DSCI351-351m-451: Class 01a, (CWRU, Pitt, UCF, UTRGV)

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11 Background

Photovoltaic (PV) modules consist of solar cells, polymers and glass

- When exposed in outdoor conditions
  - (in the presence of humidity, UV irradiation and temperature)
- PV modules experience degradation
  - In turn, the polymers also degrade
- Hence, it is important to understand
  - the packaging strategies and their role in degradation

Packaging strategies involve various components

- Solar cell type
- Polymeric materials
  - Encapsulants:
    * Protect solar cells from external conditions and mechanical impacts
    * Provide electrical isolation as well as structural support [1]
  - Backsheets: provide stability against UV irradiation and moisture
    * Have good reflectance and low water vapor permeability [2,3]
- Module architecture: rear layer of the PV module
  - Is it glass (double glass or DG) versus polymer (glass/backsheet or GB)?

Ethylene vinyl acetate has been around as the polymeric encapsulant for several decades

- It is a cheaper option and
  - numerous long-term studies have been performed to understand its behavior

- It is not really the best because it undergoes chemical degradation
  - In the presence of high temperature and UV irradiation
- There are emerging materials
  - like polyolefin elastomer (POE) and thermoplastic polyolefin (TPO)
  - But how well do they actually perform?

Degradation takes several decades to manifest

- Laboratory-based accelerated exposures
  - try and mimic outdoor degradation of PV modules
- And it takes only a few days to months
  - for exposure to complete in accelerated conditions

In this study, 4-cell PV modules (referred to as minimodules)

- were fabricated at the SDLE Research Center
- Using EVA and POE as the encapsulants
- DG and GB module architectures
  - Double Glass (DG)
  - Glass / Backsheet (GB)
- Two types of exposure
  - mDH (80°C and 85% relative humidity)
  - mDH + FSL: combination of mDH with 420 Wm^{-2} light
- 2520 hours of exposure
  - Adding up to 5 exposure time steps
  - Baseline (step 0) measurements are also included
- Now, we want to compare across encapsulants and architectures
  - (PV minimodule variants) across exposures
  - Using 83.4% and 95% confidence intervals (CIs)
  - And inference by eye

Note that each variant has 2 minimodules,

- corresponding to 8 cell-level measurements
- Improves statistical significance of results
- Reduces the standard error by $\sqrt{8}$

12 Confidence intervals and inference by eye

For null hypothesis testing at a 5% significance level

- We make use of various statistical measures like t-tests, p-values and CIs

95% CIs are the most popular ones

- Correspond to 5% significance level
- 95% capture rate used for 1 sample t-test
  - i.e. the estimated mean is in the 95% CI range, 95% of the times
- Used to identify PV module variants that are durable/degrading

In the case of 2 sample t-test, 83.4% CIs are used

- Enables rank-ordering of variants that are significantly different from each other

Inference by eye was first described by Cumming et al. [4]

- If we have two independent groups
  - When ends of 95% CIs touch each other, the p-value corresponds to ~0.01
  - When ends of 83.4% CIs touch each other, the p-value is ~0.05

Using these ideas,

- we can compare between PV minimodule variants

13 About the dataset

This dataset consists of 14 variables

- ID: minimodule name followed by cell number
  - Cell number can go from 1-4
- mobr: manufacturer (CWRU)
- ecp: encapsulant (EVA/POE)
- arch: minimodule architecture (GB/DG)
- expt: exposure type (mDH/mDH+FSL)
- dy: time in decimal year
  - Usually, we have years as whole numbers
  - Decimal year means that there are decimal numbers (like 0.38765)
- es: exposure step (end of exposure corresponds to step 5)
- n__Pmp__IV: normalized power from current-voltage measurements
- ci__n__Pmp variables
  - 83.4% versus 95%
  - 'up' means upper confidence limit
  - 'mean' means mean of the measurements
  - 'low' means lower confidence limit

14 Code to plot confidence intervals

The following code chunk pertains to

- power output data from current-voltage curves
- for 4-cell minimodules fabricated at CWRU.

```
# load relevant packages
library(magrittr)
library(tidyverse)
```

```
## -- Attaching packages --------------------------------------- tidyverse 1.3.1 --

## v ggplot2 3.3.6      v purrr   0.3.5
## v tibble  3.1.7      v dplyr   1.0.10
## v tidyr   1.2.1      v stringr 1.4.1
## v readr   2.1.3      v forcats 0.5.2

## -- Conflicts ------------------------------------------ tidyverse_conflicts() --
## x tidyr::extract()   masks magrittr::extract()
## x dplyr::filter()    masks stats::filter()
## x dplyr::lag()       masks stats::lag()
## x purrr::set_names() masks magrittr::set_names()
```

```
library(ggplot2)
library(dplyr)
library(latex2exp)
```

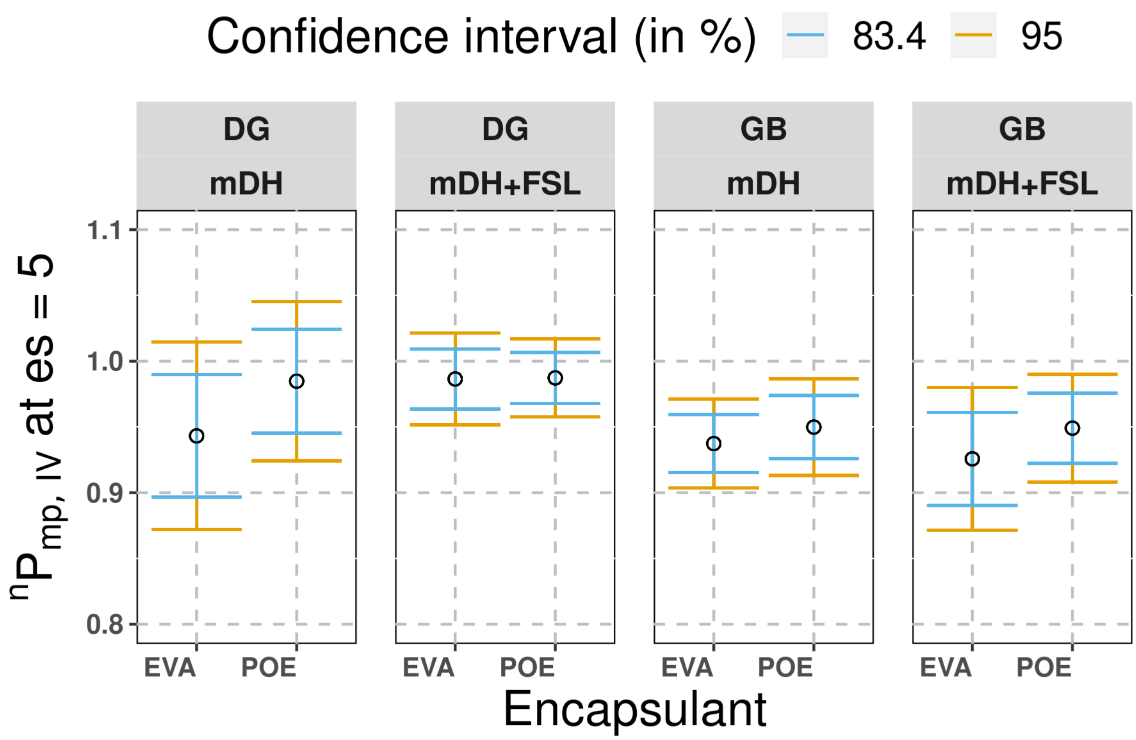
```
# load the data frame
ind_mod <- read.csv("./data/cwru_df.csv", stringsAsFactors = F)

# defining plot theme
```

```r
# feel free to customize it as per your preferences
plot_theme <-
  theme(
    panel.background = element_rect(fill = "white", colour = "black"),
    panel.grid.major = element_line(colour = "gray", linetype = "dashed"),
    axis.text = element_text(size = 12, face = "bold"),
    axis.text.x = element_text(size = 10,
                               face = "bold",
                               hjust = 1),
    axis.text.y = element_text(size = 10,
                               face = "bold",
                               hjust = 1),
    axis.title = element_text(size = 18),
    strip.text = element_text(size = 12, face = "bold"),
    text = element_text(size = 18),
    panel.spacing = unit(1, "lines"),
    legend.position = "top"
  )
```

```r
# CI plot with facet grid
# both 83.4% and 95% CIs are included
# now we can compare across different encapsulants and architectures
# at the end of exposure cycle
# feel free to choose color palettes of your choice; a good source is coolors.co
ind_mod %>%
  ggplot() +
  facet_grid(~ `arch` + `expt`) +
  geom_errorbar(
    aes(
      ymax = ci_n_Pmp_IV_up_95,
      ymin = ci_n_Pmp_IV_low_95,
      y = n_Pmp_IV,
      x = reorder(ecp, n_Pmp_IV),
      color = "#E69F00"
    )
  )  +
  geom_errorbar(
    aes(
      ymax = ci_n_Pmp_IV_up_83.4,
      ymin = ci_n_Pmp_IV_low_83.4,
      y = n_Pmp_IV,
      x = reorder(ecp, n_Pmp_IV),
      color = "#56B4E9"
    )
  ) +
  geom_point(
    aes(y = ci_n_Pmp_IV_mean_95, x = ecp),
    shape = 1,
    size = 2,
    color = "black"
  ) +
  coord_cartesian(y = c(0.8, 1.1)) + # n_Pmp_IV
  labs(y = TeX('$^{n}P_{mp, IV}$ at es = 5'),
       x = 'Encapsulant',
```

```
      color = "Confidence interval (in %)") +
  scale_color_manual(labels = c("83.4", "95"),
                     values = c("#56B4E9","#E69F00")) +
  plot_theme
```



15 Interpretation

15.1 83.4% CIs

It can be seen that there is no significant impact of encapsulant type

- i.e. 83.4% CIs overlap in each of the architecture/exposure type categories

Between categories,

- EVA-based minimodules (GB in mDH and mDH+FSL exposures)
  - are significantly different

- From DG in mDH+FSL exposure

In the case of other minimodule categories,

- they seem to be similar to each other
- Due to overlapping 83.4% CIs

15.2 95% CIs

GB minimodules are seen to be experiencing power loss

- Estimated means for the GB minimodules:
  - indicate that the power loss is about 5-6% on average

DG minimodules in mDH exposure

- seem to be exhibiting different trends with encapsulant type
- The ones with EVA have more power loss than the POE type

CIs for DG minimodules in mDH exposure have relatively wider CIs

- Affecting our understanding of the effect

16 References

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2. Jorma Peltola. New Era in Backsheet Materials? EQ Magazine, September 2016. URL https://www.eqmagpro.com/wp-content/uploads/2016/12/PV-New-Era-in-Backsheet-Materials.pdf.

3. P.Hülsmann and G.M.Wallner. Permeation of water vapour through polyethylene terephthalate (PET) films for back-sheets of photovoltaic modules. Polymer Testing, 58:153–158, April 2017. ISSN 0142-9418. doi:10.1016/j.polymertesting.2016.11.028. https://dx.doi.org/10.1016/j.polymertesting.2016.11.028

4. Geoff Cumming and Sue Finch. Inference by Eye: Confidence Intervals and How to Read Pictures of Data. American Psychologist, 60(2):170–180, 2005. ISSN 1935-990X(Electronic),0003-066X(Print). doi:10.1037/0003-066X.60.2.170. https://dx.doi.org/10.1037/0003-066X.60.2.170