pearllaboratories
2649 E. Mulberry Unit 15
Fort Collins, CO 80524

Technical Memo: Modeling Mismatch in PV Systems

Prepared By: MPropst, AOlsson

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OBJECTIVE:

The purpose of this document is to summarize the sources of "mismatch" that affect PV system performance over time and provide a guideline to selecting values in PVSyst that most closely represent your system. Mismatch refers to the electrical losses incurred when PV modules or strings of modules operating on a single inverter MPP tracker, exhibit different I-V and P-V characteristics. There are many factors to consider that are specific to each system so a range of values is given for each component of possible mismatch. A good approximation of parallel mismatch, for example, is given by the following:

> *Mismatch Loss = (Total System Max Power)- Σ(String Max Power) ÷(Total System Max Power)*

Given that no two modules (or strings of modules) will ever be electrically identical, mismatch should never be discounted to 0%.

Sources of Mismatch:

There are many sources that can result in mismatch loss. Mismatch lowers the energy production of a system. Some sources of mismatch include uneven soiling, shading, thermal gradients across the array, cloud shading and edge effects, voltage drop in conductors, variable cell degradation, and manufacturing parametric variability. Each of these may have significant impact on the energy production of a particular PV system. The default value for mismatch loss is -1% in current versions of PVSyst. This value is low when accounting for all possible sources of mismatch. Mismatch is one of the available knobs a system modeler has at his disposal. PVSyst uses this parameter as a system de-rate, or a one-time haircut in energy yield. However, mismatch loss is actually the sum of all the sources listed below:

- Manufacturer Module Mismatch
- Thermal Gradients across an array
- Uneven soiling
- Cloud shading
- Voltage drop across conductors
- Variable degradation rates

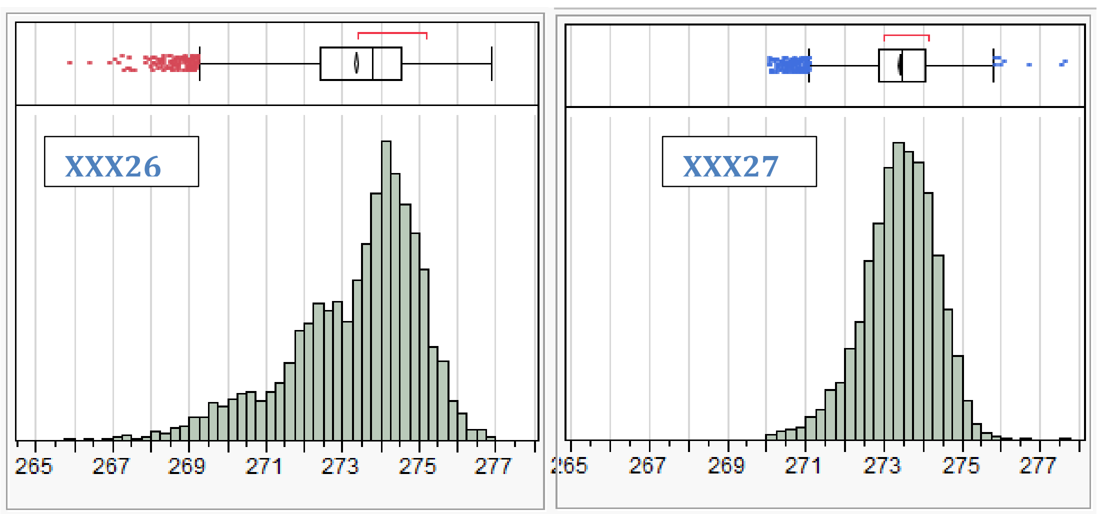
We will define these types of mismatch and provide considerations for determining the electrical loss associated with each.

Manufacturers Module Mismatch-

Module Mismatch as recommended by the module manufacturer represents the manufacturing variation inherent in the process only. This value is typically based on the impact of the distribution of module parameters randomly distributed in a system. Most manufacturers have dialed in process controls and report “module mismatch” to be between -0.2% to -1.0%.

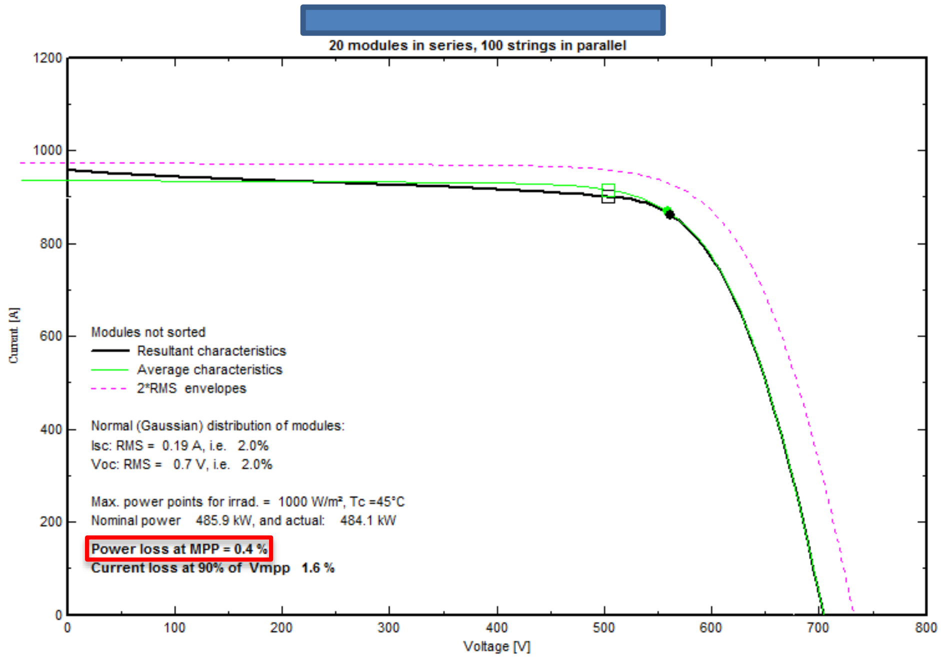
A summary of the electrical parameters as well as the distributions are given below for a c-Si module manufacturer:

MODEL	SAMPLE SIZE	Pmax	Data Sheet
XXX265	5393 modules	273.4W +/- 1.6W	265W -0W/+13W
XXX270	8430 modules	273.4W +/- 0.9W	270W -0W/+13.5W



1: Flash test distribution of electrical data from a Si Module manufacturer.

The manufacturing tolerances and normal distribution of parameters results in some mismatch losses. Using the above example for manufacturing flash test data and the PVSyst mismatch tool, a calculation for a system of 20 modules per string and 100 strings in parallel results in mismatch losses of -0.4%. The input parameters used to calculate this composite curve are the manufacturing variation in Isc and Voc. For this simulation a root-mean-square value for Isc and Voc of +/- 2% was used.



2 Composite curve result from the PVSyst Mismatch tool calculation using the manufacturer's flash data from figure 1.

The calculation above illustrates just one component of mismatch. In this example, the manufacturer, even with tight process controls, still contributes -0.4% to total mismatch loss.

Based on our experience with manufacturing and installations, it is common for modules to come off of the manufacturing line and into boxes sequentially. They are then installed directly from boxes in a similar order. Sequential modules are most similar to one and other and are likely to be neighbors in an installation. Modules many days or months apart in the manufacturing process have more inherent mismatch in electrical characteristics as well as degradation rates.

Thermal Gradients-

Thermal Gradients across an array will result in a non-uniformity between string voltages. Temperature coefficients are typically -0.45%/C for power and -0.35%/C for voltage in silicon technologies. Depending on environmental and design factors for each system, the edge of array modules can be as much as 20C cooler than the modules in the center of the array (source Trina Solar, “Module Mismatch in Commercial Arrays”, 2012). Given the temperature coefficients, this results in a 7% voltage difference between edge strings and center strings. Measured thermal data across several ground mounted systems is shown below. This data shows a 3C to 10C temperature difference from extreme edge of array modules to center of array modules or 1% to 3.5% difference in voltage.

NW		1	2	3	4	5	6	7	8	9	10	11	12		1	2	3	4	5	6	7	8	9	10	11	12		1	2	3	4	5	6	7	8	9	10	11	12	NE
	1	45	46	48	48	51	51	52	53	52	51	50	49	1	49	50	50	51	52	54	55	54	53	52	51	50	1	49	50	50	51	52	53	53	52	51	51	49	48	
	2	46	47	48	49	51	52	52	53	51	50	49	49	2	49	50	52	53	54	54	55	55	54	53	51	50	2	49	49	50	51	51	52	53	52	52	50	49	48	
SW	3	45	45	46	48	49	50	50	51	50	49	48	48	3	49	49	50	50	51	51	52	53	52	50	50	49	3	49	49	49	50	51	52	52	51	50	48	48	47	SE

3 3 high, portrait installation in TX, string temperature delta of 5C, module delta of 7C

NW		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SW	1	50	50	51	50	51	52	52	53	54	54	53	54	55	55	56	55	56	57

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
56	57	57	57	56	56	56	57	56	55	56	57	57	56	56	55	55	56

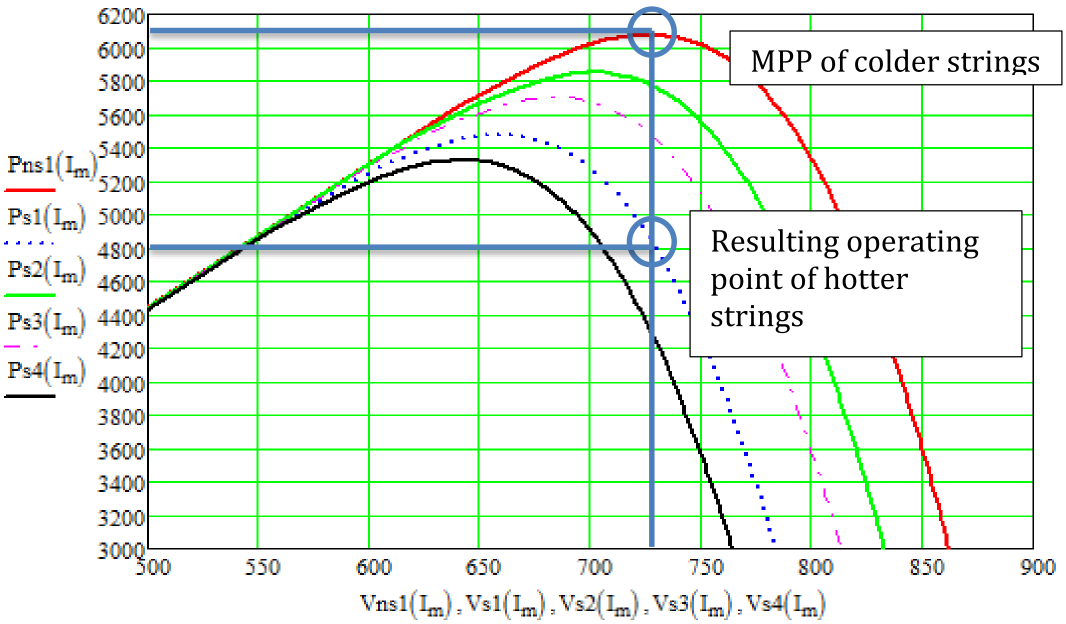
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	NE
55	55	56	56	54	54	54	55	54	54	54	53	53	53	52	50	51	50	SE

4 1 high, portrait installation in Germany, 3 strings along one row, string temperature delta of 3C, module delta of 10C

NW		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	SW
NE	1	46	46	48	49	49	50	50	50	49	50	50	50	51	51	50	1	54	55	57	58	58	58	59	59	58	57	57	58	56	57	56	SE

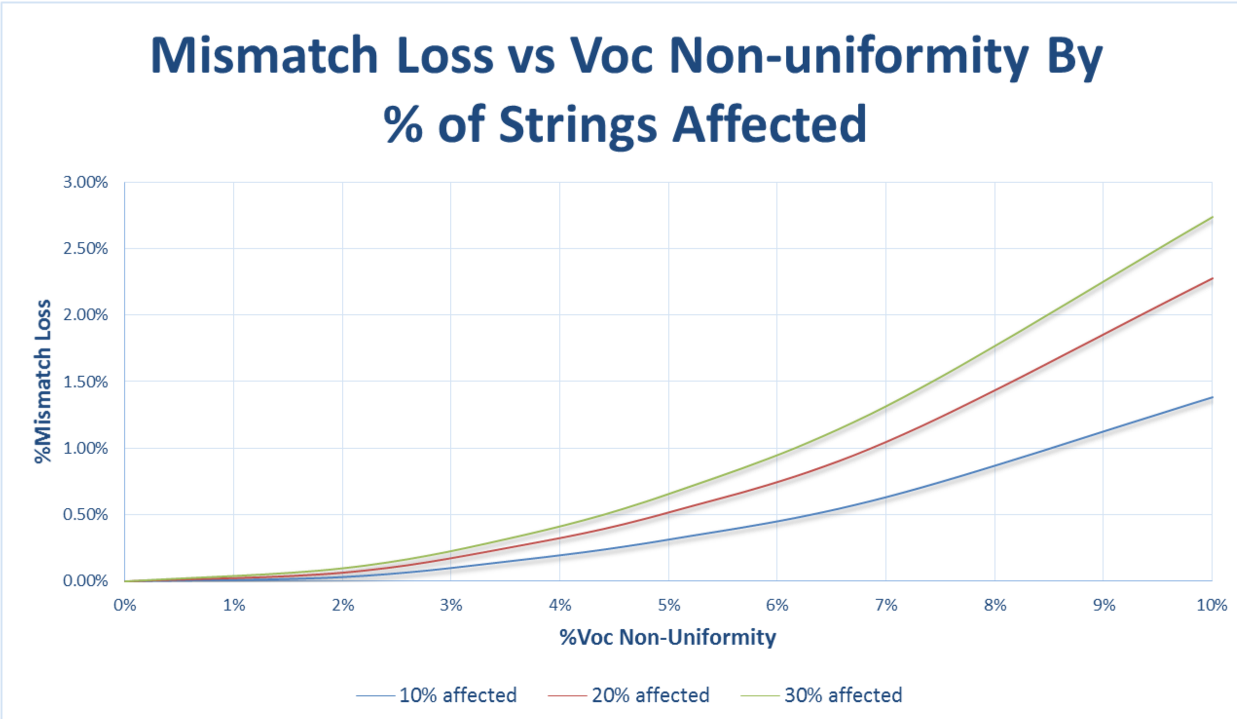
5 Rooftop, 5deg tilt installation in AZ, 10C string delta, 13C module delta

The amount of mismatch loss these gradients cause depends on the percentage of the array that is affected. As more and more strings are operating at the higher temperature, the loss due to mismatch goes down because the max power point is dominated by the strings operating at a lower voltage (the hotter ones). The P-V curves for strings in an array are shown below. The solid blue line shows the MPP of the total undisturbed array and where that point lies on the strings which are 20C hotter given by the dashed blue curve (center of flat roof top for example). In this case, the MPP of the system will force the hottest strings to operate at a point which is 21% below the power output of the undisturbed strings.



6 P-V curves for strings operating at various temperatures

Calculating the amount of mismatch loss expected for varying Voc non-uniformity is shown below. The various lines in the graph represent a different percentage of the array that is affected by the lower voltage (or hotter temperature).



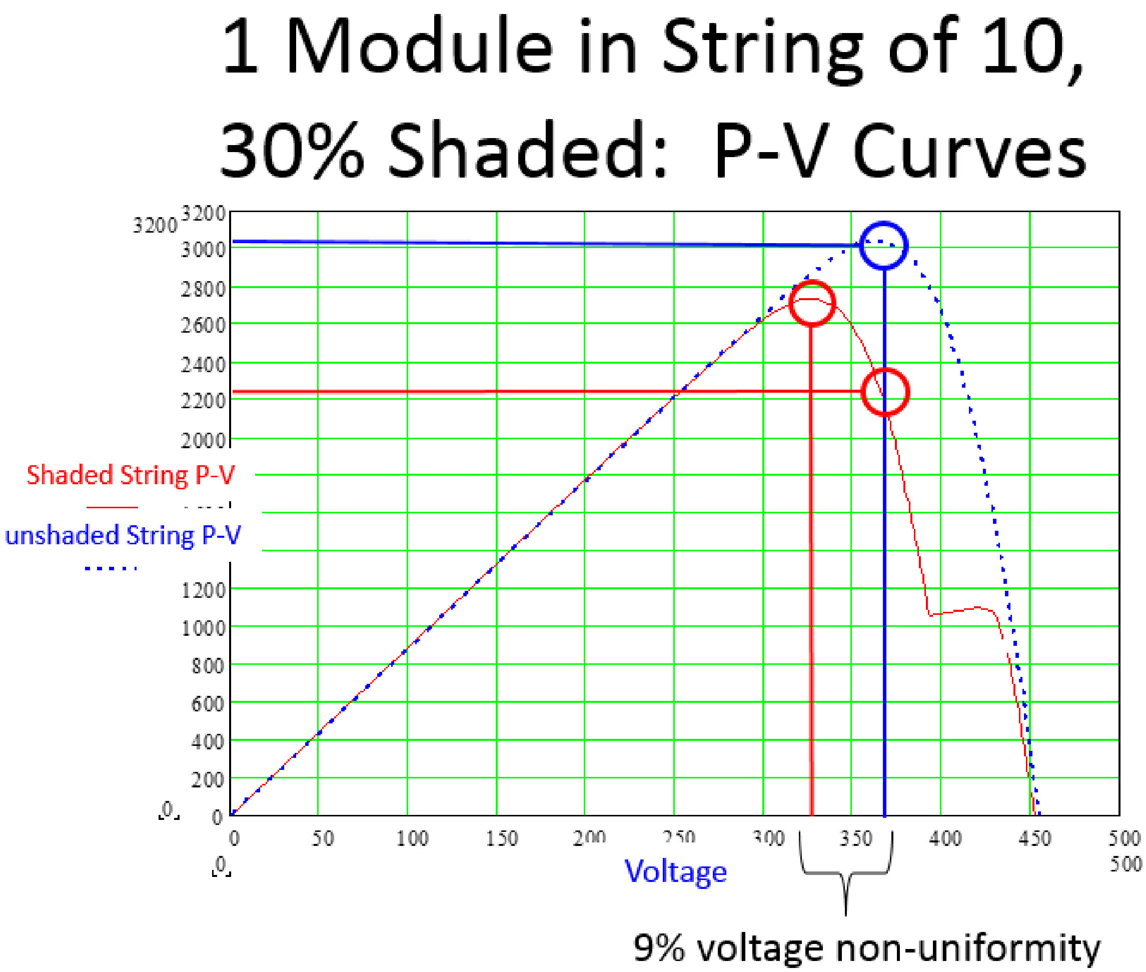
7 %Mismatch Loss due to non-uniformity in voltage by varying amounts of the array affected.

Voltage non-uniformity, by itself, does not have a significant negative impact on mismatch loss until you reach >5% non-uniformity. Analyzing the mismatch loss due to the thermal gradient caused voltage non-uniformity shown for the system in Figure 3 is explained below. For a 10C thermal gradient and 30% of your array affected (as is the case with figure 5), an additional loss of -0.4% should be added to total mismatch losses. Analyzing the thermal gradient across multiple installations in multiple climates, it should be understood that there is always at least a small thermal gradient. This thermal gradient has been measured as small as 3C and as large as 20C. What percentage of the array is affected is key to determining the impact the voltage non-uniformity will have on the system mismatch losses.

Uneven Soiling-

Uneven soiling occurs when modules/strings at edges of the array see a higher amount of dust and debris than those embedded in the center of the array. This is usually due to service roads or aisles where operation and maintenance work can occur, near inverters and sheds. Ground cover can make this more or less prevalent and "uneven". For example, a site that requires significant amounts of mowing and weed removal may see similar amounts of dust kick up uniformly across the array. Systems that are bound on one side with a service road will see dust kick up primarily on that edge of the system.

The affect this has on the energy yield of a system is similar to shading one or two modules in a string. The resulting P-V curves for the partially shaded (soiled) string is below:



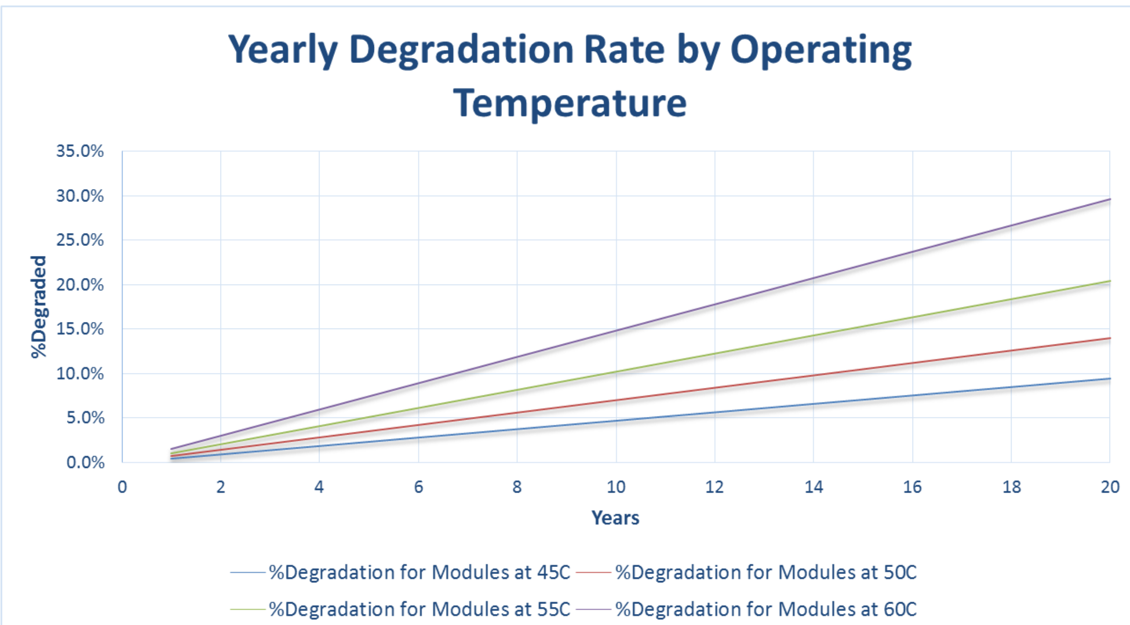
8 **P-V curve for partially shaded string resulting in 9% voltage non-uniformity**

The simulation result above shows how the partially shaded or soiled string will behave when forced to the same operating point as unshaded strings. A consideration for the percentage of strings affected must be made to accurately estimate the additional mismatch losses that might be expected. Using the 10-module string results above, we see a 9% voltage non-uniformity. Based on our previous analysis shown in Figure 7, a 9% voltage non-uniformity affecting 10% of your strings results in an additional 1.2% mismatch loss.

Variable Degradation Rates-

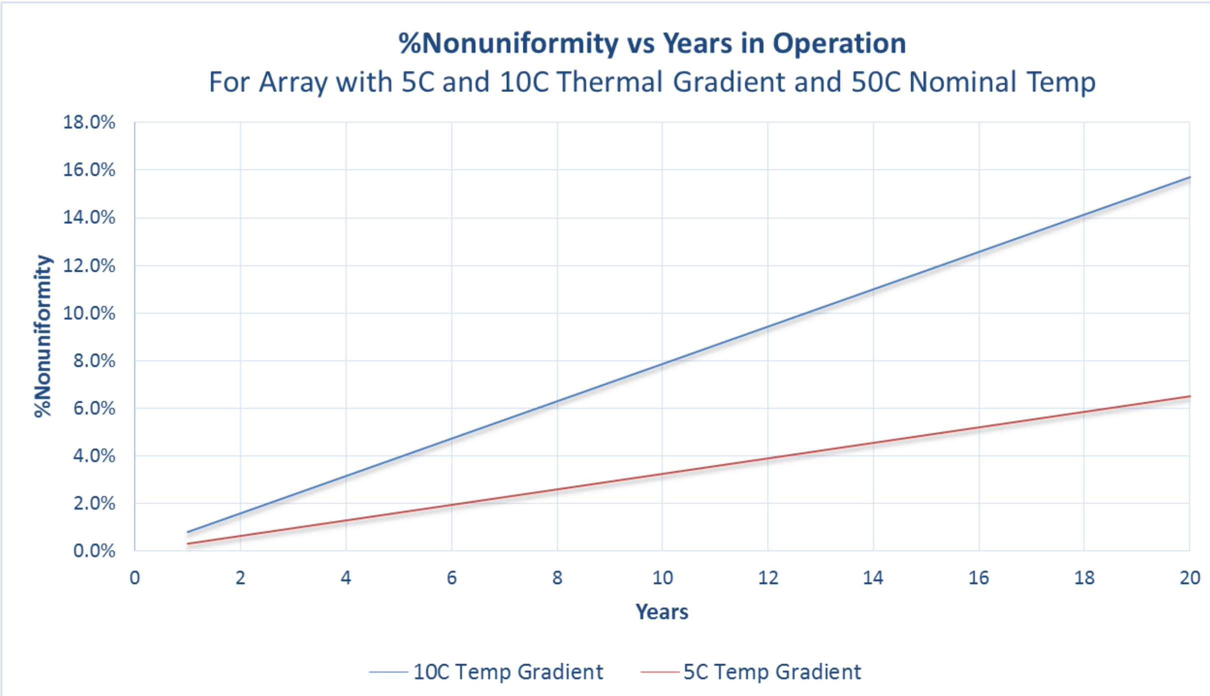
Degradation rates may also vary across an array. Typical degradation rates are reported as -0.5% to -1% per year. Since that degradation could be in either current (Isc and Imp) and/or voltage (Voc and Vmp), then the mismatch losses due to voltage non-uniformity will increase over time. Using the commonly reported acceleration factor of 0.7eV and a baseline operating temperature of 45C, we can compute that for every 10C increase in operating temperature, the degradation rate roughly doubles causing the voltage non-uniformity due to the thermal gradient effect mentioned above to be compounded over time.

The degradation rates for modules operating at 45C, 50C, 55C, 60C using an acceleration factor of 0.7eV are shown below. It is not unlikely, given the thermal gradient data collected on operational systems presented in figures 3, 4, and 5, that modules/strings will be degrading at a rate associated with both the 45C (blue) line as well as the 55C (green) line within the same system.



9 % degraded per year for varying operating temperatures

To properly account for the energy loss due to mismatch over the life of a system, a consideration for the thermal gradient as well as the variable degradation rate needs to be taken. The impact of variable degradation rates due to measured thermal gradients on voltage non-uniformity are shown below. Using a 10C thermal gradient, the year 1 Voltage non-uniformity is only 0.8% which results in a negligible mismatch loss of -0.003%. However, this voltage non-uniformity increases to 8% by year 10 which results in a mismatch loss of -1.8%.



10 %Non-uniformity vs years for 10C and 5C thermal gradient

Variable degradation rates can also be inherent to the modules, although this should be quite small. The degradation rates discussed here are only those due to the compounding thermal gradients.

Voltage Drop in Conductors-

The ohmic losses in a system are usually quite small. These losses are handled in PVSyst under "Ohmic Losses" and default to conductor sizing which results in minimal losses. However, there could be an additional mismatch loss due to unequal or variable voltage drop in conductors. Very long runs for strings residing furthest from the inverter, for example, will have a larger voltage drop which results in a voltage non-uniformity string to string. While this is quite small and as shown previously has little impact on mismatch loss until the non-uniformity reaches >5%, this could be added to other forms of non-uniformity and result in a value that will impact overall losses and subsequent energy yield.

CONCLUSION:

There are many components that make up a system's total losses due to mismatch. Since this is the primary de-rate available for modeling in PVSyst, it is important to understand all that it encompasses. Module manufacturers will recommend a value that represents the module mismatch as delivered from the manufacturer. It does not include any of the system level parameters that impact mismatch. Each system is different due to layout, components, climate, ground cover, etc. Multiple sources of mismatch will add together at the system level to equal total mismatch loss. This paper discusses a few most likely sources of the non-uniformities and how they contribute to mismatch losses. It is very unlikely that none of these exist in a system. Manufacturer's Module Mismatch, Thermal Gradients, and Variable degradation rates all exist at some level in every system. Some of these losses are compounded over time. Be mindful of the lifetime of the system and how to best represent total energy yield expected. Possible sources of mismatch and ranges of mismatch loss are given below:

TYPE	DEFINITION	Mismatch Loss	Considerations
Mfg Module Mismatch	Variation in electrical parameters due to process variation	0.2% to 1%	Defined by the manufacturer, the distribution in parametric values from the manufacturing process.
Thermal Gradients	Difference in temperature across modules within an array	0% to 1.5%	Size and layout of the array, tilt, racking, ground cover, climate. This will likely not degrade or improve over time.
Uneven Soiling	Non-uniform soiling of module surfaces	0% to 2%	Size and layout of the array, tilt, climate, ground cover. Modules and strings near edge of array or service "roads" will soil more quickly.
Cloud Shading	Power spikes (increases and decreases) due to clouds passing over an array	0% to 0.1%	Very hard to predict, overall impact integrated across a year is small, these are short duration spikes.
Voltage Drop in Conductors	Voltage drop along the home run cabling to the inverters	0% to 0.5%	Size and layout of the array, adequately sized cabling and/or matched cable lengths wherever possible
Variable Degradation	Cells and modules may degrade at different rates	0% to 2.5%	Compounded by thermal gradients, rates roughly double for every 10C increase in operating temperature. This value will increase over time.
	TOTAL:	**0.2% to 8.1%**	**Huge range in possible values, likely increases over time**