface Field
- Previous standard in c-Si manufacturing.
- ~ 20% cell efficiency (p-type mono wafer, ITRPV)

Application 2 – Improvements to c-Si cells

A: Al-BSF



B: PERC

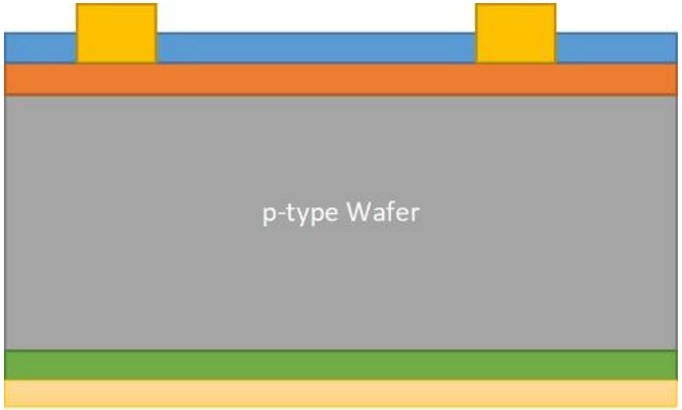


B: PERC

- Passivated Emitter and Rear Cell
- Improved rear, higher Eff
- New standard in c-Si manufacturing.
- ~21.3% eff (p-type mono, ITRPV)

Application 2 – Improvements to c-Si cells

A: Al-BSF



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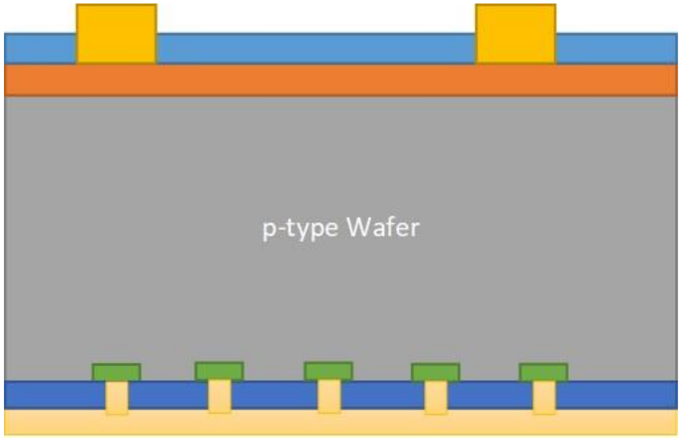
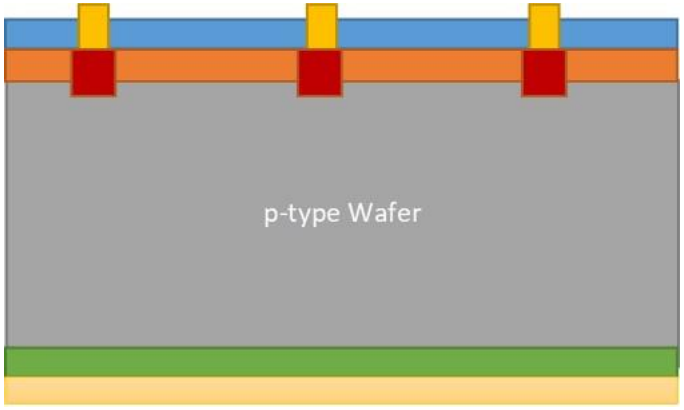


C: Al-BSF + LDSE

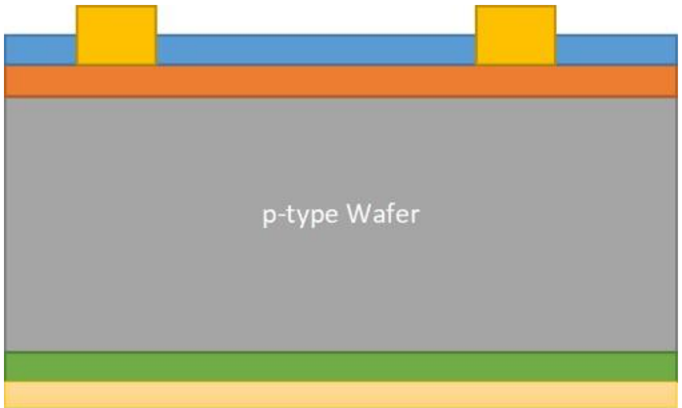


C: Al-BSF + LDSE

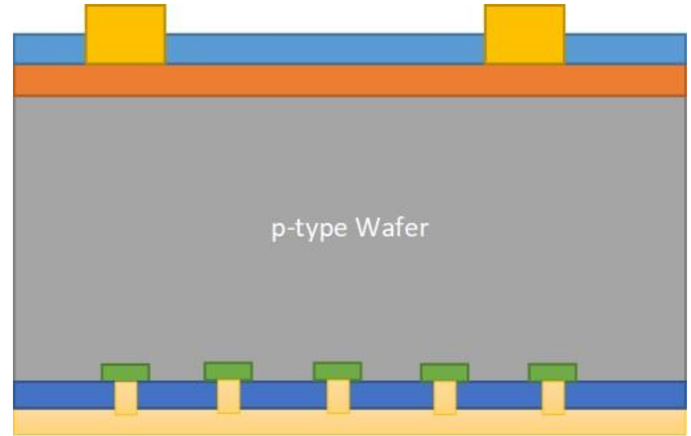
- Laser Doped Selective Emitter
- Improved front, higher Eff
- Suntech Pluto
- Estimate potential ~0.5%abs better than A

Application 2 – Improvements to c-Si cells

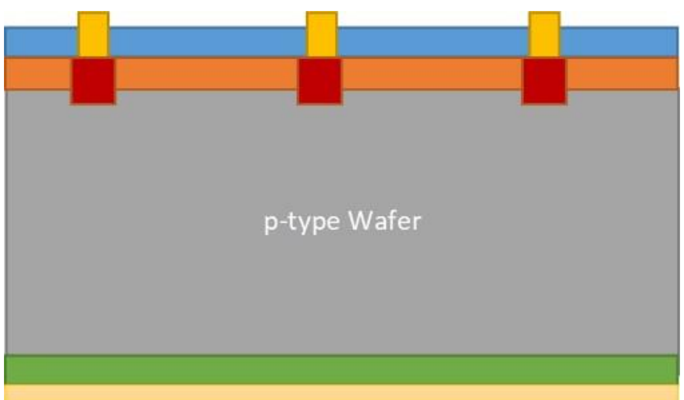
A: Al-BSF



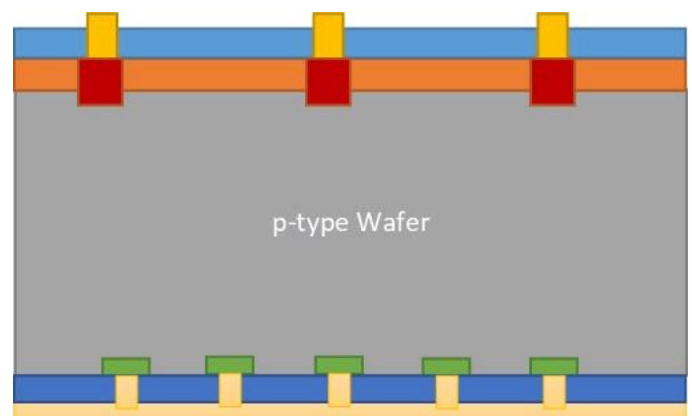
B: PERC



C: Al-BSF + LDSE



D: PERC + LDSE

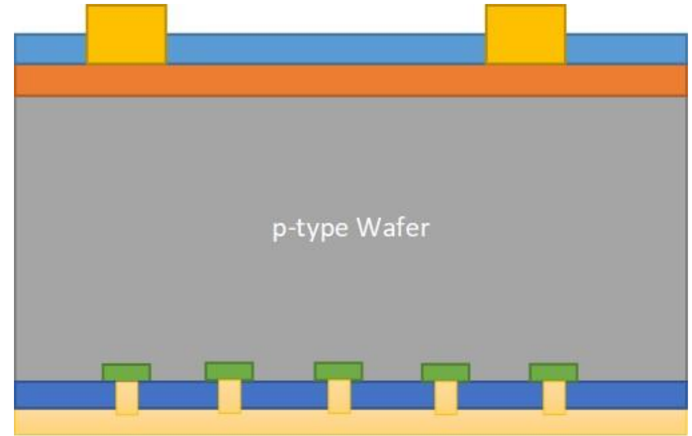


Application 2 – Improvements to c-Si cells

Question:

- Is LDSE worth adding to a PERC cell?
- Higher cost, but higher efficiency.
- Estimate potential ~0.9%abs better than B

B: PERC



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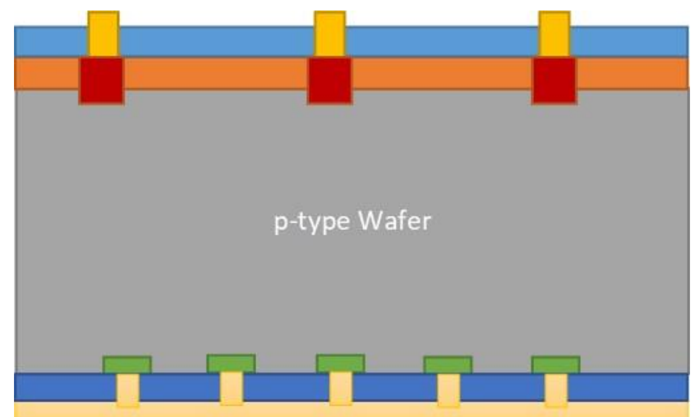
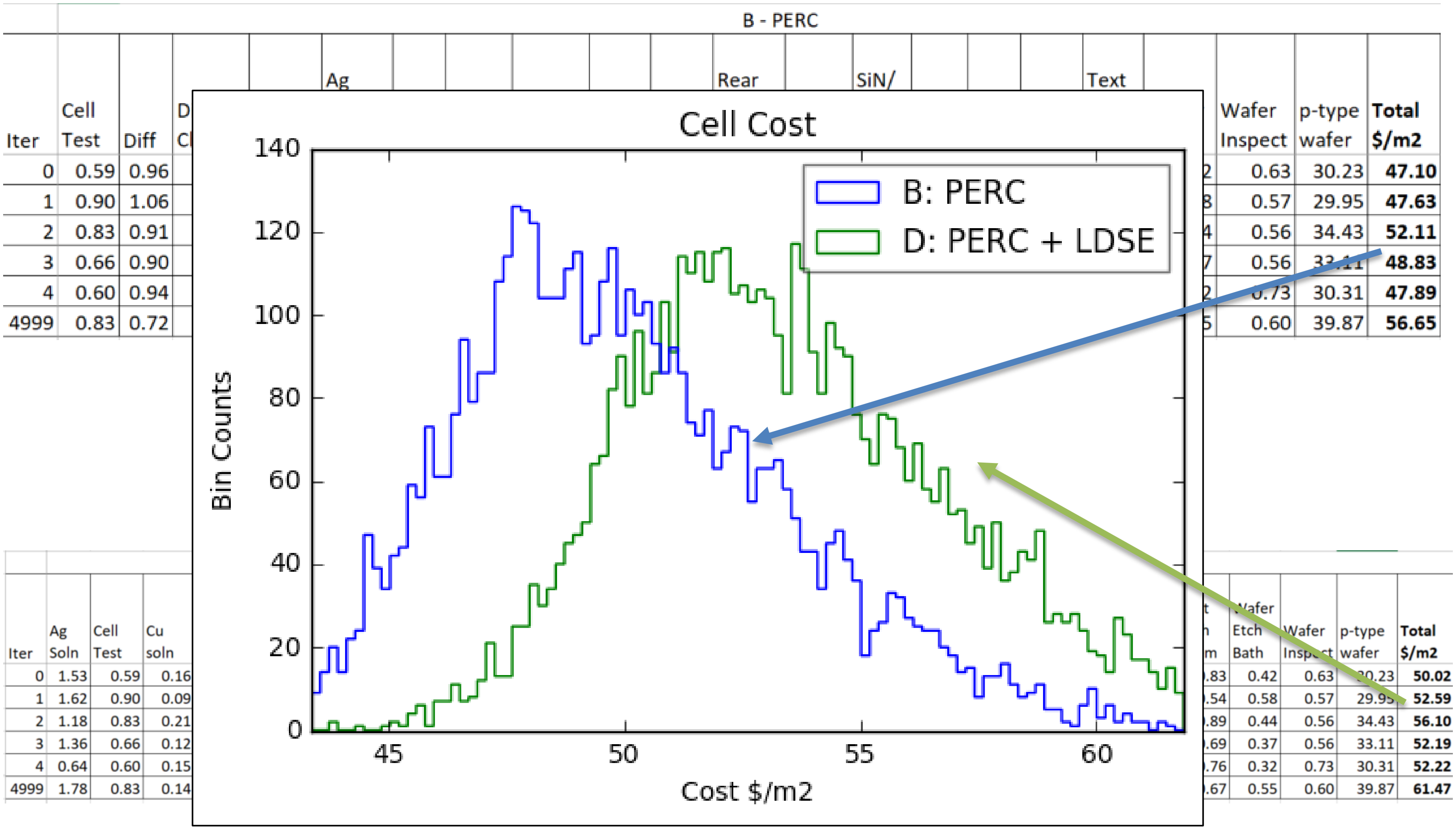
D: PERC + LDSE



Data Sources

- Processing Details
  - PERC - Sunrise
  - LDSE – UNSW publications
- Cost Details
  - PERC, Module – Michael Woodhouse (NREL)
  - LDSE – UNSW
- Efficiency
  - PERC – ITRPV
  - PERC + LDSE – Extrapolated UNSW publications
- Wafer/Module Market Pricing
  - EnergyTrend, Bloomberg, PVXchange

Simultaneous Monte Carlo Analysis



Simultaneous Monte Carlo Analysis

B - PERC

Iter	Cell Test	Diff	Diff Chem	Firing	Ag Paste F	SiN	SiN R	PECVD Chem	PERC Laser	Rear AlOx	Rear Etch chem	Paste R	SiN/ AlOx gases	Rear Etch	SP R	SP F	Text Etch chem	Wafer Etch	Wafer Inspect	p-type wafer	**Total $/m2**
0	0.59	0.96	1.50	0.47	2.29	0.58	0.38	1.61	0.70	1.61	1.21	1.78	0.19	0.60	0.42	0.09	0.83	0.42	0.63	30.23	**47.10**
1	0.90	1.06	1.25	0.36	1.53	0.69	0.24	1.64	0.79	2.06	1.22	2.11	0.22	1.19	0.52	0.17	0.54	0.58	0.57	29.95	**47.63**
2	0.83	0.91	2.27	0.33	1.49	0.52	0.30	1.68	0.51	2.07	1.41	2.00	0.21	0.62	0.44	0.17	0.89	0.44	0.56	34.43	**52.11**
3	0.66	0.90	1.42	0.41	2.08	0.60	0.34	1.35	0.84	1.68	1.11	1.31	0.14	0.73	0.31	0.18	0.69	0.37	0.56	33.11	**48.83**
4	0.60	0.94	2.70	0.43	1.43	0.79	0.31	1.68	0.64	1.42	1.29	2.29	0.18	0.50	0.36	0.15	0.76	0.32	0.73	30.31	**47.89**
4999	0.83	0.72	2.59	0.52	1.55	0.64	0.31	1.12	0.75	1.39	1.37	1.60	0.17	0.70	0.52	0.15	0.67	0.55	0.60	39.87	**56.65**

D - PERC + LDSE

Iter	Ag Soln	Cell Test	Cu soln	Diff	Diff Chem	Dope spray	Dope Laser	Firing	Ni Soln	Oxi	SiN	SiN R	PECVD chem	PERC Laser	Phosph Acid	Plating Bath	Rear AlOx	Rear Etch chem	Rear Pastes	SiN/ AlOx gases	Rear etch bath	SP Rear	Sinter	Text Etch chem	Wafer Etch Bath	Wafer Inspect	p-type wafer	**Total $/m2**
0	1.53	0.59	0.16	0.96	1.50	0.18	0.78	0.47	0.30	0.51	0.58	0.38	1.61	0.70	0.04	1.41	1.61	1.21	1.78	0.19	0.60	0.42	0.39	0.83	0.42	0.63	30.23	**50.02**
1	1.62	0.90	0.09	1.06	1.25	0.17	1.49	0.36	0.35	0.61	0.69	0.24	1.64	0.79	0.05	2.01	2.06	1.22	2.11	0.22	1.19	0.52	0.27	0.54	0.58	0.57	29.95	**52.59**
2	1.18	0.83	0.21	0.91	2.27	0.20	1.07	0.33	0.45	0.64	0.52	0.30	1.68	0.51	0.04	1.56	2.07	1.41	2.00	0.21	0.62	0.44	0.30	0.89	0.44	0.56	34.43	**56.10**
3	1.36	0.66	0.12	0.90	1.42	0.20	0.99	0.41	0.32	0.75	0.60	0.34	1.35	0.84	0.04	1.62	1.68	1.11	1.31	0.14	0.73	0.31	0.24	0.69	0.37	0.56	33.11	**52.19**
4	0.64	0.60	0.15	0.94	2.70	0.26	1.56	0.43	0.25	0.58	0.79	0.31	1.68	0.64	0.04	2.21	1.42	1.29	2.29	0.18	0.50	0.36	0.21	0.76	0.32	0.73	30.31	**52.22**
4999	1.78	0.83	0.14	0.72	2.59	0.20	1.15	0.52	0.17	0.60	0.64	0.31	1.12	0.75	0.09	2.13	1.39	1.37	1.60	0.17	0.70	0.52	0.26	0.67	0.55	0.60	39.87	**61.47**

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Simultaneous Monte … sis

Iter	Cell Test	Diff	Diff Chem	Firing	Ag Paste F	SiN	SiN R	PECVD Chem	PERC Laser	Rear AlOx	…	Text Etch Chem	Wafer Etch	Wafer Inspect	p-type wafer	Total $/m2
0															30.23	
1															29.95	
2															34.43	
3															33.11	
4															30.31	
4999															39.87	

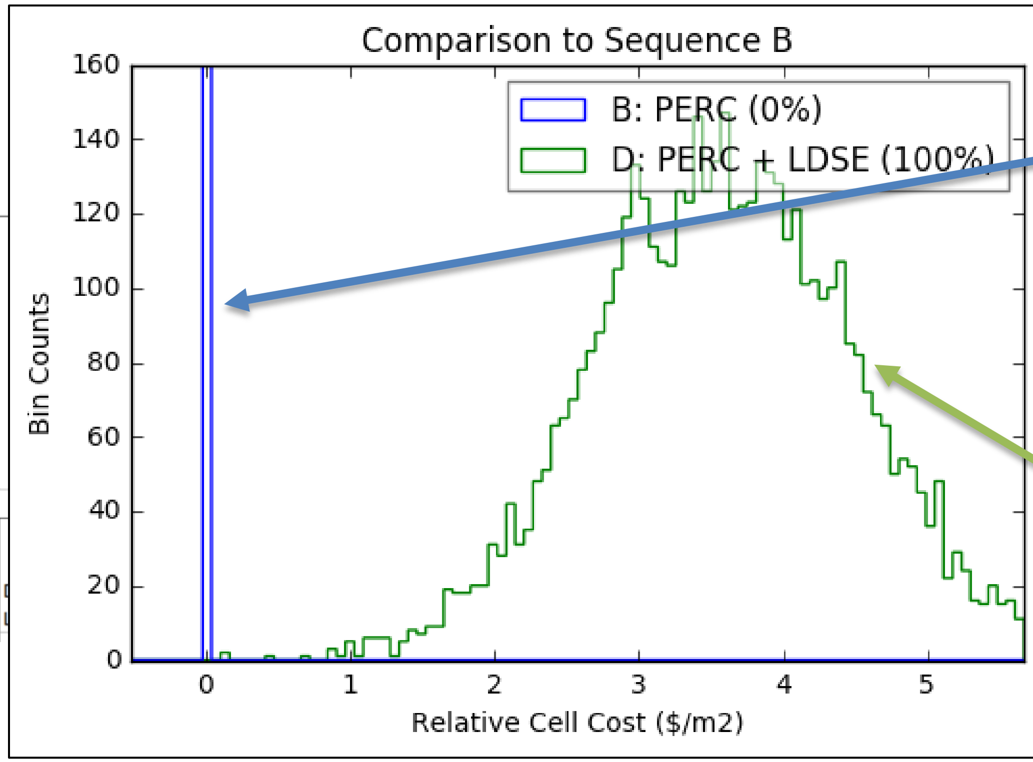
Wafer Inspect	p-type wafer	Total $/m2
	30.23	
	29.95	
	34.43	
	33.11	
	30.31	
	39.87	

Iter	Ag Soln	Cell Test	Cu soln	Diff	Diff Chem	Dope spray	Dope Laser	Firing	Ni Soln	Oxi	SiN	SiN R	PECVD chem	PERC Laser	Pho Acid	…	SP Rear	Sinter	Text Etch chem	Wafer Etch Bath	Wafer Inspect	p-type wafer	Total $/m2	T c $
0																						30.23		
1																						29.95		
2																						34.43		
3																						33.11		
4																						30.31		
4999																						39.87		

Wafer Inspect	p-type wafer	Total $/m2
	30.23	
	29.95	
	34.43	
	33.11	
	30.31	
	39.87	

Simultaneous Monte Carlo Analysis

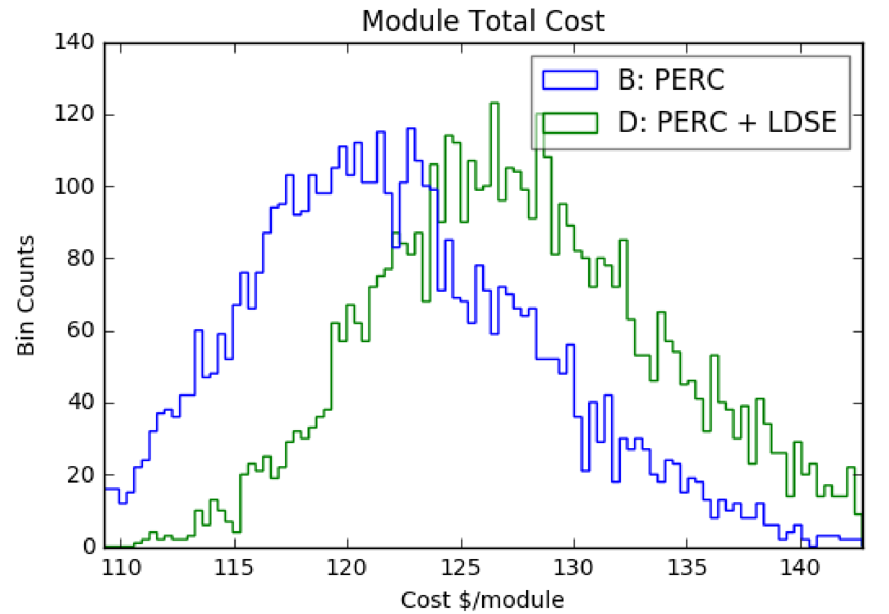
	B - PERC																					
Iter	Cell Test	Diff	Diff Chem	Firing	Ag Paste F	SiN	SiN R	PECVD Chem	PERC Laser	Rear AlOx	Rear Etch chem	Paste R	SiN/ AlOx gases	Rear Etch	SP R	SP F	Text Etch chem	Wafer Etch	Wafer Inspect	p-type wafer	**Total $/m2**	**Total cf B $/m2**
0																					**47.10**	**0.00**
1																					**47.63**	**0.00**
2																					**52.11**	**0.00**
3																					**48.83**	**0.00**
4																					**47.89**	**0.00**
4999																					**56.65**	**0.00**

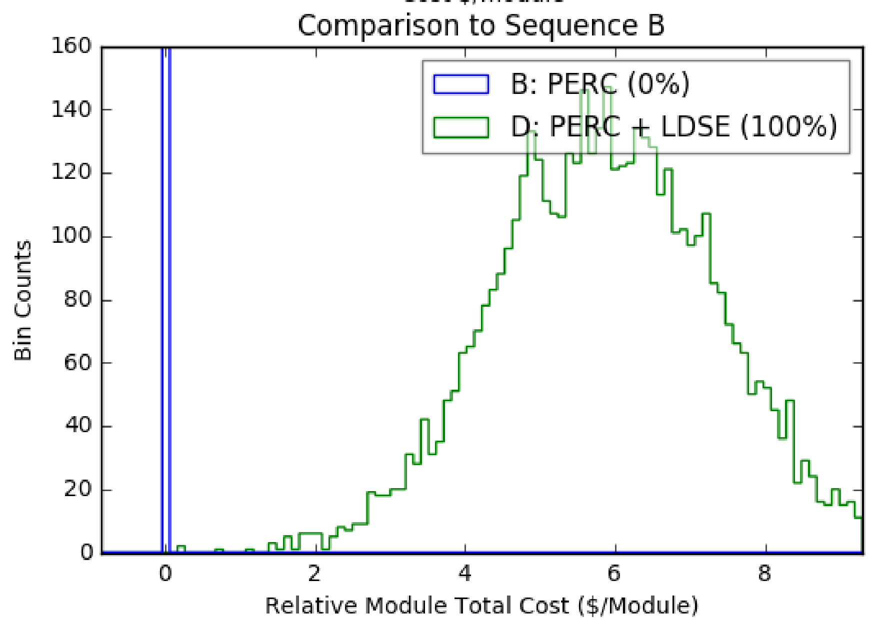


Iter	Ag Soln	Cell Test	Cu soln	Diff	Diff Chem	Dope spray	Text Etch chem	Wafer Etch Bath	Wafer Inspect	p-type wafer	**Total $/m2**	**Total cf B $/m2**
0											**50.02**	**2.92**
1											**[illegible]**	**4.95**
2											**56.10**	**3.99**
3											**52.19**	**3.36**
4											**52.22**	**4.33**
4999											**61.47**	**4.82**

Module fabrication costs

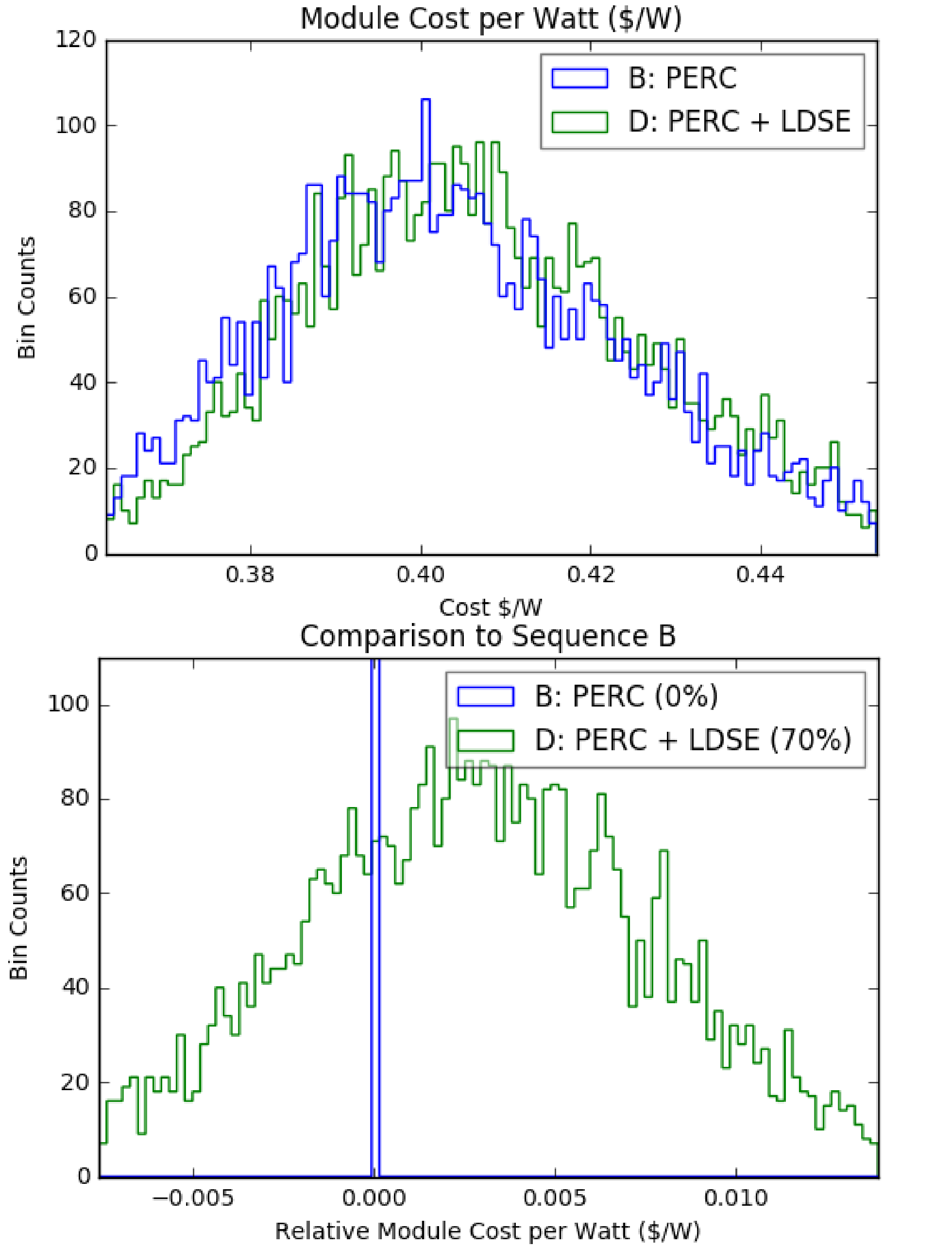
Seq	Iter	Cell Cost $/m2	Cell Yield (%)	Module Conv ($/mod)	Module Cost ($/mod)
B	0	47.1	99.1	40.96	119
B	1	47.6	99.4	40.09	119
B	2	52.1	99.2	38.72	125
B	3	48.8	98.6	42.80	124
B	4	47.9	98.9	39.17	119
B	4999	56.7	97.9	40.26	135
D	0	50.0	99.3	40.96	124
D	1	52.6	99.3	40.09	127
D	2	56.1	98.6	38.72	132
D	3	52.2	98.7	42.80	130
D	4	52.2	99.3	39.17	125
D	4999	61.5	99.7	40.26	141





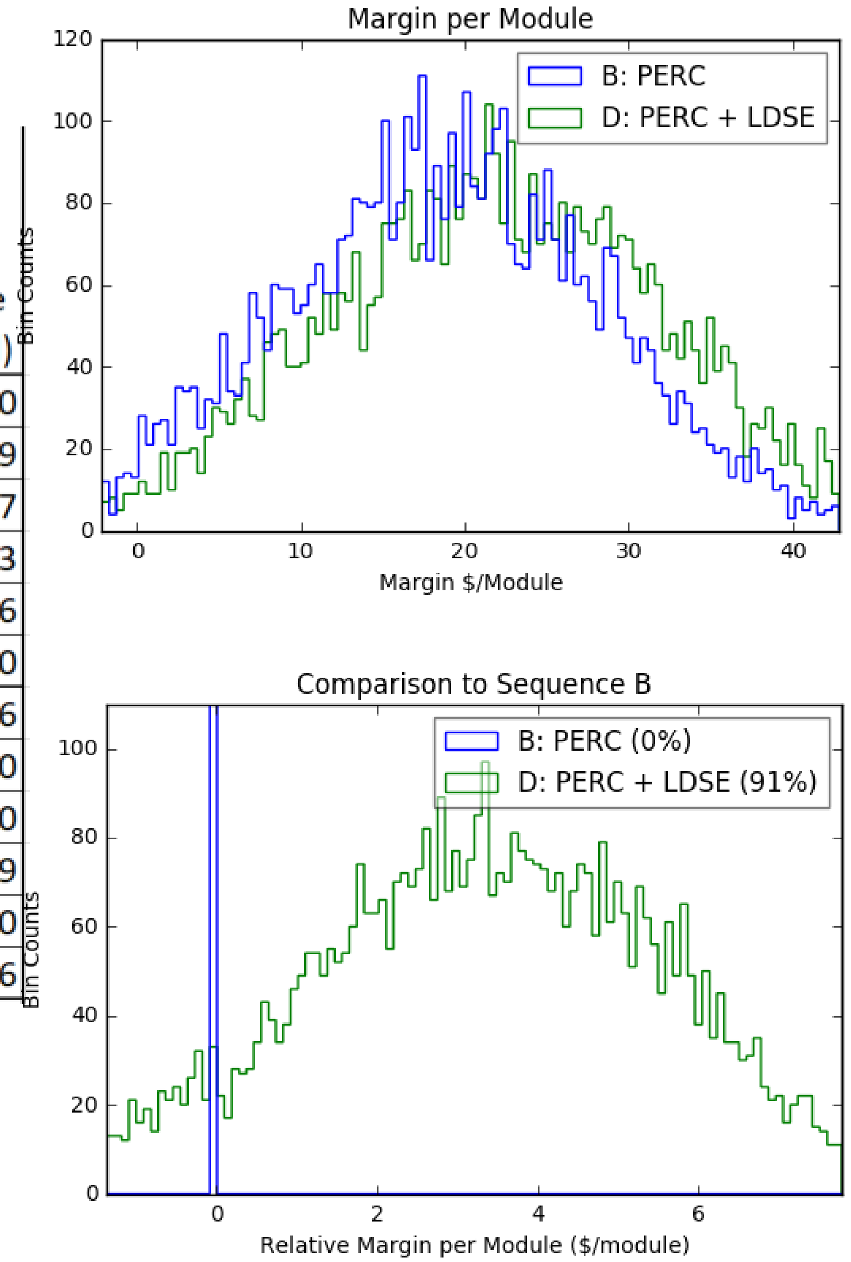
Efficiency

Seq	Iter	Mod Cost ($/mod)	Cell Eff (%)	CTM Power Ratio	Mod Power (W)	Mod Cost ($/W)
B	0	119	21.0	0.976	297	0.400
B	1	119	21.5	0.989	309	0.384
B	2	125	21.4	0.981	305	0.409
B	3	124	21.5	0.977	306	0.406
B	4	119	21.4	0.984	306	0.388
B	4999	135	21.1	0.971	298	0.453
D	0	124	21.8	0.976	310	0.399
D	1	127	22.3	0.989	320	0.396
D	2	132	22.3	0.981	318	0.415
D	3	130	22.5	0.977	319	0.406
D	4	125	22.1	0.984	316	0.397
D	4999	141	22.3	0.971	314	0.450

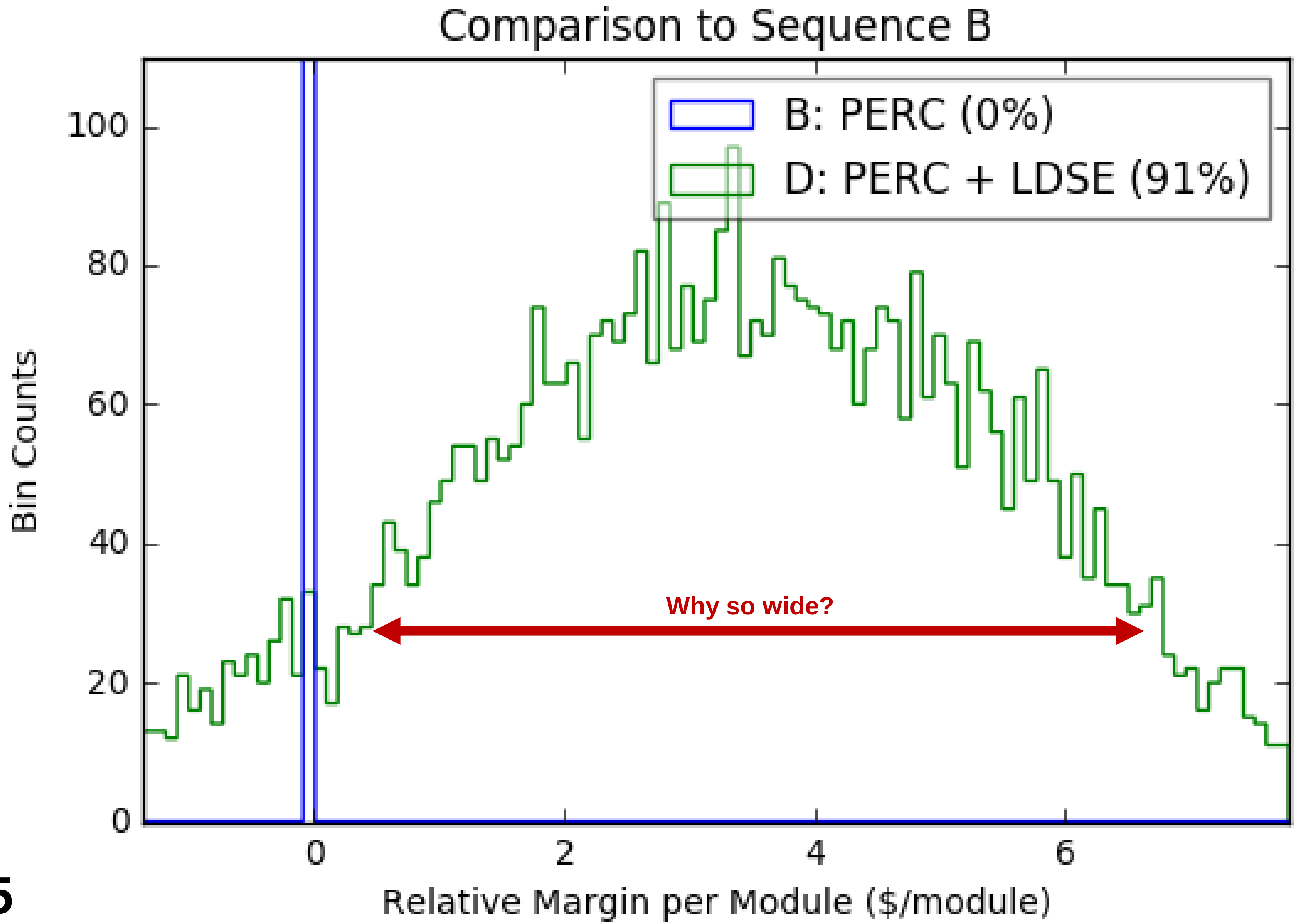


Market Price -> Margin

Seq	Iter	Mod Cost ($/mod)	Mod Power (W)	Base-line price ($/W)	Power Premium (c/W /W)	Selling Price ($/mod)	Margin Per Module ($/mod)
B	0	119	297	0.45	0.07	136	17.0
B	1	119	309	0.47	0.12	154	34.9
B	2	125	305	0.47	0.08	149	23.7
B	3	124	306	0.42	0.05	132	8.3
B	4	119	306	0.44	0.05	137	18.6
B	4999	135	298	0.45	0.13	139	4.0
D	0	124	310	0.45	0.07	144	20.6
D	1	127	320	0.47	0.12	163	36.0
D	2	132	318	0.47	0.08	158	26.0
D	3	130	319	0.42	0.05	140	10.9
D	4	125	316	0.44	0.05	143	18.0
D	4999	141	314	0.45	0.13	153	11.6

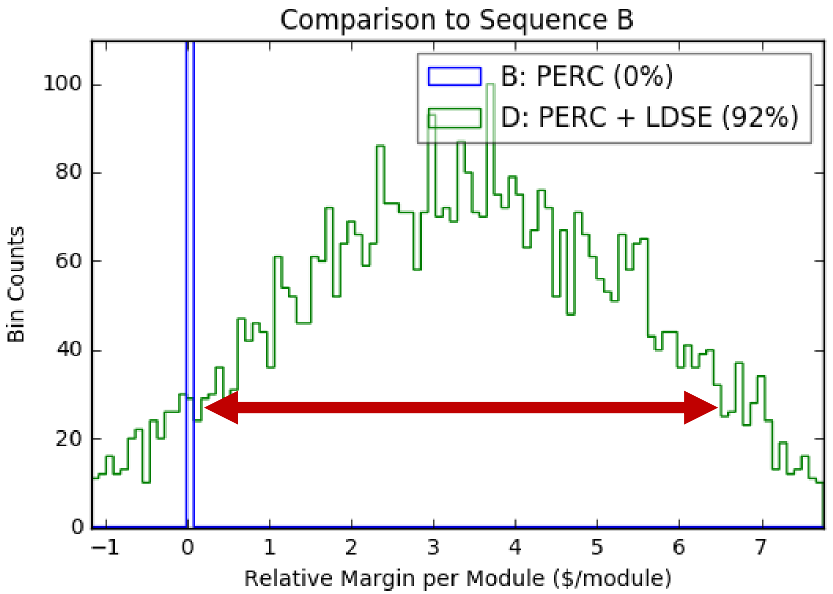


Margin per module



Uncertainty in the Margin difference

- Process costs (Normalised uncertainty)
  - – Common processes
  - – + oxide, Laser doping, plating, sinter
  - – - front silver screenprint
- Efficiency boost from LDSE
- Difference in cell fabrication yield
- Market module price
- High power price premium



Linear Regression – contribution to variance

Parameter	Range (10^{th} – 90^{th} percentile)	Contribution to uncertainty (%)
Efficiency difference	0.7 – 1.0 %abs	30%
Power Premium	0.05 – 0.12 c/W per additional module W	24%
Yield Difference	+/– 1 %	11%
Ag plating solution	0.56 – 1.7 $/m2	10%
Front Ag paste cost	1.2 – 2.2 $/m2	9%

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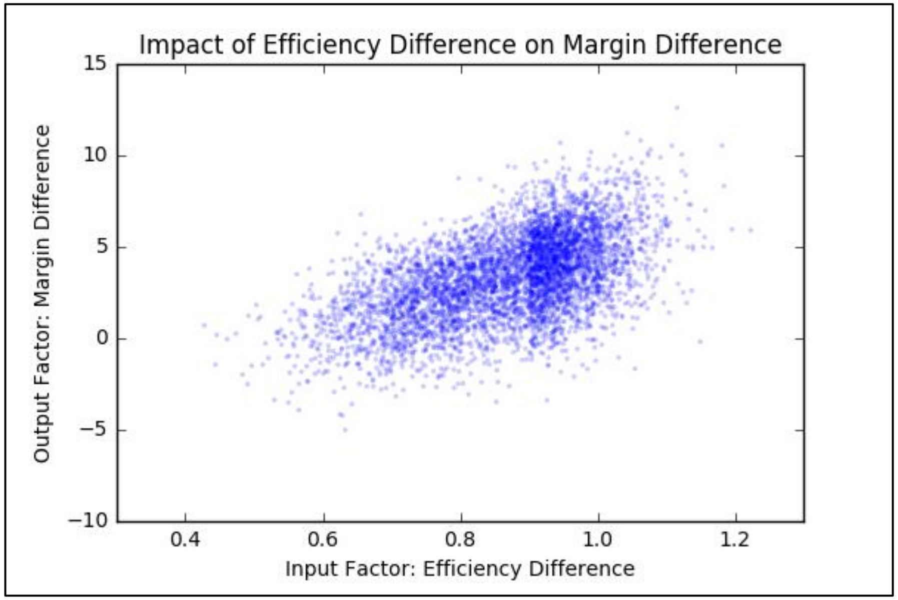
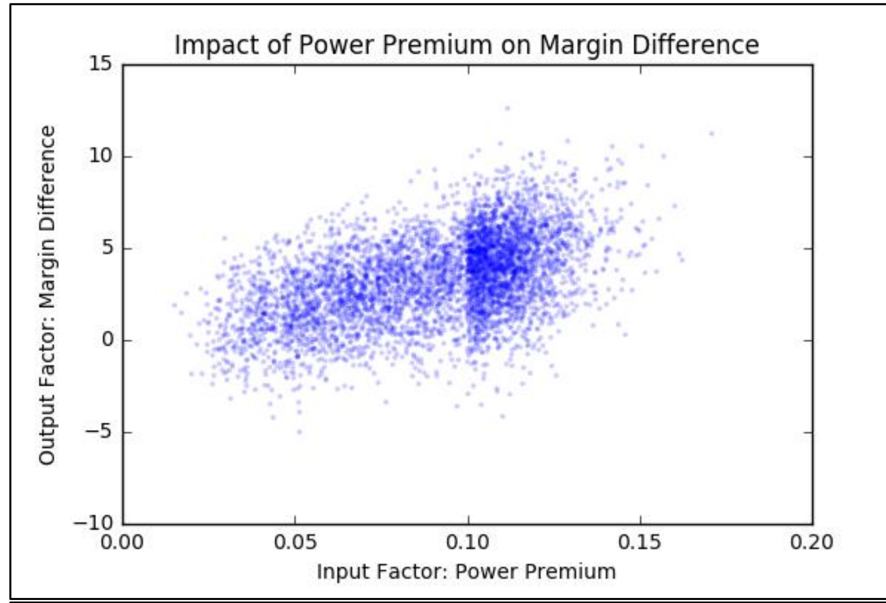
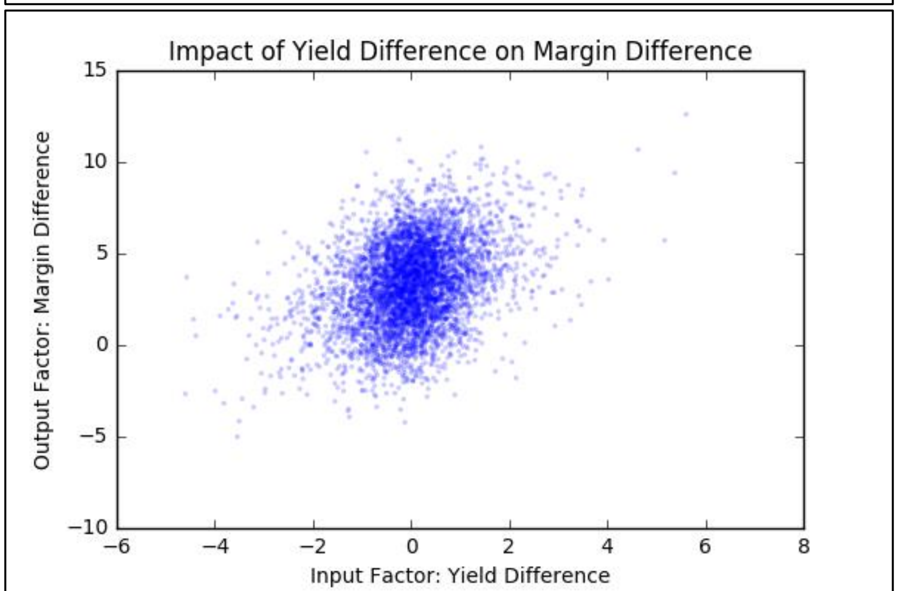
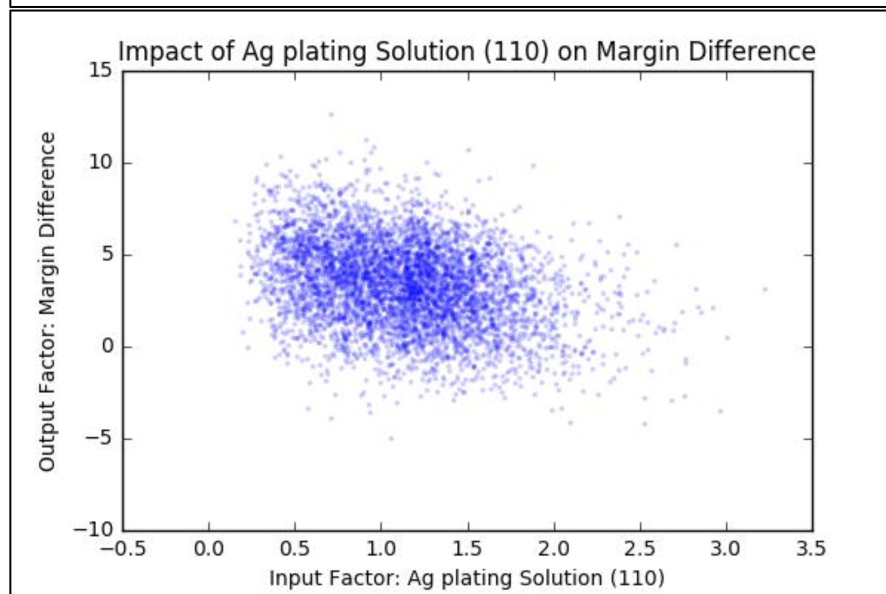
Graphical Representation









Analysis 2 – Conclusions

- LDSE front with PERC rear has promise.
  - $/W basis - Not beneficial at module level
  - Margin basis - looks attractive, but uncertainty
    - Performance (efficiency gain, production yield)
      - Prove in the lab?
    - Price premium. Can we be more confident of this?
    - Individual process costs - less relevant.
- More Details:
  - *Paper in Preparation.*
  - Advanced Hydrogenation is also analysed.

Summary

- Cost analysis method and benefits
  - **Monte Carlo uncertainty** -> Less time/effort required.
  - **Normalised uncertainty** –> Focus process development and cost analysis efforts.
  - **Simultaneous monte carlo** -> distinguish incremental improvements.
  - **Contribution to variance** -> identify critical cost, performance or market parameters.
- Technologies discussed
  - **Perovskite - on glass.**
  - **c-Si - PERC and LDSE.**

Special Thanks

- **Cost Analysis Methodology:** Renate Egan, Martin Green, Rhett Evans, Anita Ho-Baillie, Paul Basore (NREL/DOE), Michael Woodhouse (NREL)
- **Thin film Si –** Sergey Varlamov
- **Perovskite on Glass:** Anita Ho-Baillie, Trevor Young, UNSW perovskite group, Monash Uni perovskite group.
- **Perovskite R2R:** Doojin Vak, Mei Gao and CSIRO printing group
- **c-Si:** Stuart Wenham, Hydrogenation Group, SIRF, Budi Tjahjono (Sunrise)

Interested in analyzing your technology?

- Australian Centre for Advanced Photovoltaics (ACAP)
- n.chang@unsw.edu.au

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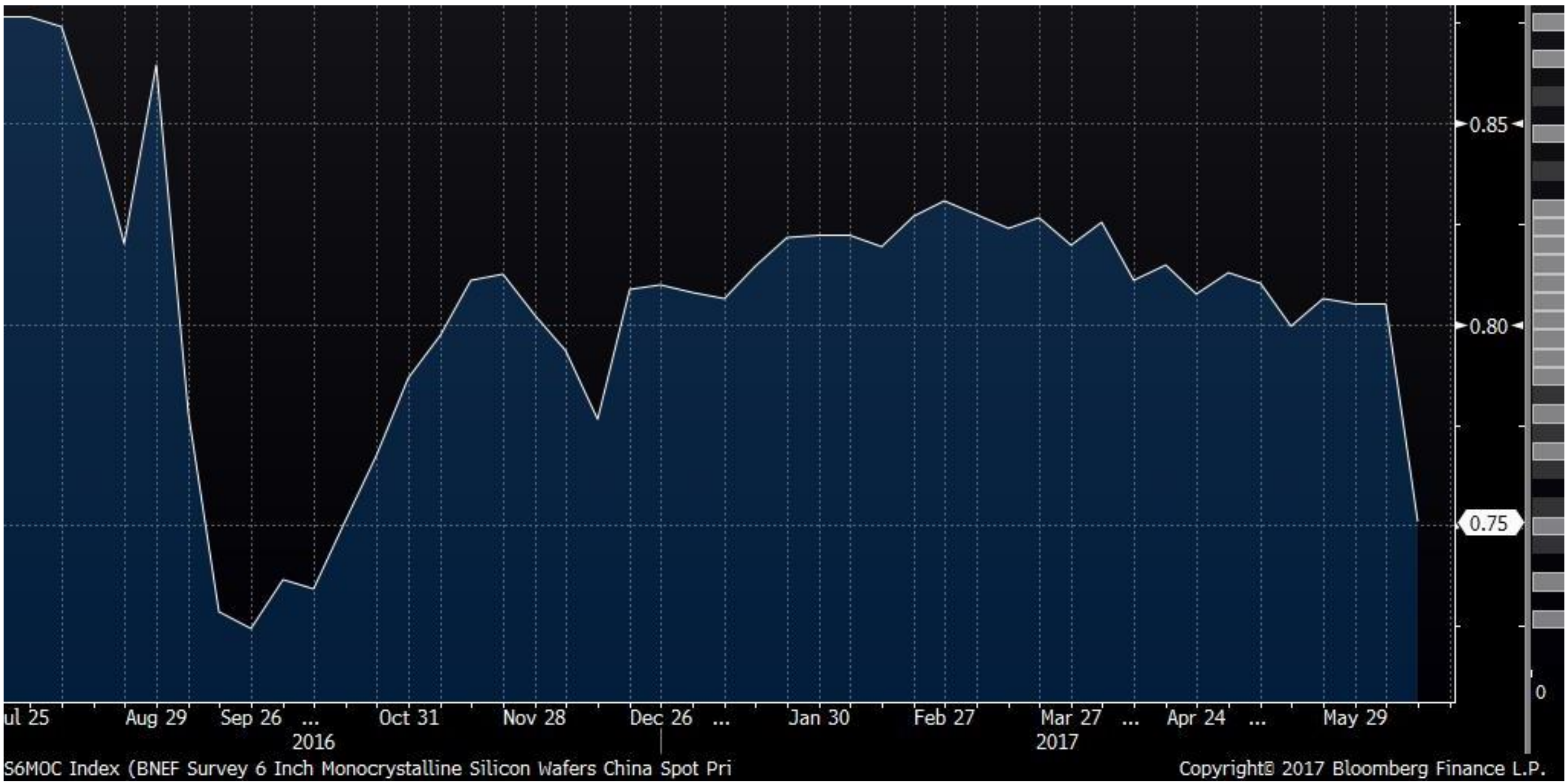
Responsibility for the views, information or advice expressed herein is not accepted by the Australian Government.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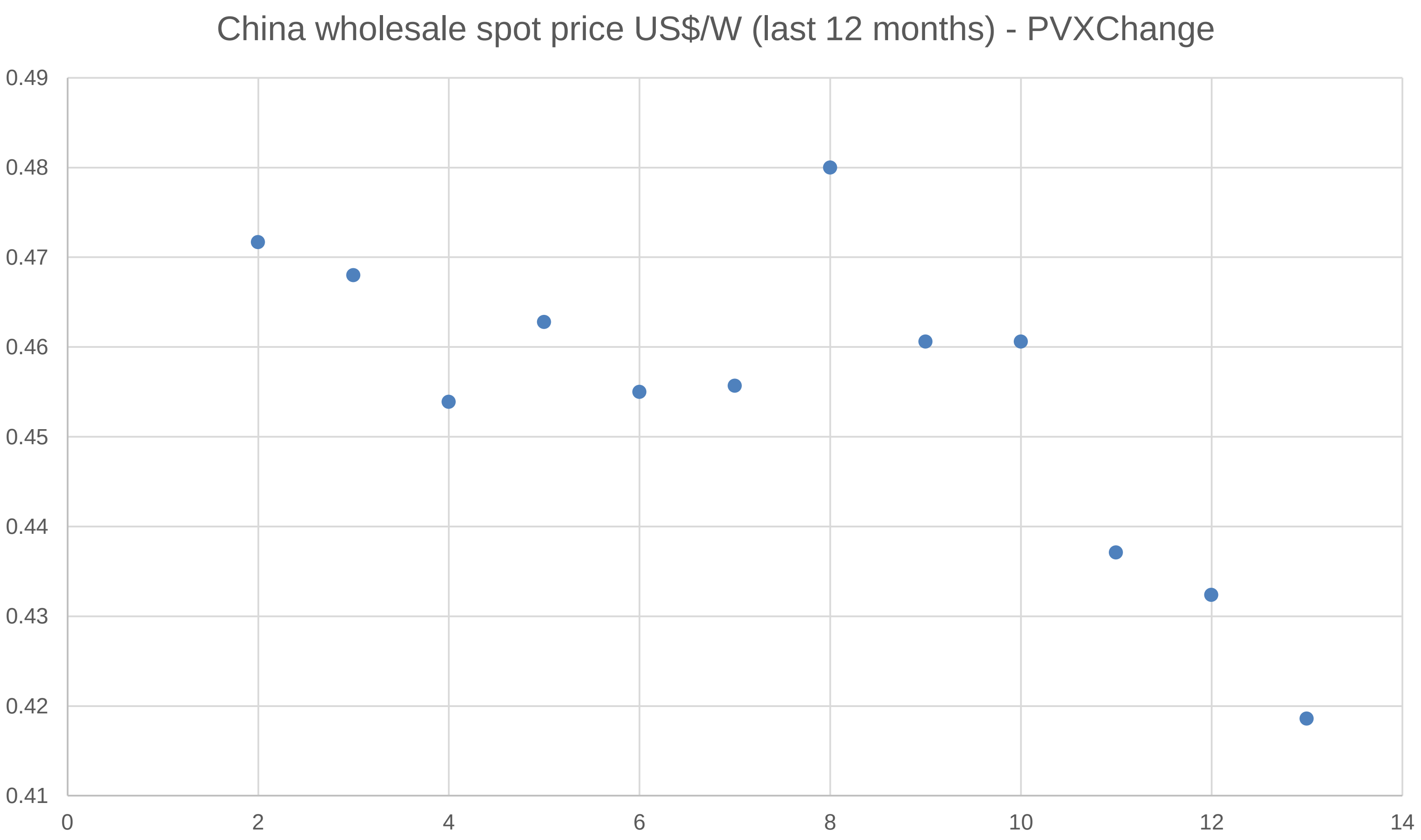

China wholesale spot price US$/W (last 12 months) - PVXChange
0.49
0.48
0.47
0.46
0.45
0.44
0.43
0.42
0.41
0
2
4
6
8
10
12
14