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RELIABILITY REVIEW

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CONTENTS

1. Introduction
2. The forces of nature
3. Degradation effects

This lecture is based on:

- M. Aghaei et al., RSER 2022
- Some personal views

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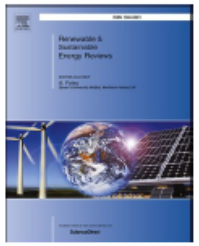

Review of degradation and failure phenomena in photovoltaic modules

M. Aghaei [a,b], A. Fairbrother [c], A. Gok [d], S. Ahmad [e,f], S. Kazim [e,f], K. Lobato [g], G. Oreski [h], A. Reinders [a,i], J. Schmitz [j], M. Theelen [k], P. Yilmaz [j,k], J. Kettle [l,*]

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1. INTRODUCTION

RECAP: SOLAR MODULE REQUIREMENTS

A good solar module:

- Is cheap to produce
- Uses no scarce materials
- Produces much more energy than it took to make it
- Requires no maintenance
- Works for more than 20 years

NOT ONLY EFFICIENCY MATTERS!

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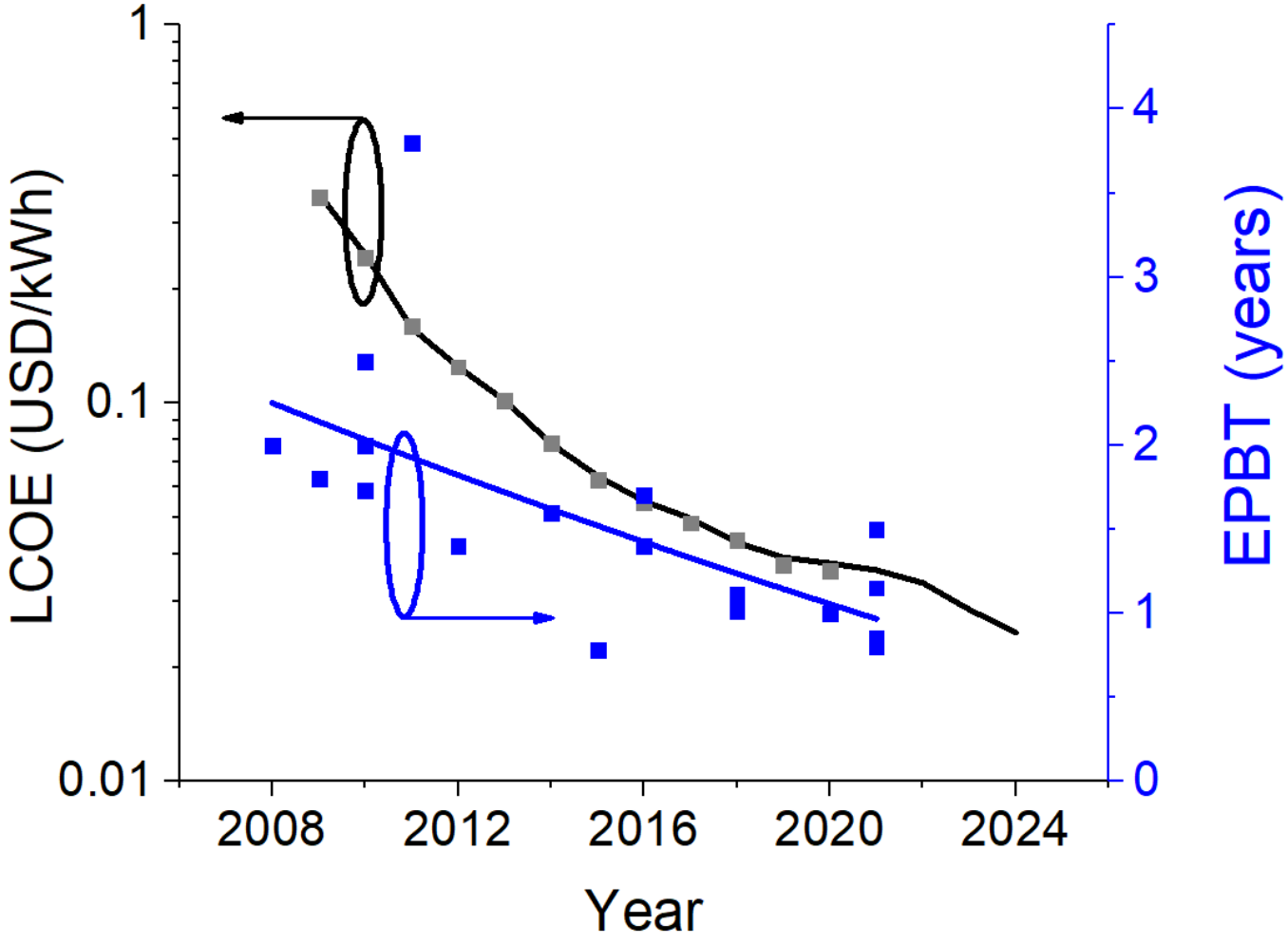
Levelized cost of electricity (LCOE) (€ / kWh):
How much electrical energy can we produce per invested €?

Energy Pay Back Time (EPBT) (years):
How long does it take for a solar module to generate the energy that was used to produce it?

Reliability:
What is the probability that a module survives a given time in the field under specified conditions?

SOME NUMBERS
LCOE AND EPBT

- Nice trends:
  LCOE and EPBT decrease
- Note the scales!



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SOME NUMBERS
PV IN MASS PRODUCTION

Technology	Year > 10%	2020 market share	Record efficiency	EPBT (years)
Mono-Si	1957	66.6%	26.7%	1.4-7.3
Poly-Si	1984	28.4%	24.4%	0.8-4.2
CdTe	1981	4.1%	22.1%	0.8-2.7
CIGS	1981	0.8%	23.4%	1.3-2.8
a-Si:H	1992	0.1%	14.0%	1.1-3.2

- Mono-Si is hard to beat! Good specs + economy of scale
- a-Si:H has little perspective in this market
- All listed technologies reach > 20 years lifetime

SOME NUMBERS
EMERGING TECHNOLOGIES

Technology	Year > 10%	Record efficiency	EPBT (years)	Best outdoor lifetime (years)
Dye-Sensitized	1997	12.3%	0.6-1.8	< 2
Organic	1984	17.5%	0.1-1	~2
Perovskite	1981	25.5%	0.2-5.4	< 0.5

- Attractive Energy Pay Back Times
- Long-term stability needs breakthroughs
- Light-induced degradation is a fundamental (intrinsic) problem
- Oxygen/moisture induced degradation can be solved by encapsulation

WHAT INVESTORS NEED

1. Guaranteed lifetime
2. Guaranteed energy production
3. Guaranteed market price

1*2*3 = Predictable return-on-investment

Can we guarantee lifetime?

- Solar module vendors do it: ~25 years.
- How can they be so sure?

RELIABILITY ESTIMATION

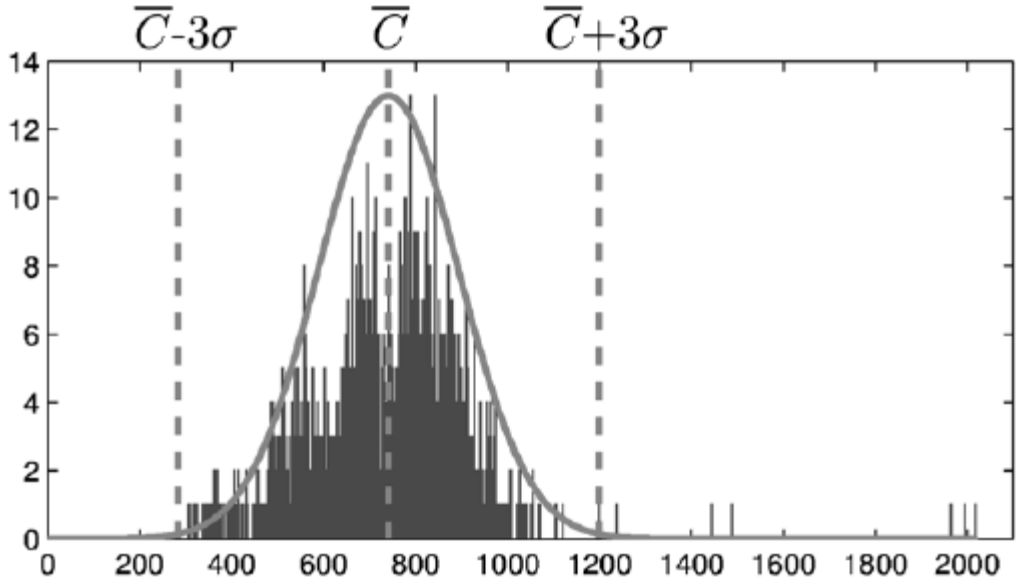
Reliability engineering:

- Monitor modules in the field
- Develop special stress tests
- Try different things
- Develop reliability models

Knowledge → prediction

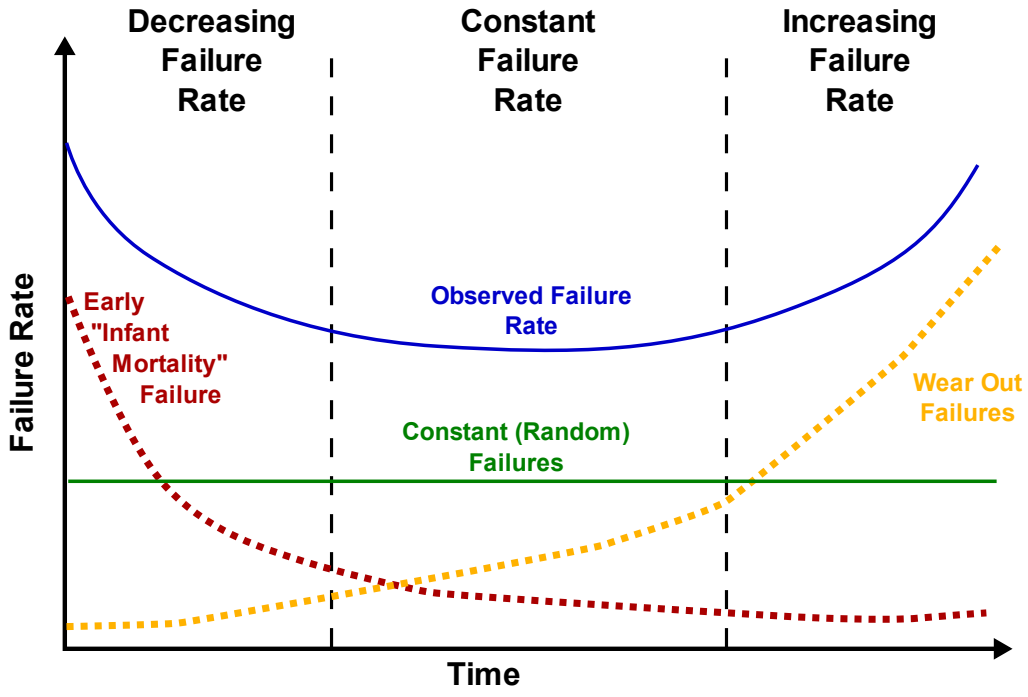
Use statistics (properly)

Include safety margins



Always hoping for decent probability density functions without outlyers…

THE BATHTUB CURVE



Early failures:

- Poor production quality
- Identify the bad parts by testing

Random failures:

- Also related to quality (material strength)

Wear out failures:

- Everything breaks eventually

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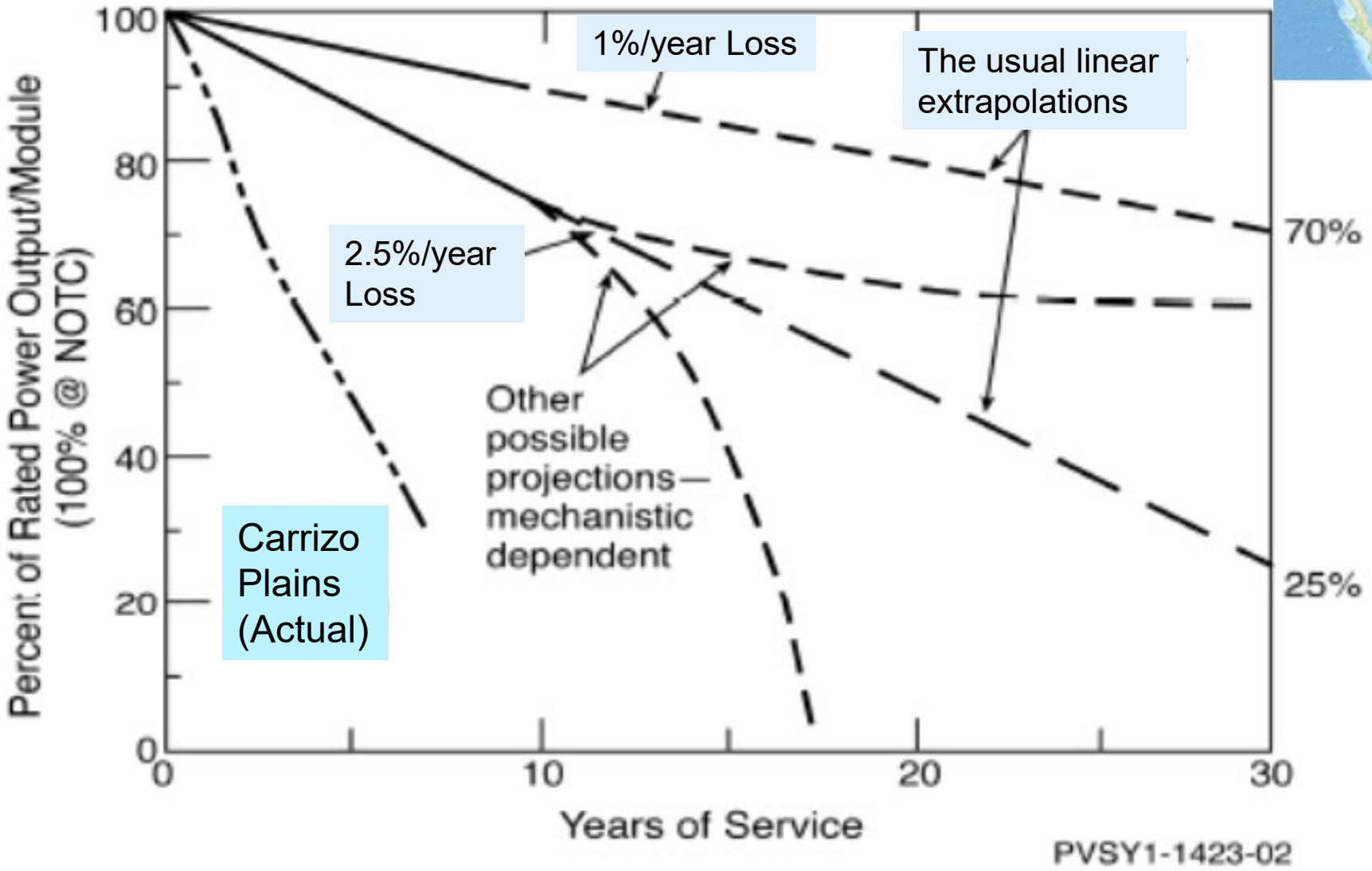
2. NATURE'S ATTACKS ON SOLAR MODULES

PV IN THE CARRIZO PLAIN – 1983

100,000 MODULES, ONCE THE LARGEST PV SITE IN THE WORLD



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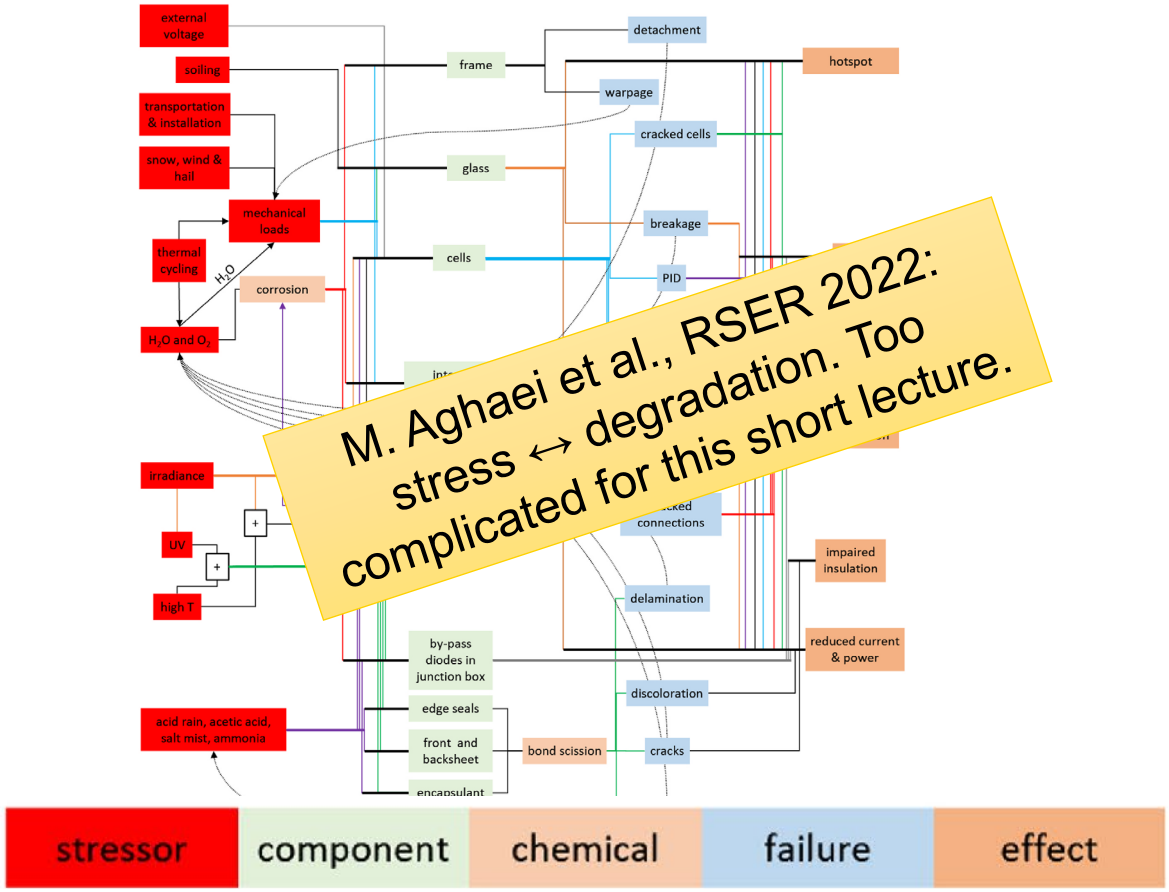
STRESS FACTORS ON MODULES

- Mechanical loads
  - installation, snow, wind, hail
- Temperature cycles
- H_2O, O_2
- Light (esp. UV)
- Dirt (soiling)
- Chemicals: ammonia, salt, acid rain, acidic acid
- External voltage



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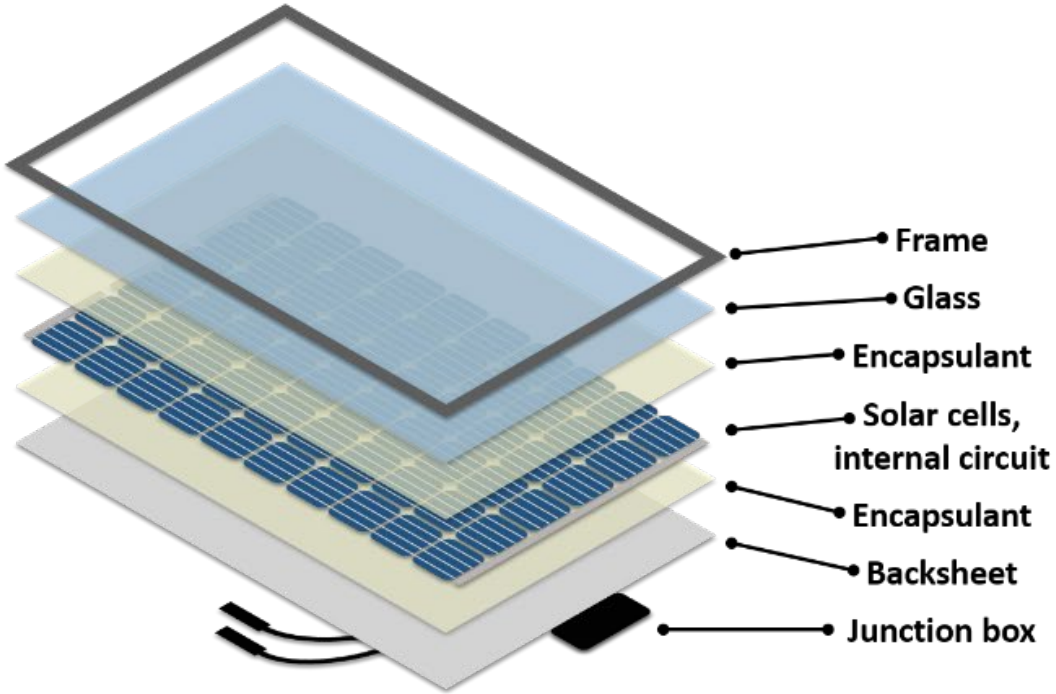
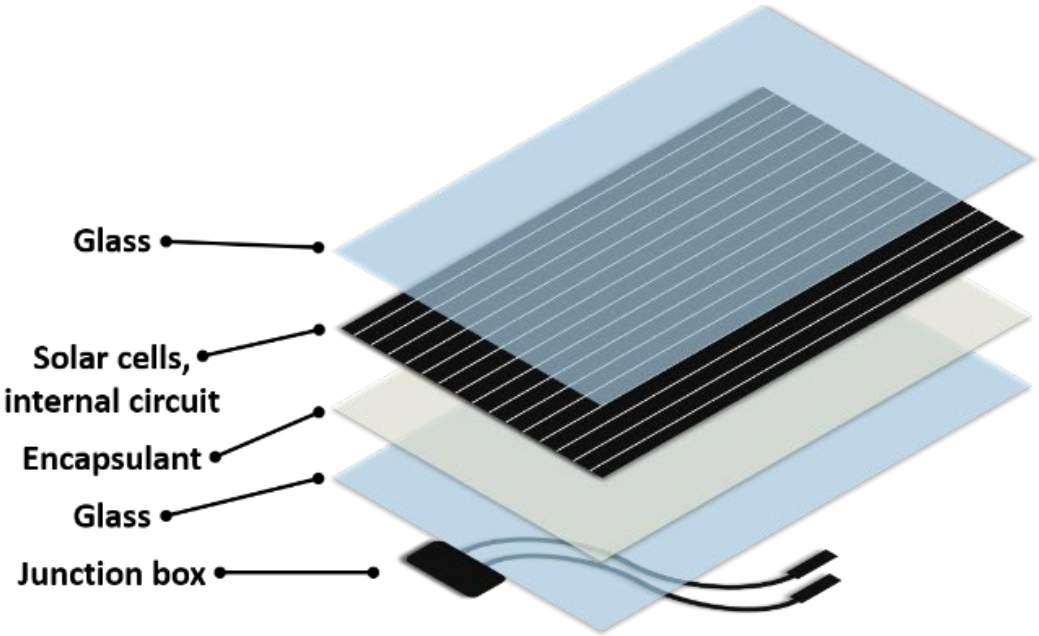
MODULE COMPOSITION (TYPICAL)

c-Si module



CdTe module



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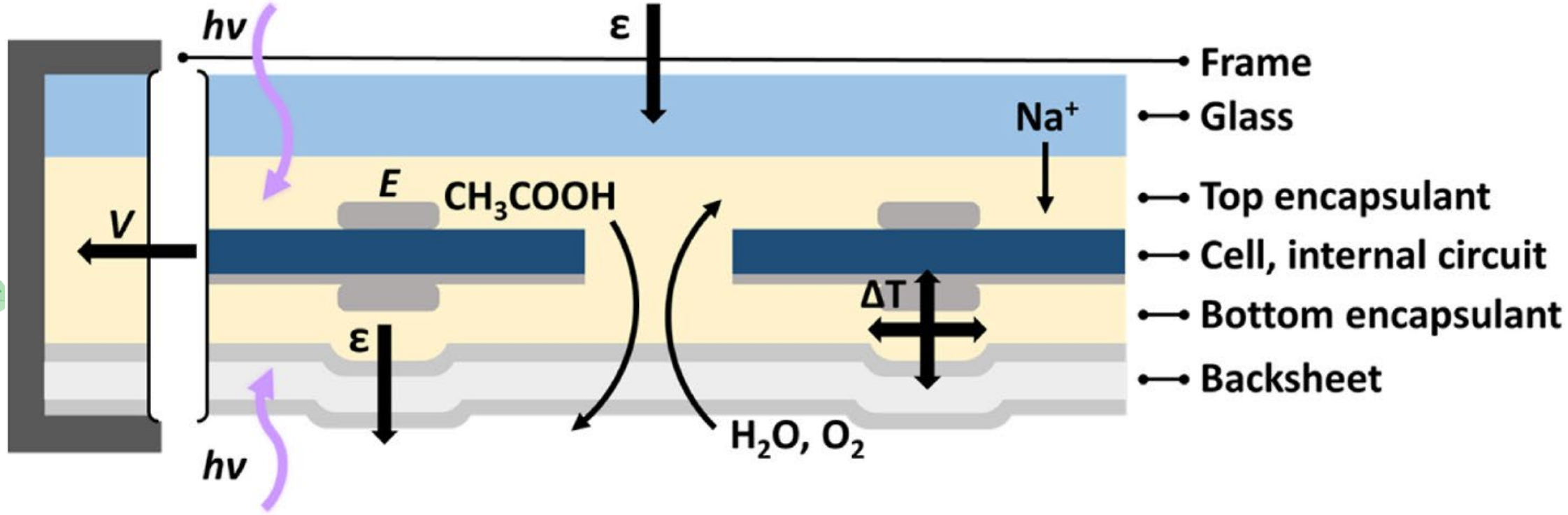
C-SI MODULES: NATURE ATTACKS



Actors: light (*hv*), strain (*ε*), voltage bias (*V*), diffusion (CH_3COOH, H_2O, O_2, Na^+), electric field (*E*), and thermomechanical strain (ΔT).

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3. CONSEQUENCE: DEGRADATION AND FAILURE

FAILURE CATEGORIES FOR PV MODULES

- Electrical circuit failures (outside the module)
- Encapsulant discoloration and delamination
- Corrosion (in warm and humid climates; or close to the sea)
- Potential-Induced Degradation (under high voltage)
- Cell fracture, e.g. from (hail)storms

FAILURE CATEGORIES FOR PV MODULES

- Electrical circuit failures
- Encapsulant discoloration and delamination
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Most common: junction box failure

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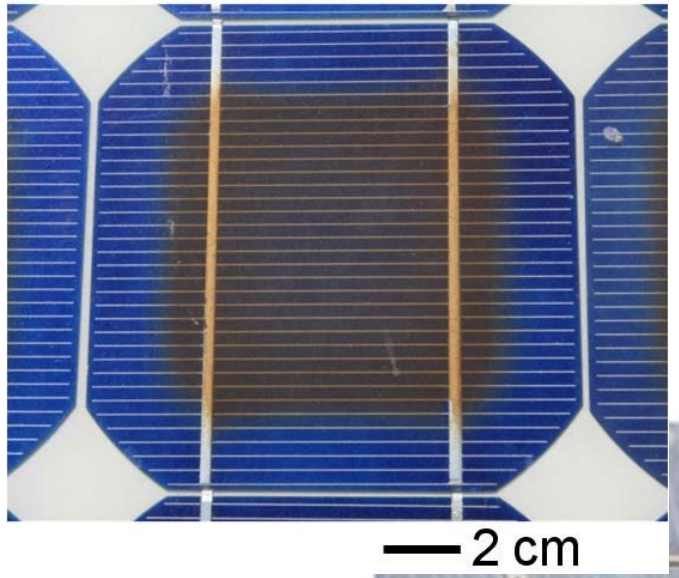
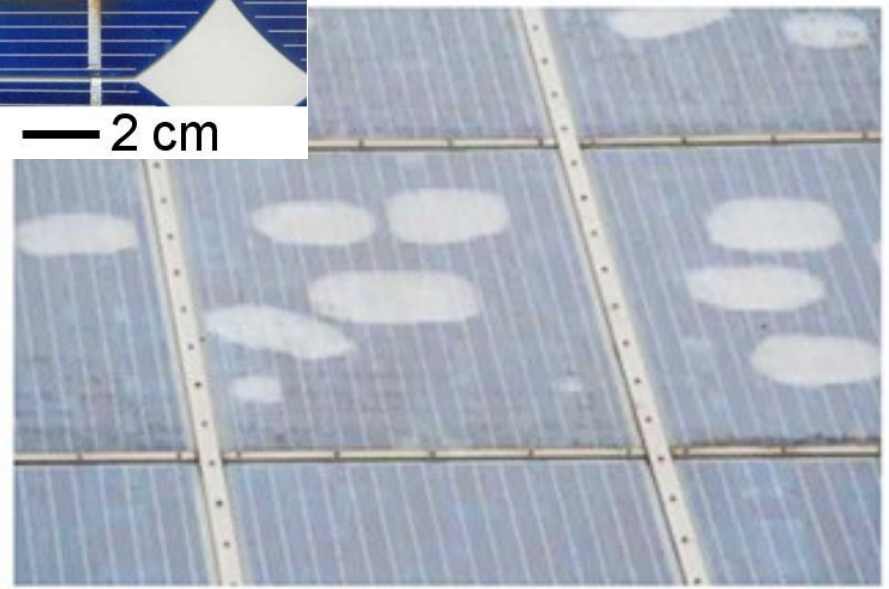


discoloration



delamination

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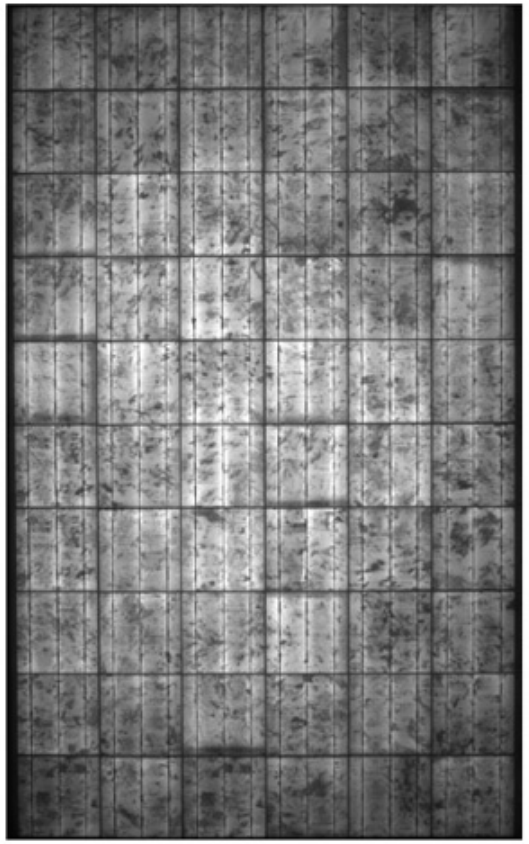

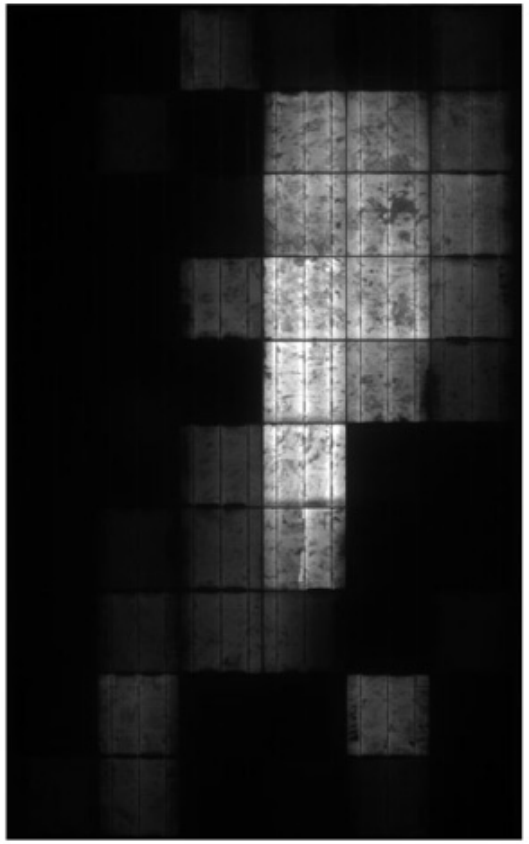

See Thursday lecture of Mahmoud Dhimish!

FAILURE CATEGORIES FOR PV MODULES

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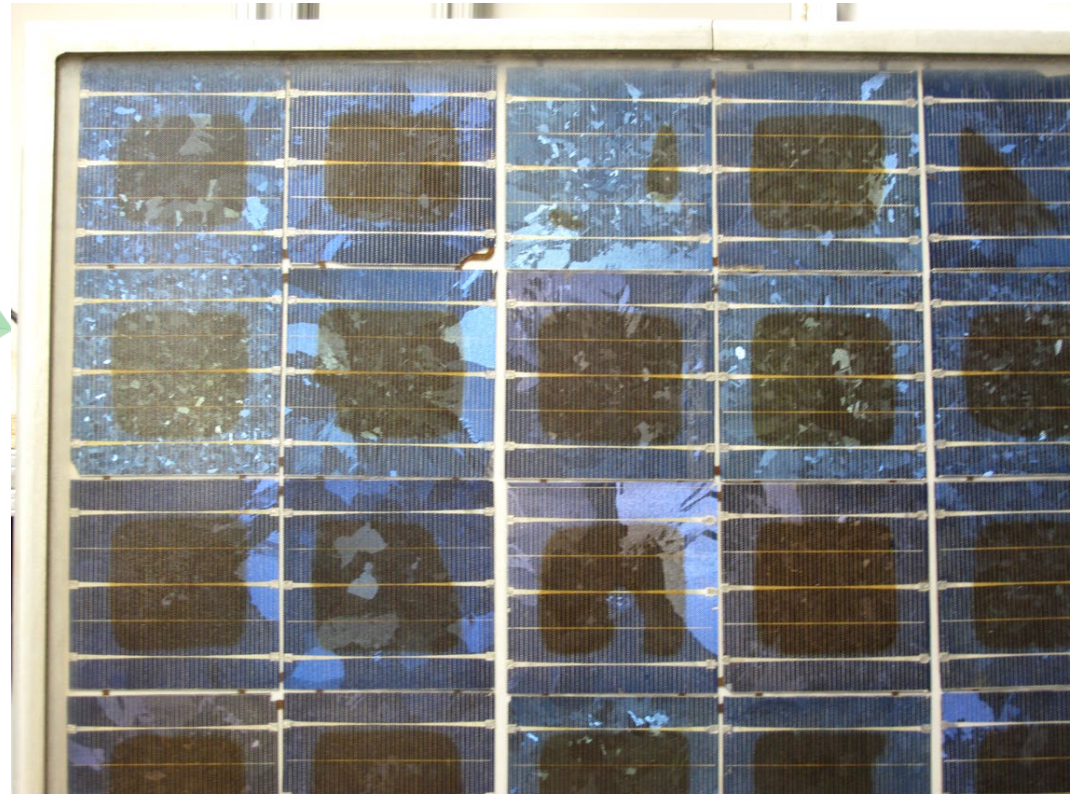
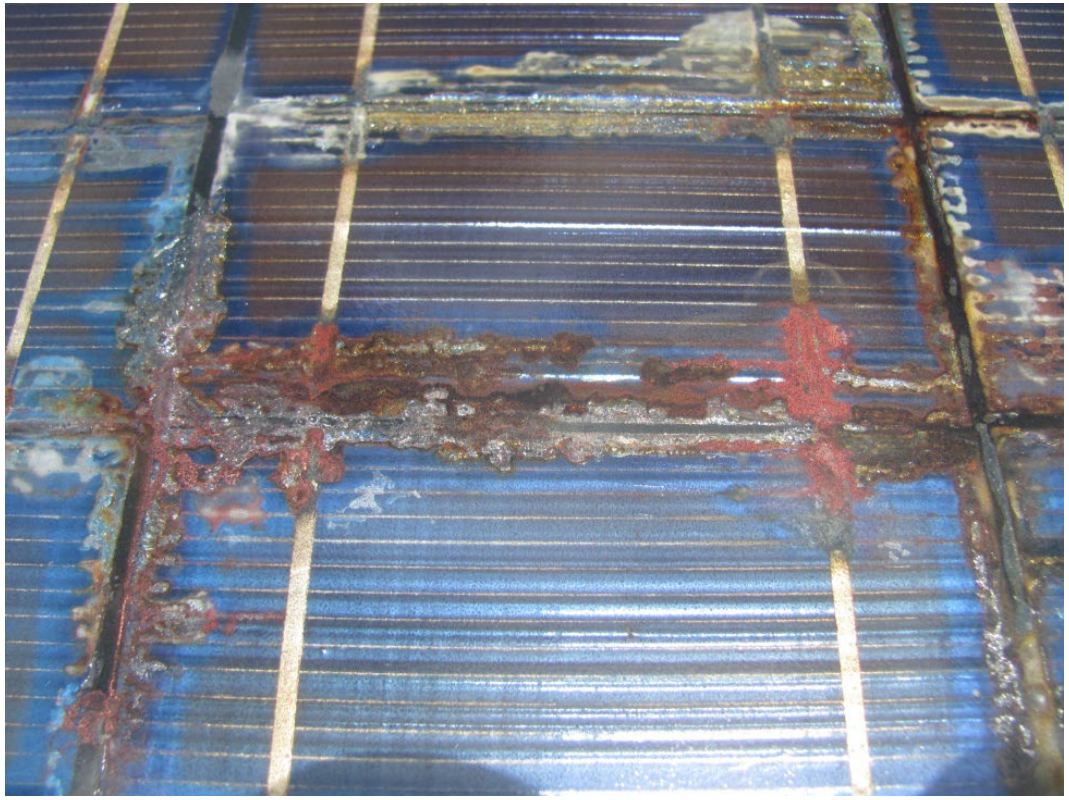
YOUR TURN NOW: RECOGNIZE THE FAILURE(S)



Silicon PV module after ~20 years in the field.



Silicon PV module after 22 years in Florida.

Figures from: Reinders, Verlinden, Van Sark and Freundlich: Photovoltaic Solar Energy

WRAP-UP

Covered:

- Basics of reliability
- Importance for PV systems
- Main stress factors
- Degradation and failure mechanisms in PV

Closing remarks:

- Few-decade lifetime is a necessity
- Cost, materials, convenience
- Match lifetime of a building?
- Emerging technologies: work

THANK YOU FOR YOUR ATTENTION.

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