MODULE FAILURE IDENTIFICATION BY ANALYSIS OF THE LIGHT AND DARK I-V CHARACTERISTICS

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Outline

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II. Methodology

III. Experimental results
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- Degradation of the electrical circuit (increased series-resistance only)
- Mechanical degradation of the solar cells (mixed losses)
- Potential-induced degradation (shunting and recombination losses)

IV. Summary and conclusions

Introduction

- Failure identification in PV modules requires specialized hardware and diagnostic process depending on the type of failure.

- We aim to develop an I-V based diagnostic method for identifying degradation modes such as:
  1. **Optical losses**: shading, soiling, encapsulation discoloration, delamination.
  2. **Degradation of the external circuit of the PV module**: degraded cell-interconnect ribbons, wiring, junction box and connectors.
  3. **Mechanical degradation of the solar cells**: cell cracks and fractures.
  4. **Potential-induced degradation** (PID) of the solar cells.

- Combines the strengths of both light I-V and dark I-V characterization.

- Machine-analysis friendly. The method can be used as a laboratory diagnostic tool for PV modules.

- It has potential for field applications (I-V tracers, module integrated converters) for long-term reliability monitoring of PV modules.

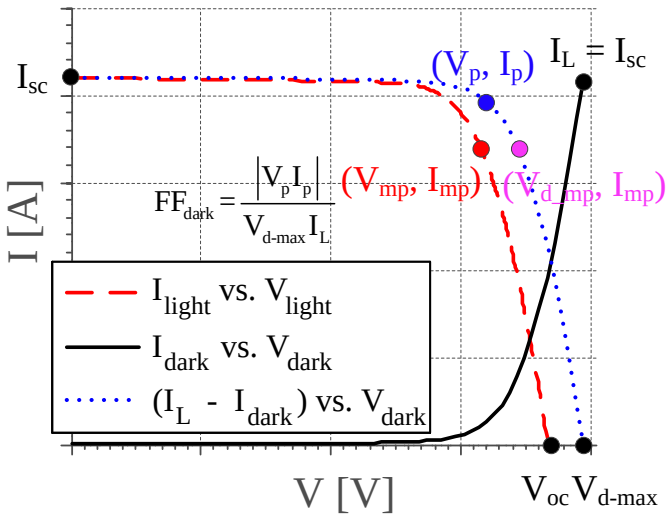
Methodology – Identifying optical and electrical losses

1. Measure the light (LIV) and dark I-V (DIV) characteristics of the PV module before and after the degradation

2. Calculate LIV parameters that are sensitive to **both optical and electrical losses** (*FF*, I_{sc}, V_{oc})

3. Calculate DIV parameters that are sensitive **only to electrical losses** (FF_{dark}, $V_{d\text{-}max}$, V_p)

4. Calculate the $R_{s\text{-}ld}$ parameter which is able to identify increased **module series-resistance losses**.



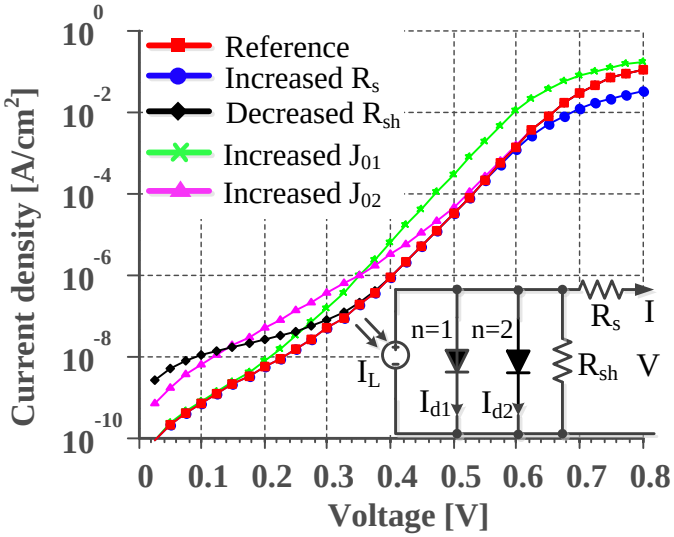
$$R_{s-ld} = \left.\frac{V_{d-mp} - V_{mp}}{I_{mp}}\right|_{|I_{dark}| = I_{sc} - I_{mp}}$$

Methodology – Identifying shunting and recombination losses

Usual approach:

- Curve fit the I-V characteristic to a solar cell model (ex. Two-diode model)
- Analyse the model parameters to identify the defects/failures
- **Pros:**
  - Model parameters have a well-known correlation with physical properties of the PV device
- **Cons:**
  - The model identification/curve fitting is resource intensive, and usually must be assisted
  - The model may fail in case of PV modules with inhomogeneous distributed failures/cell mismatch (example PID)

Simulated DIVs of a c-Si solar cell with different degradation modes



Methodology – Identifying shunting and recombination losses

Proposed method:

4. Calculate the $J_{Loss}(V)$ curve from the DIV

$$\ln(J) = \frac{q}{nkT}V + \ln(J_0)$$

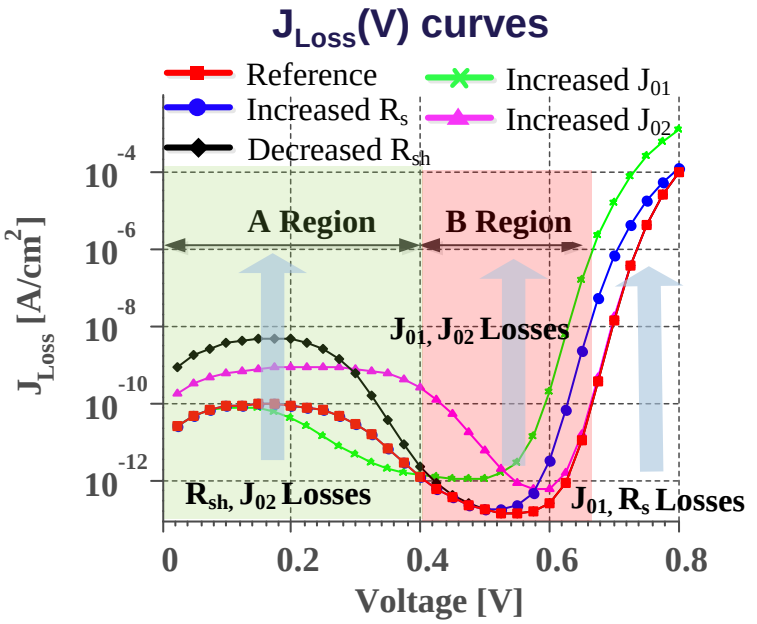
$$J_{Loss}(V_k) = J_0(V_k) = \exp\left[\frac{\ln(J_{k-1})V_k - \ln(J_k)V_{k-1}}{V_k - V_{k-1}}\right]$$

5. Calculate the $J_{Loss\text{-}A}$ (R_{sh} + J_{02}) and $J_{Loss\text{-}B}$ (J_{01} + J_{02}) to identify **shunting** and **recombination losses**.

$$J_{Loss-A} = \max\left[J_{Loss}(V)\right], \; for \; 0.1 < V < 0.4 - \text{Region A}$$

$$J_{Loss-B} = \min\left[J_{Loss}(V)\right], \; for \; 0.4 < V < 0.66 - \text{Region B}$$

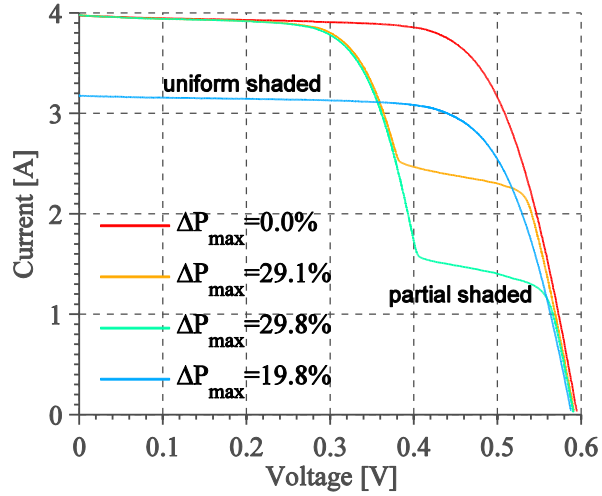
6. Analyse the LIV and DIV parameters to **identify the dominant degradation modes**:
   - Degradation of the electrical circuit: increased series-resistance
   - PID: shunting + recombination losses
   - Mechanically degraded cells: shunting + recombination losses + increased series-resistance



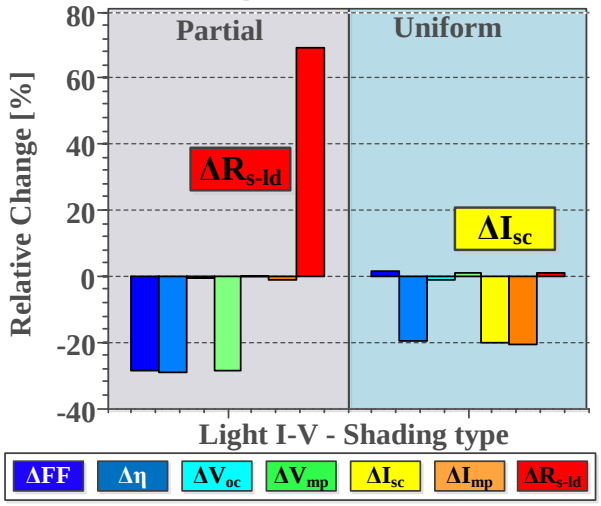
Experimental results – Optical losses

- PV modules are affected by **partial** and **uniform** type shading **differently**
- **Optical losses/shading** only affects the **LIV curve and parameters, not the DIV**
- This is **most relevant for field applications**, and **can help optimize the maintenance actions**, for e.g.: clean modules, remove shading vs. replace module, wiring, etc.

LIV curves affected by shading



LIV parameters

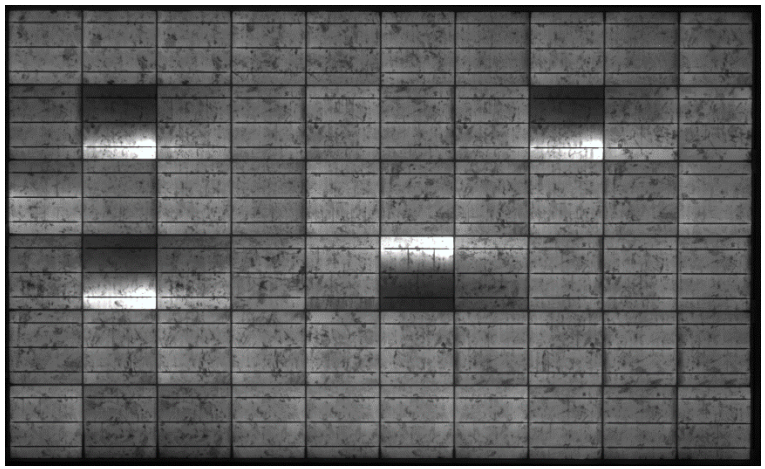


Experimental results – Degradation of the electrical circuit

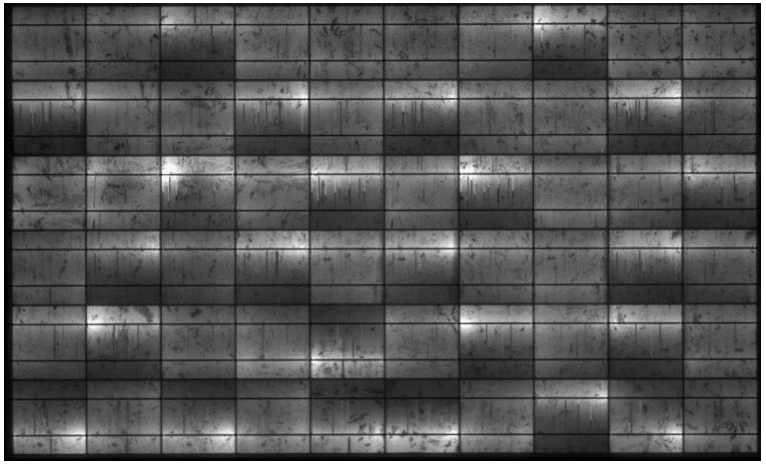
- PV modules with **open-circuited cell interconnects**
- Four standard 60 cell multi-crystalline PV modules were tested (R1 to R4) with increasing degradation levels

Module	R1	R2	R3	R4
ΔP_{max} [%]	-1.7	-3.1	-5.5	-6.4
ΔFF[%]	-1.84	-2.74	-5.18	-6.1

Module R1

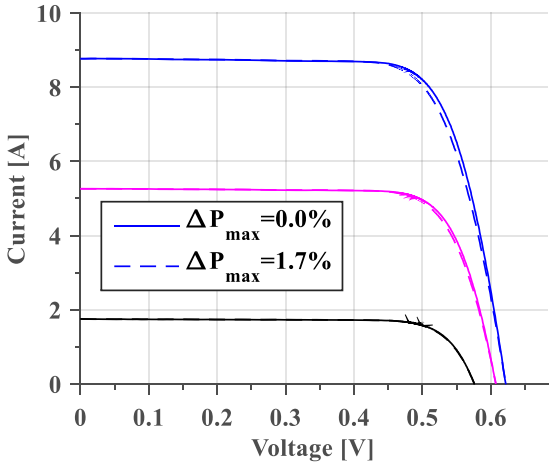


Module R4



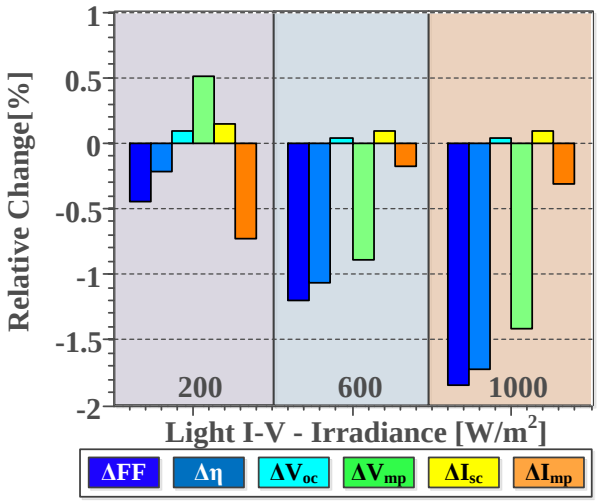
Experimental results – Degradation of the electrical circuit

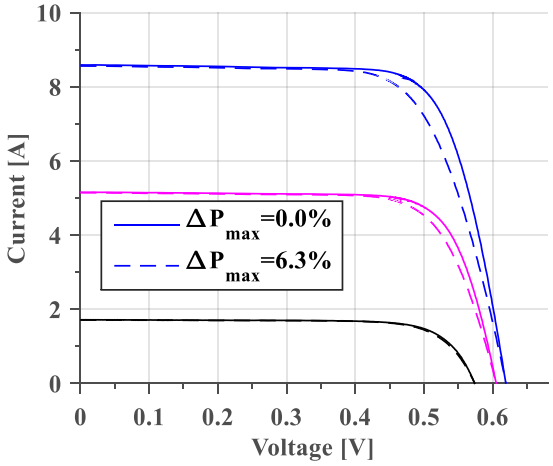
LIV curves



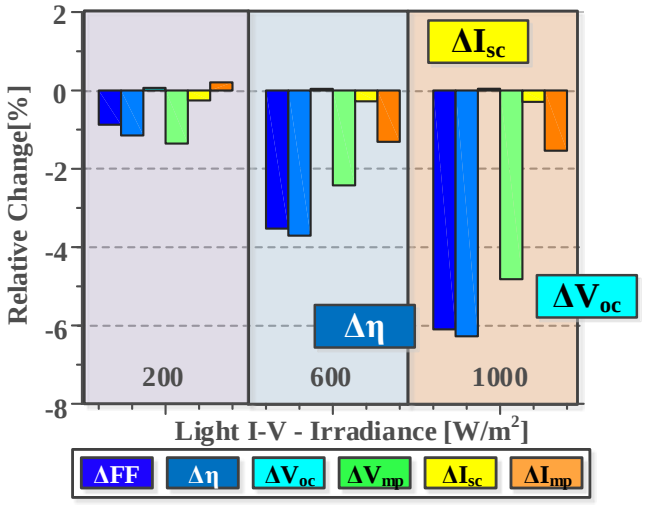
Module R1

LIV Parameters





Module R4



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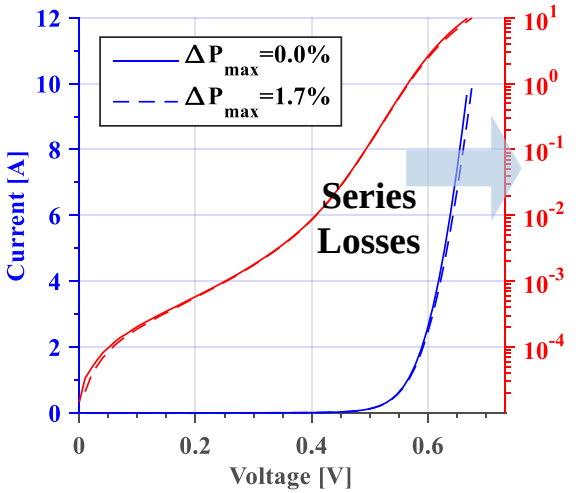
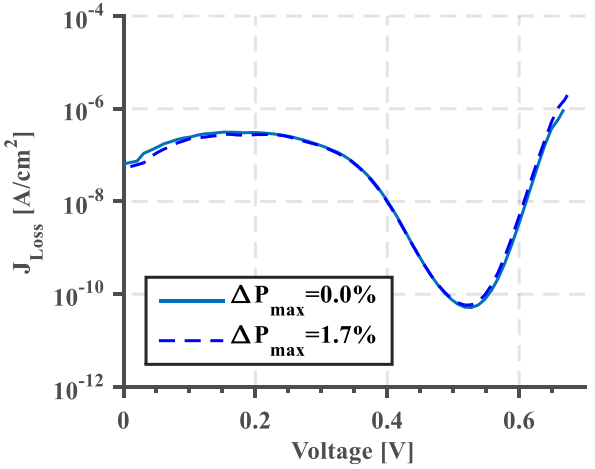
Experimental results – Degradation of the electrical circuit

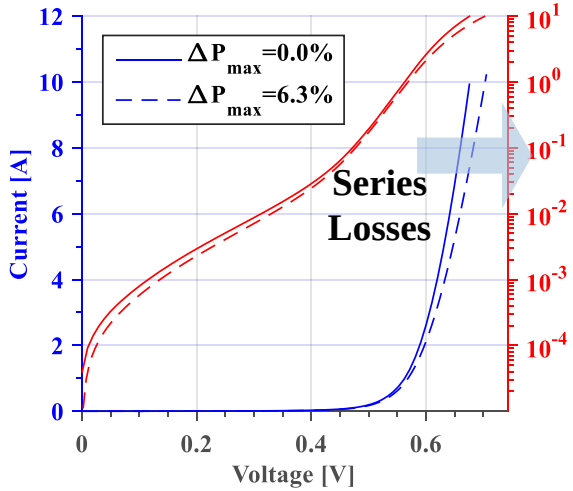
DIV curves



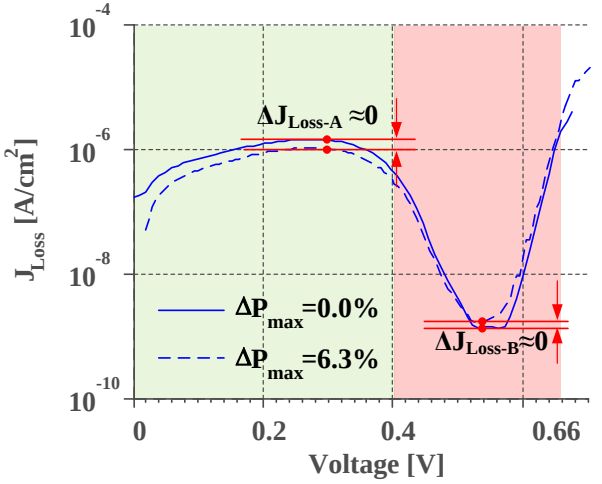
Module R1

J_{Loss}(V) curves





Module R4



Experimental results – Degradation of the electrical circuit

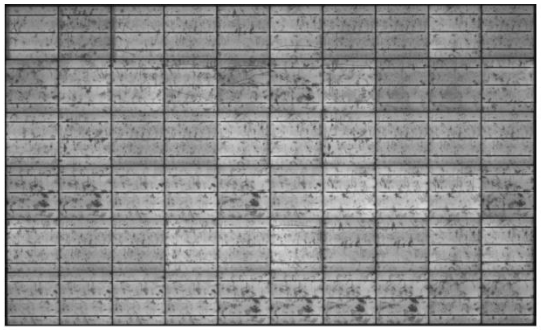
- **Only the series resistance** of the modules **increases.**
- $R_{s\text{-}Id}$ and $V_{d\text{-}max}$ can be used to identify this degradation mode.
- Changes in $J_{Loss\text{-}A}$ and $J_{Loss\text{-}B}$ **are negligible** compared to the other degradation modes.
- High ilumination efficiency decreases most.

DIV parameters

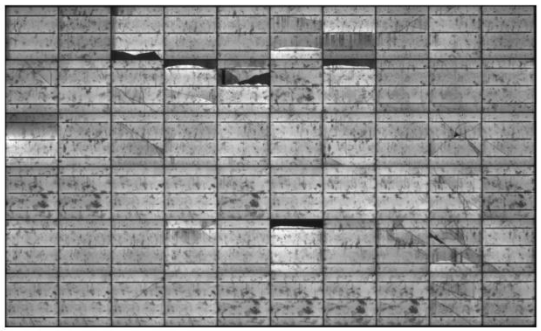
Module	R1	R2	R3	R4
ΔP_{max} [%]	-1.7	-3.1	-5.5	-6.3
ΔFF_{dark} [%]	-0.84	-1.06	-1.95	-2.77
$\Delta V_{d\text{-}max}$ [%]	**1.04**	**1.76**	**2.88**	**3.84**
ΔV_{p} [%]	0.02	-0.14	1.24	1.18
$\Delta R_{s\text{-}Id}$ [%]	**22.4**	**38.2**	**65.8**	**76.2**
$\Delta J_{Loss\text{-}B}$ [%]	12.9	10.76	32.1	25.9
$\Delta J_{Loss\text{-}A}$ [%]	-10.4	-30	-11.8	-27.8

Experimental results – Mechanical degradation of the solar cells

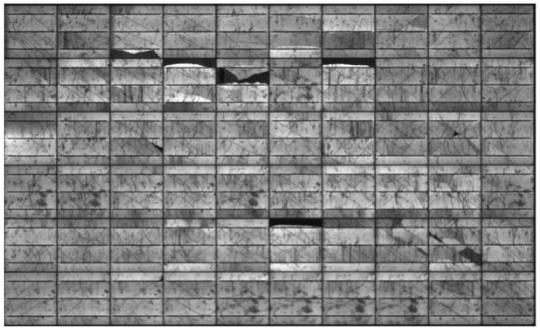
- A standard 60 cell multi-crystalline PV module was stressed by mechanical loading and humidity freeze cycles.
- Three different levels of degradation were measured.



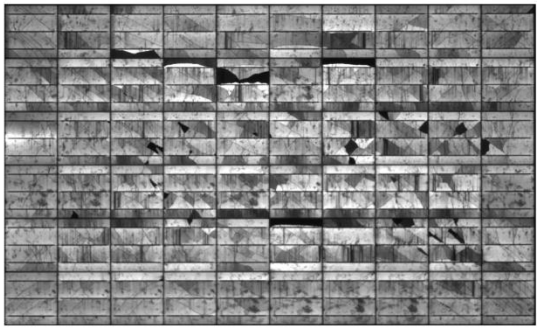
a) Initial



b) ΔP_{max}=-2.8%

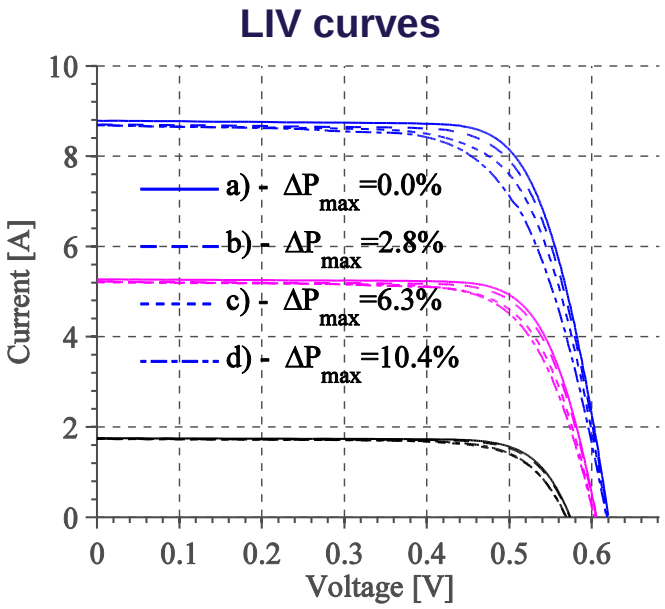


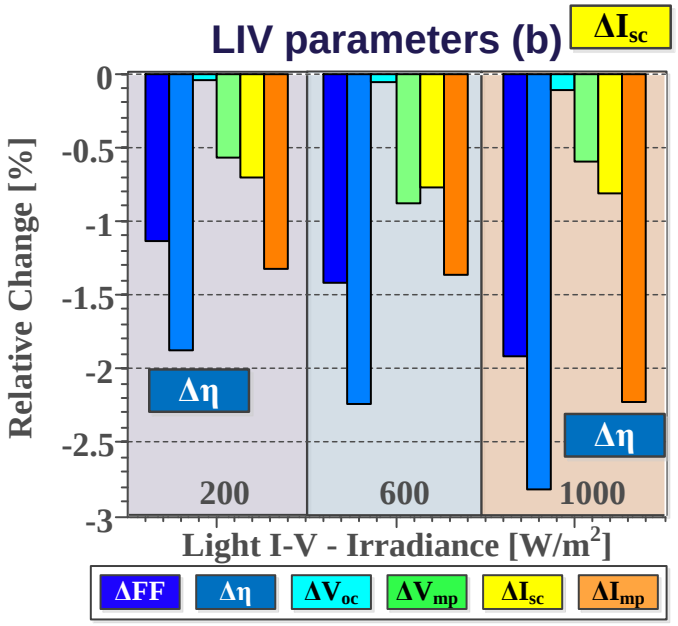
c) ΔP_{max}=-6.3%



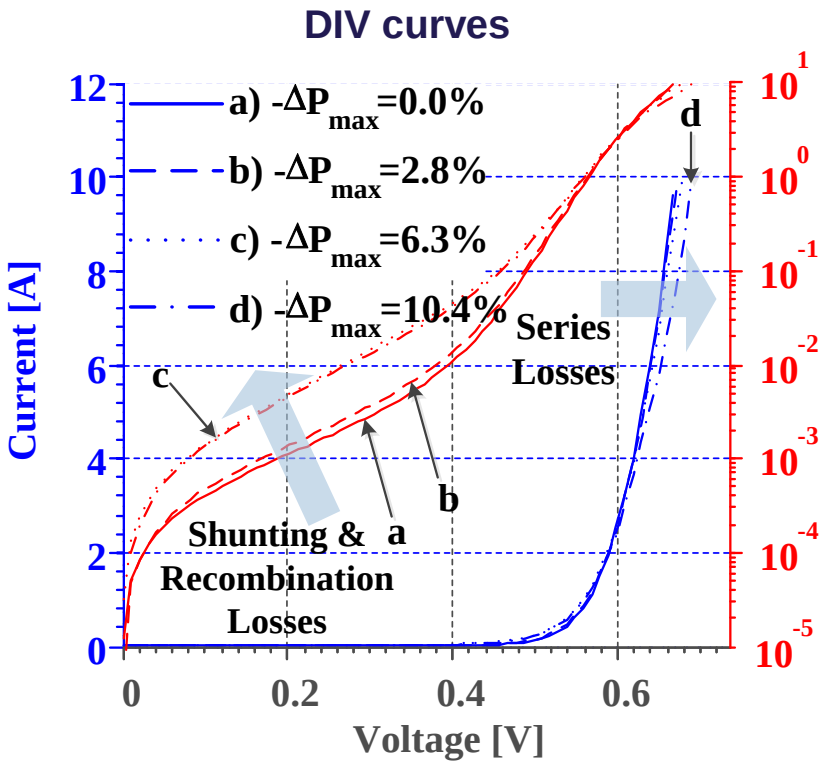
d) ΔP_{max}=-10.4%

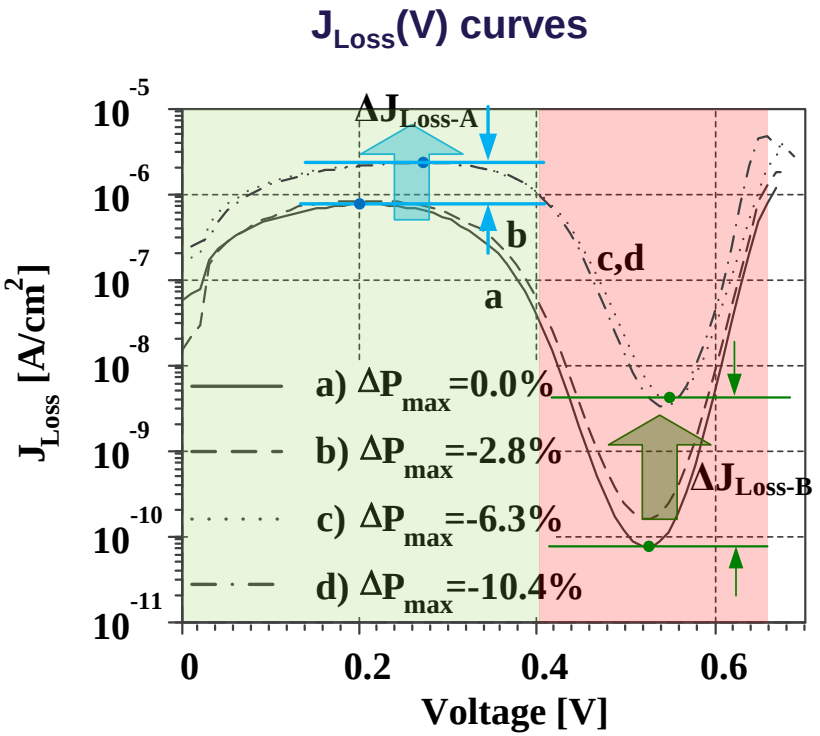
Experimental results – Mechanical degradation of the solar cells





Experimental results – Mechanical degradation of the solar cells





Experimental results – Mechanical degradation of the solar cells

- Module experiences **mixed degradation modes**: series resistance increase, shunting, and recombination losses.
- I_{sc}, $R_{s\text{-}ld}$, $J_{Loss\text{-}A}$, $J_{Loss\text{-}B}$ can be used to identify this degradation mode.
- Both one-sun and low-light efficiency decrease.

DIV parameters

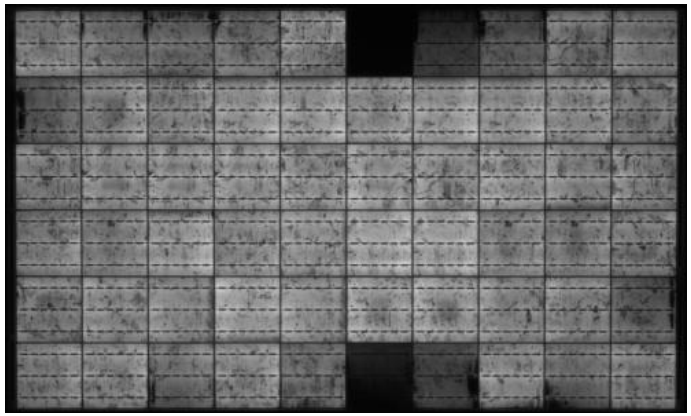
Load. Seg.	b	c	d
ΔP_{max} [%]	-2.8	-6.3	-10.4
ΔFF_{dark} [%]	-0.8	-2.7	-4.3
$\Delta V_{d\text{-}max}$ [%]	0.3	1	2.9
ΔV_{p} [%]	-1.8	-1.8	-1.8
$\Delta R_{s\text{-}ld}$ [%]	**17.8**	**37.9**	**87.6**
$\Delta J_{Loss\text{-}B}$ [%]	**117.5**	**5141**	**4421**
$\Delta J_{Loss\text{-}A}$ [%]	10.3	207	201

Experimental results – Potential-induced degradation

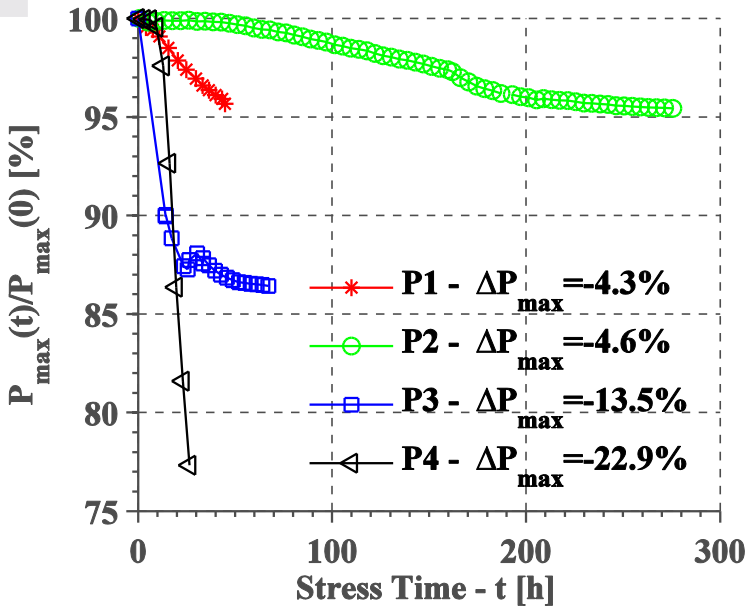
- PID was reproduced by means of **damp-heat stress testing (60 °C/85 %RH)** with **applied system voltage bias (-1000 V).**
- Four standard 60 cell multi-crystalline PV modules (P1 to P4) were tested with sustained different levels of degradation

Module	P1	P2	P3	P4
ΔP_{max} [%]	-4.3	-4.6	-13.5	-22.9
ΔFF[%]	-3.82	-4.04	-12.25	-18.2
ΔV_{oc} [%]	-0.36	-0.34	-1.24	-6.05
ΔI_{sc} [%]	-0.17	-0.24	-0.17	0.4

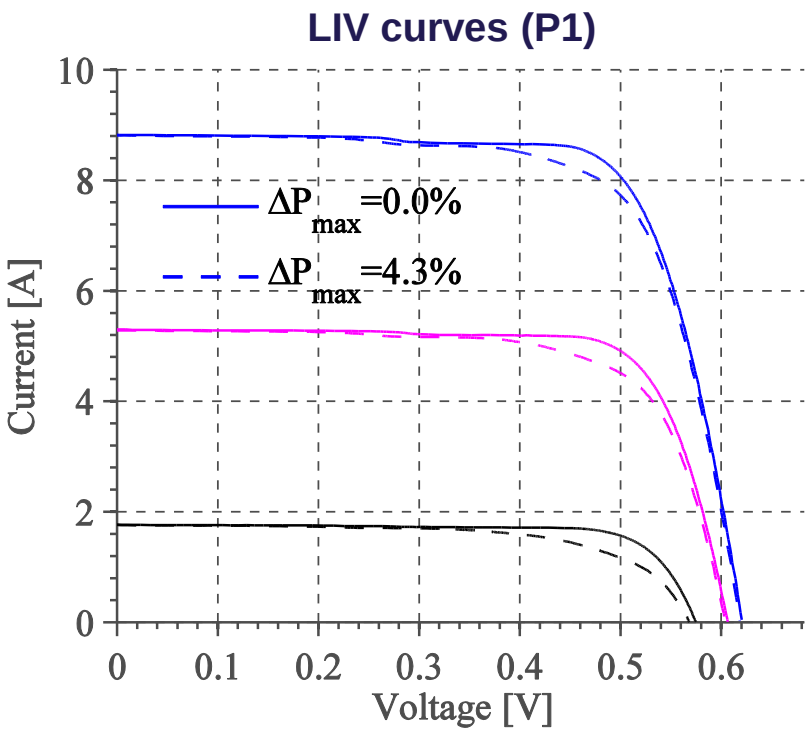
EL image of module P3

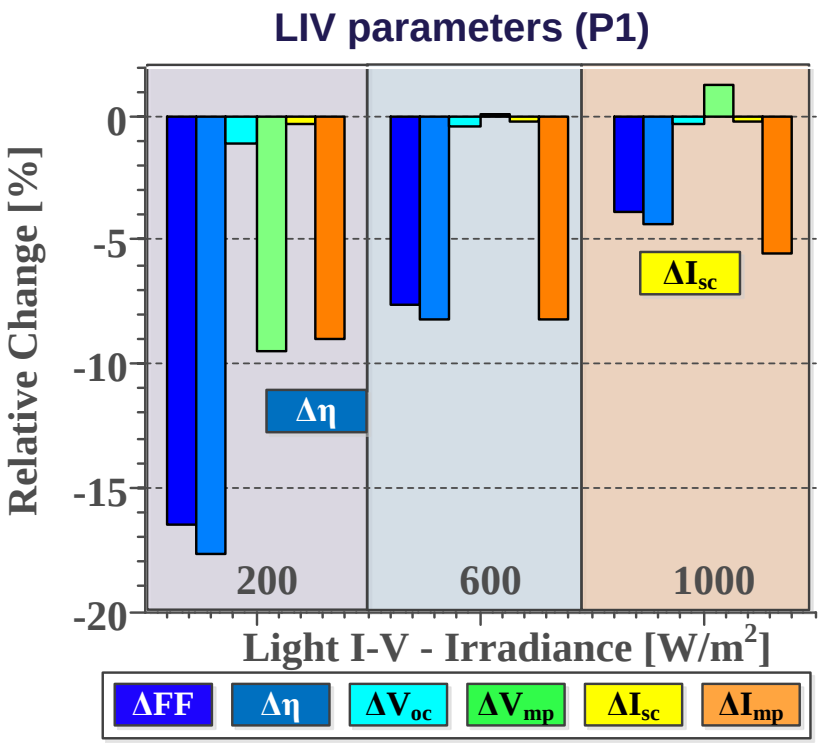


STC P_{max} degradation



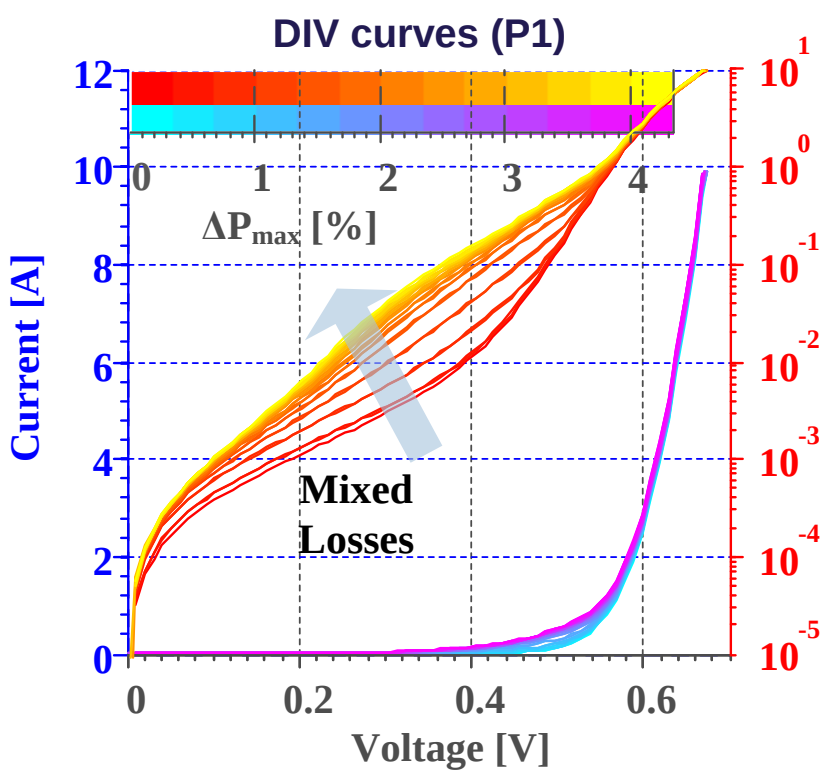
Experimental results – Potential-induced degradation

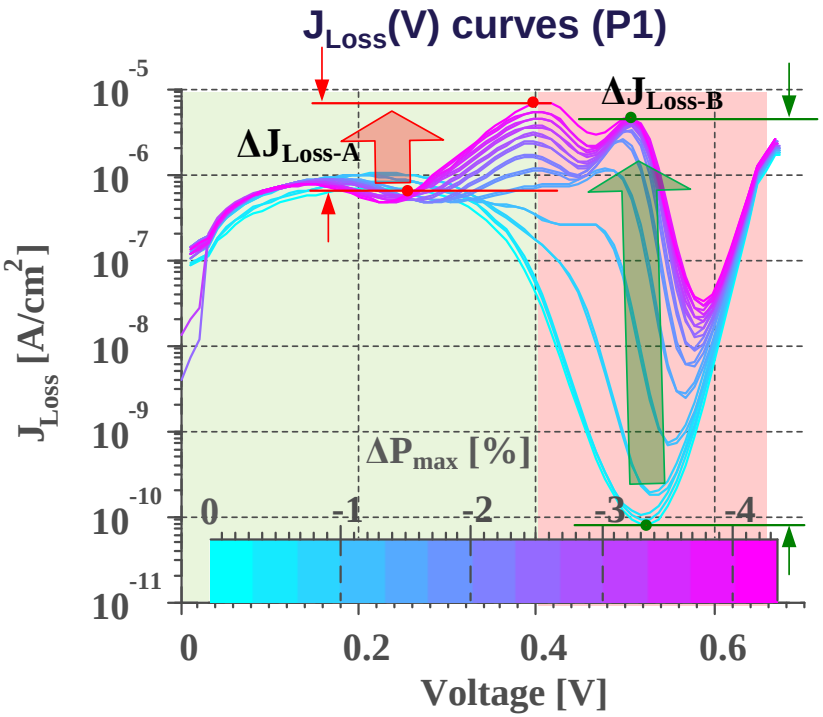




Experimental results – Potential-induced degradation

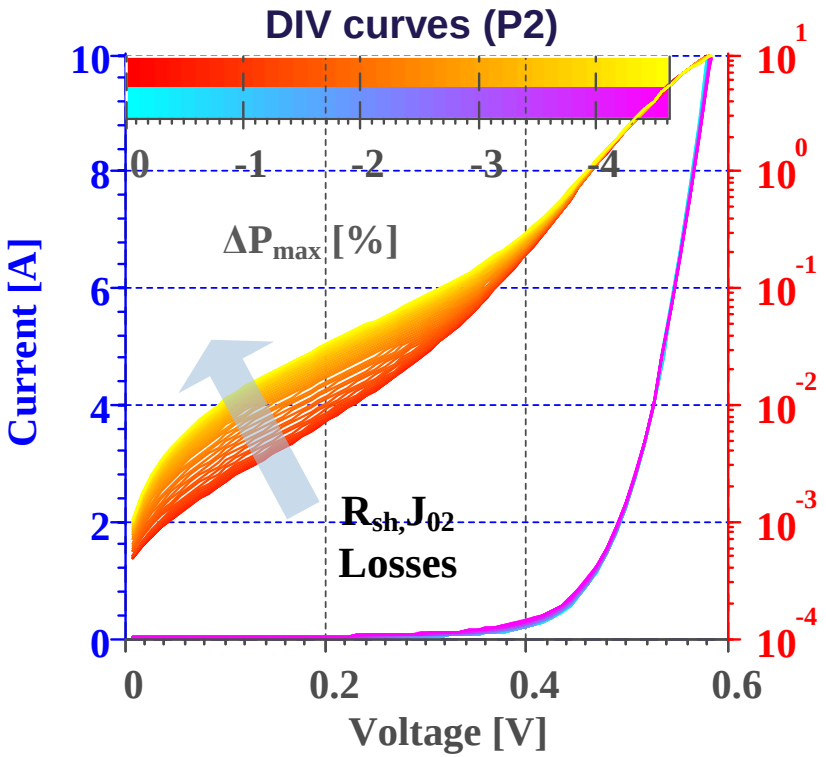
- Module design P1 was sensitive to PID

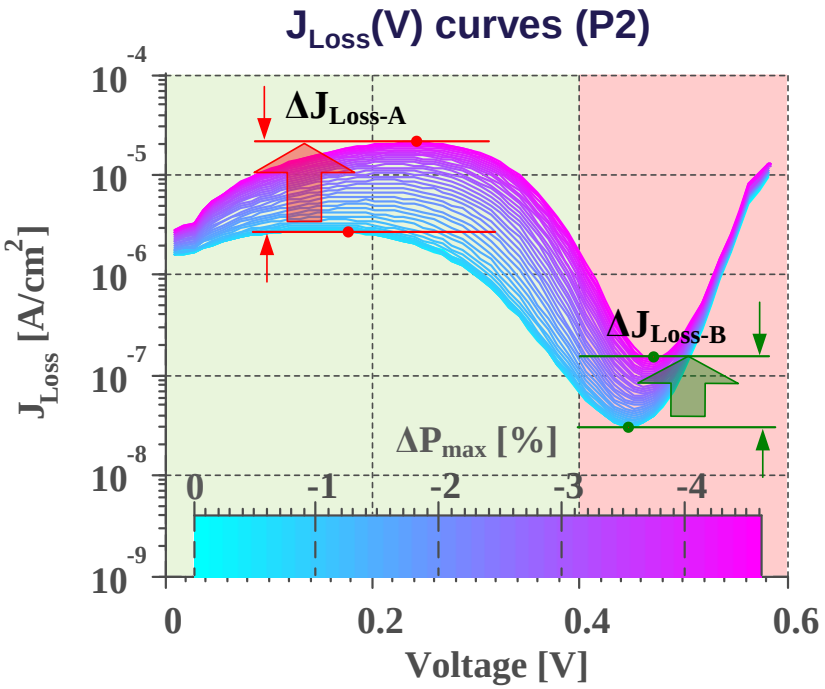




Experimental results – Potential-induced degradation

- Module design P2 was specified as high PID resistant in the datasheet.





Experimental results – Potential-induced degradation

- Module experiences shunting and recombination losses.
- $J_{Loss\text{-}A}$ and $J_{Loss\text{-}B}$ increase significantly.
- I_{sc} and $R_{s\text{-}ld}$ does not change significantly.
- Low-light efficiency decreases most.

DIV parameters

Module	P1	P2	P3	P4
ΔP_{max} [%]	-4.3	-4.6	-13.5	-22.9
ΔFF_{dark} [%]	-4.05	-3.86	-11.6	-17.1
$\Delta V_{d\text{-}max}$ [%]	-0.6	0.45	-1.13	-5.3
ΔV_{p} [%]	-0.01	0.01	-3.84	-15.3
$\Delta R_{s\text{-}ld}$ [%]	-2.9	3	3.56	9.2
$\Delta J_{Loss\text{-}B}$ [%]	**4.1e4**	**5.2e3**	**5.2e5**	**9.9e5**
$\Delta J_{Loss\text{-}A}$ [%]	**857**	**1.6e3**	**55**	**454**

Summary and conclusions

- We proposed a set of new diagnostic parameters that are sensitive to the degradation of the DIV, as well as to shunting and recombination losses.
- These diagnostic parameters, combined with LIV performance and series resistance measurements can enhance the degradation mode identification possibilities compared to light or DIV measurements alone.
- These diagnostic parameters can be used to identify: optical losses, PID, cell cracks, and cell fractures.

	Light I-V*					Dark I-V*				
Degr. mode	FF	$FF_{low\text{-}light}$	I_{sc}	V_{oc}	$\Delta R_{s\text{-}Id}$	FF_{dark}	$V_{d\text{-}max}$	V_p	$J_{Loss\text{-}B}$	$J_{Loss\text{-}A}$
Optical loss	↓↑	↓↑	↓	↓	↓↑	0	0	0	0	0
Electrical loss	↓↓	↓	↓	0	↑↑	↓↓	↑	↑	0	0
Cell damage	↓	↓	↓	↓	↑↑	↓	↑	↓	↑↑↑	↑↑
PID	↓↓	↓↓↓	0	↓	0	↓↓	↓↓	↓	↑↑↑↑	↑↑↑

*Legend: ↓↑ - inconsistent variation; ↓ - small decrease; ↓↓ - substantial decrease; ↓↓↓ - large decrease; 0 - no significant change; ↑ - small increase; ↑↑ - substantial increase; ↑↑↑ - large increase; ↑↑↑↑ - very large increase.

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