CHALLENGES OF DESIGNING AND OPERATING PV PLANTS UNDER CHILEAN CONDITIONS

Centro de Pesquisa e Capacitacao em Energia Solar de Universidade Federal de Santa Catarina

Florianópolis, Brasil

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fotovoltaica ufsc

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Outline

- Chile
  - Market & Operating conditions
- PV Technology Trends
  - Advanced services for the industry
- Soiling
  - Phenomena description
  - Impact
  - Optimal economic management
- Key takeaways

Bloomberg.

Ph: Jamey Stillings

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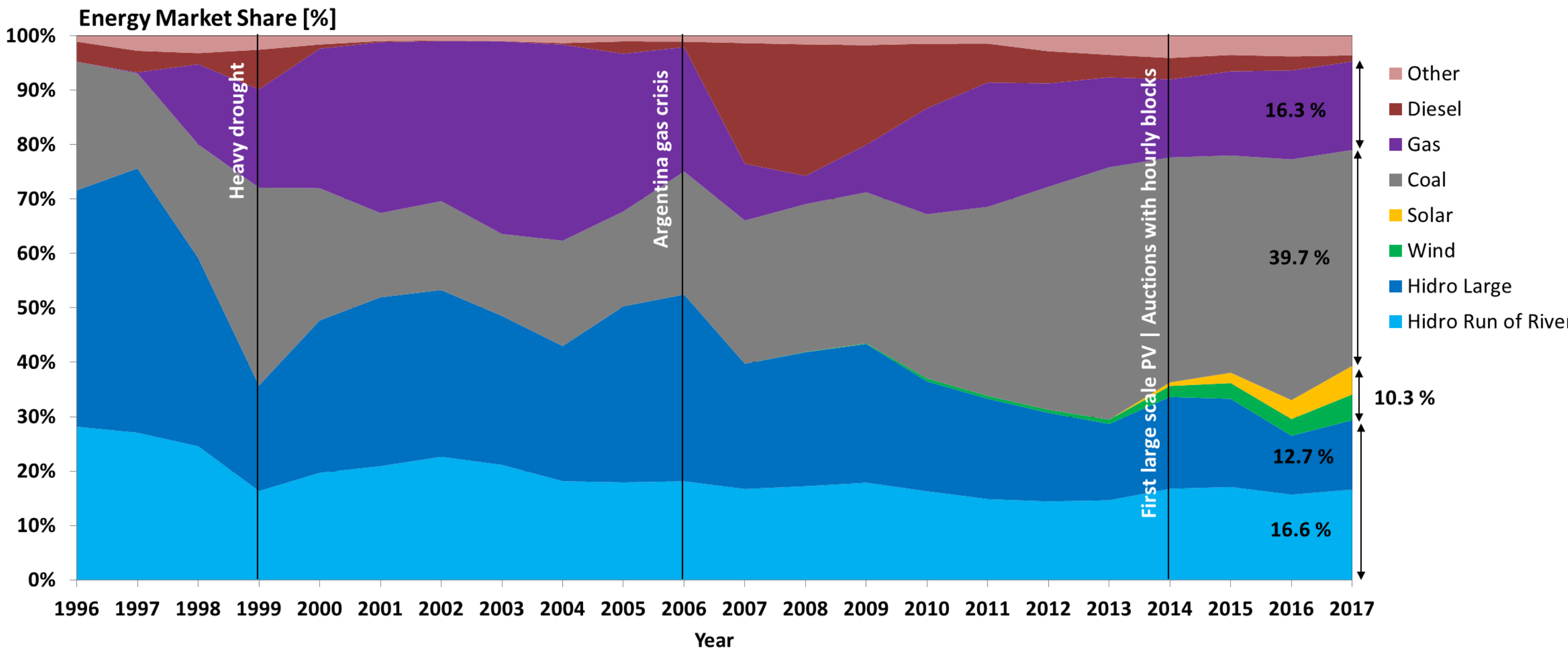
Market Conditions | Energy

- Hydro and fossil fuels dominates the market (86.4 %)
  - Solar (PV) and wind are the fastest growing technologies in energy and capacity terms



CSET with National Energy Commission data.

Market Conditions | Energy | 'Specific yield'

- Hydro power plants portfolio presents lower capacify factors (new normal?)
- Wind development matures locating and finding better capacity factor sites
- Solar PV is expected to stay constant or decrease due to exploitment of lower irradiation zones (thanks to lower CapEx)

CSET with National Energy Commission data.

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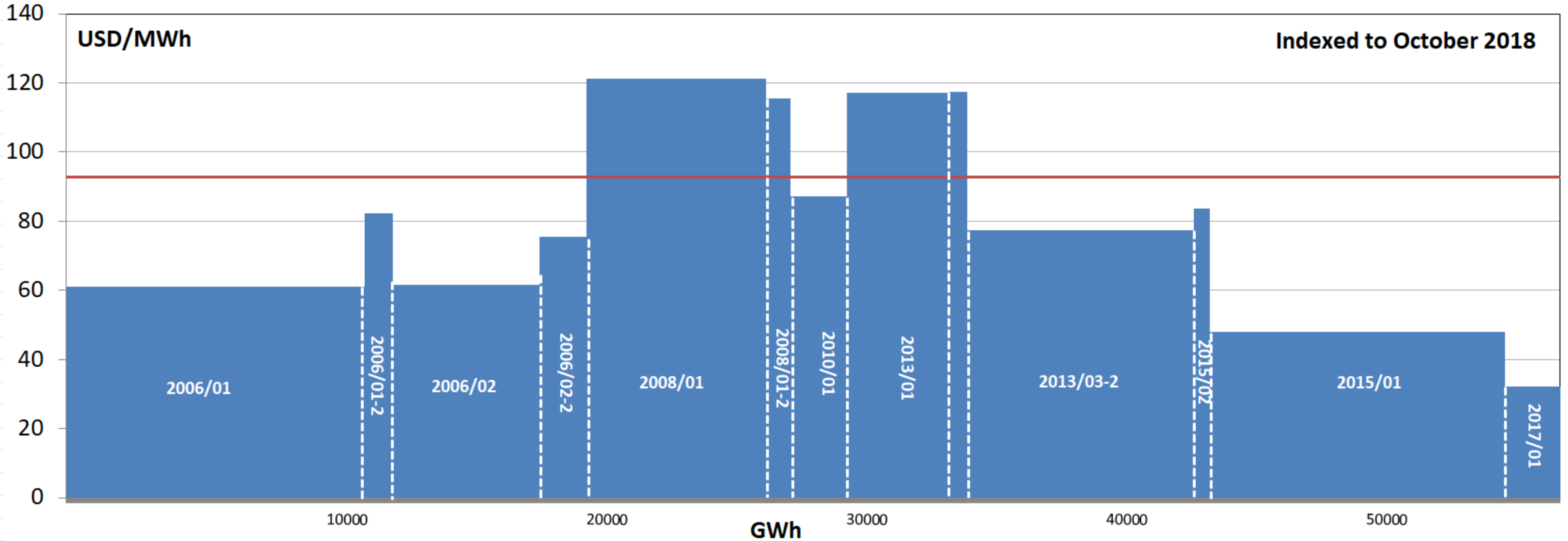
Market Conditions | Regulated client auctions

- Solar (PV), wind and hydro (amortized)
  - No new coal plants are foreseen in the future (social, environmental and economic drivers)
  - No new large hydro (dams) plants are foreseen in the future (only run of the river | social)
  - Even CCGTs are having issues earning PPAs (CSP at 48 USD/MWh)



CSET with National Energy Commission data.

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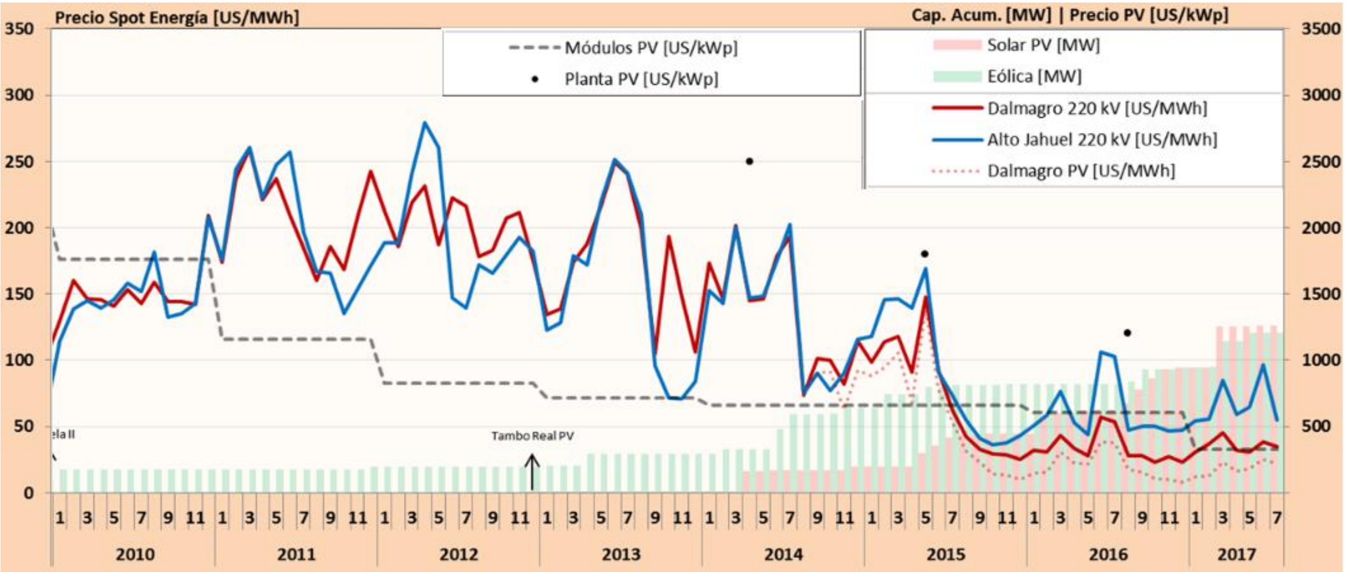
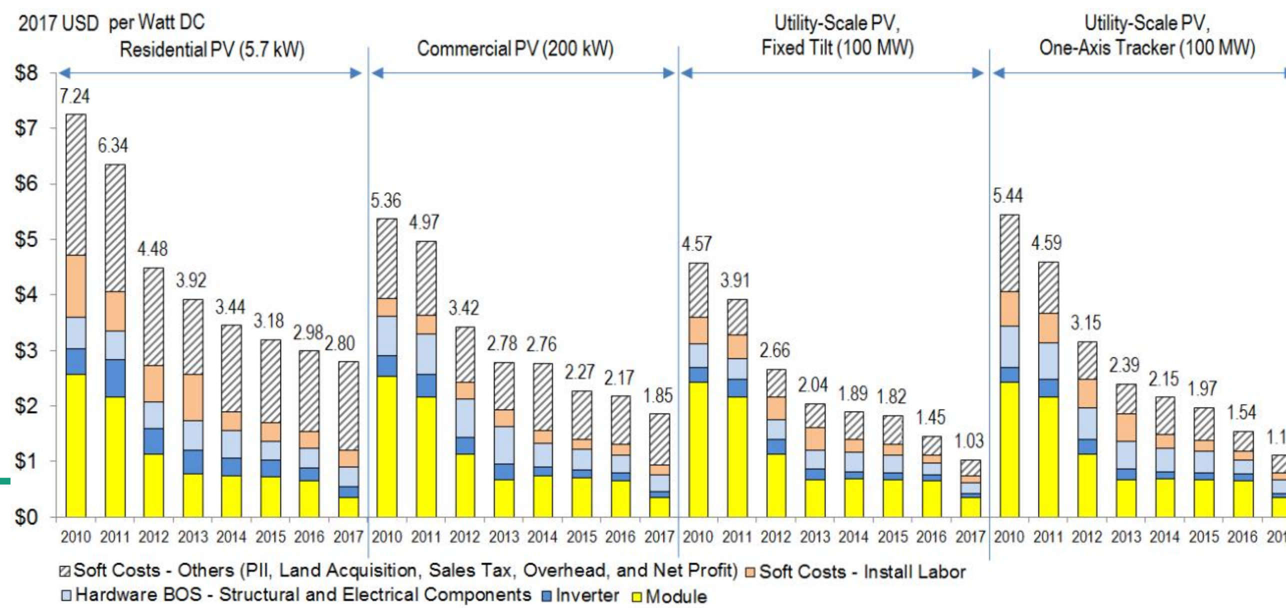
Market Conditions | Technology trends | Past



Large Scale PV plants in Chile. Source CSET.

Solar (PV) has substantially dropped in price in the last 7 years.



PV systems prices in USA. Source NREL, DOE.

Market Conditions | Technology trends | Present

CAPEX -Tracker			
Item	**USD**	**USD/Wp**	**%**
Modules	35,000,000	0.350	**35.9%**
Structure	15,000,000	0.150	**15.4%**
Inverter	6,000,000	0.060	**6.1%**
Electric installation	4,500,000	0.045	**4.6%**
Civil Works	9,756,917	0.098	**10.0%**
Cabling DC - AC	2,300,000	0.023	**2.4%**
Construction management	2,927,075	0.029	**3.0%**
EPC management	2,927,075	0.029	**3.0%**
Others	3,414,921	0.034	**3.5%**
Combiner Boxes	1,463,537	0.015	**1.5%**
Engineering	400,000	0.004	**0.4%**
SCADA	350,000	0.004	**0.4%**
Substation (S)	12,000,000	0.120	**12.3%**
Transmission Line (TL - 5 km)	1,529,642	0.015	**1.6%**
Total	**97,569,167**	**0.976**	**100.0%**
BOS	**62,569,167**	**0.626**	**64.1%**
BOS (w/o S & TL)	**49,039,525**	**0.490**	**50.3%**

Cost structure for a 100 MWp plant in Chile. Source CSET 2017.

Large scale solar (PV) costs less than 1 USD/Wp turn-key since 2017.

Valores referenciales de sistemas fotovoltaicos, generación y retorno de inversión (Santiago)

ACESOL

Potencia sistema olar (kWp)	Ejemplos de segmentos de uso	Superficie requerida neta (incl separación entre filas)	Valor aprox. en USD/Wp	Valor total aprox. Pesos $	Ahorro vida útil	Retorno inversión en años	Valor kWh red eléctrica en Pesos $	Valor kWh solar en Pesos $
2,5	Casas, pequeño comercio. **Valores con IVA**	7 (11) m2	USD 2,38	3.808.000	8.390.000	11,3	106,3 / 61,5	38,1
5	Casas, pequeño comercio, riego. **Valores con IVA**	35 (55) m2	USD 2,14	6.854.400	16.780.000	10,2	106,3 / 61,5	34,3
30	Edificios, comercio, riego	210 (330) m2	USD 1,40	26.880.000	69.960.000	9,6	58,3	22,4
100	Comercio, industria	700 (1.100) m2	USD 1,00	64.000.000	233.200.000	6,9	58,3	16,0
500*	Industria, autoconsumo	3.500 (5.500) m2	USD 0,90	288.000.000	1.166.000.000	6,2	58,3	14,4
3000**	PMGD	21.000 (33.000) m2	USD 0,80	1.536 MM	6.144.000.000	6,2	51,2	14,4

onsideraciones: 1 USD = 640 $, valor BT1 $106,3 IVA incluido y excedentes $61,5 IVA incluido,5. Se considera 0% autoconsumo 50% venta de excedentes, generación anual 1600kWh/kWp (Santiago).

Para sistemas >100kWp no aplica ley actual 20.571, se considera 100% autoconsumo. Modificación de ley 0.571 en curso.

*PMGD: venta de energía a precio nudo, posible combinación con autoconsumo. Tramitación requiere eclaración de Impacto Ambiental (<=3MW)

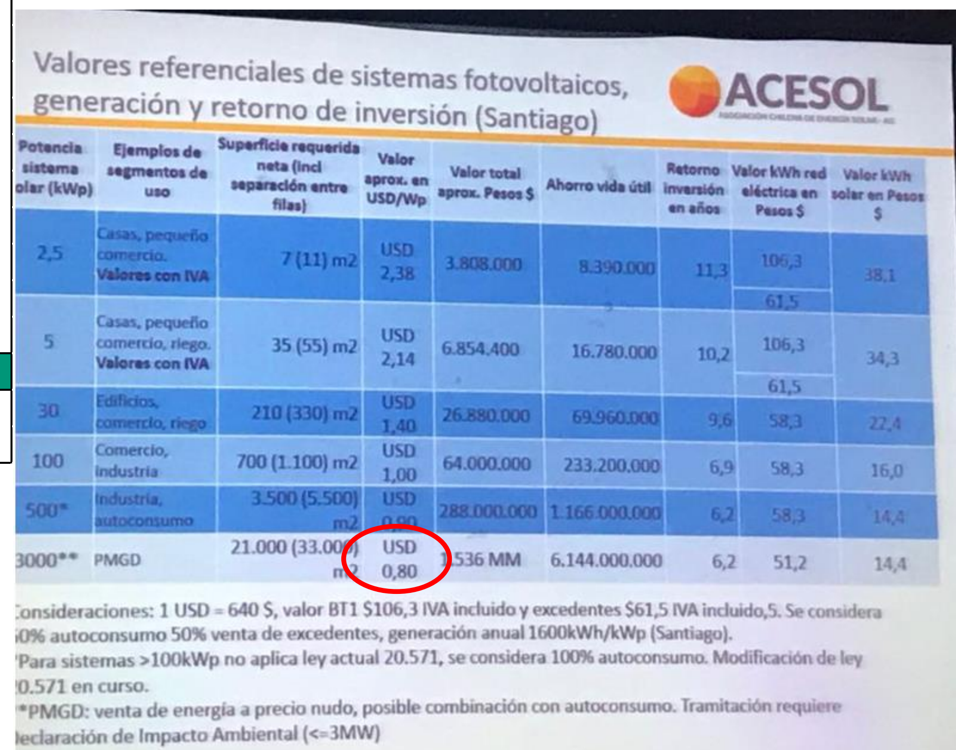
Meeting Banco estado Agosto 2018. Source ACESOL.

Market Conditions | Technology trends | Present

CAPEX -Tracker			
Item	**USD**	**USD/Wp**	**%**
Modules	25,000,000	0.250	**29.4%**
Structure	15,000,000	0.150	**17.6%**
Inverter	6,000,000	0.060	**7.0%**
Electric installation	4,500,000	0.045	**5.3%**
Civil Works	8,514,681	0.085	**10.0%**
Cabling DC - AC	2,300,000	0.023	**2.7%**
Construction management	2,554,404	0.026	**3.0%**
EPC management	2,554,404	0.026	**3.0%**
Others	2,980,138	0.030	**3.5%**
Combiner Boxes	1,463,537	0.015	**1.7%**
Engineering	400,000	0.004	**0.5%**
SCADA	350,000	0.004	**0.4%**
Substation (S)	12,000,000	0.120	**14.1%**
Transmission Line (TL - 5 km)	1,529,642	0.015	**1.8%**
Total	**85,146,806**	**0.851**	**100.0%**
BOS	**60,146,806**	**0.601**	**70.6%**
BOS (w/o S & TL)	**46,617,165**	**0.466**	**54.7%**

Cost structure for a 100 MWp plant in Chile. Source CSET 2017.

Large scale solar (PV) costs less than 1 USD/Wp turn-key since 2017.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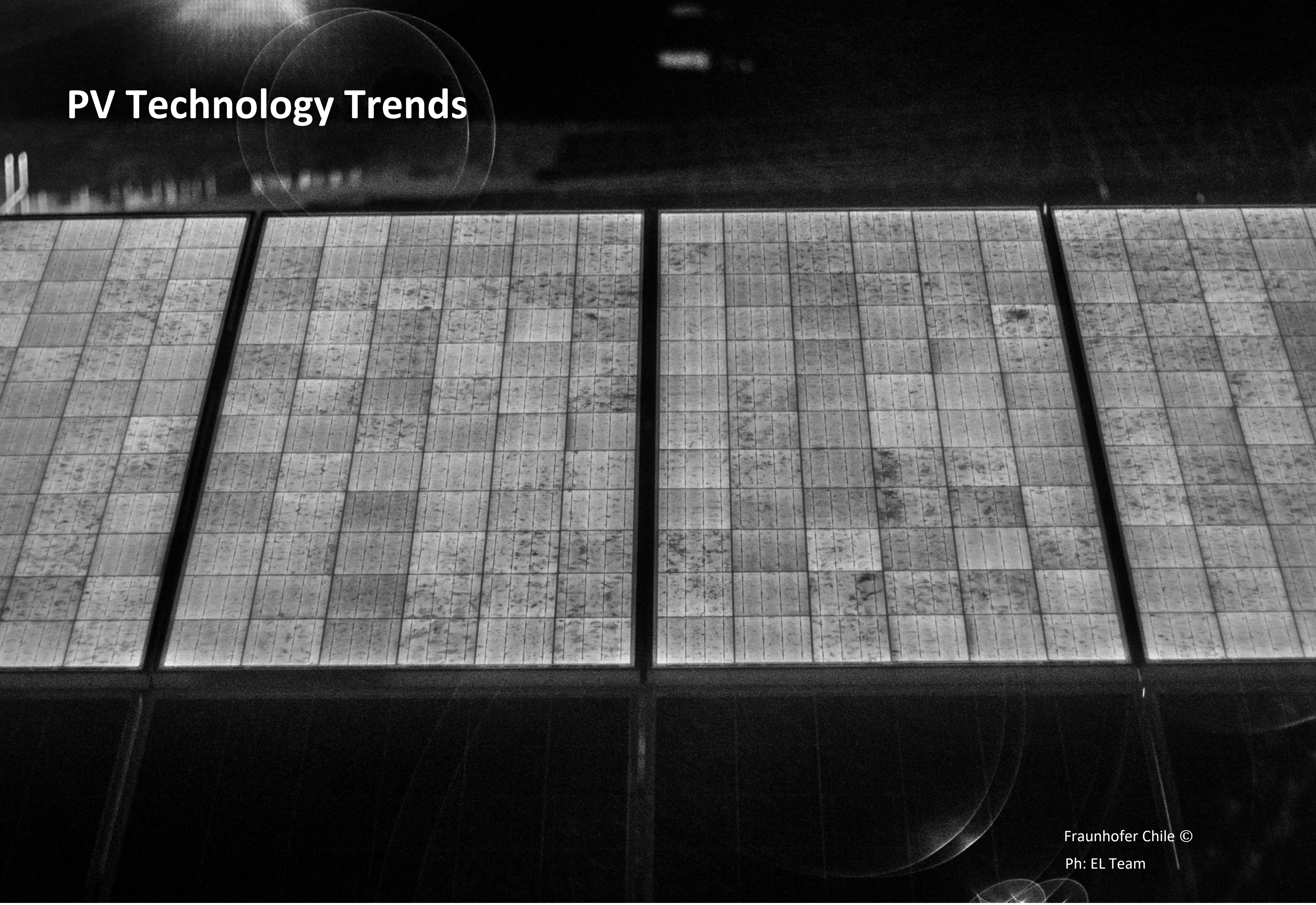
PV Technology Trends



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Ph: EL Team

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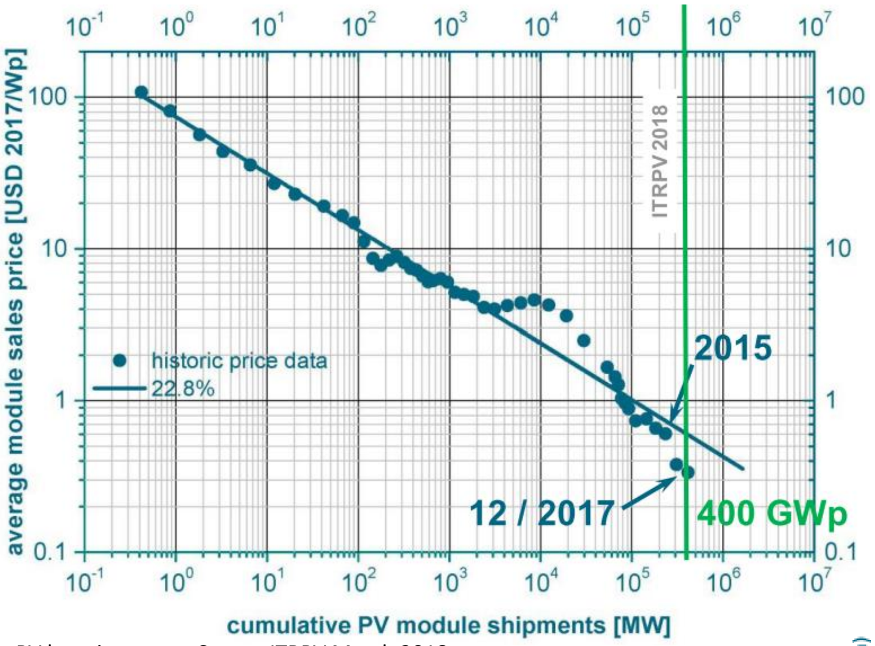
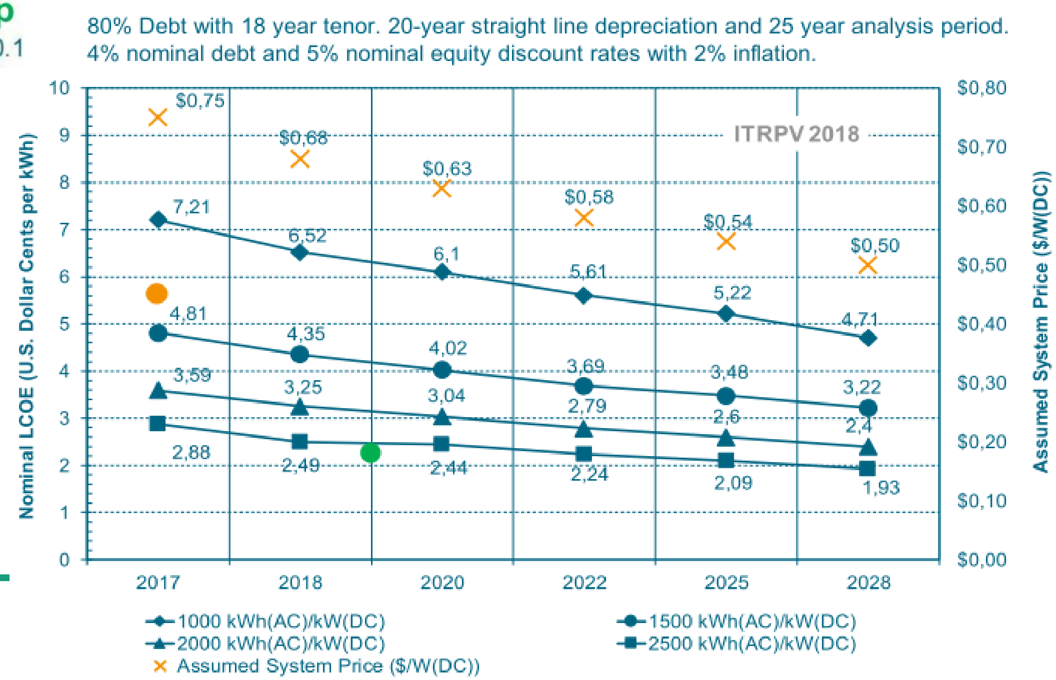
Technology trends| Future



PV learning curve. Source ITRPV March 2018.

Price (CAPEX of PV plant) is expected to drop 7 %/year during the next 5 years.



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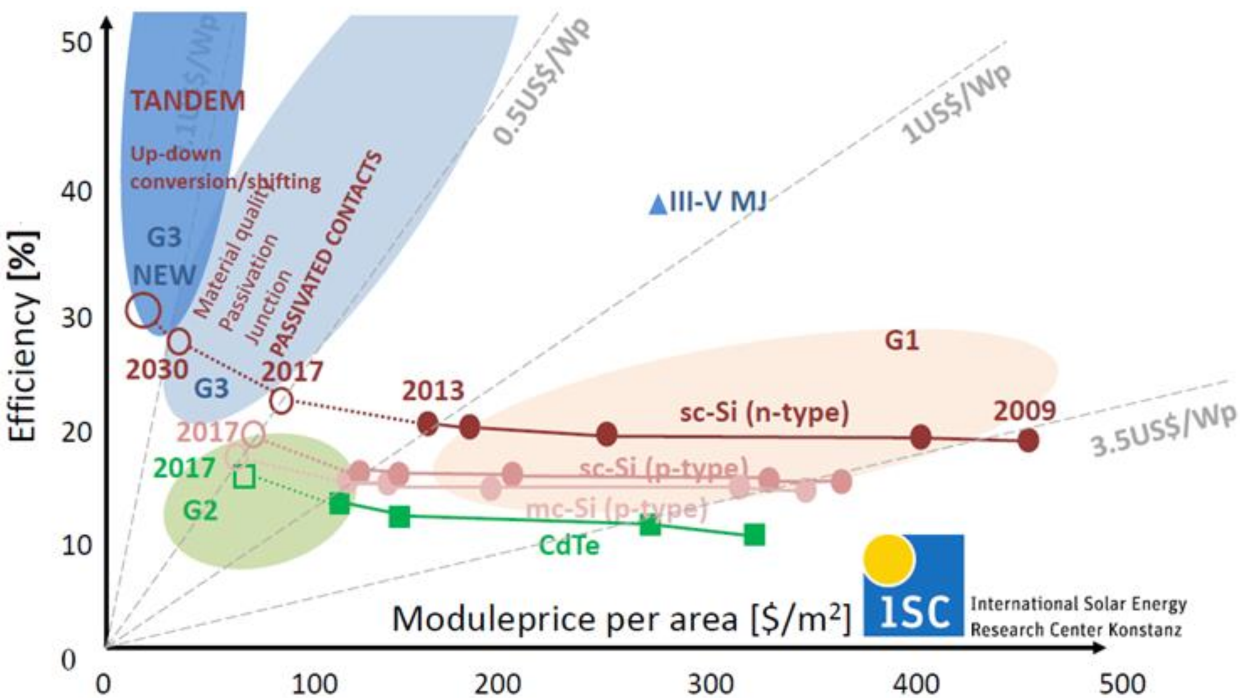
Expected PV LCOE for different specific yields. SourceITRPV March 2018.

Technology trends | Power density

- During ‘high module’ price *era* cheap, poly-Si was king for utility scale in Chile
- During ‘low module’ price *era* technology election is not that simple
- Low LCOEs in conjunction with lower weight of modules on the CapEx structure demand for high power density modules
  - mono/poly | PERX | n/p-type | Mono/Bi-facial | Half-Cut Cell | HJT | IBC | etc…



Kopecek & Libal, PVTech,27 May 2015, 17 July 2015
Limit for industrial c-Si solar cells reached in 2030: what next?

R. Kopecek, Intersolar Munich, June 20, 2018

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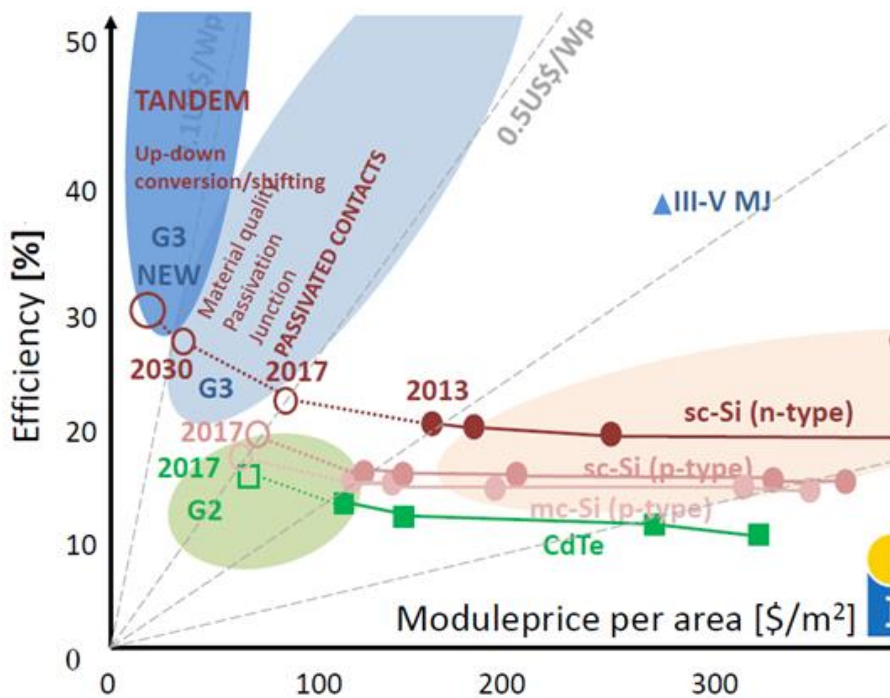

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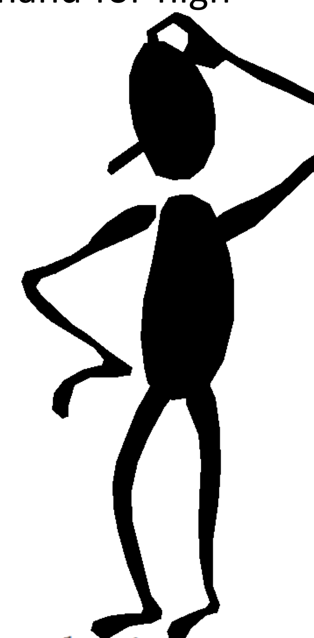
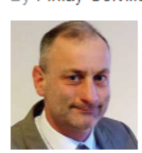


New module suppliers and technologies to create more opportunities and risks to developers and EPCs

Jul 09, 2018 11:54 AM BST | 1 Share

By Finlay Colville, Head of Solar Intelligence, Solar Media



Finlay Colville joined Solar Media in June 2015 as head of the new Solar Intelligence activities. Until October 2014, he was vice president and head of solar at NPD Solarbuzz. Widely recognised as a leading authority on the solar PV industry, he has presented at almost every solar conference and event worldwide, and has authored hundreds of technical blogs and articles in the past few years. He holds a BSc in Physics and a PhD in nonlinear photonics.

Technology trends | Advanced Services for Industry

- Advance performance measuring
  - On-site MPP evaluation of performance
  - Minutely IV curves & meteo data
  - On-site degradation & soiling studies
  - New technology analysis (i.e. bifacial, half-cut cell, etc…)
- Deployed platforms
  - Diego de Almagro Technology Platform
    - 12 IV channels & meteo
  - PSDA
    - 6 IV channels & meteo
- Why performing on-site analysis?
  - Better understanding of the site specific conditions for **maximizing the financial yield of the solar PV asset and decreasing uncertainty**

Solar Platform of Diego de Almagro. Operated by CSET. CSET.

Solar Platform of Atacama Desert. Ferrada.

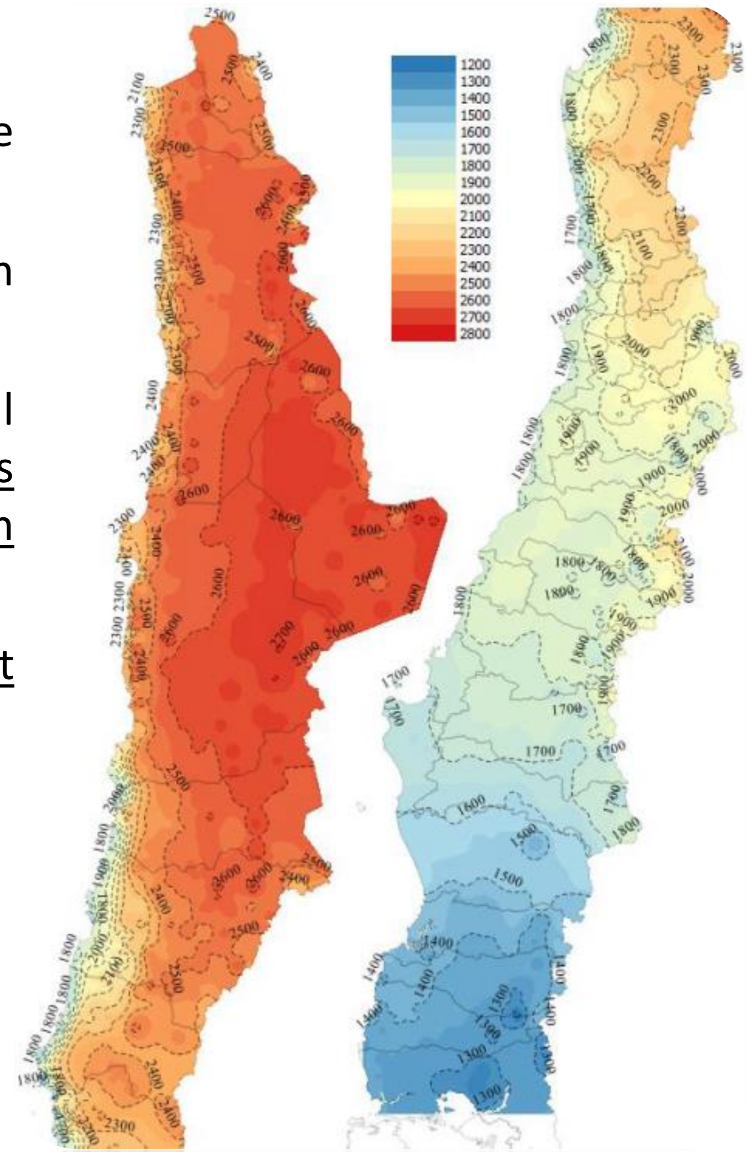
Solar Platform at Santiago de Chile. Dictuc.

Soiling

Fraunhofer Chile ©

Operating Conditions | Soiling

- Chile has one of the best solar irradiation resource (GHI and DNI) in the world
- Large temperature gradients pose degradation challenges to Bill of Materials (BoM). i.e. coatings
- High soiling rates add challenges to the optimal management of solar fields, especially when plants operate on mature and competitive markets with seasonal varying price signals
  - No PoC[1] PPAs (hourly/seasonal varying spot energy price)
  - No must run policies for NCRE[2] (curtailments exist)



GHI map of Chile in kWh/m^2-year. CSET SolarGis Data.

1) Point of Connection
2) Non Conventional Renewable Energy

Soiling | Phenomenon | Physics

Figgis et al. 2017.

- Soiling is the phenomenon of **deposition**, **rebound**, **resuspensio**n and **accumulatio**n in time of airborne particles over a surface (PV glass).

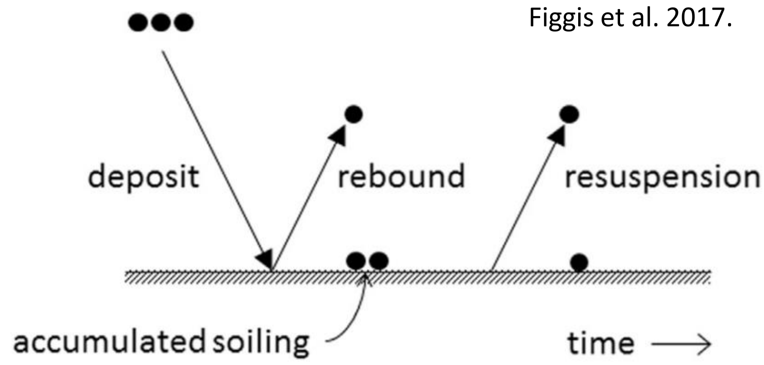


Fig. 1. Soiling is the net result of particle deposition, rebound, and resuspension. The mechanisms can be modeled and summed to describe dust accumulation over time.

Soiling | Phenomenon | Physics

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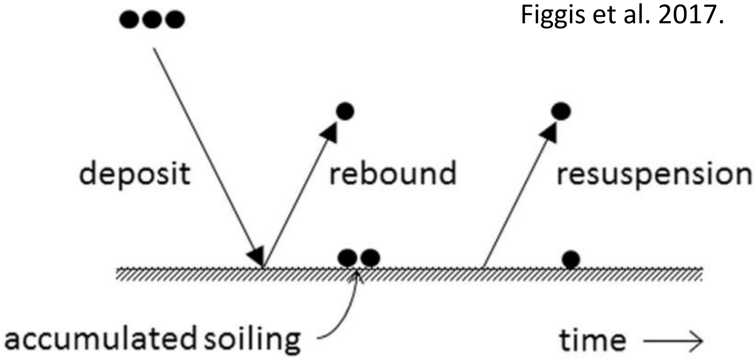
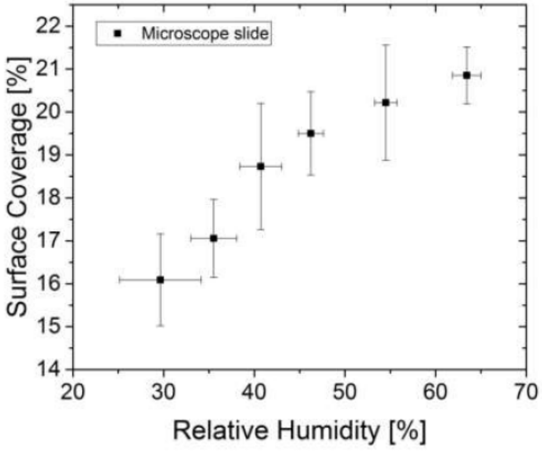


Fig. 1. Soiling is the net result of particle deposition, rebound, and resuspension. The mechanisms can be modeled and summed to describe dust accumulation over time.

- Deposition, rebound and resuspension is a function of wind speed.

- Accumulation, aglomeration and cementation is a function of humidity and dust composition.



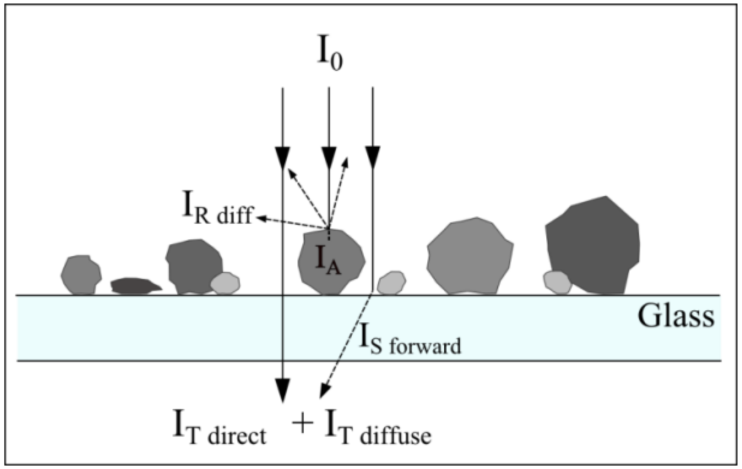
- High relative humidity → increased adhesion due to capillary forces

Ilse et al. Fraunhofer CSP 2017.

Soiling | Phenomenon | Physics

- Physics is hard to model and highly depends on the structural dynamics of the soiling with the surface (glass, coatings and water) and it's interaction with incoming light (direct and diffuse).

PV: Glass transparent cover



Wolfertstetter et al. 2018.

Soiling | Areas of study

- Physics
  - Deposition and interaction of materials, particles and weather
    - Weather data
- Chemistry
  - New composition of materials
    - Materials
- Economics
  - Economic impact & modeling of soiling

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- Physics
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- Levelized Cost of Electricity
  - Lower yield
  - Higher O&M cost
    - Non-linear LCOE increase

$$LCOE = \frac{Investment + \sum_{t=1}^{20} \frac{O\&M_t}{(1+d)^t}}{\sum_{t=1}^{20} \frac{G_t}{(1+d)^t}}$$

Soiling | Soiling economics cont'd

- Levelized Cost of Electricity
  - Lower yield (MWh/year)
  - Higher O&M cost (kWp/year)
    - Non-linear LCOE increase (USD/MWh)
- Is soiling management easy to calculate?
  - Spot price or PPA at PoC (USD/MWh)
  - Cleaning type
    - Cleaning cost (USD/MWp)
    - Cleaning speed (MWp/day)
  - Soiling ratio (% cleanliness)
  - Soiling rate (%/day)

Soiling | Soiling economics cont'd

- Non-linear economic impact of soiling has a non-marginal effect on LCOE

Capex	1.0	USD/Wp
Opex	10.0	USD/kWp/Year
Years	20.0	Years
Discount rate	10.0%	%/Year
Degradation	0.50%	%/Year

LCOE (USD/MWh)					
Δ Yield | Δ Opex	0%	5%	10%	15%	20%
0.0%	44.10	44.27	44.45	44.62	44.79
-2.5%	45.23	45.41	45.59	45.76	45.94
-5.0%	46.42	46.60	46.79	46.97	47.15
-7.5%	47.68	47.86	48.05	48.24	48.42
-10.0%	49.00	49.19	49.39	49.58	49.77
-12.5%	50.40	50.60	50.80	50.99	51.19
-15.0%	51.88	52.09	52.29	52.49	52.70
-17.5%	53.46	53.66	53.87	54.08	54.29
-20.0%	55.13	55.34	55.56	55.77	55.99

% Var. LCOE	USD/kWp/Year	10.0	10.5	11.0	11.5	12.0
kWh/kWp	Δ Yield | Δ Opex	0%	5%	10%	15%	20%
3,000	0.0%	0.0%	0.4%	0.8%	1.2%	1.6%
2,925	-2.5%	2.6%	3.0%	3.4%	3.8%	4.2%
2,850	-5.0%	5.3%	5.7%	6.1%	6.5%	6.9%
2,775	-7.5%	8.1%	8.5%	9.0%	9.4%	9.8%
2,700	-10.0%	11.1%	11.5%	12.0%	12.4%	12.9%
2,625	-12.5%	14.3%	14.7%	15.2%	15.6%	16.1%
2,550	-15.0%	17.6%	18.1%	18.6%	19.0%	19.5%
2,475	-17.5%	21.2%	21.7%	22.2%	22.6%	23.1%
2,400	-20.0%	25.0%	25.5%	26.0%	26.5%	27.0%

Soiling | Soiling economics cont'd

- Non-linear economic impact of soiling has a non-marginal effect on LCOE
- This effect is greater under low CapEx scenarios

Capex	0.7	USD/Wp
Opex	10.0	USD/kWp/Year
Years	20.0	Years
Discount rate	10.0%	%/Year
Degradation	0.50%	%/Year

LCOE (USD/MWh)					
Δ Yield | Δ Opex	0%	5%	10%	15%	20%
0.0%	31.91	32.08	32.25	32.43	32.60
-2.5%	32.73	32.90	33.08	33.26	33.44
-5.0%	33.59	33.77	33.95	34.13	34.32
-7.5%	34.50	34.68	34.87	35.06	35.24
-10.0%	35.45	35.65	35.84	36.03	36.22
-12.5%	36.47	36.66	36.86	37.06	37.26
-15.0%	37.54	37.74	37.95	38.15	38.35
-17.5%	38.68	38.89	39.10	39.31	39.52
-20.0%	39.89	40.10	40.32	40.53	40.75

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2,775	-7.5%	8.1%	8.7%	9.3%	9.9%	10.5%
2,700	-10.0%	11.1%	11.7%	12.3%	12.9%	13.5%
2,625	-12.5%	14.3%	14.9%	15.5%	16.1%	16.8%
2,550	-15.0%	17.6%	18.3%	18.9%	19.6%	20.2%
2,475	-17.5%	21.2%	21.9%	22.5%	23.2%	23.8%
2,400	-20.0%	25.0%	25.7%	26.4%	27.0%	27.7%

Soiling | Soiling economics cont'd

- Non-linear economic impact of soiling has a non-marginal effect on LCOE
- This effect is greater under low CapEx scenarios
- Or low capital cost scenarios

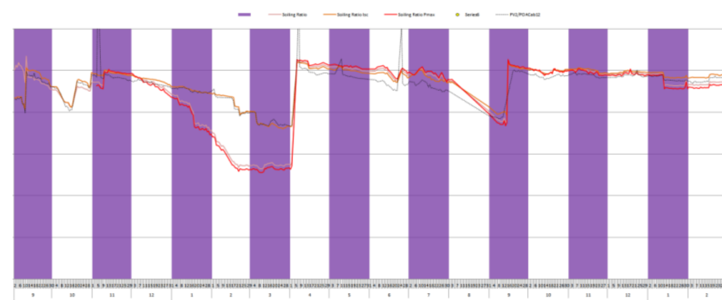
Capex	0.7	USD/Wp
Opex	10.0	USD/kWp/Year
Years	20.0	Years
Discount rate	6.0%	%/Year
Degradation	0.50%	%/Year

LCOE (USD/MWh)					
Δ Yield | Δ Opex	0%	5%	10%	15%	20%
0.0%	24.71	24.88	25.06	25.23	25.41
-2.5%	25.34	25.52	25.70	25.88	26.06
-5.0%	26.01	26.19	26.38	26.56	26.74
-7.5%	26.71	26.90	27.09	27.28	27.47
-10.0%	27.46	27.65	27.84	28.04	28.23
-12.5%	28.24	28.44	28.64	28.84	29.04
-15.0%	29.07	29.28	29.48	29.68	29.89
-17.5%	29.95	30.16	30.37	30.58	30.80
-20.0%	30.89	31.11	31.32	31.54	31.76

% Var. LCOE	USD/kWp/Year	10.0	10.5	11.0	11.5	12.0
kWh/kWp	Δ Yield | Δ Opex	0%	5%	10%	15%	20%
3,000	0.0%	0.0%	0.7%	1.4%	2.1%	2.8%
2,925	-2.5%	2.6%	3.3%	4.0%	4.7%	5.5%
2,850	-5.0%	5.3%	6.0%	6.7%	7.5%	8.2%
2,775	-7.5%	8.1%	8.9%	9.6%	10.4%	11.2%
2,700	-10.0%	11.1%	11.9%	12.7%	13.5%	14.2%
2,625	-12.5%	14.3%	15.1%	15.9%	16.7%	17.5%
2,550	-15.0%	17.6%	18.5%	19.3%	20.1%	21.0%
2,475	-17.5%	21.2%	22.1%	22.9%	23.8%	24.6%
2,400	-20.0%	25.0%	25.9%	26.8%	27.6%	28.5%

Solution | Proactive soiling management

- Offered service
  - Soiling analysis of the plant of interest
  - Optimal soiling management software for PV plants (365 days)
  - Inputs:
    - Real soiling curves(%/day per month)
    - Real expected production curve (MWh | 8760)
    - Spot pricing of electricity (or PPA) (US/MWh | 8760)
    - Costs of cleaning technologies(US/MWp | MWp/día)
  - Output
    - Optimal cleaning policy (day and type)
- Experience
  - Helping to manage the soiling of 500+ MWp of capacity in Chile
- Why using **O**ptimal **SO**iling **M**anagement **M**odel (**OSOMM**)?
  - Prices of electricity vary during the year and so do soiling conditions. Balancing the cost of cleaning and opportunity of increasing revenues through the production of electricity is a delicate exercise. With the OSOMM model you can perform that task and reach the optimal financial soiling levels for your solar portfolio



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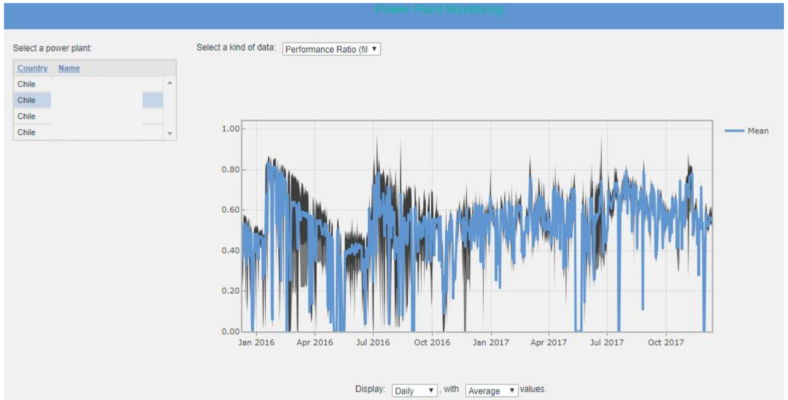
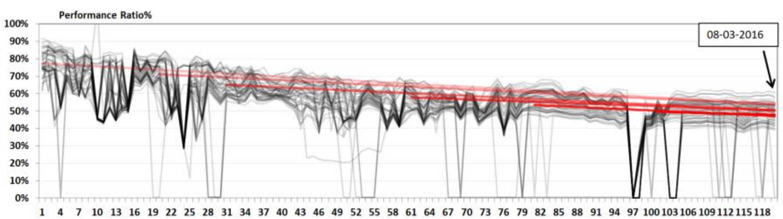
Optimal management platform (SaaS)

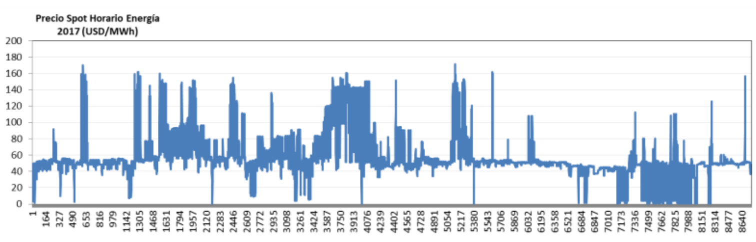
Historical Soiling | Seasonal expected soiling ranges



Historical Soiling | Short term soiling rates

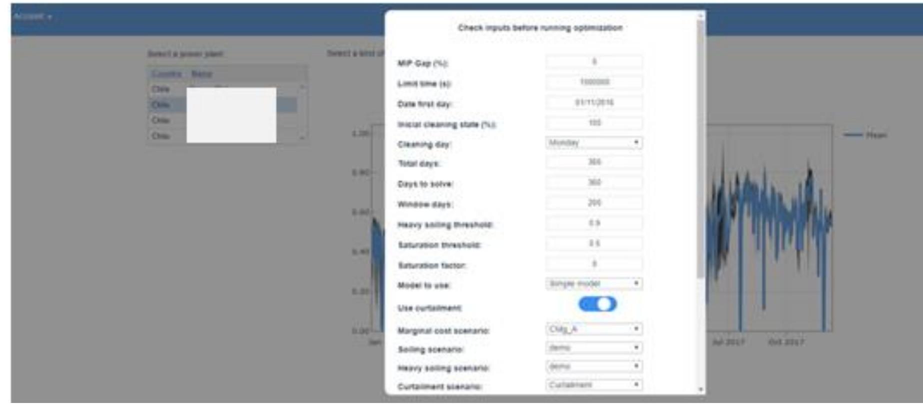


Spot price of energy

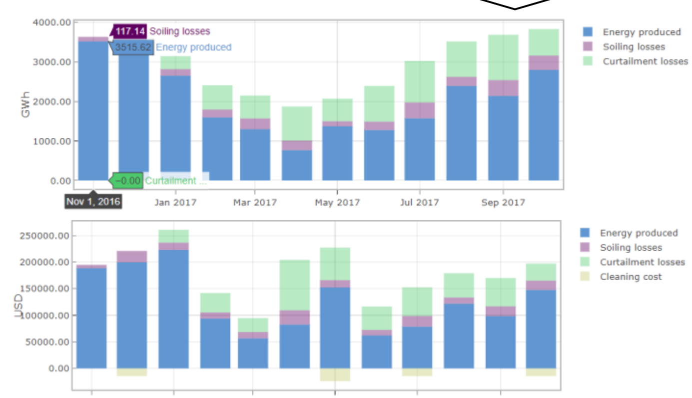


Cleaning cost and efficiencies

Management platform visualization



Optimal cleaning policy



Start cleaning	Stop cleaning	Cleaning method	Cost (USD)
2016-12-19	2017-01-04	slow	**14.400**
2017-05-01	2017-05-03	medium	
2017-07-17	2017-08-02	slow	**14.400**
2017-10-02	2017-10-18	slow	**14.400**

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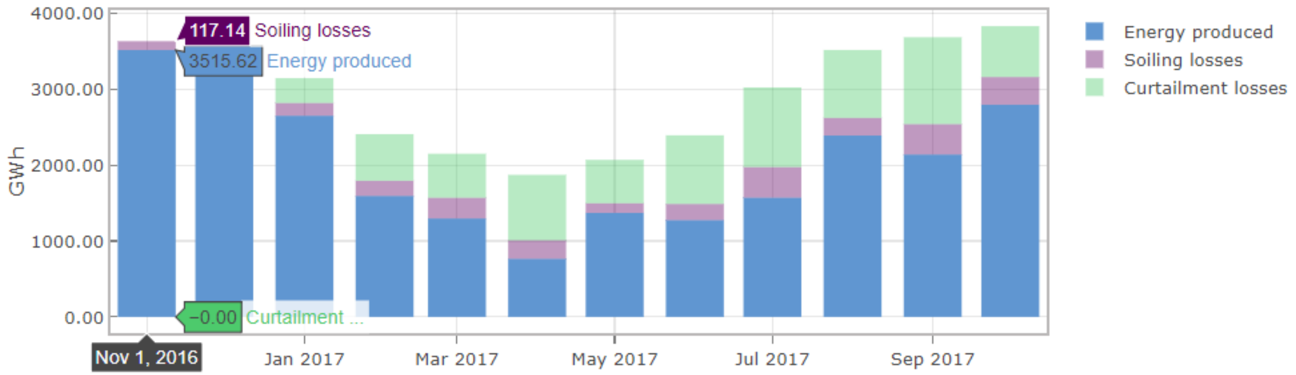
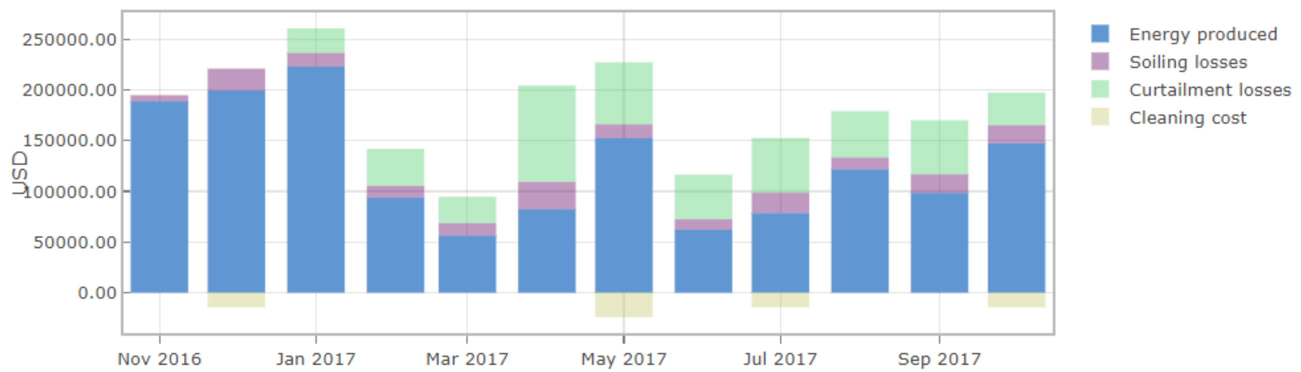
Optimal management platform (SaaS)

Optimized energy balance



Optimized revenues balance



Cleaning Schedule

Start cleaning	Stop cleaning	Cleaning method	Cost (USD)
2016-12-19	2017-01-04	slow	14.400
2017-05-01	2017-05-03	medium	
2017-07-17	2017-08-02	slow	14.400
2017-10-02	2017-10-18	slow	14.400

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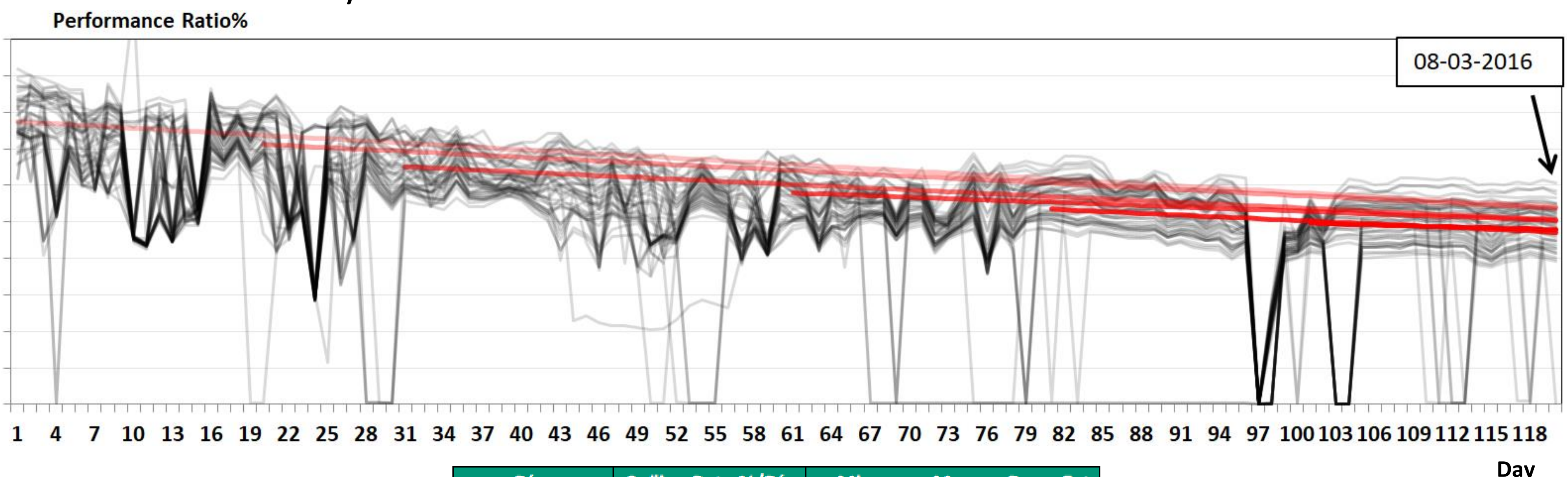
What have we learned of soiling in Chile

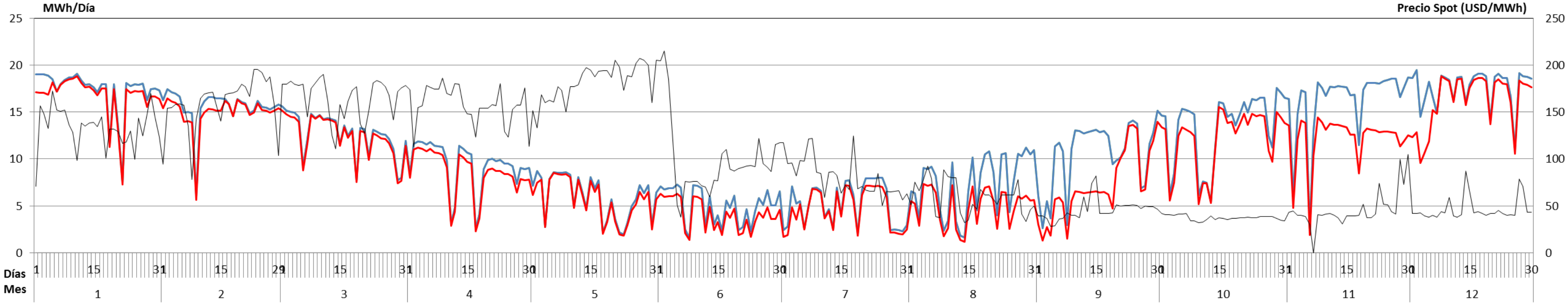
- Soiling rates range from 0.05 to 0.8 %/day in Chile
  - Soiling rate is heavily site specific
- Periodicity of soiling
  - Seasonal but no TMY for soiling -> Static cleaning policy could yield sub-optimal financial yields for solar assets

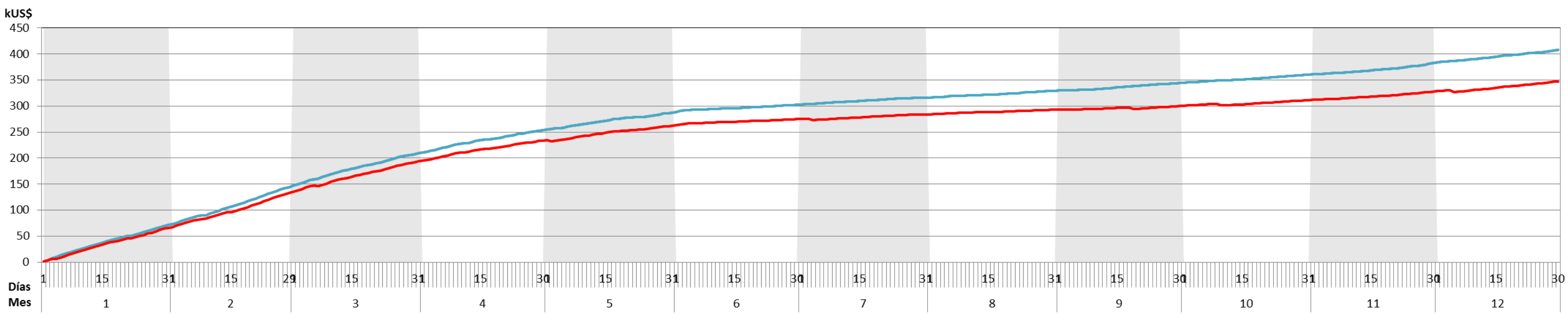


Días	Soiling Rate %/Día	Min	Max	Desv. Est.
20				
40				
60				
90				
101				
120				

Proactive and optimal management of solar field

- 1.4 MWp fixed tilt PV (1.15 DC/AC ratio with poly-Si), with hourly energy spot prices from year **2015**, yields annual **optimal energy losses of 12.4 %. Initial soiling ratio of 90 %** and **conservative cleaning costs of 1000 USD/MWp**. Deterministic optimization (perfect information).





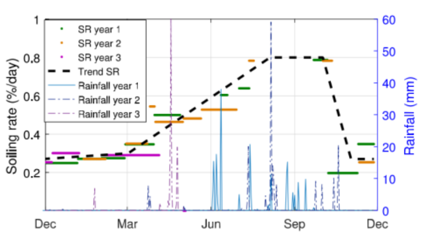


Fig. 5. Technology-averaged soiling rate for the period of study. To underline the seasonality of soiling phenomenon, the different years are superimposed. The horizontal length of each bar corresponds to the number of days without rain or cleaning events. An empirical trend is represented and rainfall for the different years is also plotted (right y-axis).

Besson et al. Fraunhofer CSET 2017.

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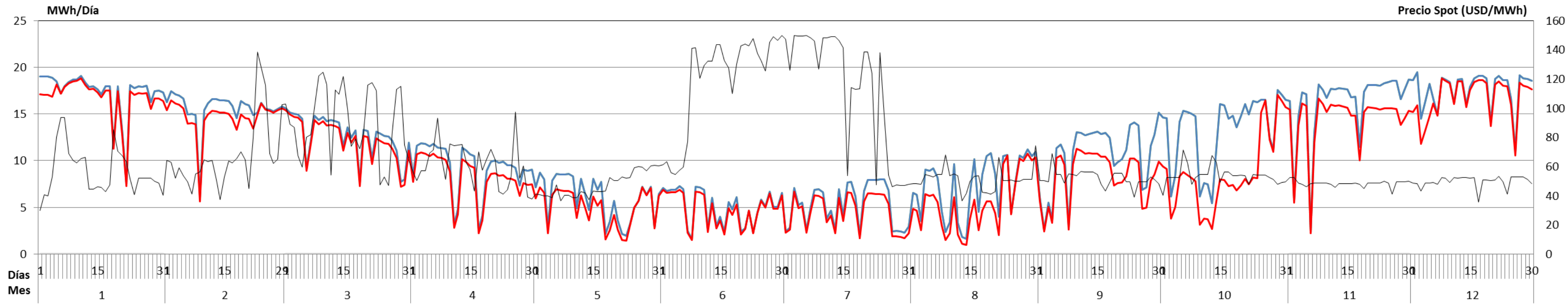

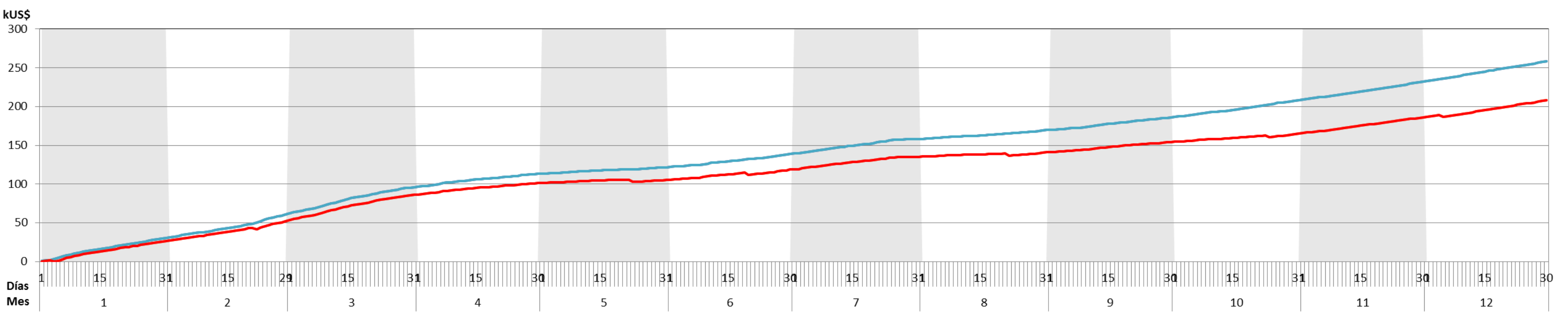

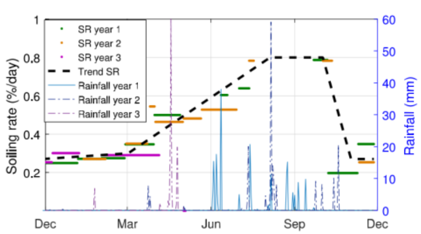

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Balance ideal [kUS$]

Balance afecto a curtailment y ensuciamiento [kUS$]

Nivel de limpieza óptimo [%]

Besson et al. Fraunhofer CSET 2017.

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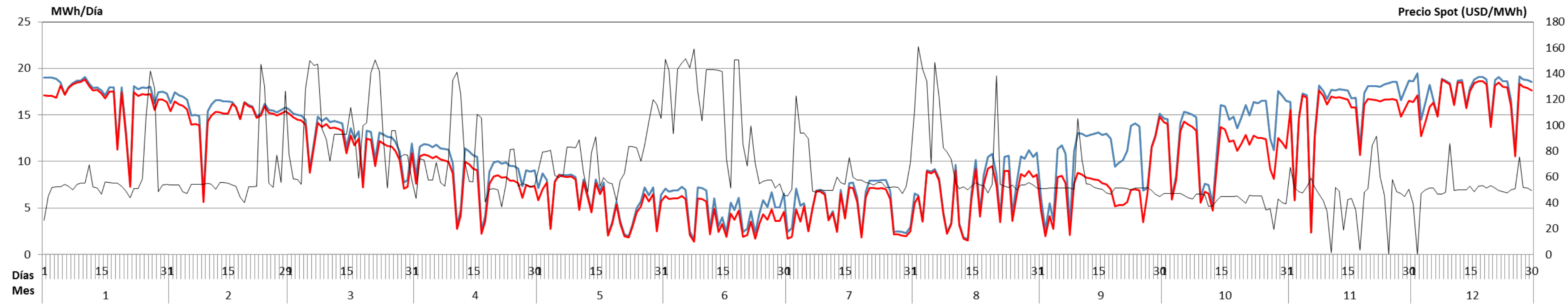
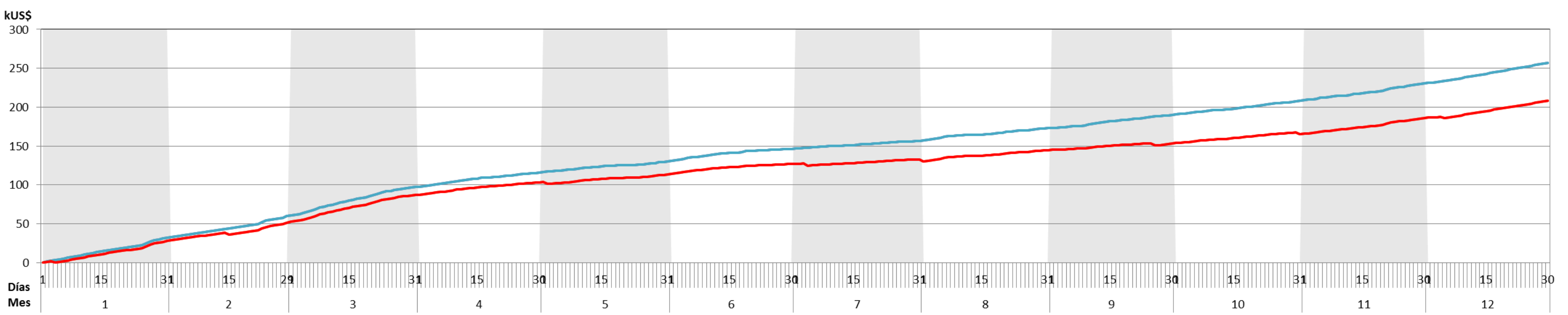
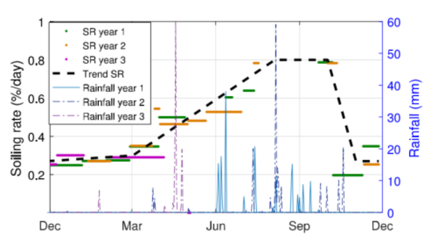
Proactive and optimal management of solar field

- 1.4 MWp fixed tilt PV (1.15 DC/AC ratio with poly-Si), with hourly energy spot prices from year **2017**, yields annual **optimal energy losses of 9.9 %. Initial soiling ratio of 90 %** and **conservative cleaning costs of 1000 USD/MWp**. <u>Deterministic optimization (perfect information).</u>







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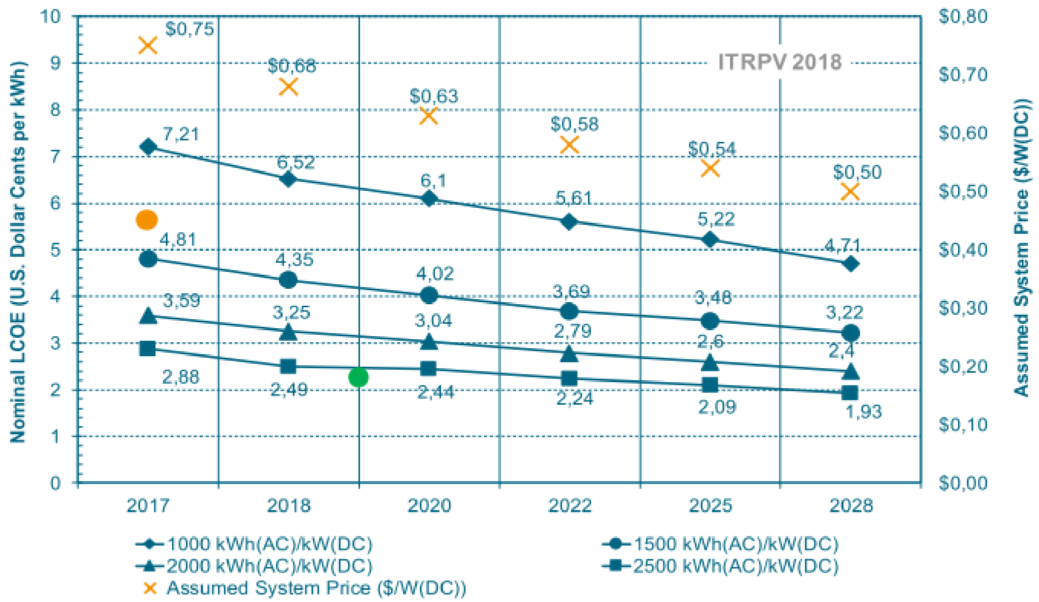
Soiling | Recalling CapEx trend



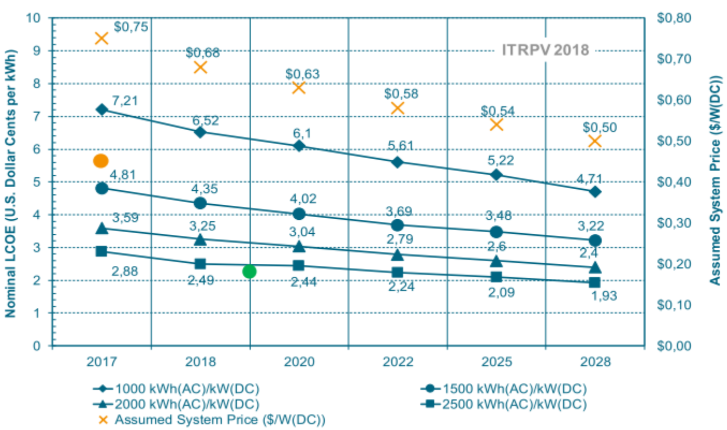
Expected PV LCOE for different specific yields. SourceITRPV March 2018.

Soiling | Recalling CapEx trend

- Extremely low CapEx scenarios are even more sensitive to soiling

Capex	0.5	USD/Wp
Opex	10.0	USD/kWp/Year
Years	20.0	Years
Discount rate	6.0%	%/Year
Degradation	0.50%	%/Year

LCOE (USD/MWh)					
Δ Yield | Δ Opex	0%	5%	10%	15%	20%
0.0%	18.64	18.82	18.99	19.17	19.34
-2.5%	19.12	19.30	19.48	19.66	19.84
-5.0%	19.63	19.81	19.99	20.17	20.36
-7.5%	20.16	20.34	20.53	20.72	20.91
-10.0%	20.72	20.91	21.10	21.30	21.49
-12.5%	21.31	21.51	21.71	21.90	22.10
-15.0%	21.93	22.14	22.34	22.55	22.75
-17.5%	22.60	22.81	23.02	23.23	23.44
-20.0%	23.31	23.52	23.74	23.96	24.18



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Key takeaways

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- Competitive landscape worldwide demands for low(er) LCOEs for PV
  - Given the relative weight of module cost on a full PV plant cost structure, large power density are the trend for further lowering LCOE
  - New module technologies arise, thus new questions have to be answered together with studies

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- On-site analysis meteo conditions and module technologies allows to decrease financial uncertainty and better technology pick

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Any Questions?

We have best solutions for your PV plant

Contact:

M.Sc. Gonzalo Ramírez-Sagner
gonzalo.ramirez@fraunhofer.cl

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Center for Solar Energy Technology

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