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THE SENSITIVITY OF LCOE TO PV TECHNOLOGY INCLUDING DEGRADATION, SEASONAL ANNEALING, SPECTRAL AND OTHER EFFECTS

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ABSTRACT: The "levelised cost of energy" (LCOE) [1] estimates the cost in ¢/kWh over the lifetime of a system including initial investments, operation and maintenance etc. Many LCOE studies seem to analyse the costs and finance well but do not tend to simulate the PV technology dependent energy generation at such a detailed level. This work models the relative "(energy yield difference)/(cost of product change)" for many sites worldwide as changes in terms of understandable values [2] such as reducing NOCT (nominal operating cell temperature) which could be lowered by a process with quantifiable additional costs such as adding cooling fins to the back of a module. It also allows the differences between PV technologies (e.g. seasonal annealing, spectral response, degradation etc.) to be modelled which was so far not included in [2]. It is shown that the soiling behaviour dominates the cost in regions with long periods without rainfall, seasonal annealing has a large effect (up to 11% in hot climates if the annealing rate is+0.4%/K) made but this depends on how the initial Pmax declaration is (i.e. whether the module is preconditioned to the outdoor metastable state and whether this is higher, similar or lower than indoor measurements). Changes in the lifetime of the PV and Inverter are shown to allow an increase in ASP (average selling price) of 2:1 for the longest lifetimes and a decrease in ASP to 44% default for the shortest lifetimes studied .(for the same default c/kWh)

Keywords : LCOE, Modelling, Energy Yield, Sensitivity, Simulation

1 INTRODUCTION

The Levelised Cost of Energy LCOE [1] is the price of electricity including all the lifetime costs including initial investment, finance costs, operations and maintenance in equation <1>

$$\mathbf{LCOE} = \frac{\sum_{y=1}^{n} \frac{\text{All costs}}{(1+r)^{y}}}{\sum_{y=1}^{n} \frac{\text{Electricity generated}}{(1+r)^{y}}} \qquad <1>$$

where r=discount rate (% inflation per year), n=lifetime of the system in y=years.

A simple program was developed [2] to estimate the relative LCOE at different sites and to use it to determine the sensitivity in ¢/kWh to the variability and uncertainty in various electrical, thermal, mechanical and cost inputs.

2 CALCULATIONS

Many of these default LCOE inputs are site and time specific but estimates were obtained and compared with published data for the default fixed values listed in table I.

Calculating the difference between the default and "better" values will give the sensitivity of energy yield individually or in combination to input changes.

Table I : Example inputs in this LCOE study and how their performance values may be improved.

LCOE input: Comment (How to improve ?)	Default	Better	Unit
Dirt: Daily soil increase (washing, cleaning ?)	0.25	0.1	%/ d
Rain: Min. day rainfall to clean (stay clean coating ?)	2	1	mm
AOI: Angular reflectance (ARC, textured glass)	85	95	%@ 75°
Blue: Eff@AM1/Eff@AM1.5 (Improve blue response)	100	105	%
Anneal: Gain after hot weather (see seasonal anneal section)	0	0.4	%/ K
NOCT: (Passive cooling fins ?)	47	37	C
Gamma: $1/P_{MAX} * dP_{MAX}/dT$ (reduces with high Voc)	- 0.35	- 0.25	%/ K
LLEC: Eff_{200}/Eff_{1000} W/m² Improve Rshunt, uniformity	95	100	%

This model calculates "relative changes in LCOE quantified versus known some physical values" e.g. the PV low light level efficiency change (LLEC), the P_{MAX} temperature coefficient gamma etc.

An hourly simulation program has been written by SRCL which calculates the power at each stage listed in Table II – the 7 stages in **bold** are those discussed further in this work.

Table II: List of different stages used by the SRCL simulation program to calculate hourly power losses.

1 Wp nominal/nameplate (LID, tolerance)
2 **Degradation** (yearly)
3 Tilted plane irradiance
4 Shading (self, near and horizon)
5 Snow cover
6 **Soiling** (daily drop, cleaning, rain washing)
7 **Angle of Incidence** (reflectance losses)
8 **Spectrum** (response where Air mass (AM) <>1.5)
9 **Seasonal annealing** (higher efficiency after hot periods)[6]
10 **Thermal losses** (NOCT, mounting, Gamma)
11 Constant dc loss
12 **Low light efficiency**
13 Module mismatch
14 I²R dc
15 Inverter turn on
16 Max power tracking Vmp
17 Inverter efficiency
18 Constant ac loss
19 Clipping (e.g. P_{PV}> P_{INV})
20 Transformer efficiency
21 Constant Transformer loss
22 I²R ac

The sensitivity of LCOE to some of these changes was previously calculated at 3 different sites at low (Munich), medium (Madrid) and high (Albuquerque) insolations but more sites have now been used shown in Table III from a commercial weather data generator.

The values of weighted ambient temperature <2> are plotted against tilted plane irradiance in figure 1 – this shows that most of the sites are on a straight band from "cool and dull" to "hot and bright" with some sites deviating due to geographical reasons such as equatorial cloud (Singapore), monsoon (Mumbai) or lower than expected temperatures due to altitude (La Paz and Albuquerque). All temperate sites (absolute|latitude| >23.45°) had tilts of 30° towards the equator, other sites had a 10° (for rain run off to minimise dirt).

$$T_{AMB.G} = \frac{\Sigma(T_{AMB} * G_I)}{\Sigma G_I} \qquad <2>$$

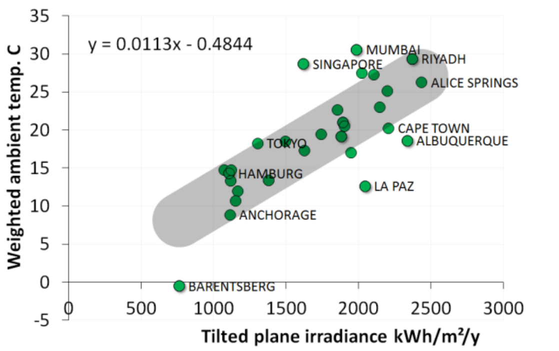

Figure 1: Weighted ambient temperature vs. tilted plane irradiance for >30 sites worldwide.

Table III: Meteorological comparison of 8 sites studied

	Latitude deg	Altitude m	Tilted plane irrad kWh/m²/y	Weighted Ambient Temperature C	Yearly Rainfall mm	Consecutive dry days #
HAMBURG	53.6	1	1107	14	758	16
SINGAPORE	1.3	30	1620	29	2177	9
MADRID	40.4	608	1880	19	409	36
SYDNEY	-33.9	0	1894	21	1206	17
MUMBAI	19.0	0	1988	31	2134	176
LA PAZ	-16.5	3620	2046	13	529	32
ALBUQUERQUE	35.1	1565	2337	19	231	40
RIYADH	24.7	701	2370	29	87	257

Some of the important loss stage inputs from table II to be modelled in this work include :

Soiling: Modelled as a decrease in current by a defined factor [dirt]/day, then to zero loss each time there is a rainfall more than [rain]/ day – figure 2 shows typical data for Madrid with the soiling worst after a few weeks dry weather in August.

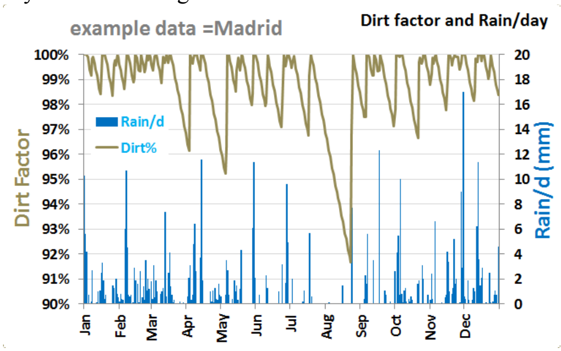

Figure 2: Example Dirt factor and rain per day in Madrid with lowest rainfall around August.

Angle of incidence: The reflectivity of a solar module increases as the incident angle goes from normal to a grazing incidence, this is modelled in figure 3 and is quantified by the current loss at 75°. Note that AR coatings [3] and textured glass will tend to improve this ratio. A tracker would result in lower angle of incidence losses as it turns to face the sun.

The ASHRAE reflectivity model by Souka and Safat is used with its b0 parameter as defined in equation <3>. (See pvpmc.org [7] for a better explanation.)

$$IAM_B = 1 - b_0 \left(\frac{1}{\cos(\theta)} - 1 \right) \qquad <3>$$

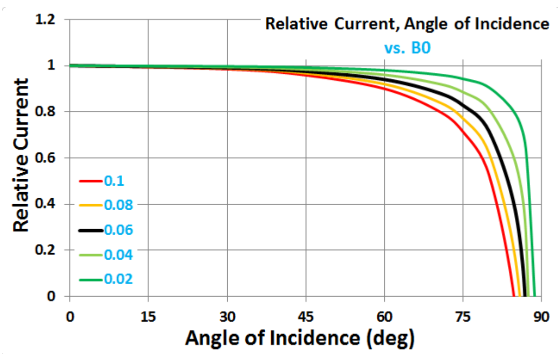

Figure 3: Relative current vs. angle of incidence and B0.

Spectral response: A blue sensitive single junction device (such as a-Si) will have a higher than expected Isc (and therefore Pmax) under bluer sky locations such as deserts. This is modelled in figure 4 by comparing a linear change in efficiency vs. Air mass with the value characterised as "$efficiency_{AM1.0}$/ $efficiency_{AM1.5}$". In future work this will be extended to model the red response too for multi junction devices.

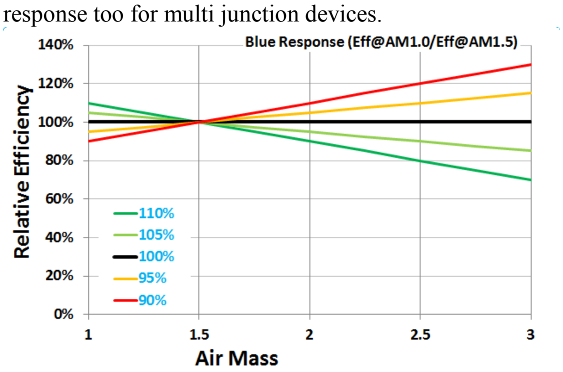

Figure 4: Relative efficiency vs. AM and Blue factor

Seasonal annealing of efficiency: Some thin film devices work at a higher efficiency after periods of high temperatures (summer/autumn) than they do after colder periods (winter). This was quantified in [6] where the authors measured arrays of amorphous Silicon modules for a year of exposure at three sites with different climates (table IV). They found that after a year allowed for stabilisation the efficiency of the arrays tended to asymptote to a figure related to the mean temperature at the site.

Table IV: Meteorological parameters for three sites Ruther [6] and a "typical PR" of a-Si modules at each site.

	Latitude +N °	Tilted Plane Insolation kWh/m²/y	Weighted Ambient Temperature C	Weighted Module Temperature C	Stabilised PR
Phoenix US	33	2373	27	52	*93%*
Florianolis BR	-28	1687	23	44	*91%*
Denver US	40	1977	15	39	*88%*

Note that the rate of rise of PR vs. weighted Tmodule (assuming an NOCT of 47C suggests that there should be a relative performance increase of around 0.45% for each 1C rise in weighted module temperature).

For technologies such as c-Si (which doesn't show thermal annealing) there is an initial decline (LID) in performance to a stabilised efficiency, CIGS may improve after outdoor exposure to a higher stabilised performance than on a flash tester, thin film silicon may oscillate around its indoor performance with better efficiency after high temperature weather (summer) and lower efficiency after low temperatures (winter).
The gains or losses of energy yield from any thermal annealing therefore depend on whether the initial flash test rating is representative of a stabilised low, medium or high efficiency.

Materials that are rated at their highest possible efficiency outdoors (such as CIGS) will therefore see a poorer energy yield with high rates of thermal anneal (as any cooler periods will have an efficiency below rated). Thin Film Silicon (which is usually rated at its intermediate efficiency value) will see an efficiency gain in the hotter summer and an efficiency loss in the colder winter, as there's higher insolation in the summer this will translate into a net energy gain – this effect will be further studied for a subsequent paper..

This is modelled related to the $T_{MOD.G}$ of the previous month in figure 5 showing the calculations for different values with extreme values of efficiency in August after a highest temperature in July (Northern hemisphere). Studies by the PV Systems group, Oerlikon Solar[4] and others have shown that seasonal annealing effects can result in variable efficiencies by ±5% over a year. This graph is for TF Si – where the averaged efficiency is at 100%, for technologies rated at their highest possible performance in summer then the efficiency the rest of the year would be lower than 100% nominal

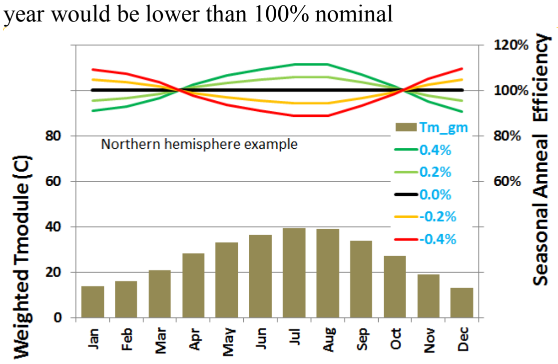

Figure 5: Seasonal thermal anneal efficiency related to the $T_{MOD.G}$ of the previous month. (In the Southern hemisphere the highest performance will be around February).

Thermal losses: This depends on calculating the module temperature which is determined by the ambient temperature, wind speed and "apparent NOCT" (related to mounting) then the efficiency due to the gamma rating of the module temperature as shown in figures 6 and 7 respectively.

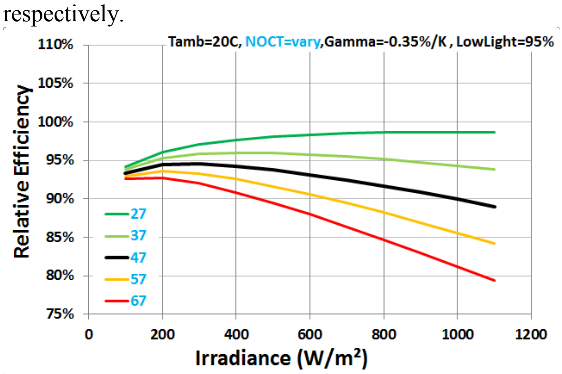

Figure 6: Relative efficiency vs. irradiance and NOCT.

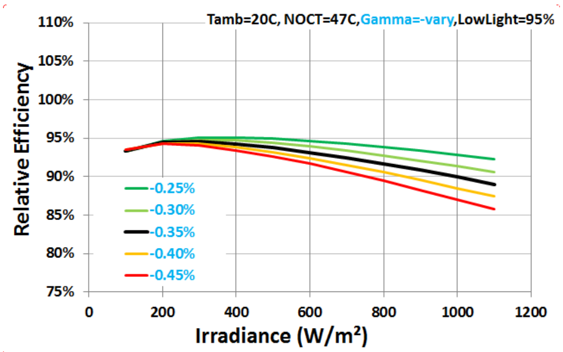

Figure 7: Relative efficiency vs. irradiance and Gamma.

Low light efficiency: The efficiency of a PV module at low light levels (usually defined as 200W/m² as in EN50380). Figure 8 shows the performance against variable Low light level coefficients (note that the high irradiance performance will fall due to module temperatures so the efficiency$_{200W/m^2}$ / efficiency$_{1000W/m^2}$ does not equal the LLEC coefficient.

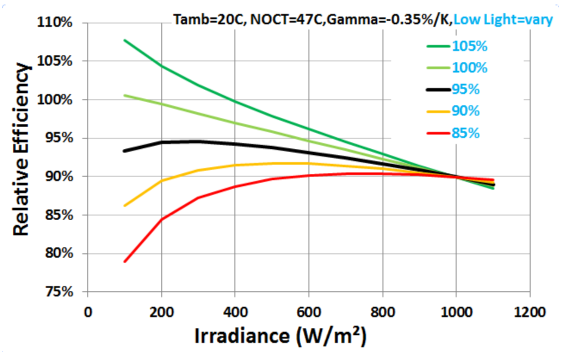

Figure 8: Relative efficiency vs. irradiance and Low light efficiency.

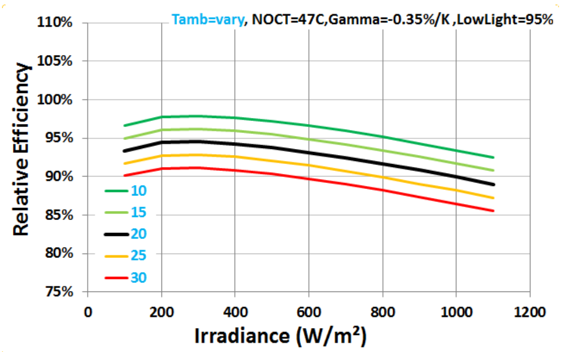

Figure 9: Relative efficiency vs. Irradiance and ambient temperature.

Improving the Low light efficiency might increase the $/Wp costs if extra process steps or more stringent binning is required (rejecting underperforming cells, modules).

The SRCL simulation program was run to calculate the energy yield gain by improving each of the parameters in Table I in turn. Table V shows some of the relative kWh improvements at eight sites.

Table V: Energy changes in %/kWh for “better vs. default” improvements for eight inputs from table I.

Unit	%/d	mm	%	%	%/K	C	%/K	%
Default	0.25	2	85	100	0	47	-0.35	95
Better	0.1	1	95	105	0.4	37	-0.25	100
Parameter	Dirt/ Day	Min Rain	Off Axis	Blue Response	Thermal Anneal	NOCT	Gamma	Low light
HAMBURG	0.4%	0.1%	0.9%	2.0%	2.4%	2.3%	0.7%	2.4%
SING'PORE	0.1%	0.1%	0.7%	-0.7%	9.3%	2.8%	2.6%	1.8%
MADRID	0.9%	0.6%	1.3%	1.1%	6.4%	3.1%	1.8%	1.4%
SYDNEY	0.3%	0.1%	0.9%	0.8%	7.2%	3.1%	2.0%	1.4%
MUMBAI	4.9%	0.1%	0.9%	0.0%	11.3%	3.3%	3.2%	1.3%
LA PAZ	1.4%	0.5%	1.3%	0.4%	4.7%	3.3%	1.3%	1.2%
ALB'QUE	1.1%	0.3%	1.2%	1.2%	7.5%	3.6%	2.1%	1.0%
RIYADH	13.3%	0.3%	1.1%	0.2%	11.4%	3.6%	3.2%	1.0%

Large gains are by improving the daily dirt in Mumbai and Riyadh, these are the regions with the longest dry periods such that a high soiling/day worsens the output considerably until it rains. This has little effect in places such as Hamburg where it rains each month.

Improving the NOCT value (for example with cooling fins or better thermal design) has a higher effect in the higher irradiance sites such as Albuquerque/Riyadh (3.6% vs. 2.3% in Hamburg) whereas improving LLEC (low light efficiency) has the biggest effect in places like Hamburg with a higher percentage of insolation at lower irradiance (2.4% vs. 1.0% at high insolation locations).

3 LCOE CALCULATIONS

The above has only looked at the sensitivity of energy yield changes to input parameters but the total energy yield is also determined by changes year by year (for degradation) and the total cost of energy depends on the absolute cost per module, array or balance of systems and then the fractional cost of the complete system.
Table VI lists the default inputs in a simple LCOE model to analyse the likely relative changes (Note that Area cost fraction will be PV efficiency dependent).

Table VI: Default inputs for cost and lifetime

	Cost Fraction	Lifetime y	Degradation %/y
Inflation			3%/y
PV	50%	25y	-0.5%/y
Inverter	10%	10y	n/a
BOS	30%	n/a	n/a
Area	10%	n/a	n/a

As an example, a process cost that adds 10% to the PV module would add 5% to the system, if this was to produce >5% more kWh/kWp then this is cost effective.
Table VII shows calculations for the relative c/kWh for the default setup at a site with 1800 kWh/m² insolation. Tracking is not yet implemented in this model.

Table VII: Relative LCOE Costs

A) Relative cost/kWh

PV lifetime y	Inverter Lifetime years: 3	5	**10**	15	20
10	2.33	1.85	1.61	1.61	1.61
15	1.83	1.49	1.32	1.16	1.16
25	1.61	1.22	1.00	0.90	0.89
35	1.47	1.11	0.87	0.80	0.74
45	1.41	1.06	0.81	0.71	0.69

B) Relative cost/kWh

PV lifetime y	PV degradation %/y: -1.00%	-0.75%	**-0.50%**	-0.25%	0.00%
10	1.64	1.62	1.61	1.59	1.57
15	1.36	1.34	1.32	1.29	1.27
25	1.05	1.03	1.00	0.97	0.95
35	0.93	0.90	0.87	0.84	0.82
45	0.88	0.84	0.81	0.78	0.74

C) Relative ASP for default kWh

PV lifetime y	PV degradation %/y: -1.00%	-0.75%	**-0.50%**	-0.25%	0.00%
10	0.44	0.45	0.45	0.46	0.47
15	0.58	0.60	0.61	0.63	0.65
25	0.91	0.95	1.00	1.05	1.11
35	1.15	1.24	1.34	1.45	1.58
45	1.32	1.45	1.61	1.81	2.04

Table VII.A gives the relative $/kWh vs. PV and inverter lifetimes, improving the lifetime of the module from 25 to 45y and the inverter from 10 to 20y reduces the c/kWh to 69%.

Table VII.B shows the LCOE sensitivity to PV degradation from -1%/y to 0%/y. At the default pv lifetime of 25y the $/kWh sensitivity is 5% for every 0.5% degradation/y change

Table VII.C looks at what the cost of the module in relative $/Wp would need to be to maintain as constant the default $/kWh. A lower value than shown would lower the $/kWh, higher would raise it. If the PV module were improved so that the lifetime was 45y and the degradation 0 then an relative price in $/Wp of less than 2.04 would improve the LCOE. However for a module of 10y lifetime and a degradation of -1%/y it would need to be a cost of less than 44% of the nominal module to give a lower LCOE (in C) a high value is good as you need to price your modules below this value)

4 DETERMINING PV COEFFICIENTS WITH THE LOSS FACTORS MODEL

A "loss factors model" (LFM) as shown in figure 10 and equation 3 [5] developed in cooperation with Oerlikon solar can be used to determine the sensitivity of the PV performance for many technologies to inputs such as low light irradiance, angle of incidence, temperature coefficients, NOCT, spectral response, seasonal annealing etc.

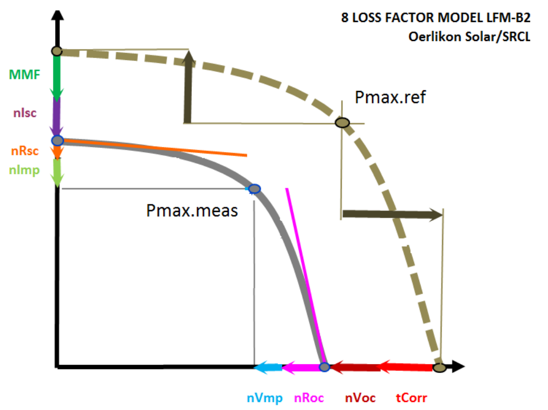

Figure 10: Loss factors model : PV Systems Group, Oerlikon Solar.

The loss factors model characterises the IV curve by calculating the PF_{DC} (= measured dc efficiency/nominal dc efficiency) as the product of 6 normalised, orthogonal parameters (nIsc, nRsc, nImp, nVmp, nRoc and nVoc) with two correction factors for module temperature (Tcorr) and Spectral module mismatch factor (mmf) as in equation <4>.

$$PF_{DC} = [MMF * (nIsc * tCorrIsc) * nRsc * nImp] * [nVmp * nRoc * (nVoc * tCorrVoc)] \quad \textbf{<4>}$$

Analysing these coefficients vs. time, irradiance, angle of incidence and other weather parameters allows each of the 9 loss stage parameters in table V to be quantified as described in table VIII.

Figure 11 plots typical temperature and spectrally corrected data from a thin film module in Arizona for the 6 independent parameters in figure 10. Smooth logarithmic fits are made to each of the 6 parameters and the values of these together with the temperature and spectral correction values and the thermal, aoi and soiling corrections determined by longer term studies are fed back into the LCOE performance models as listed in Table VIII.

It is often useful to calculate the apparent NOCT aNOCT of the module calculated as

$$aNOCT = 20 + \frac{0.8}{Gi}(Tmod - Tamb) \quad <5>$$

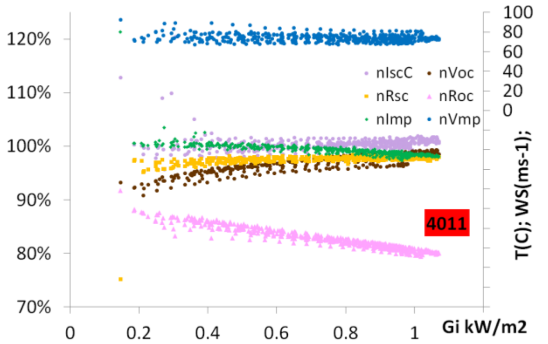

Figure 11: Typical 6 Loss factors model parameters (temperature and spectrally corrected) vs. Irradiance for a module in Arizona Sep-10 to Apr-12 (data: PV Systems group, Oerlikon Solar).

Table VIII: How to determine the Loss stage coefficients with the Loss Factors model.

Loss Stage	How to determine with LFM
Degradation	Rate of drop in PF_{DC} /year
Dirt/Day	nIsc fall with time on dry days
Minimum rain	nIsc rise after high precipitation days
Off axis	PF_{DC} vs. AOI and Beam fraction
Blue response	nIsc vs. Air Mass <AM1.5
Thermal anneal	PF_{DC} vs. $T_{MOD.G}$ previous month
NOCT	T_{MOD} interpolated around NOCT<5>
Gamma	$d(PF_{DC})/dT_{MOD}$ at high G, ~AM1.5
Low Light	PF_{DC}@200W/m²/PF_{DC}@1000W/m²

5 CONCLUSIONS

- A detailed study of hourly irradiance at >30 sites worldwide show that the most important terms in energy yield can be characterised by the tilted plane insolation, ambient temperature weighted by irradiance, rainfall and consecutive days without significant rainfall.

- A sophisticated model has been developed to characterise the energy yield improvements from improvements to 8 individual losses as in Table 1.

- As expected Low light efficiency improvements of modules benefit mostly poor insolation climates whereas Gamma improvements for modules work best for high temperature climates.

- However both of these values are smaller than the benefits in reducing daily soiling where there is a long period without significant rainfall.

- The apparent gains or losses of energy yield from any thermal annealing depend on whether the initial flash test rating is representative of a stabilised low, medium or top efficiency. If rated at a high efficiency such as with preconditioned CIGS(high Wp) then the energy yield would appear lower in terms of kWh/kWp than if at a rating similar to indoor performance such as TF-Si.

- Reduced LCOE could be achieved by a module of 45y lifetime and 0% degradation allowing to charge two times the default Average sales price (ASP) in $/Wp, however for a module with only 10y lifetime and -1%/y degradation it would need to be less than 12% of the normal ASP ($/Wp) cost of a module of 25y lifetime and -0.5% degradation per year.

6 ACKNOWLEDGEMENTS

Stefan Sellner et al, PV Systems Group Oerlikon solar. Ricardo Ruther for permission to publish his data and helpful comments. Norbert Kleber (Sensing Solutions) for help in database analysis

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