Rico Meier[1→2], Ian M. Slauch[1], Mariana I. Bertoni[1]

Characterization of Lamination Progress with Ultrasound

[1]School of Electrical, Computer and Energy Engineering, Arizona State University

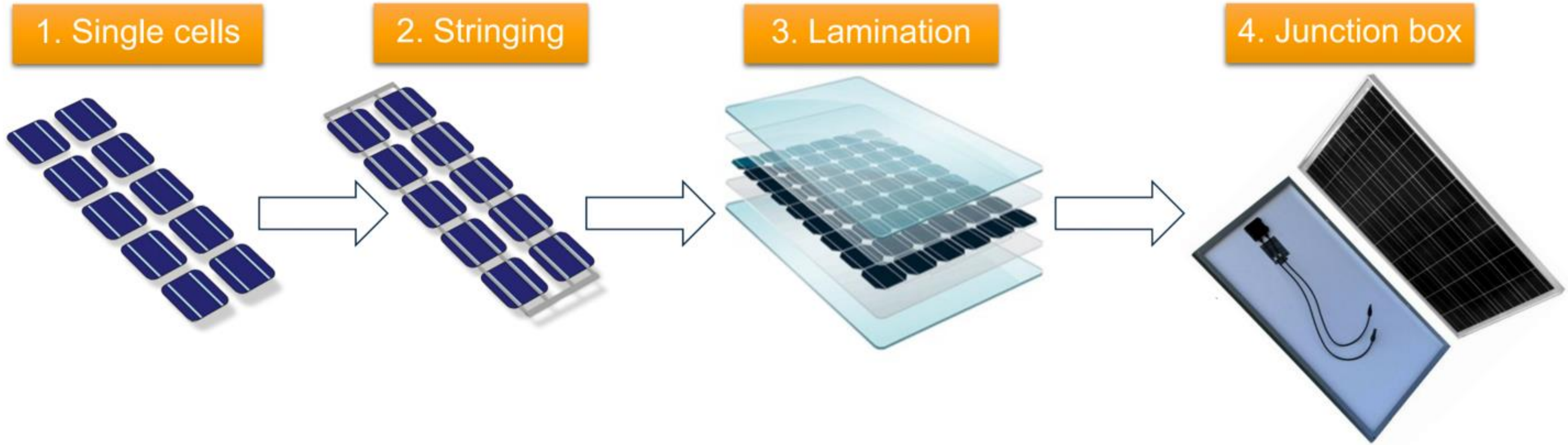
[2]School of Engineering: Energy and Information, HTW Berlin - University of Applied Sciences

rico.meier@htw-berlin.de

DEfECT laboratory

Hochschule für Technik und Wirtschaft Berlin
University of Applied Sciences

Module Manufacturing



Single cells are tested (I-V curve @ STC*) and sorted (similar current/power).

Cells are connected (in series or parallel) to match the module power output.

Stringed cells are protected with a front glass and a rear cover. Two polymeric foils (encapsulant) provide the adhesion between components.

The junction box is glued at the rear and an aluminum frame is placed around the module.

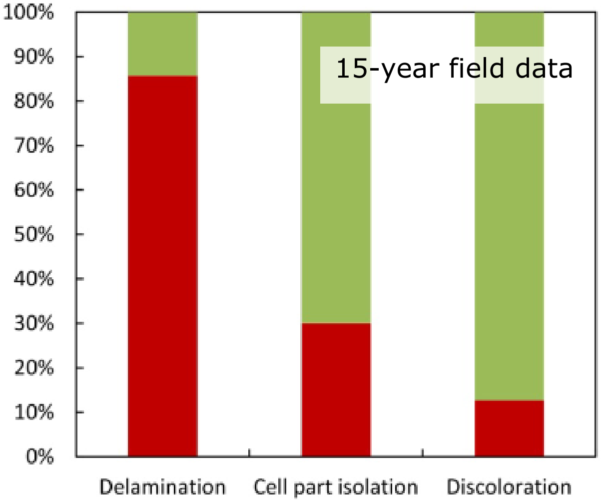
[1] O. A. Arruti, Solar PV Modules: Market Trends, Materials & Manufacturing Processes, PV Systems Technologies and Design, GoPV Project Summer School, June 2022

Delamination is an Important Failure Mode

Tasks of the encapsulation:

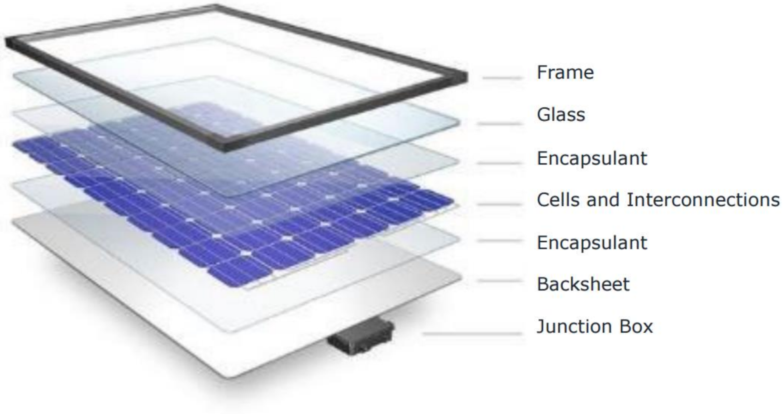
- Electrical Isolation
- Mechanical Stability
- Moisture/O_2 Barrier
- Optical Coupling
- UV Filtering

- 80% of modules show delamination < 15 years [1]!

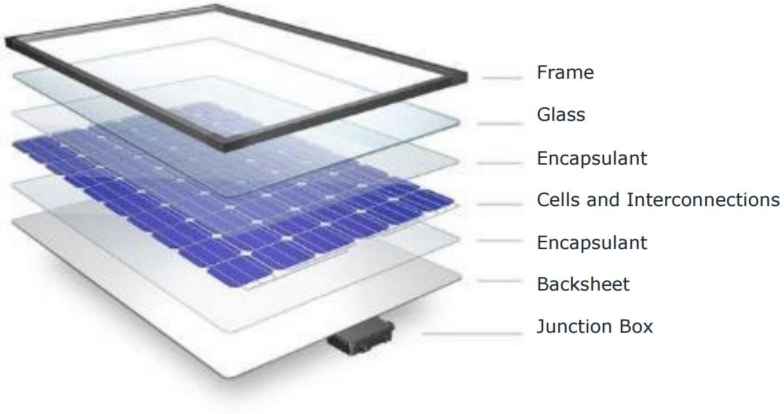


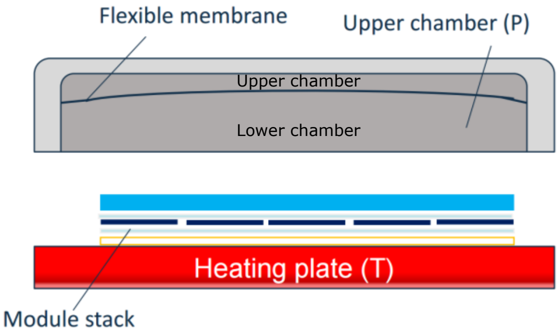
[1]M. Köntges, S. Kurtz, C. Packard, U. Jahn, K. A. Berger, and K. Kato, "Performance and reliability of photovoltaic systems: subtask 3.2: Review of failures of photovoltaic modules: IEA PVPS task 13: external final report IEA-PVPS," International Energy Agency, Photovoltaic Power Systems Programme, Sankt Ursen, 2014.
https://www.photovoltaik.eu/solarmodule/polymeranalyse-fuer-eva-folie

The Lamination Process



The Lamination Process

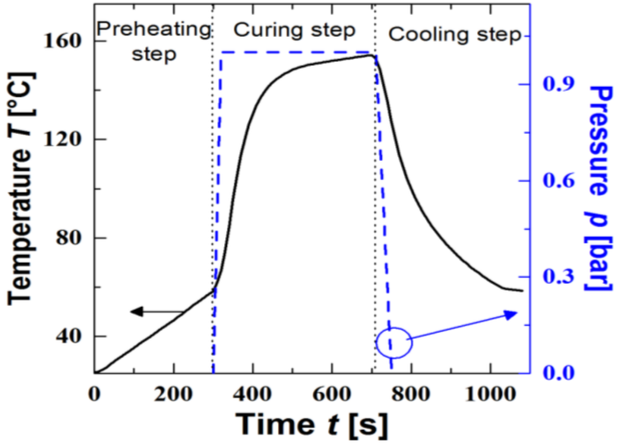




Lamination "recipe" $f(T,p,t)$:

- Specific to the individual material (about 20 min)

1. **Pre-heating Step:** Upper and lower chamber are evacuated
   → Air removal to minimize foid formation
   → Softening the encapsulant
2. **Curing Step:** Heating
   → enhancing adhesion, cross-linking reaction (gel content >80%)
3. **Cooling Step:** Cool to RT

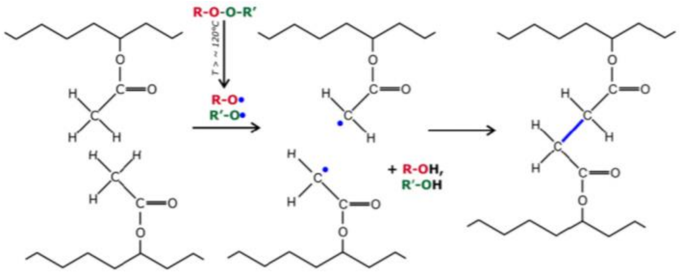


[1]O. A. Arruti, Solar PV Modules: Market Trends, Materials & Manufacturing Processes, PV Systems Technologies and Design, GoPV Project Summer School, June 2022

Ethylene Vinyl Acetate (EVA) Characteristics

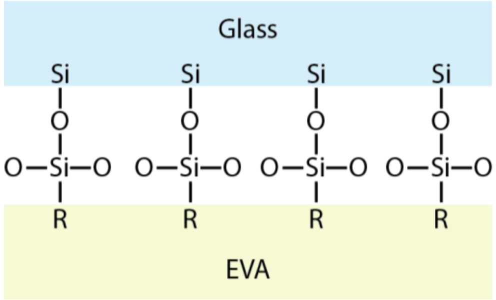
Crosslinking

→ Mechanical stability, transparency



Adhesion

→ Siloxane Bonding



Characterization Techniques:
Differential Scanning Calorimetry (DSC),
Soxhlet Extraction

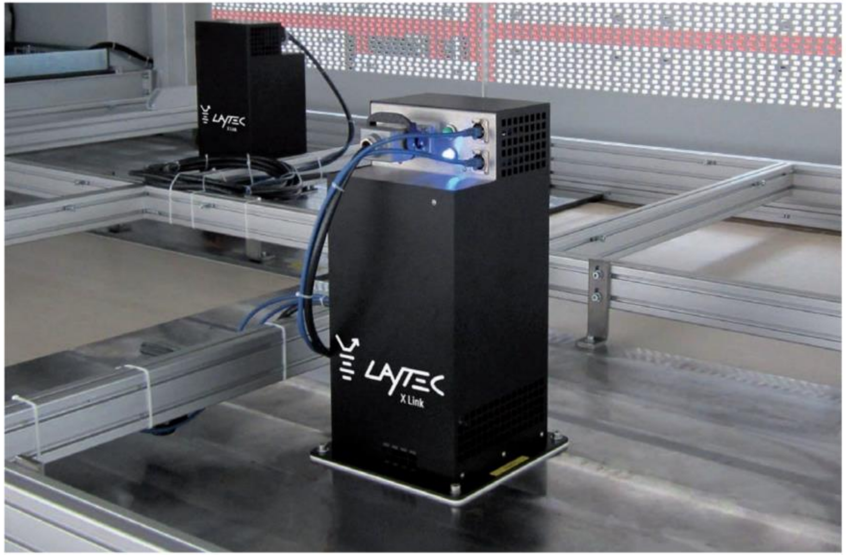
Characterization Techniques:
Peel Test, Single-Cantilever Beam Test

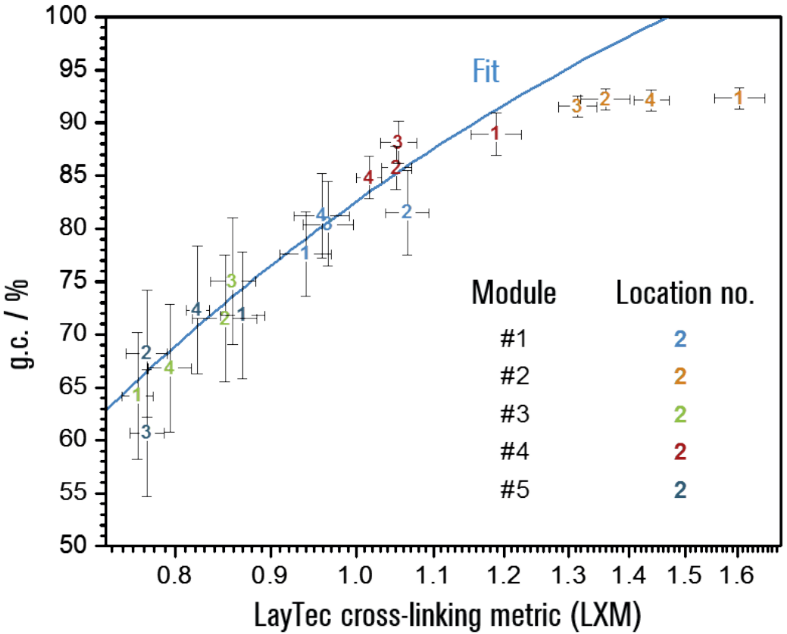
These are destructive methods!

→ Not suited for production / field testing

Ch. Hirschl, L. Neumaier, W. Mühleisen, M. Zauner, G. Oreski, G.C. Eder, S. Seufzer, Ch. Berge, E. Rüland, M. Kraft, In-line determination of the degree of crosslinking of ethylene vinyl acetate in PV modules by Raman spectroscopy, Sol. Energy Mater. Sol. Cells 152 (2016) 10–20.

Laytec X Link®





- Uses indentation analysis to probe EVA from the backside
  → not suited for Glass/Glass-Modules

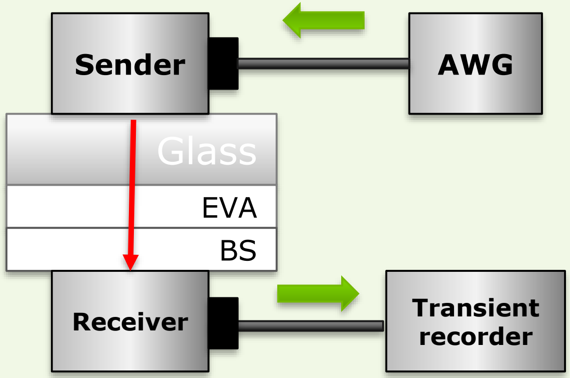
https://www.laytec.de/xlink/

Ethylene Vinyl Acetate (EVA) Characteristics

Crosslinking

→ Mechanical stability, transparency

Volume wave transmission method (1)



Longitudinal wave transmission (red) through the sample

Adhesion

→ Siloxane Bonding

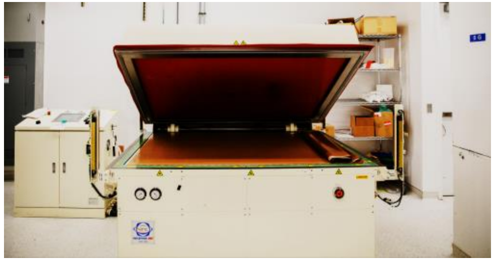
High-frequency Lamb wave method (2)

Leaky Lamb wave transport consisting of longitudinal (red) & transversal (blue) partial waves

Crosslinking – Characterization Procedure

Sample Fabrication

Variation of Lamination Profile



https://cores.research.asu.edu/solar-fab/equipment/44-npc-laminator

Sample	Vaccum Time [min]	Initial Press [min]	Bladder Pressure [kPa]	Final Press [min]
5 min	4.5	1.5	96	5
6 min				6
10 min				10
15 min				15
18 min				18
50 min				50

3.2mm glass

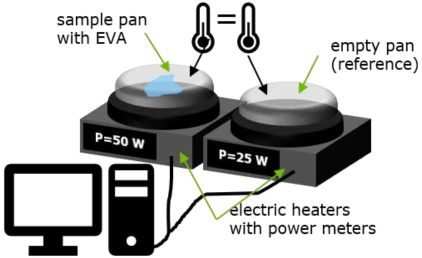
400µm EVA

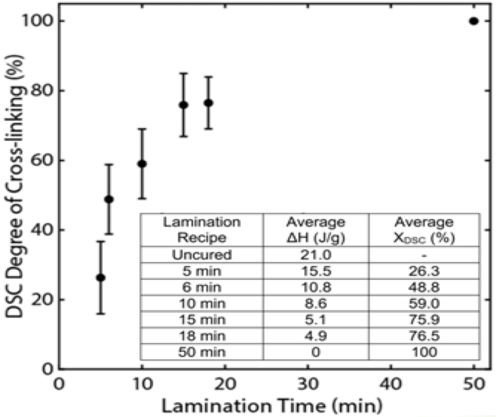
250µm Backsheet

Conventional Characterization ⟺ US-Characterization

Differential Scanning Calorimetry

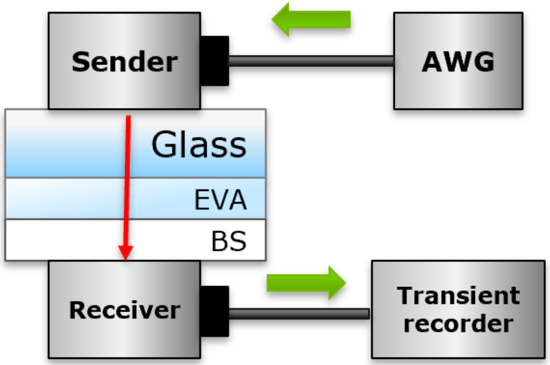
Heating both pans with constant temperature ramp (10 K/min)



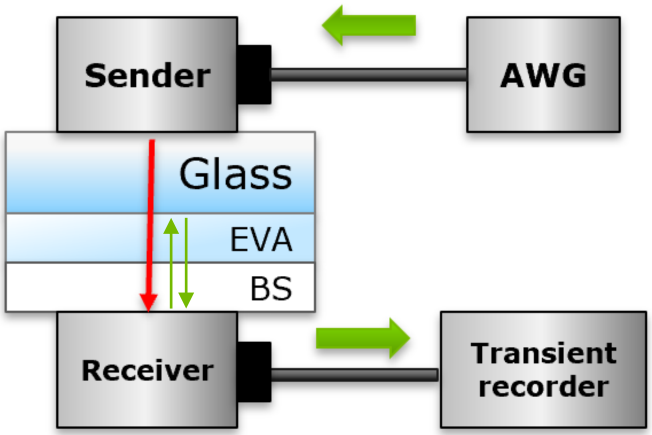


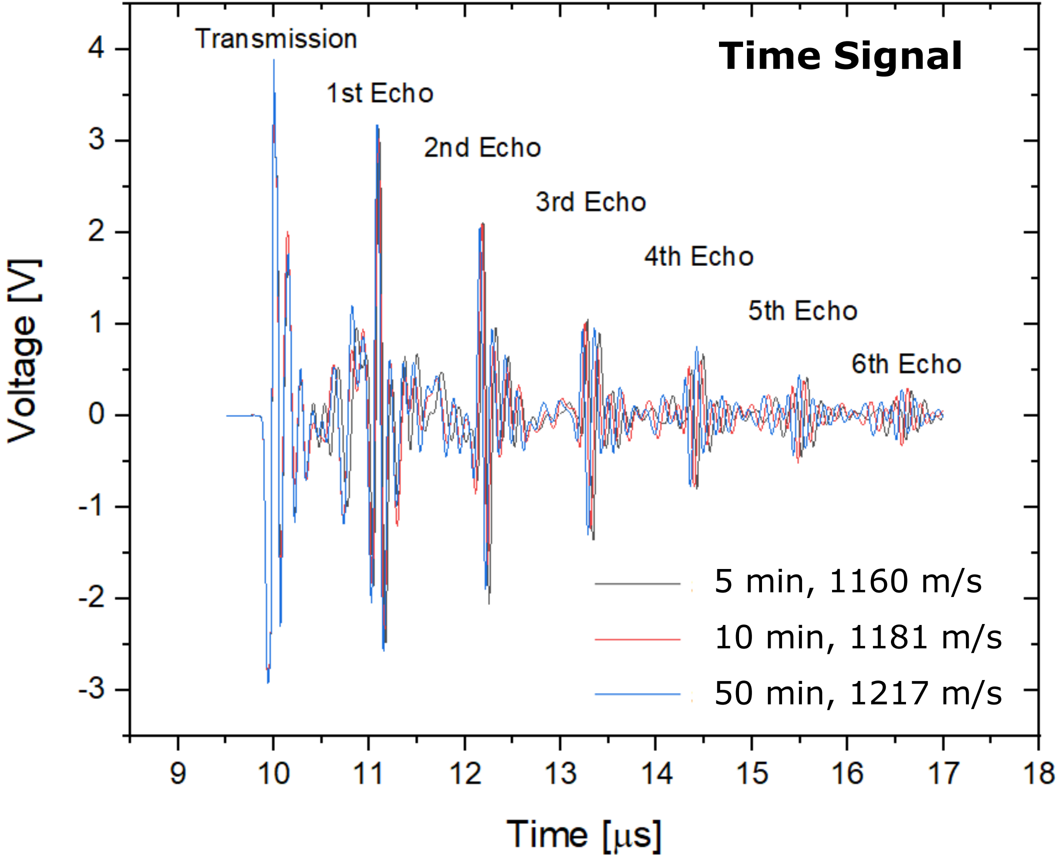
Lamination Recipe	Average ΔH (J/g)	Average X_{DSC} (%)
Uncured	21.0	-
5 min	15.5	26.3
6 min	10.8	48.8
10 min	8.6	59.0
15 min	5.1	75.9
18 min	4.9	76.5
50 min	0	100

Longitudinal wave speed and attenuation



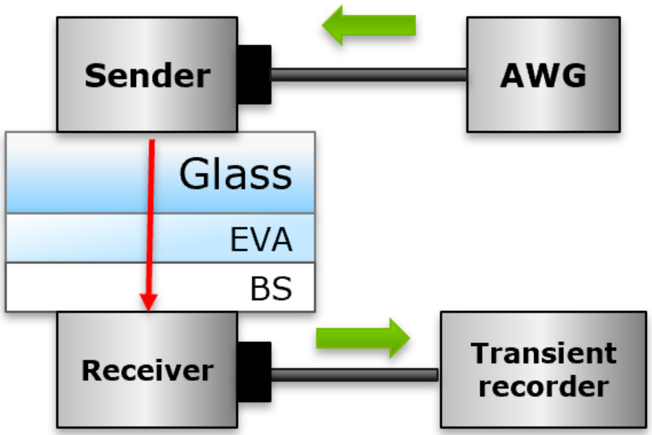
Crosslinking Analysis: US Transmission

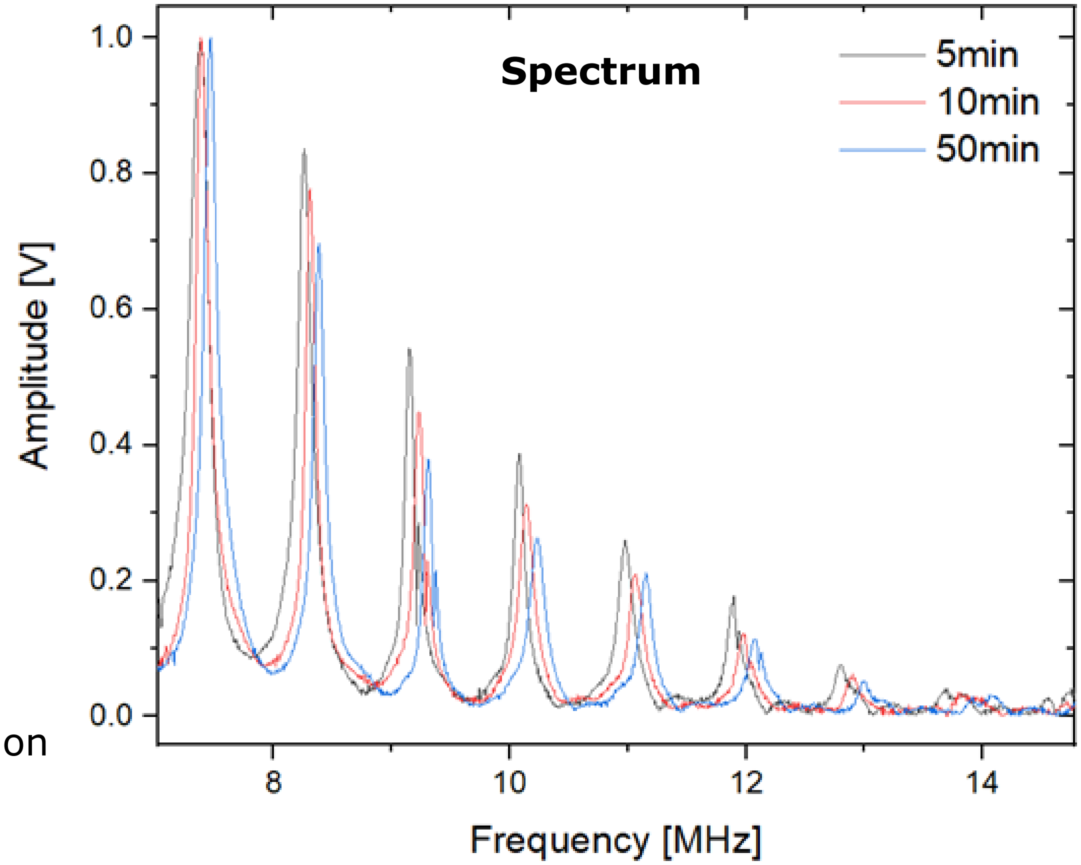




- Decrease in ToF with lamination time → (1) increase in elastic modulus or (2) reduction in thickness

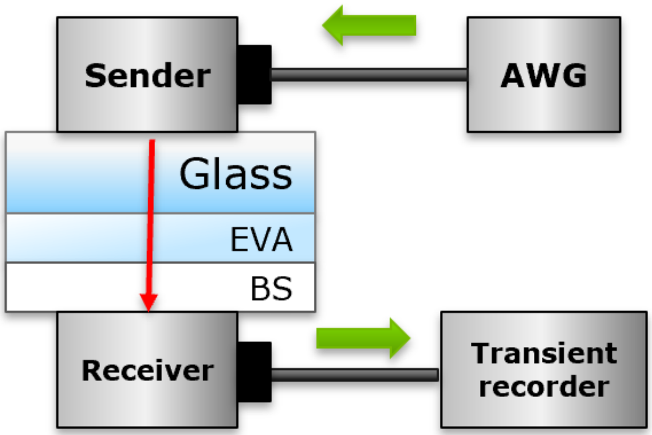
Crosslinking Analysis: US Transmission



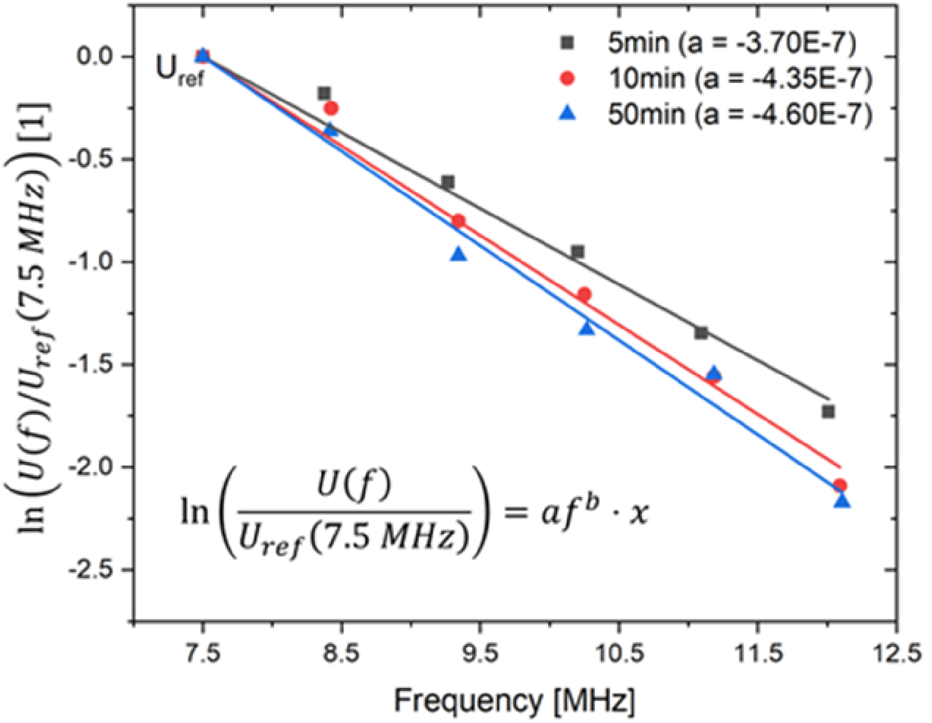


- Increase in Eigenfrequency
  → (1) increase in elastic modulus
  or (2) reduction in thickness
- Increase in high-frequency attenuation
  → change in EVA properties

Crosslinking Analysis: US Transmission

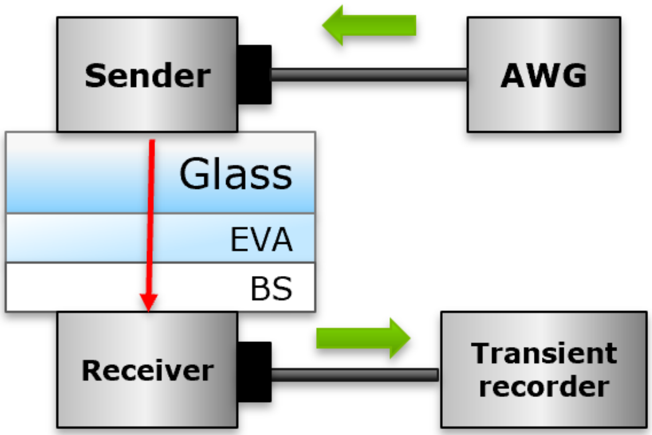


Spectrum

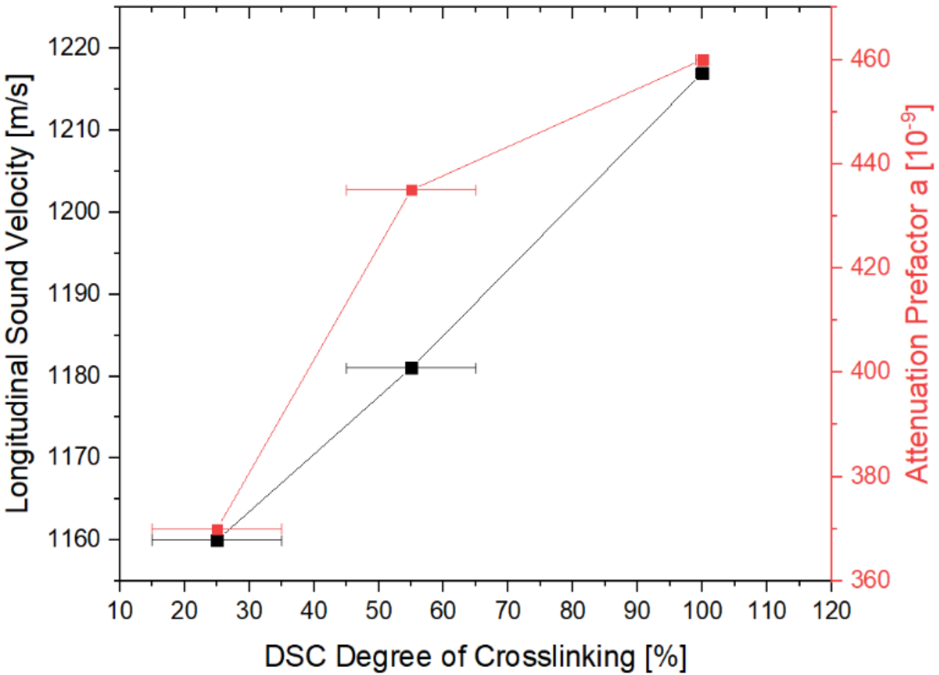


- Increase in Eigenfrequency
  → (1) increase in elastic modulus
  or (2) reduction in thickness
- Increase in high-frequency attenuation
  → change in EVA properties

Crosslinking Analysis: US Transmission



Summary



- Calibration of the model by conventional methods for each specific EVA
  → Once calibrated, methods provide non-destructive addition/alternative

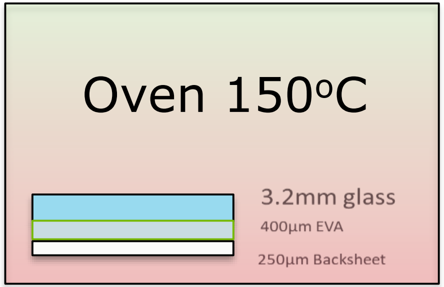
Control measurement: Crosslinking in an Oven

- No lamination pressure
- Same sample measured after different curing durations

} const. thickness

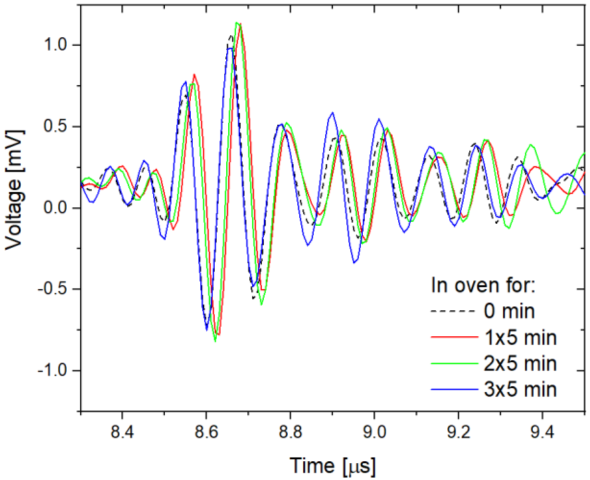
2min laminated sample:

- multiple 5min intervals in oven for sequential crosslinking

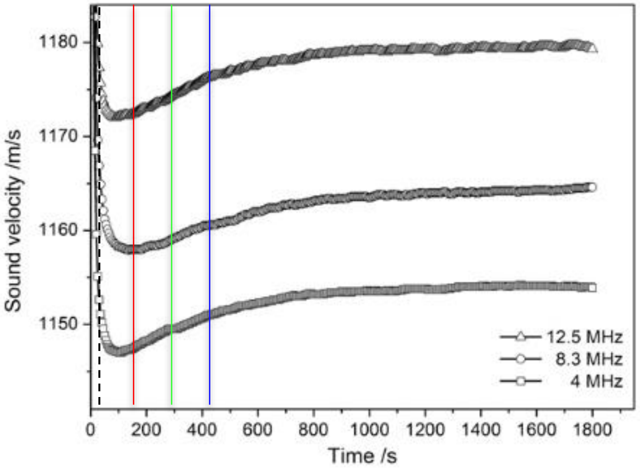


5 min oven ≈ 2min>140°C

<u>Time Signal</u>



<u>Comparison with Literature [1]</u>



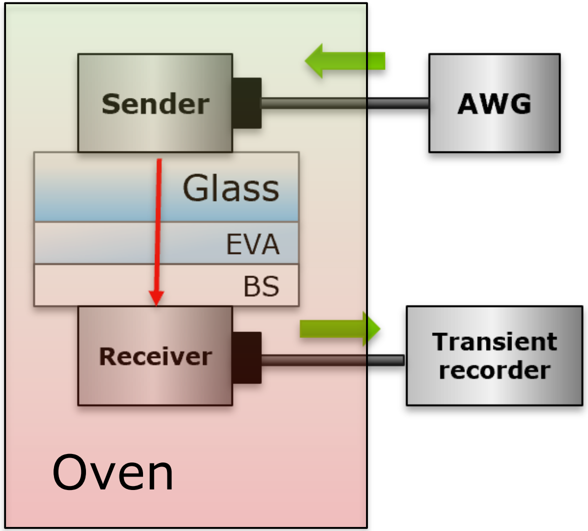
→ After initial drop, sound velocity increases with lamination time

[1] W. Stark et al., "Investigation of the crosslinking behaviour of ethylene vinyl acetate (EVA) for solar cell encapsulation by rheology and ultrasound", *Polymer Testing 31 (2012)*, 904–908

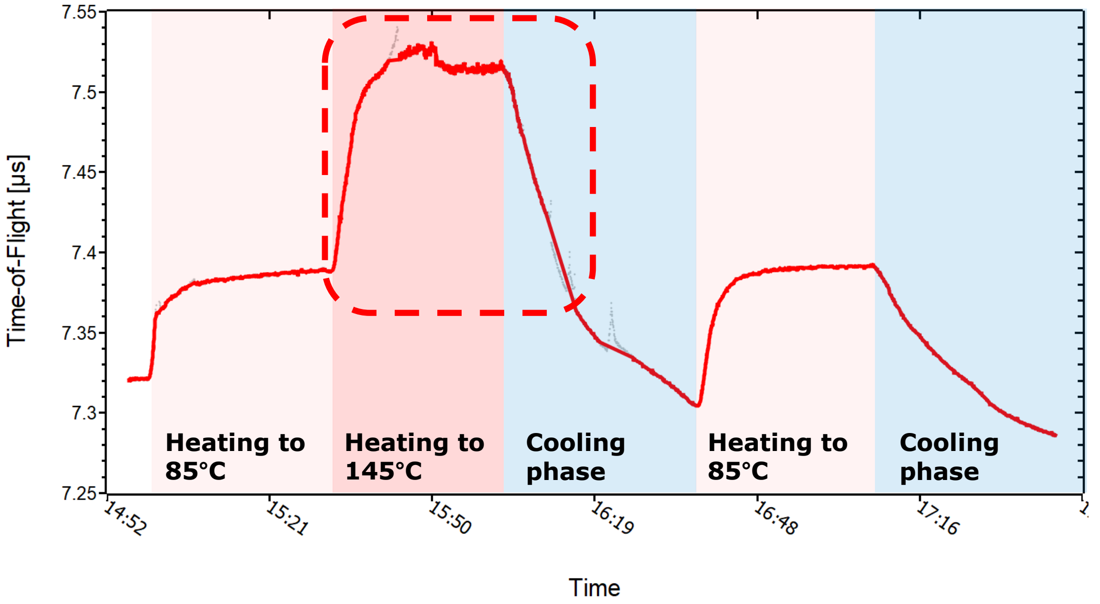
Transmission measurement during Crosslinking Process

Setup modifications:

- thin, high temperature transducer (1.5 mm, up to 200°C)
- Measurement during crosslinking process



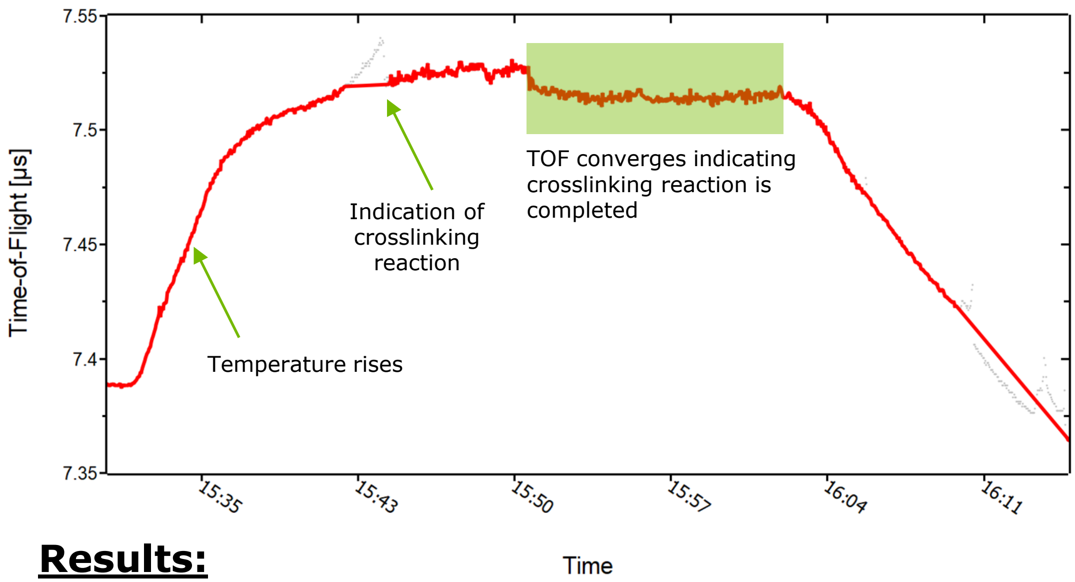
Measurement Results



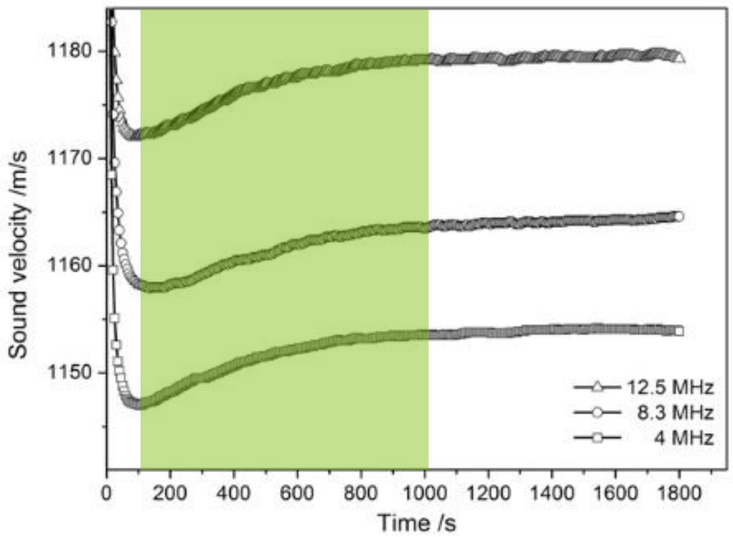
Transmission measurement during Crosslinking Process

:DEfECT laboratory

Heating step to 145°C



Comparison with Literature [1]



Results:

- Elastic constants (sound velocities) are highly temperature dependent
- Changes due to crosslinking are small in comparison (around 16 ns)
- Crosslinking reaction alters ultrasonic signal → adds noise (to cross-correlation result)
- Crosslinking reaction first increases than decreases ToF (as reported in literature)
- ToF plateaus after 15 min → indicates that crosslinking is completed

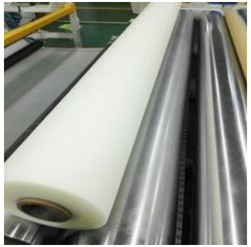
[1] W. Stark et al., "Investigation of the crosslinking behaviour of ethylene vinyl acetate (EVA) for solar cell encapsulation by rheology and ultrasound", *Polymer Testing 31 (2012)*, 904–908

ASU htw

Application

- Effects of environment and aging have not been investigated (yet!)
  → Ideal for non-destructive EVA characterization in module production:

  a) **EVA quality inspection**:
  - previous aging or pre-crosslinking

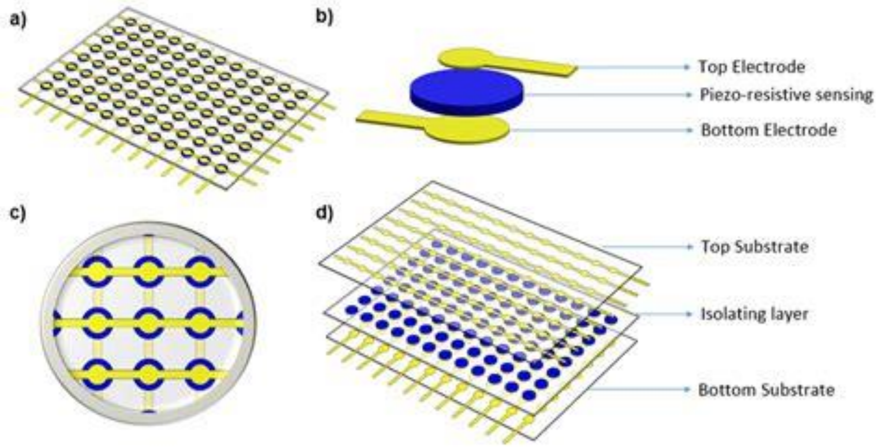
  b**) Optimization of lamination process parameter**:
  - crosslinking analysis (optimization of lamination duration)

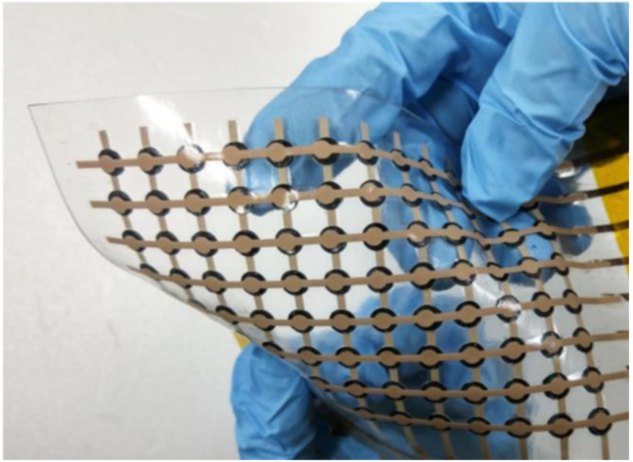
  

→ **After automation/process integration:**
Non-destructive EVA characterization of ALL manufactured modules (instead of sequential destructive testing)

Next Steps

- **Industrial Prototype**
  - Sensor-array for measuring different module locations at once





Next Steps

- **Follow-up project:**
  - Aging of solar modules in the field → ultrasonic sensor for degradation characterization

Goal: to expand the method to evaluate module health
- during field and accelerated aging (temperature, humidity, UV, stress)
- incorporating different encapsulants (EVA, POE) and backsheets

The ultimate goal is a module polymer degradation model based on ultrasonic measurables enabling an estimation of the remaining module's lifetime.

Acoustic Fingerprint

- Volumen- und Lambwellen
  - Schallgeschwindigkeiten(*f*)
  - Dämpfungseigenschaften(*f*)

https://fmcna.com/insights/amr/2019/seeing-through-sound--acoustic-fingerprinting/

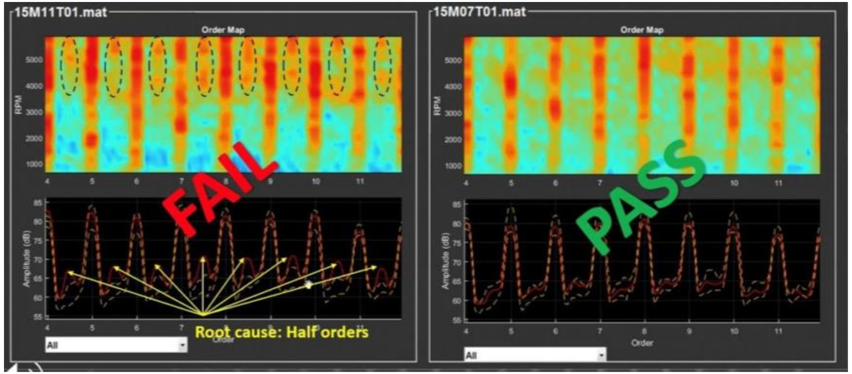
Next Steps

- **Follow-up project:**
  - Aging of solar modules in the field → ultrasonic sensor for degradation characterization

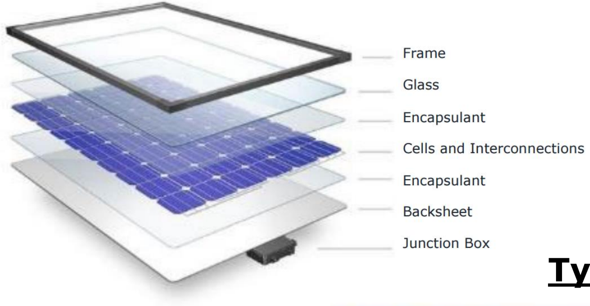
Goal: to expand the method to evaluate module health
- during field and accelerated aging (temperature, humidity, UV, stress)
- incorporating different encapsulants (EVA, POE) and backsheets

The ultimate goal is a module polymer degradation model based on ultrasonic measurables enabling an estimation of the remaining module's lifetime.

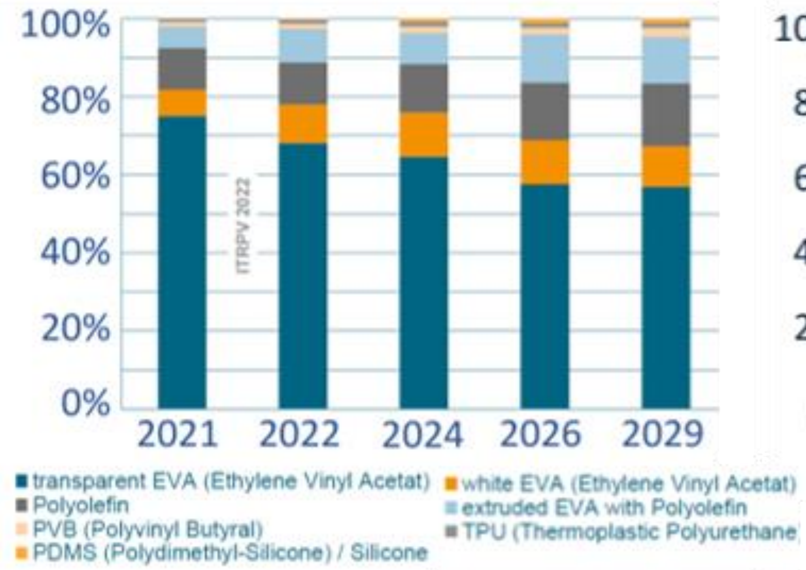
<u>Acoustic Fingerprint</u>



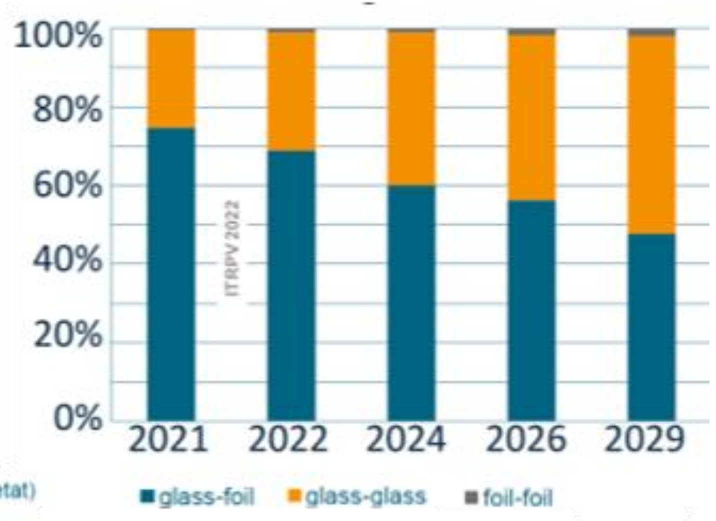
The Solar Module



Types of Encapsulants



Glass-Glass vs. Glass-Backsheet



[1]O. A. Arruti, Solar PV Modules: Market Trends, Materials & Manufacturing Processes, PV Systems Technologies and Design, GoPV Project Summer School, June 2022

Hochschule für Technik
und Wirtschaft Berlin

University of Applied Sciences

www.htw-berlin.de