# Choice Paper Simulation

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## Table of contents

Techno-economic analysis of agrivoltaic systems in Alabama. A paper for Choice Magazine, AAEA.

# 1 Setting Up

## 1.1 Housekeeping

```
rm(list = ls()) # Clean the environment.
options(
  warn=0, # Warnings. options(warn=-1) / options(warn=0)
  scipen=999 # No scientific notations.
  )
```

## 1.2 Working directory

Codes and output are suppressed. Errors and warnings are visible. No warning and no error means code is working as it should.

## 1.3 Load libraries

```
library(tidyverse, warn.conflicts = FALSE, quietly = TRUE)
```

```
-- Attaching core tidyverse packages ------------------------ tidyverse 2.0.0 --
v dplyr     1.1.4     v readr     2.1.5
v forcats   1.0.0     v stringr   1.5.1
v ggplot2   3.5.1     v tibble    3.2.1
v lubridate 1.9.3     v tidyr     1.3.1
v purrr     1.0.2
-- Conflicts ------------------------------------------ tidyverse_conflicts() --
x dplyr::filter() masks stats::filter()
x dplyr::lag()    masks stats::lag()
i Use the conflicted package (<http://conflicted.r-lib.org/>) to force all conflicts to becom
```

```r
library(psych, warn.conflicts = FALSE, quietly = TRUE)
library(likert,  warn.conflicts = FALSE, quietly = TRUE) # Likert Items
library(mice,  warn.conflicts = FALSE, quietly = TRUE)
library(openxlsx2, warn.conflicts = FALSE, quietly = TRUE)
library(ggpubr, warn.conflicts = FALSE, quietly = TRUE) # Scatter plot
library(gmodels,  warn.conflicts = FALSE, quietly = TRUE) # Crosstab
library(reshape2, warn.conflicts = FALSE, quietly = TRUE) # Reshape data
library(pacman,  warn.conflicts = FALSE, quietly = TRUE) # Package Management
library(progress, warn.conflicts = FALSE, quietly = TRUE) #progress bar
library(arrow, warn.conflicts = FALSE, quietly = TRUE) #progress bar
```

### 1.4 Theme for plots

Setting theme for plots:

## 2 Import data

Import necessary data.

### 2.1 Tomato

- Yield = Total tomato production (total bucket of 25 lb) from 1 acres of land which varies from 10% to 200% of total production (100%). The range was simulated by multiplying 100% yield by yldvar.
- yldvar = Yield variation parameter ranges from 10% to 200%.
- Rev17 to Rev23 = Revenue for price ranges of \$17 to \$23 per bucket of tomato.
- Total cost = Total cost of production for the given yield.
- rolac17 to rolac23= Return to operator, labor and capital for price range of \$17 to \$23.
- operator Cost = Operator labor cost at \$15/hour for given yield. For 100% yield, total hours = 90.
- rlc17 to 23 = Return to land and capital after subtracting operator cost from total revenue.

```r
tomato <- read_xlsx("Data/Parameters.xlsx",
                    sheet = "Tomato",
                    start_row = 2,
                    start_col = 9,
                    skip_empty_rows = TRUE,
                    skip_empty_cols = TRUE,
                    col_names = TRUE) %>%
  rename(yield = Yield,
         yldvar = `Yield Variation (%)`)
str(tomato)
```

```
'data.frame':	21 obs. of  25 variables:
 $ yldvar       : num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield        : num  2720 2584 2448 2312 2176 ...
 $ Rev17        : num  46240 43928 41616 39304 36992 ...
 $ Rev18        : num  48960 46512 44064 41616 39168 ...
 $ Rev19        : num  51680 49096 46512 43928 41344 ...
 $ Rev20        : num  54400 51680 48960 46240 43520 ...
 $ Rev21        : num  57120 54264 51408 48552 45696 ...
 $ Rev22        : num  59840 56848 53856 50864 47872 ...
 $ Rev23        : num  62560 59432 56304 53176 50048 ...
 $ Total Cost   : num  24561 23863 23165 22467 21769 ...
 $ rolac17      : num  21679 20065 18451 16837 15223 ...
 $ rolac18      : num  24399 22649 20899 19149 17399 ...
 $ rolac19      : num  27119 25233 23347 21461 19575 ...
 $ rolac20      : num  29839 27817 25795 23773 21751 ...
 $ rolac21      : num  32559 30401 28243 26085 23927 ...
 $ rolac22      : num  35279 32985 30691 28397 26103 ...
 $ rolac23      : num  37999 35569 33139 30709 28279 ...
 $ Operator Cost: num  2700 2565 2430 2295 2160 ...
 $ rlc17        : num  18979 17500 16021 14542 13063 ...
 $ rlc18        : num  21699 20084 18469 16854 15239 ...
 $ rlc19        : num  24419 22668 20917 19166 17415 ...
 $ rlc20        : num  27139 25252 23365 21478 19591 ...
 $ rlc21        : num  29859 27836 25813 23790 21767 ...
 $ rlc22        : num  32579 30420 28261 26102 23943 ...
 $ rlc223       : num  35299 33004 30709 28414 26119 ...
```

```r
head(tomato); tail(tomato)
```

```
  yldvar yield Rev17 Rev18 Rev19 Rev20 Rev21 Rev22 Rev23 Total Cost  rolac17
```

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 2.0 | 2720 | 46240 | 48960 | 51680 | 54400 | 57120 | 59840 | 62560 | 24560.62 | 21679.38 |
| 4 | 1.9 | 2584 | 43928 | 46512 | 49096 | 51680 | 54264 | 56848 | 59432 | 23862.62 | 20065.38 |
| 5 | 1.8 | 2448 | 41616 | 44064 | 46512 | 48960 | 51408 | 53856 | 56304 | 23164.62 | 18451.38 |
| 6 | 1.7 | 2312 | 39304 | 41616 | 43928 | 46240 | 48552 | 50864 | 53176 | 22466.62 | 16837.38 |
| 7 | 1.6 | 2176 | 36992 | 39168 | 41344 | 43520 | 45696 | 47872 | 50048 | 21768.62 | 15223.38 |
| 8 | 1.5 | 2040 | 34680 | 36720 | 38760 | 40800 | 42840 | 44880 | 46920 | 21070.62 | 13609.38 |

| | rolac18 | rolac19 | rolac20 | rolac21 | rolac22 | rolac23 | Operator Cost | rlc17 |
|---|---|---|---|---|---|---|---|---|
| 3 | 24399.38 | 27119.38 | 29839.38 | 32559.38 | 35279.38 | 37999.38 | 2700 | 18979.38 |
| 4 | 22649.38 | 25233.38 | 27817.38 | 30401.38 | 32985.38 | 35569.38 | 2565 | 17500.38 |
| 5 | 20899.38 | 23347.38 | 25795.38 | 28243.38 | 30691.38 | 33139.38 | 2430 | 16021.38 |
| 6 | 19149.38 | 21461.38 | 23773.38 | 26085.38 | 28397.38 | 30709.38 | 2295 | 14542.38 |
| 7 | 17399.38 | 19575.38 | 21751.38 | 23927.38 | 26103.38 | 28279.38 | 2160 | 13063.38 |
| 8 | 15649.38 | 17689.38 | 19729.38 | 21769.38 | 23809.38 | 25849.38 | 2025 | 11584.38 |

| | rlc18 | rlc19 | rlc20 | rlc21 | rlc22 | rlc223 |
|---|---|---|---|---|---|---|
| 3 | 21699.38 | 24419.38 | 27139.38 | 29859.38 | 32579.38 | 35299.38 |
| 4 | 20084.38 | 22668.38 | 25252.38 | 27836.38 | 30420.38 | 33004.38 |
| 5 | 18469.38 | 20917.38 | 23365.38 | 25813.38 | 28261.38 | 30709.38 |
| 6 | 16854.38 | 19166.38 | 21478.38 | 23790.38 | 26102.38 | 28414.38 |
| 7 | 15239.38 | 17415.38 | 19591.38 | 21767.38 | 23943.38 | 26119.38 |
| 8 | 13624.38 | 15664.38 | 17704.38 | 19744.38 | 21784.38 | 23824.38 |

| | yldvar | yield | Rev17 | Rev18 | Rev19 | Rev20 | Rev21 | Rev22 | Rev23 | Total Cost | rolac17 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 0.5 | 680 | 11560 | 12240 | 12920 | 13600 | 14280 | 14960 | 15640 | 14090.62 | -2530.617 |
| 19 | 0.4 | 544 | 9248 | 9792 | 10336 | 10880 | 11424 | 11968 | 12512 | 13392.62 | -4144.617 |
| 20 | 0.3 | 408 | 6936 | 7344 | 7752 | 8160 | 8568 | 8976 | 9384 | 12694.62 | -5758.617 |
| 21 | 0.2 | 272 | 4624 | 4896 | 5168 | 5440 | 5712 | 5984 | 6256 | 11996.62 | -7372.617 |
| 22 | 0.1 | 136 | 2312 | 2448 | 2584 | 2720 | 2856 | 2992 | 3128 | 11298.62 | -8986.617 |
| 23 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10600.62 | -10600.617 |

| | rolac18 | rolac19 | rolac20 | rolac21 | rolac22 | rolac23 |
|---|---|---|---|---|---|---|
| 18 | -1850.617 | -1170.617 | -490.6174 | 189.3826 | 869.3826 | 1549.3826 |
| 19 | -3600.617 | -3056.617 | -2512.6174 | -1968.6174 | -1424.6174 | -880.6174 |
| 20 | -5350.617 | -4942.617 | -4534.6174 | -4126.6174 | -3718.6174 | -3310.6174 |
| 21 | -7100.617 | -6828.617 | -6556.6174 | -6284.6174 | -6012.6174 | -5740.6174 |
| 22 | -8850.617 | -8714.617 | -8578.6174 | -8442.6174 | -8306.6174 | -8170.6174 |
| 23 | -10600.617 | -10600.617 | -10600.6174 | -10600.6174 | -10600.6174 | -10600.6174 |

| | Operator Cost | rlc17 | rlc18 | rlc19 | rlc20 | rlc21 |
|---|---|---|---|---|---|---|
| 18 | 675 | -3205.617 | -2525.617 | -1845.617 | -1165.617 | -485.6174 |
| 19 | 540 | -4684.617 | -4140.617 | -3596.617 | -3052.617 | -2508.6174 |
| 20 | 405 | -6163.617 | -5755.617 | -5347.617 | -4939.617 | -4531.6174 |
| 21 | 270 | -7642.617 | -7370.617 | -7098.617 | -6826.617 | -6554.6174 |
| 22 | 135 | -9121.617 | -8985.617 | -8849.617 | -8713.617 | -8577.6174 |
| 23 | 0 | -10600.617 | -10600.617 | -10600.617 | -10600.617 | -10600.6174 |

```
        rlc22      rlc223
18    194.3826    874.3826
19  -1964.6174  -1420.6174
20  -4123.6174  -3715.6174
21  -6282.6174  -6010.6174
22  -8441.6174  -8305.6174
23 -10600.6174 -10600.6174
```

### 2.2 Strawberry

- Everything same as tomato.
- Numbers 3 to 9 in names are price ranges for strawberry.

```r
strawberry <- read_xlsx("Data/Parameters.xlsx",
                        sheet = "Strawberry",
                        start_row = 2,
                        start_col = 7,
                        skip_empty_rows = TRUE,
                        skip_empty_cols = TRUE,
                        col_names = TRUE) %>%
  rename(yield = Yield,
         yldvar = `Yield Variation (%)`)
str(strawberry)
```

```
'data.frame':   21 obs. of  25 variables:
 $ yldvar       : num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield        : num  6150 5842 5535 5228 4920 ...
 $ Rev3         : num  18450 17528 16605 15682 14760 ...
 $ Rev4         : num  24600 23370 22140 20910 19680 ...
 $ Rev5         : num  30750 29212 27675 26138 24600 ...
 $ Rev6         : num  36900 35055 33210 31365 29520 ...
 $ Rev7         : num  43050 40898 38745 36592 34440 ...
 $ Rev8         : num  49200 46740 44280 41820 39360 ...
 $ Rev9         : num  55350 52582 49815 47048 44280 ...
 $ Total Cost   : num  20190 19845 19499 19154 18808 ...
 $ rolac3       : num  -1740 -2317 -2894 -3471 -4048 ...
 $ rolac4       : num  4410 3525 2641 1756 872 ...
 $ rolac5       : num  10560 9368 8176 6984 5792 ...
 $ rolac6       : num  16710 15210 13711 12211 10712 ...
 $ rolac7       : num  22860 21053 19246 17439 15632 ...
 $ rolac8       : num  29010 26895 24781 22666 20552 ...
```

```
 $ rolac9       : num  35160 32738 30316 27894 25472 ...
 $ Operator Cost: num  2700 2565 2430 2295 2160 ...
 $ rlc3         : num  -4440 -4882 -5324 -5766 -6208 ...
 $ rlc4         : num  1710 960 211 -539 -1288 ...
 $ rlc5         : num  7860 6803 5746 4689 3632 ...
 $ rlc6         : num  14010 12645 11281 9916 8552 ...
 $ rlc7         : num  20160 18488 16816 15144 13472 ...
 $ rlc8         : num  26310 24330 22351 20371 18392 ...
 $ rlc9         : num  32460 30173 27886 25599 23312 ...
```

```
head(strawberry); tail(strawberry)
```

```
  yldvar  yield    Rev3  Rev4    Rev5  Rev6    Rev7  Rev8    Rev9 Total Cost
3    2.0 6150.0 18450.0 24600 30750.0 36900 43050.0 49200 55350.0   20190.49
4    1.9 5842.5 17527.5 23370 29212.5 35055 40897.5 46740 52582.5   19844.85
5    1.8 5535.0 16605.0 22140 27675.0 33210 38745.0 44280 49815.0   19499.20
6    1.7 5227.5 15682.5 20910 26137.5 31365 36592.5 41820 47047.5   19153.56
7    1.6 4920.0 14760.0 19680 24600.0 29520 34440.0 39360 44280.0   18807.91
8    1.5 4612.5 13837.5 18450 23062.5 27675 32287.5 36900 41512.5   18462.27
     rolac3     rolac4    rolac5    rolac6    rolac7    rolac8    rolac9
3 -1740.495 4409.50503 10559.505 16709.51 22859.51 29009.51 35159.51
4 -2317.350 3525.15003  9367.650 15210.15 21052.65 26895.15 32737.65
5 -2894.205 2640.79503  8175.795 13710.80 19245.80 24780.80 30315.80
6 -3471.060 1756.44003  6983.940 12211.44 17438.94 22666.44 27893.94
7 -4047.915  872.08503  5792.085 10712.09 15632.09 20552.09 25472.09
8 -4624.770  -12.26997  4600.230  9212.73 13825.23 18437.73 23050.23
  Operator Cost      rlc3      rlc4     rlc5      rlc6     rlc7     rlc8
3          2700 -4440.495  1709.505 7859.505 14009.505 20159.51 26309.51
4          2565 -4882.350   960.150 6802.650 12645.150 18487.65 24330.15
5          2430 -5324.205   210.795 5745.795 11280.795 16815.80 22350.80
6          2295 -5766.060  -538.560 4688.940  9916.440 15143.94 20371.44
7          2160 -6207.915 -1287.915 3632.085  8552.085 13472.09 18392.09
8          2025 -6649.770 -2037.270 2575.230  7187.730 11800.23 16412.73
      rlc9
3 32459.51
4 30172.65
5 27885.80
6 25598.94
7 23312.09
8 21025.23
```

```
   yldvar  yield    Rev3 Rev4    Rev5 Rev6    Rev7  Rev8    Rev9 Total Cost
```

```
18    0.5 1537.5 4612.5 6150 7687.5 9225 10762.5 12300 13837.5   15005.82
19    0.4 1230.0 3690.0 4920 6150.0 7380  8610.0  9840 11070.0   14660.17
20    0.3  922.5 2767.5 3690 4612.5 5535  6457.5  7380  8302.5   14314.53
21    0.2  615.0 1845.0 2460 3075.0 3690  4305.0  4920  5535.0   13968.88
22    0.1  307.5  922.5 1230 1537.5 1845  2152.5  2460  2767.5   13623.24
23    0.0    0.0    0.0    0    0.0    0     0.0     0     0.0   13277.59
      rolac3     rolac4     rolac5     rolac6     rolac7     rolac8     rolac9
18 -10393.32  -8855.820  -7318.320  -5780.820  -4243.320  -2705.820  -1168.320
19 -10970.17  -9740.175  -8510.175  -7280.175  -6050.175  -4820.175  -3590.175
20 -11547.03 -10624.530  -9702.030  -8779.530  -7857.030  -6934.530  -6012.030
21 -12123.88 -11508.885 -10893.885 -10278.885  -9663.885  -9048.885  -8433.885
22 -12700.74 -12393.240 -12085.740 -11778.240 -11470.740 -11163.240 -10855.740
23 -13277.59 -13277.595 -13277.595 -13277.595 -13277.595 -13277.595 -13277.595
   Operator Cost      rlc3      rlc4       rlc5       rlc6       rlc7
18           675 -11068.32  -9530.82  -7993.320  -6455.820  -4918.320
19           540 -11510.17 -10280.17  -9050.175  -7820.175  -6590.175
20           405 -11952.03 -11029.53 -10107.030  -9184.530  -8262.030
21           270 -12393.88 -11778.88 -11163.885 -10548.885  -9933.885
22           135 -12835.74 -12528.24 -12220.740 -11913.240 -11605.740
23             0 -13277.59 -13277.59 -13277.595 -13277.595 -13277.595
         rlc8       rlc9
18  -3380.820  -1843.320
19  -5360.175  -4130.175
20  -7339.530  -6417.030
21  -9318.885  -8703.885
22 -11298.240 -10990.740
23 -13277.595 -13277.595
```

### 2.3 Squash

- Everything same as tomato and strawberry.
- Numbers 11 to 17 in names are price ranges for squash.

```r
squash <- read_xlsx("Data/Parameters.xlsx",
                    sheet = "Squash",
                    start_row = 2,
                    start_col = 8,
                    skip_empty_rows = TRUE,
                    skip_empty_cols = TRUE,
                    col_names = TRUE) %>%
  rename(yield = Yield,
```

```
         yldvar = `Yield Variation (%)`)
str(squash)
head(squash); tail(squash)
```

### 2.4 Electricity price

Electricity price ranges from 1 cents to 6 cents in 0.5 cent increment. Previously, I used AL retail electricity price as described below. It's no longer in use but I put description below for the record.

Electricity price ($/kWh) was retail electricity price range for Alabama based on retail electricity price in April 2023 and April 2024 taken from DOE Database. Retail electricity price range in Alabama was from 6.44 to 15.85 cents/kWh in April 2023 and April 2024 which represents industry, commercial, and residential prices.

```
elec_price <- read_xlsx("Data/Parameters.xlsx",
                              sheet = "Electricity Price") %>%
  rename(epr_kwh = `Electricity Price ($/kWh)`)
str(elec_price)
```

```
'data.frame':   11 obs. of  1 variable:
 $ epr_kwh: num  0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05 0.055 ...
```

```
elec_price
```

```
   epr_kwh
2    0.010
3    0.015
4    0.020
5    0.025
6    0.030
7    0.035
8    0.040
9    0.045
10   0.050
11   0.055
12   0.060
```

### 2.5 PV system cost

- Data taken from "Capital Costs for Dual-Use Photovoltaic Installations: 2020 Benchmark" Table 1 and Figure 3.
- This data was used to estimate CAPEX.
- avtyps = agrivoltaic types.
- item = itemized component of system.
- cost = cost of each item.
- height = ground to panel clearance height (ft.)
- tcost = Total cost is the sum of all itemized cost for AV system. See figure 3 and table 1 in above document for more detail.

```
pvsc <- wb_read(file = "Data/Parameters.xlsx",
                sheet = "PV system Cost (NREL)",
                rows = c(1:109),
                cols = c(1:5),
                col_names = TRUE) %>%
  rename(avtyps = `AV Types`,
         item = Item,
         cost = `Cost ($/W)`,
         height = `Panel Height (ft.)`,
         tcost = `Total Cost ($/W)`
         )
str(pvsc)
```

```
'data.frame':   108 obs. of  5 variables:
 $ avtyps: chr  "Typical Fixed PV" "Typical Fixed PV" "Typical Fixed PV" "Typical Fixed PV"
 $ item  : chr  "EPC/Developer Net Profit" "Developer Overhead" "Contingency(3%)" "Interconne
 $ cost  : num  0.11 0.15 0.05 0.03 0.02 0.05 0.12 0.18 0.24 0.11 ...
 $ height: num  4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 ...
 $ tcost : num  1.53 1.53 1.53 1.53 1.53 1.53 1.53 1.53 1.53 1.53 ...
```

```
head(pvsc); tail(pvsc)
```

```
            avtyps                     item cost height tcost
2 Typical Fixed PV EPC/Developer Net Profit 0.11    4.6  1.53
3 Typical Fixed PV       Developer Overhead 0.15    4.6  1.53
4 Typical Fixed PV          Contingency(3%) 0.05    4.6  1.53
5 Typical Fixed PV      Interconnection Fee 0.03    4.6  1.53
6 Typical Fixed PV  Permitting Fee (if any) 0.02    4.6  1.53
7 Typical Fixed PV         Sale Tax (if any) 0.05    4.6  1.53
```

```
                                      avtyps                        item cost
104 PV + Crops (Reinforced Regular Mount)               EPC Overhead 0.25
105 PV + Crops (Reinforced Regular Mount) Installation and Labor Cost 0.32
106 PV + Crops (Reinforced Regular Mount)             Electrical BOS 0.38
107 PV + Crops (Reinforced Regular Mount)             Structural BOS 0.32
108 PV + Crops (Reinforced Regular Mount)              Inverter Only 0.08
109 PV + Crops (Reinforced Regular Mount)                     Module 0.40
    height tcost
104    8.2  2.33
105    8.2  2.33
106    8.2  2.33
107    8.2  2.33
108    8.2  2.33
109    8.2  2.33
```

### 2.6 Capex (NREL)

Variable Descriptions:

- Capex: Capital investment cost ($/W) to develop solar energy system. Capex includes cost of physical structure, developer's overhead and EPC/Developer's net profit.
- capex estimated as f(height, tracker) using OLS for 6.4 ft Tracking system.
- Height = ground to panel clearance in ft.
- array: Solar array. Tracker = Single axis sun tracking panels; Fixed = Non-tracking panels.
- Source: Horowitz, 2020. CAPEX AV.

```
capex <- read.table(file = "Data/CAPEX.txt",
                    header = TRUE,
                  sep = "\t") %>%
  rename(capex = cost,
         height = pheight,
         array = tracker)
str(capex)
```

```
'data.frame':   6 obs. of  3 variables:
 $ height: num  4.6 4.6 6.4 8.2 8.2 6.4
 $ capex : num  1.59 1.73 1.85 2.33 2.11 ...
 $ array : chr  "Fixed" "Tracking" "Fixed" "Fixed" ...
```

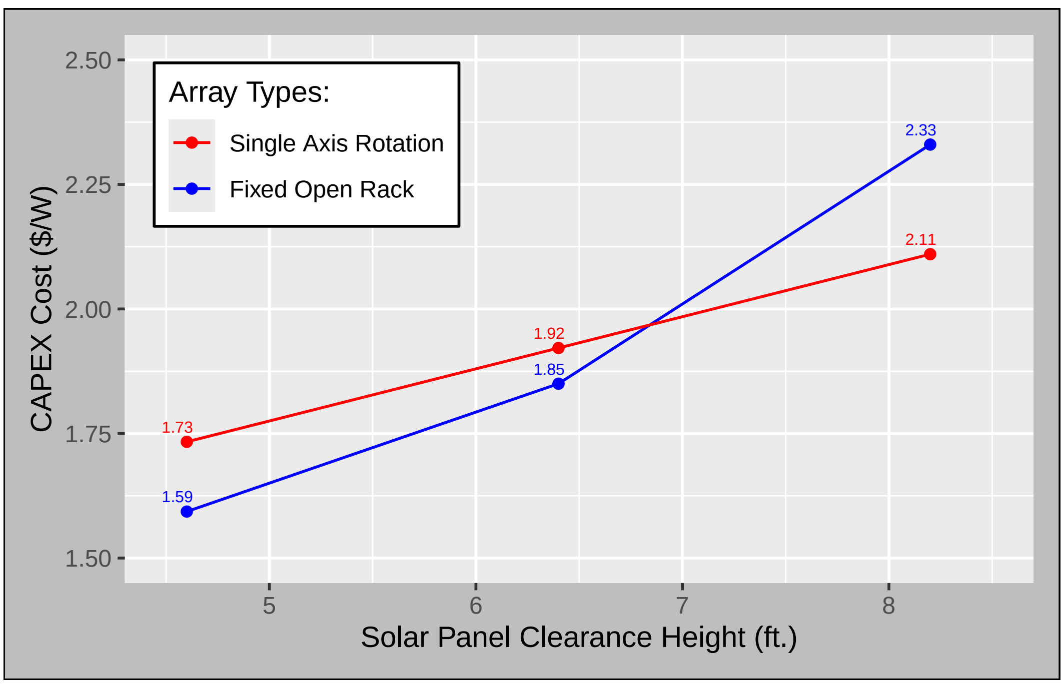
```r
capex
```

```
  height    capex    array
1    4.6 1.593333    Fixed
2    4.6 1.733333 Tracking
3    6.4 1.850000    Fixed
4    8.2 2.330000    Fixed
5    8.2 2.110000 Tracking
6    6.4 1.921667 Tracking
```

### 2.6.1 Plotting capex

```r
capex %>%
  ggplot(aes(
    x = height,
    y = capex,
    color = array,
    group = array
  )) +
  geom_point() +
  geom_line() +
  # Display the rounded capex values
  geom_text(aes(label = sprintf("%.2f", capex)),
            vjust = -0.8,
            hjust = 0.8,
            size = 2,
            check_overlap = TRUE,
            show.legend = FALSE
            ) +
  labs(
    #title = "CAPEX Cost by Solar Panel Height",
    x = "Solar Panel Clearance Height (ft.)",
    y = "CAPEX Cost ($/W)",
    color = "Array Types:"
    ) +
  scale_x_continuous(limits = c(4.5, 8.5)) +
  scale_y_continuous(limits = c(1.5, 2.5)) +
  guides(color = guide_legend(reverse = TRUE)) +
  theme(
    plot.background = element_rect(
```

```
      fill = "grey",
      color = "black"
      ),
    legend.position = "inside",
    legend.position.inside = c(0.2, 0.8),
    legend.background = element_rect(
      fill = "white",
      color = "black"
      ),
    plot.margin = margin(10, 10, 10, 10)
  ) +
  scale_color_manual(
    values = c("Fixed" = "blue",
               "Tracking" = "red"),
    labels = c("Fixed Open Rack",
               "Single Axis Rotation")
  )
```




```
# Save the plot
ggsave(
  filename = "Plots/CAPEX Solar Panels.png",
  width = 8,
```

```
  height = 6,
  units = "in"
  )
```

## 2.7 Panel Configuration

- Panel configuration and DV system output (W).

```
panconf <- wb_read(file = "Data/Parameters.xlsx",
                sheet = "Panel Spacing",
                start_row = 2,
                start_col = 1,
                skip_empty_rows = TRUE,
                skip_empty_cols = TRUE,
                col_names = TRUE)
str(panconf)
```

```
'data.frame':   21 obs. of  21 variables:
 $ Total Area (Acre)             : num  1 1 1 1 1 1 1 1 1 1 ...
 $ Total Area (Sq. Ft.)          : num  43560 43560 43560 43560 43560 ...
 $ Solar Proportion              : num  1 0.95 0.9 0.85 0.8 0.75 0.7 0.65 0.6 0.55 ...
 $ Solar Proportion Area (Sq. Ft.): num  43560 41382 39204 37026 34848 ...
 $ Solar Proportion Area (Sq.M.) : num  4047 3845 3642 3440 3237 ...
 $ Side Length (ft.)             : num  209 209 209 209 209 ...
 $ YSide Length (ft.)            : num  209 209 209 209 209 ...
 $ XSide length (ft.)            : num  209 198 188 177 167 ...
 $ Panel Length (ft.)            : num  7.75 7.75 7.75 7.75 7.75 7.75 7.75 7.75 7.75 7.75 .
 $ Row Seperator (ft.)           : num  6 6 6 6 6 6 6 6 6 6 ...
 $ Panel Width(ft.)              : num  3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 3.5 ...
 $ Panel Area (Sq. ft.)          : num  27.1 27.1 27.1 27.1 27.1 ...
 $ Panels/Row                    : num  59 59 59 59 59 59 59 59 59 59 ...
 $ Total Rows                    : num  15 14 13 12 12 11 10 9 9 8 ...
 $ Total Panels                  : num  885 826 767 708 708 649 590 531 531 472 ...
 $ Array Area (Sq. Ft.)          : num  24006 22405 20805 19204 19204 ...
 $ Array Area (Sq. M.)           : num  2230 2082 1933 1784 1784 ...
 $ XSide Open Length (ft)        : num  92 100 107 115 115 123 131 138 138 146 ...
 $ Inter Panel Spacing (ft)      : num  6 7 8 10 10 12 14 17 17 20 ...
 $ Panel Efficienfy              : num  0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 0.19 .
 $ DC System Size (kW)           : num  424 395 367 339 339 ...
```

```r
head(panconf); tail(panconf)
```

```
  Total Area (Acre) Total Area (Sq. Ft.) Solar Proportion
3                 1                43560             1.00
4                 1                43560             0.95
5                 1                43560             0.90
6                 1                43560             0.85
7                 1                43560             0.80
8                 1                43560             0.75
  Solar Proportion Area (Sq. Ft.) Solar Proportion Area (Sq.M.)
3                           43560                      4046.856
4                           41382                      3844.513
5                           39204                      3642.170
6                           37026                      3439.828
7                           34848                      3237.485
8                           32670                      3035.142
  Side Length (ft.) YSide Length (ft.) XSide length (ft.) Panel Length (ft.)
3          208.7103           208.7103           208.7103               7.75
4          208.7103           208.7103           198.2748               7.75
5          208.7103           208.7103           187.8393               7.75
6          208.7103           208.7103           177.4038               7.75
7          208.7103           208.7103           166.9683               7.75
8          208.7103           208.7103           156.5327               7.75
  Row Seperator (ft.) Panel Width(ft.) Panel Area (Sq. ft.) Panels/Row
3                   6              3.5               27.125         59
4                   6              3.5               27.125         59
5                   6              3.5               27.125         59
6                   6              3.5               27.125         59
7                   6              3.5               27.125         59
8                   6              3.5               27.125         59
  Total Rows Total Panels Array Area (Sq. Ft.) Array Area (Sq. M.)
3         15          885             24005.62            2230.195
4         14          826             22405.25            2081.516
5         13          767             20804.88            1932.836
6         12          708             19204.50            1784.156
7         12          708             19204.50            1784.156
8         11          649             17604.12            1635.477
  XSide Open Length (ft) Inter Panel Spacing (ft) Panel Efficienfy
3                     92                        6             0.19
4                    100                        7             0.19
5                    107                        8             0.19
6                    115                       10             0.19
```

| | | | |
|---|---|---|---|
| 7 | 115 | 10 | 0.19 |
| 8 | 123 | 12 | 0.19 |

| | DC System Size (kW) |
|---|---|
| 3 | 423.7371 |
| 4 | 395.4880 |
| 5 | 367.2388 |
| 6 | 338.9897 |
| 7 | 338.9897 |
| 8 | 310.7405 |

| | Total Area (Acre) | Total Area (Sq. Ft.) | Solar Proportion |
|---|---|---|---|
| 18 | 1 | 43560 | 0.25 |
| 19 | 1 | 43560 | 0.20 |
| 20 | 1 | 43560 | 0.15 |
| 21 | 1 | 43560 | 0.10 |
| 22 | 1 | 43560 | 0.05 |
| 23 | 1 | 43560 | 0.00 |

| | Solar Proportion Area (Sq. Ft.) | Solar Proportion Area (Sq.M.) |
|---|---|---|
| 18 | 10890 | 1011.7140 |
| 19 | 8712 | 809.3712 |
| 20 | 6534 | 607.0284 |
| 21 | 4356 | 404.6856 |
| 22 | 2178 | 202.3428 |
| 23 | 0 | 0.0000 |

| | Side Length (ft.) | YSide Length (ft.) | XSide length (ft.) | Panel Length (ft.) |
|---|---|---|---|---|
| 18 | 208.7103 | 208.7103 | 52.17758 | 7.75 |
| 19 | 208.7103 | 208.7103 | 41.74207 | 7.75 |
| 20 | 208.7103 | 208.7103 | 31.30655 | 7.75 |
| 21 | 208.7103 | 208.7103 | 20.87103 | 7.75 |
| 22 | 208.7103 | 208.7103 | 10.43552 | 7.75 |
| 23 | 208.7103 | 208.7103 | 0.00000 | 7.75 |

| | Row Seperator (ft.) | Panel Width(ft.) | Panel Area (Sq. ft.) | Panels/Row |
|---|---|---|---|---|
| 18 | 6 | 3.5 | 27.125 | 59 |
| 19 | 6 | 3.5 | 27.125 | 59 |
| 20 | 6 | 3.5 | 27.125 | 59 |
| 21 | 6 | 3.5 | 27.125 | 59 |
| 22 | 6 | 3.5 | 27.125 | 59 |
| 23 | 6 | 3.5 | 27.125 | 59 |

| | Total Rows | Total Panels | Array Area (Sq. Ft.) | Array Area (Sq. M.) |
|---|---|---|---|---|
| 18 | 3 | 177 | 4801.125 | 446.0391 |
| 19 | 3 | 177 | 4801.125 | 446.0391 |
| 20 | 2 | 118 | 3200.750 | 297.3594 |

```
21          1           59               1600.375             148.6797
22          0            0                  0.000               0.0000
23          0            0                  0.000               0.0000
   XSide Open Length (ft) Inter Panel Spacing (ft) Panel Efficienfy
18                    185                       92             0.19
19                    185                       92             0.19
20                    193                      193             0.19
21                    200                       NA             0.19
22                    208                       NA             0.19
23                    208                       NA             0.19
   DC System Size (kW)
18            84.74742
19            84.74742
20            56.49828
21            28.24914
22             0.00000
23             0.00000
```

## 2.8 Energy output

Energy output was simulated using NREL PV Watts Calculator.

- sprop = land proportion covered by solar in 1 acres. Value ranges from 0 to 1.
- Panels = Total number of panels in 1 acres of land.
- datalot: 1 = first simulation done for four regions of AL; 2 = second simulation done for four regions of AL. Two simulations have two unique zipcodes for each simulated region.
- al_regs = regions of Alabama
- zips = zipcodes selected from each region of AL for simulation.
- array = Fixed (open rack); 1AxisRot = 1 Axis Tracking. See above NREL tool for more detail.
- dc_kw = DC system size, calculated for each solar panel heights considering solar panels efficiency and area covered by solar panels.
- energy = total energy output ( kWh/Year) considering system parameters. Total hours considered by the model is 8,760 (See PV Watts Calculator Results > help (below the result) > results > download monthly or hourly results).

```r
energy_output <- read_xlsx("Data/Parameters.xlsx",
                           sheet = "Energy Output",
                           start_row = 1,
                           start_col = 1,
                           skip_empty_rows = TRUE,
                           skip_empty_cols = TRUE,
                           col_names = TRUE) %>%
  rename(sprop = `Solar Proportion`,
         panels = `Total Panels`,
         datalot = DataLot,
         al_regs = `Region of AL`,
         zips = ZIPCODE,
         array = `Array Type`,
         dc_kw = `DC System Size (kW)`,
         energy = `Energy (kWh/Year)`) %>%
  mutate(
    dc_kw = round(dc_kw,2),
    array = case_when(
      array == "1AxisRot" ~ "Tracking",
      array == "FixedOpen" ~ "Fixed",
      TRUE ~ array)
    )
str(energy_output)
```

```
'data.frame':   336 obs. of  8 variables:
 $ sprop  : num  1 1 1 1 1 1 1 1 0.95 0.95 ...
 $ panels : num  885 885 885 885 885 885 885 885 826 826 ...
 $ datalot: num  1 1 1 1 1 1 1 1 1 1 ...
 $ al_regs: chr  "Northern" "Northern" "Central" "Central" ...
 $ zips   : num  35801 35801 35223 35223 36117 ...
 $ array  : chr  "Tracking" "Fixed" "Tracking" "Fixed" ...
 $ dc_kw  : num  424 424 424 424 424 ...
 $ energy : num  672887 585225 668895 579758 728181 ...
```

```r
head(energy_output); tail(energy_output)
```

```
  sprop panels datalot    al_regs  zips    array  dc_kw energy
2     1    885       1   Northern 35801 Tracking 423.74 672887
3     1    885       1   Northern 35801    Fixed 423.74 585225
4     1    885       1    Central 35223 Tracking 423.74 668895
5     1    885       1    Central 35223    Fixed 423.74 579758
```

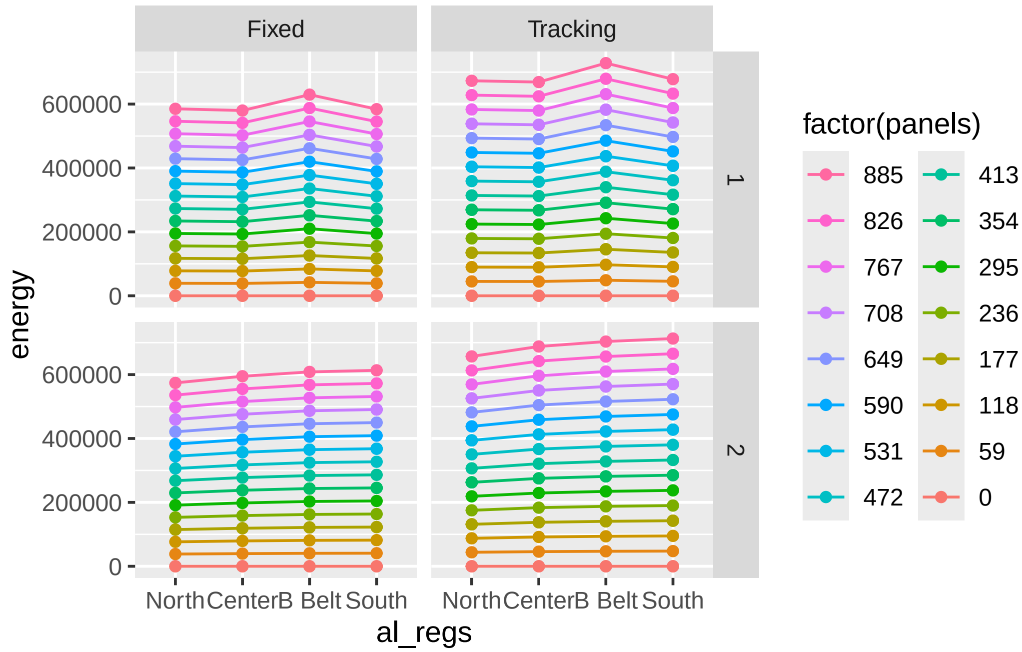
```
6     1    885       1 Black Belt 36117 Tracking 423.74 728181
7     1    885       1 Black Belt 36117    Fixed 423.74 629523
```

```
    sprop panels datalot    al_regs  zips    array dc_kw energy
332     0      0       2    Central 35136 Tracking     0      0
333     0      0       2    Central 35136    Fixed     0      0
334     0      0       2 Black Belt 36040 Tracking     0      0
335     0      0       2 Black Belt 36040    Fixed     0      0
336     0      0       2   Southern 36507 Tracking     0      0
337     0      0       2   Southern 36507    Fixed     0      0
```

### 2.8.1 Energy output by solar panels counts

Plotting Energy output by number of solar panels in one acres of AV system from fixed and single axis rotation system for two zipcodes (1, 2) within each of the four regions of AL.

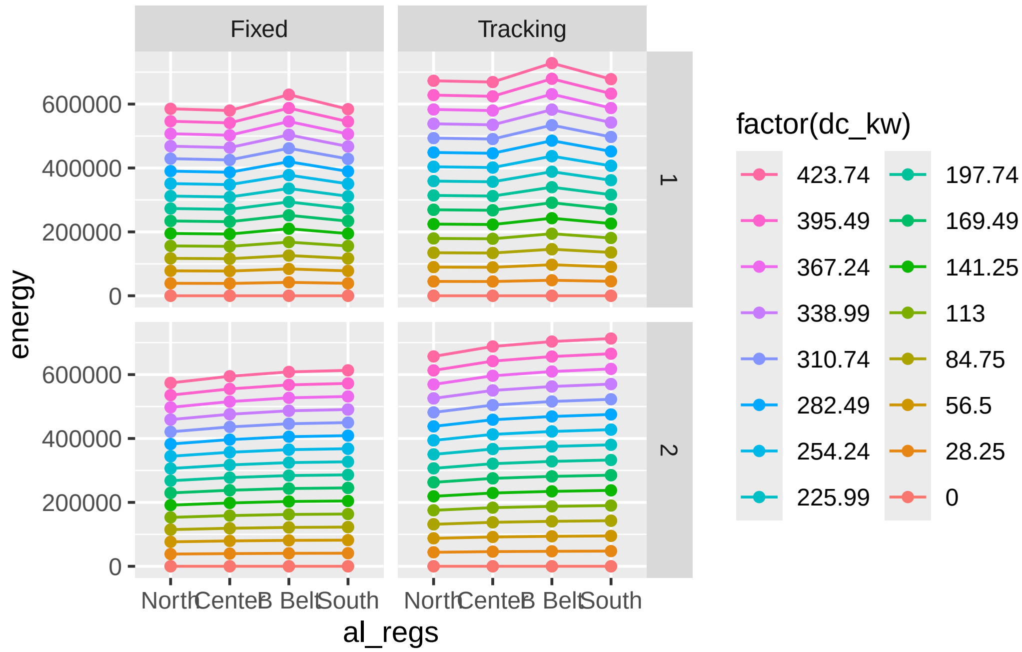
```r
lox <- c("Northern", "Central", "Black Belt", "Southern")
array_levs = c("Single Axis Rotation", "Fixed Open Rack")
datalot_levs = c("Location 1", "Location 2")
ggplot(data = energy_output,
         mapping = aes(x = al_regs,
                       y = energy,
                       #fill = energy,
                       color = factor(panels),
                       group = factor(panels))) +
  geom_line()+
  geom_point() +
  facet_grid(datalot~array) +
  scale_x_discrete(limits = lox,
                   labels = c("North", "Center", "B Belt", "South")) +
  guides(color = guide_legend(ncol = 2, reverse = TRUE))
```




### 2.8.2 Energy output by DC System Size

Plotting Energy output by DC System Size from fixed and single axis rotation system for two zipcodes (1, 2) within each of the four regions of AL.

```
lox <- c("Northern", "Central", "Black Belt", "Southern")
ggplot(data = energy_output,
        mapping = aes(x = al_regs,
                      y = energy,
                      #fill = energy,
                      color = factor(dc_kw),
                      group = factor(dc_kw))) +
  geom_line()+
  geom_point() +
  facet_grid(datalot~array) +
  scale_x_discrete(limits = lox,
                   labels = c("North", "Center", "B Belt", "South")) +
  guides(color = guide_legend(ncol = 2, reverse = TRUE))
```




# 3 Solar Energy Calculation

## 3.1 Simulation for energy revenue

- elcprc = electricity price. See Electricity price data for more detail.
- elcrev = Revenue from electricity for given electricity prices. See "energy output" and "electricity price" dataset for more details.
- I filtered datalot 2–I did not take average of "energy" from datalot 1 and datalot 2–to minimize computation time.

```
# Convert to data frames if they are not already
matrix1 <- energy_output  %>%
  group_by(sprop, al_regs, array, dc_kw, panels) %>%
  dplyr::filter(datalot == 2) %>%
  # Compute mean of datalot 1 and datalot 2:
  summarise(
    energy = mean(energy),
    .groups = 'drop'
    ) # dimension of matrix is 168*6
matrix2 <- elec_price # dimension of matrix is 11*1
```

```r
# Initialize the result data frame
# energy_revenue <- data.frame(matrix(nrow = 1848, ncol = 9))
energy_revenue <- data.frame(
  matrix(nrow = nrow(matrix2)*nrow(matrix1),
         ncol = ncol(matrix2)+ncol(matrix1)+1))

# Variable to keep track of the row index in the result matrix
row_index <- 1

# Loop through each value of the second matrix
for (i in 1:nrow(matrix2)) {
  # Loop through each value of the second matrix
  for (j in 1:nrow(matrix1)) {
    # First matrix, second matrix, combined two matrices.
    new_row <- c(matrix1[j, ],
                 matrix2[i, ],
                 matrix1$energy[j] * matrix2$epr_kwh[i])
    # Assign the new row to the result matrix
    energy_revenue[row_index, ] <- new_row
    # Increment the row index
    row_index <- row_index + 1
  }
}
# Name the columns
colnames(energy_revenue) <- c(colnames(matrix1), "elcprc", "elcrev")
# Check for any NAs in the result
if(any(is.na(energy_revenue))) {
  na_indices <- which(is.na(energy_revenue), arr.ind = TRUE)
  print(paste("NAs found at rows:", unique(na_indices[, 1])))
} else {
  print("No NAs found in the result data frame.")
}
```

```
[1] "No NAs found in the result data frame."
```

```r
str(energy_revenue)
```

```
'data.frame':   1848 obs. of  8 variables:
 $ sprop  : num  0 0 0 0 0 0 0 0 0.05 0.05 ...
 $ al_regs: chr  "Black Belt" "Black Belt" "Central" "Central" ...
```

```
 $ array  : chr  "Fixed" "Tracking" "Fixed" "Tracking" ...
 $ dc_kw  : num  0 0 0 0 0 0 0 0 0 0 ...
 $ panels : num  0 0 0 0 0 0 0 0 0 0 ...
 $ energy : num  0 0 0 0 0 0 0 0 0 0 ...
 $ elcprc : num  0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 ...
 $ elcrev : num  0 0 0 0 0 0 0 0 0 0 ...
```

```
head(energy_revenue); tail(energy_revenue)
```

```
  sprop    al_regs    array dc_kw panels energy elcprc elcrev
1     0 Black Belt    Fixed     0      0      0   0.01      0
2     0 Black Belt Tracking     0      0      0   0.01      0
3     0    Central    Fixed     0      0      0   0.01      0
4     0    Central Tracking     0      0      0   0.01      0
5     0   Northern    Fixed     0      0      0   0.01      0
6     0   Northern Tracking     0      0      0   0.01      0
```

```
     sprop  al_regs    array  dc_kw panels energy elcprc   elcrev
1843     1  Central    Fixed 423.74    885 594824   0.06 35689.44
1844     1  Central Tracking 423.74    885 688037   0.06 41282.22
1845     1 Northern    Fixed 423.74    885 574020   0.06 34441.20
1846     1 Northern Tracking 423.74    885 656889   0.06 39413.34
1847     1 Southern    Fixed 423.74    885 613342   0.06 36800.52
1848     1 Southern Tracking 423.74    885 712873   0.06 42772.38
```

### 3.2 Simulation 2 for energy revenue

This simulation has same result as above (Cross checking above code and output). Results are suppressed but errors and warnings are not. No error and no warnings means code is working as it should.

```
## | results='hide'
# Sample data
set.seed(123)
matrix1 <- energy_output # dimension of matrix is 176*7
matrix2 <- elec_price # dimension of matrix is 11*1

# Initializing the result matrix
result_matrix <- data.frame(matrix(ncol = nrow(matrix2),
                                   nrow = 0))
colnames(result_matrix) <- c(colnames(matrix1),  "elcrev", "elcprc")
```

```
# Loop to multiply first and second matrices
for (i in 1:nrow(matrix2)) {
  temp_matrix <- matrix1
  temp_matrix$E_Prc <- matrix2[i, ]
  temp_matrix$E_Rev <- matrix1$energy[j] * matrix2$epr_kwh[i]
  result_matrix <- rbind(result_matrix, temp_matrix)
}
str(result_matrix)
head(result_matrix); tail(result_matrix)
```

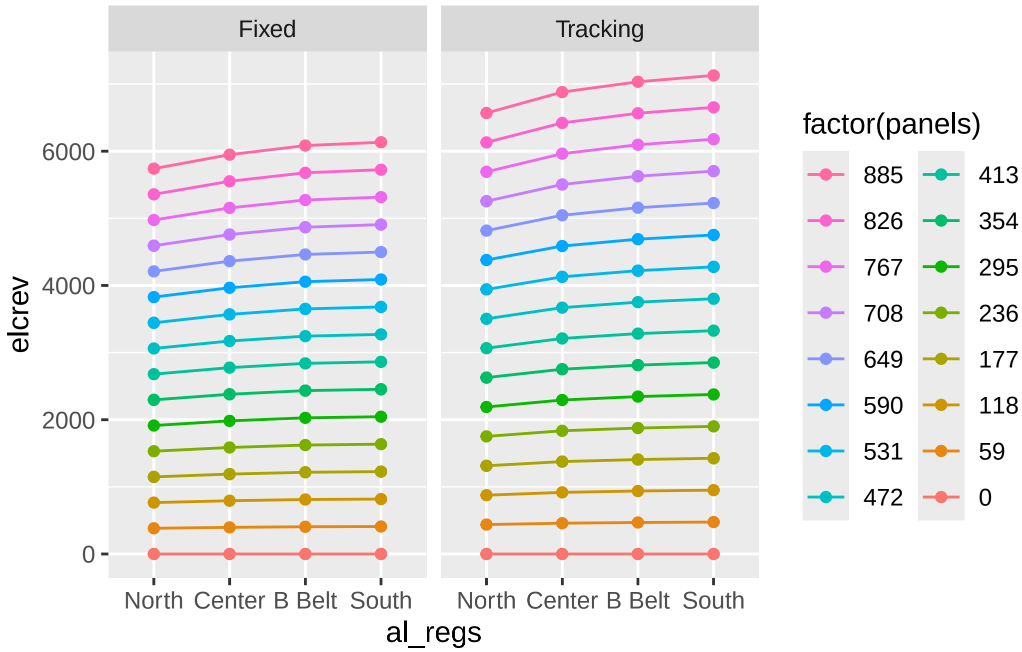
## 3.3 Plotting revenue from energy production

### 3.3.1 Breakdown by number of solar panels

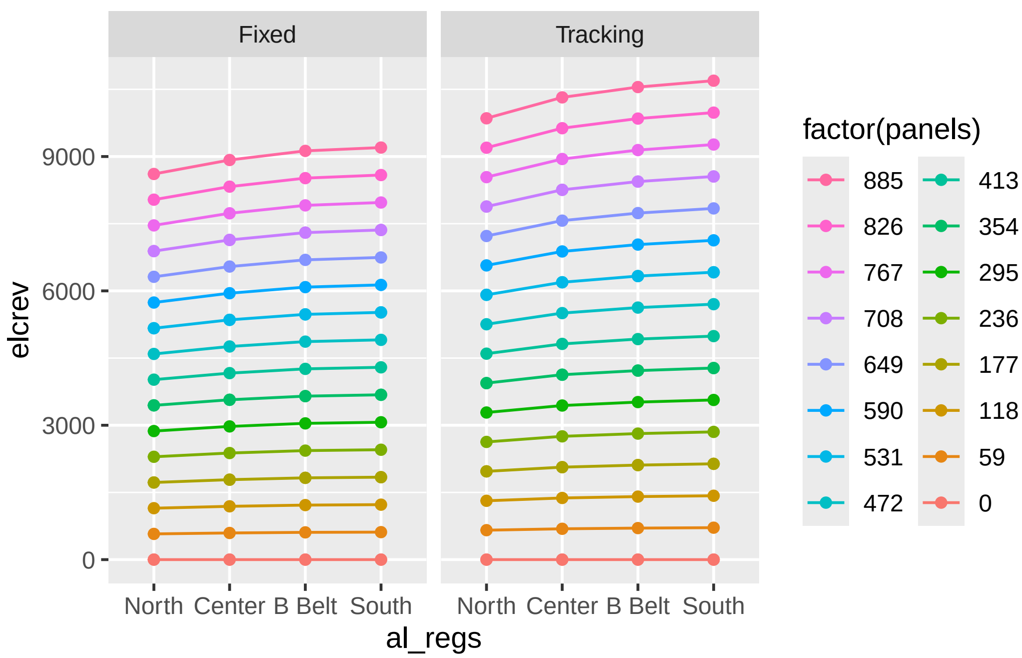
I am using data from simulation 1 for this visualization. This code plots one chart per electricity cost. There are 11 electricity cost resulting into 11 charts. Electricity revenue is average revenue of first and second lots of simulation.

```
lox <- c("Northern", "Central", "Black Belt", "Southern")
array_levs = c("Single Axis Rotation", "Fixed Open Rack")
datalot_levs = c("Location 1", "Location 2")
for (i in unique(energy_revenue$elcprc)) {
 a = ggplot(data = (energy_revenue %>%
  dplyr::filter(elcprc == i)),
         mapping = aes(x =al_regs,
                       y = elcrev,
                       #fill = energy,
                       color = factor(panels),
                       group = factor(panels)))+
  geom_line()+
  geom_point()+
  facet_grid(.~array) +
  scale_x_discrete(limits = lox,
                   labels = c("North", "Center", "B Belt", "South")) +
   guides(color = guide_legend(ncol = 2, reverse = TRUE))
 cat("Electricity Price = ", i)
 print(a)
}
```

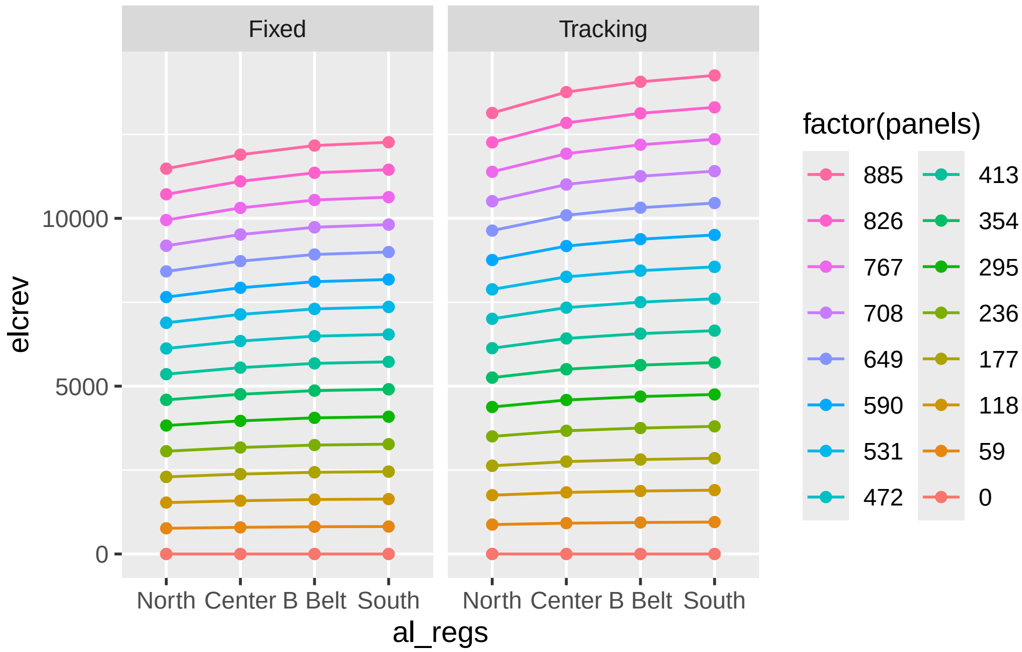
```
Electricity Price =  0.01
```



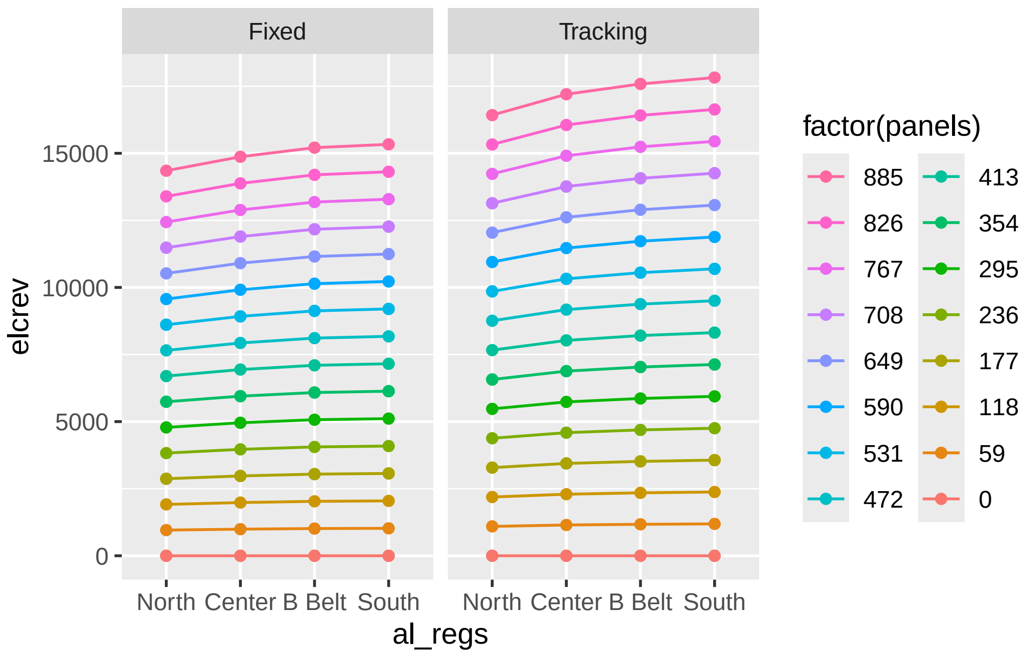

Electricity Price = 0.015



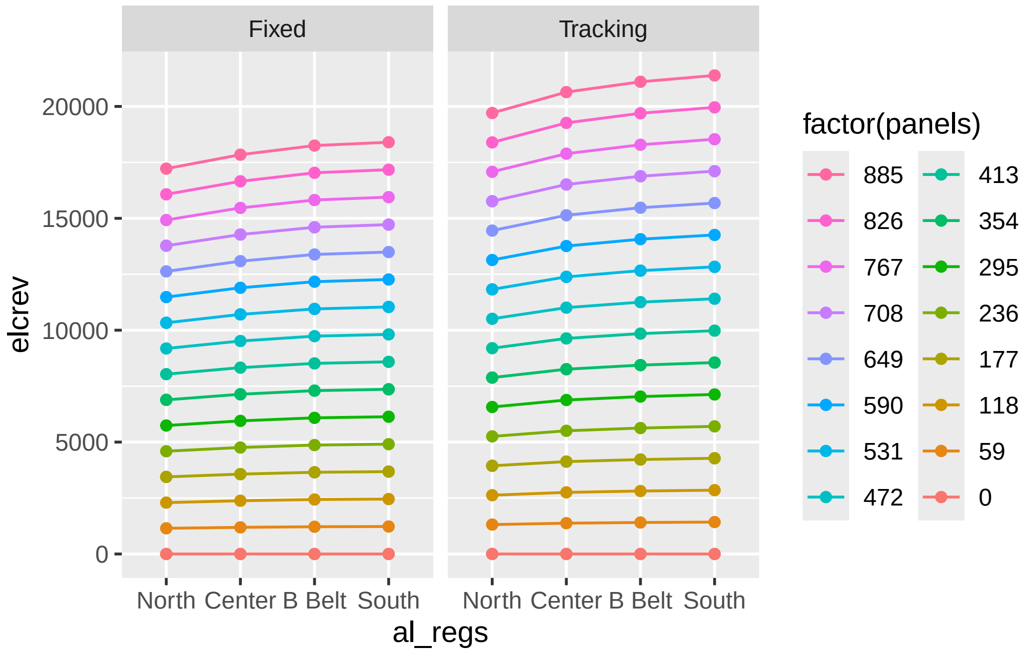

Electricity Price = 0.02



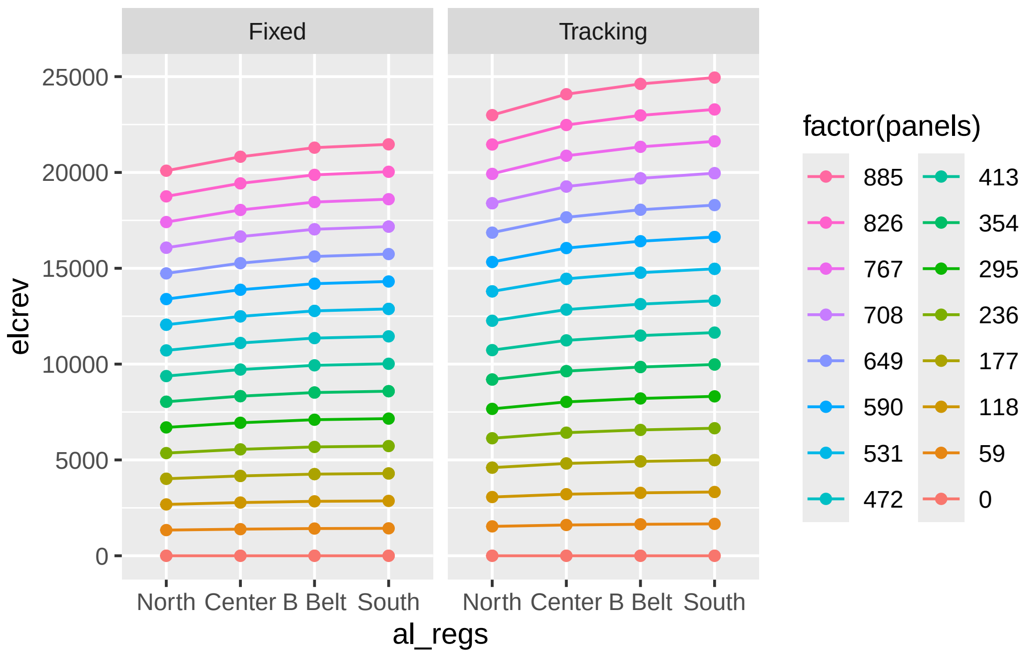

```
Electricity Price =  0.025
```



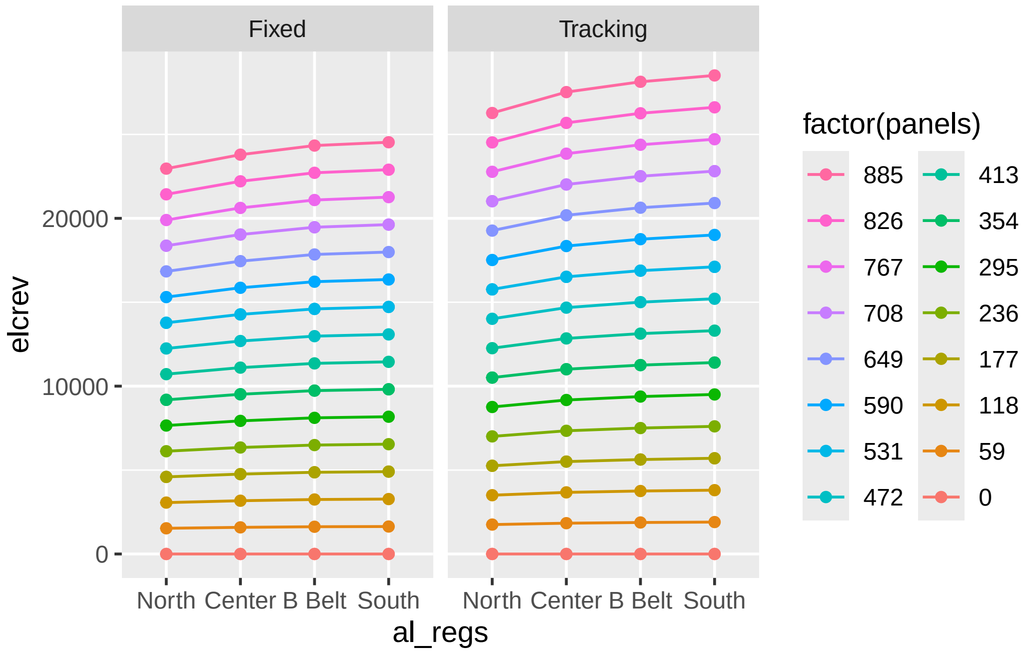

```
Electricity Price =  0.03
```



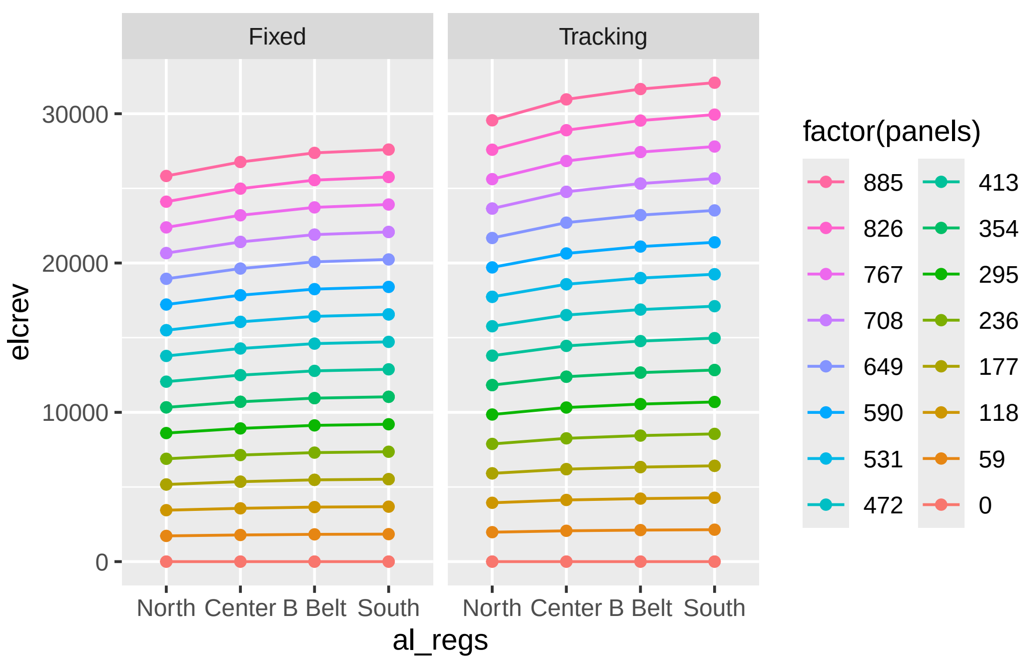

```
Electricity Price =  0.035
```



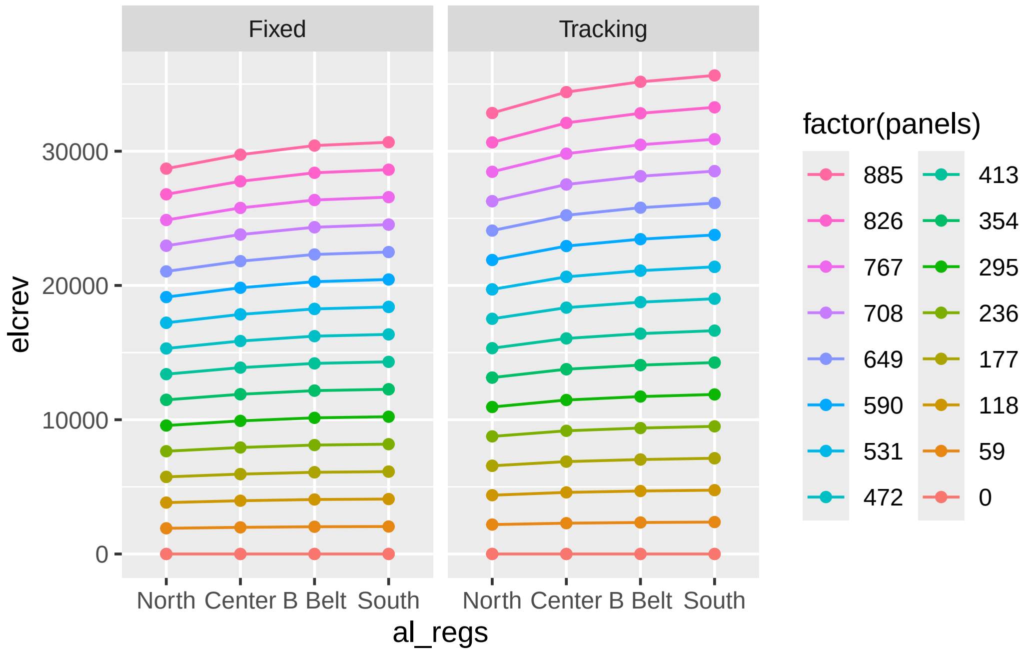

```
Electricity Price =  0.04
```



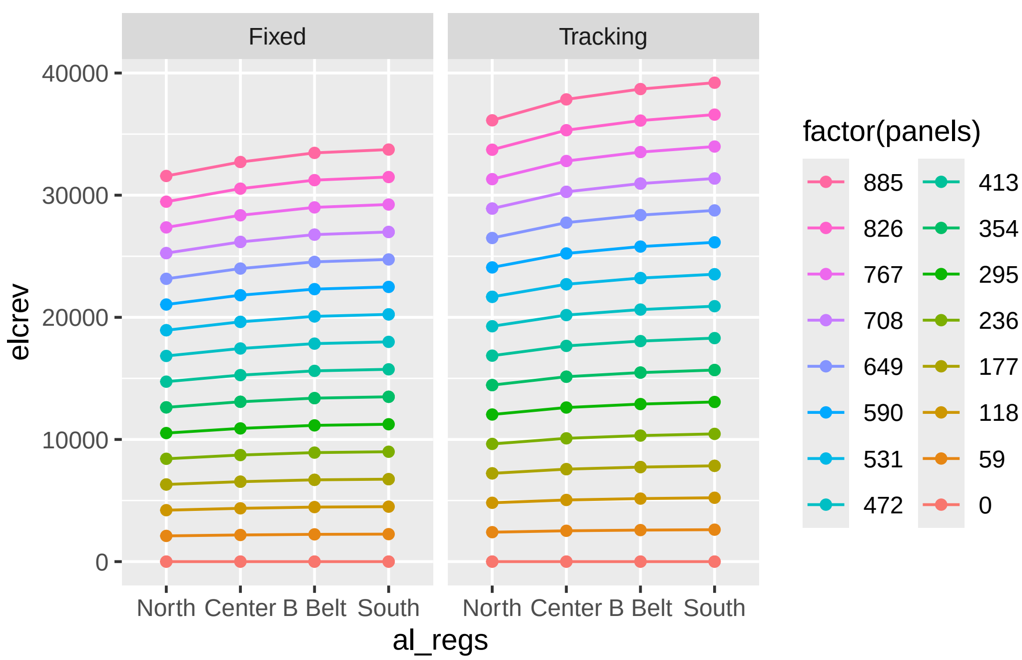

```
Electricity Price =  0.045
```



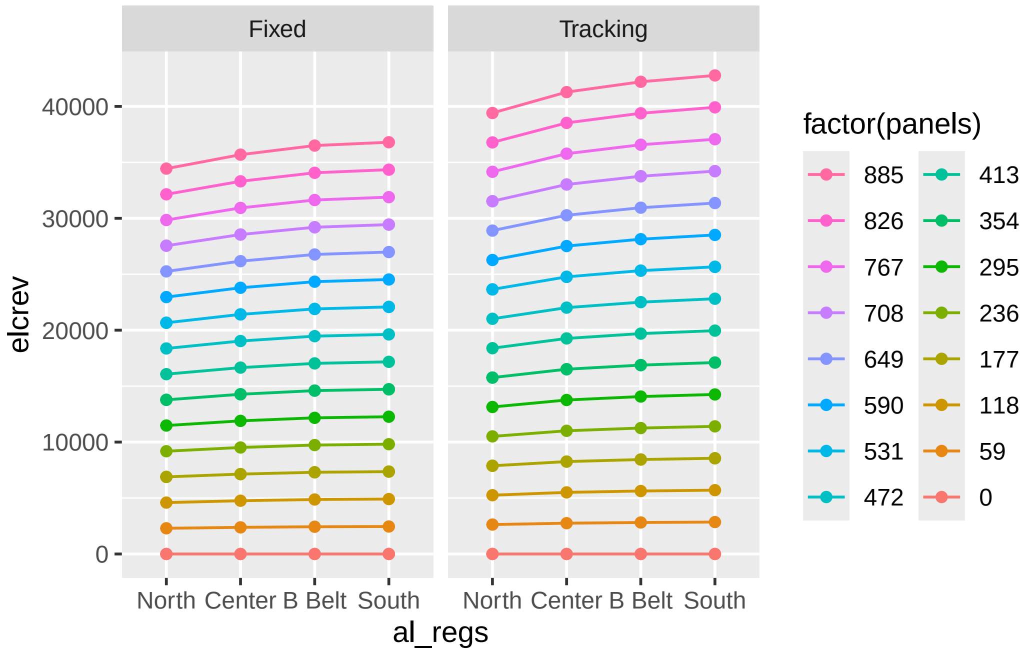

```
Electricity Price =  0.05
```




Electricity Price =  0.055




Electricity Price =  0.06



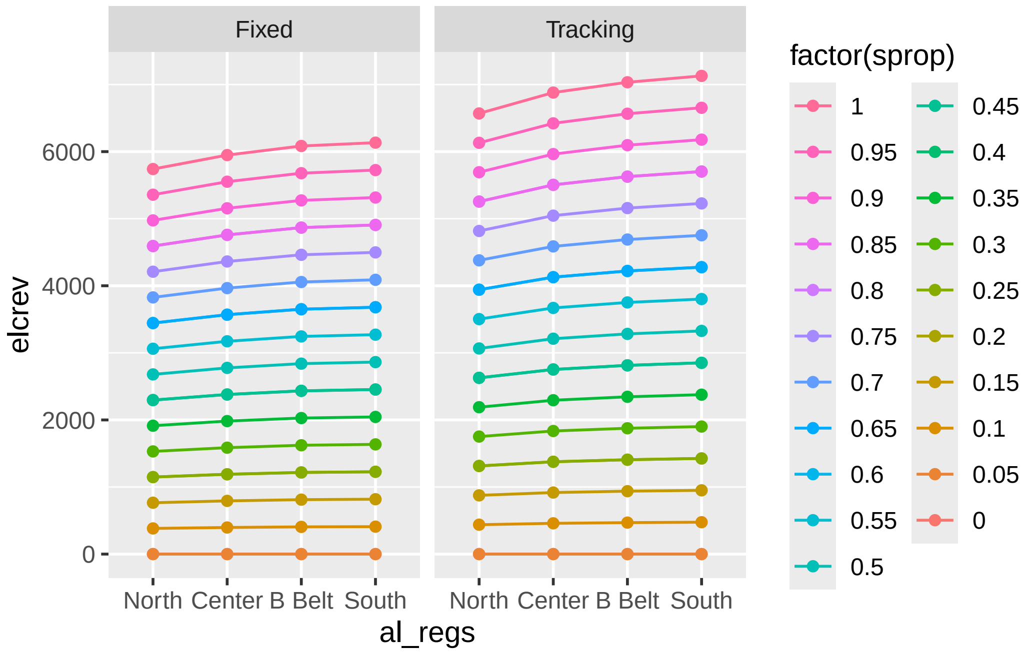

### 3.3.2 Breakdown by proportion of land under solar

- Two proportions may have same number of solar panels (Eg. 0.80 and 0.85, 0.20 and 0.25). So, total lines in the chart may not match with total number of legend levels. Some proportions are overlapping in the chart. See panel configuration for more detail.

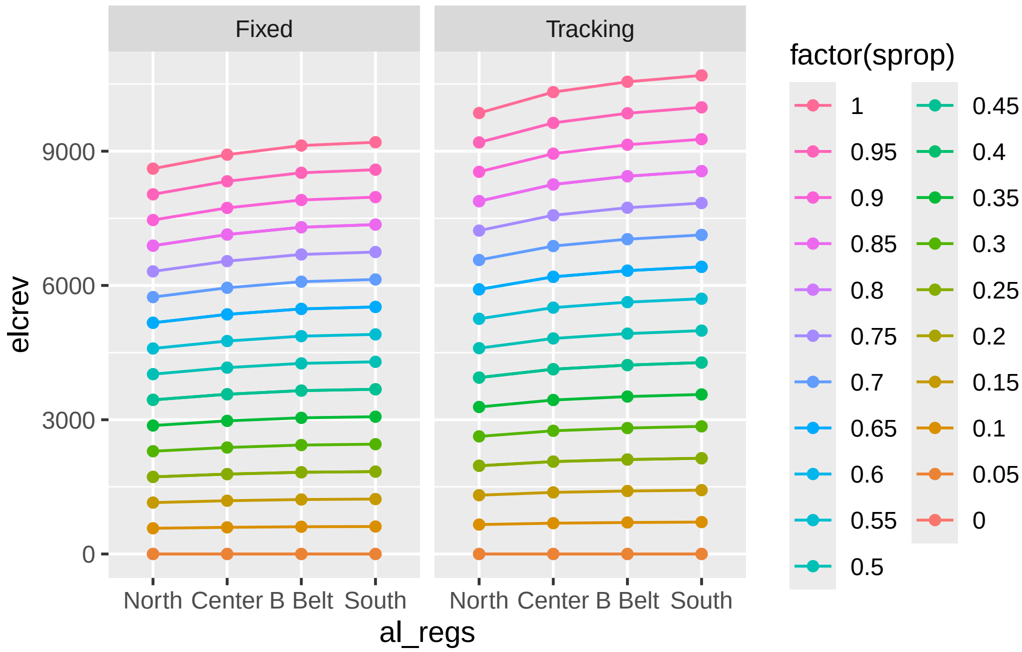
```
lox <- c("Northern", "Central", "Black Belt", "Southern")
array_levs = c("Single Axis Rotation", "Fixed Open Rack")
datalot_levs = c("Location 1", "Location 2")
for (i in unique(energy_revenue$elcprc)) {
 a = ggplot(data = (energy_revenue %>%
  dplyr::filter(elcprc == i)),
         mapping = aes(x =al_regs,
                       y = elcrev,
                       #fill = energy,
                       color = factor(sprop),
                       group = factor(sprop)))+
  geom_line()+
  geom_point()+
  facet_grid(.~array) +
  scale_x_discrete(limits = lox,
                   labels = c("North", "Center", "B Belt", "South")) +
```

```
  guides(color = guide_legend(ncol = 2, reverse = TRUE))
 cat("Electricity Price = ", i)
 print(a)
}
```

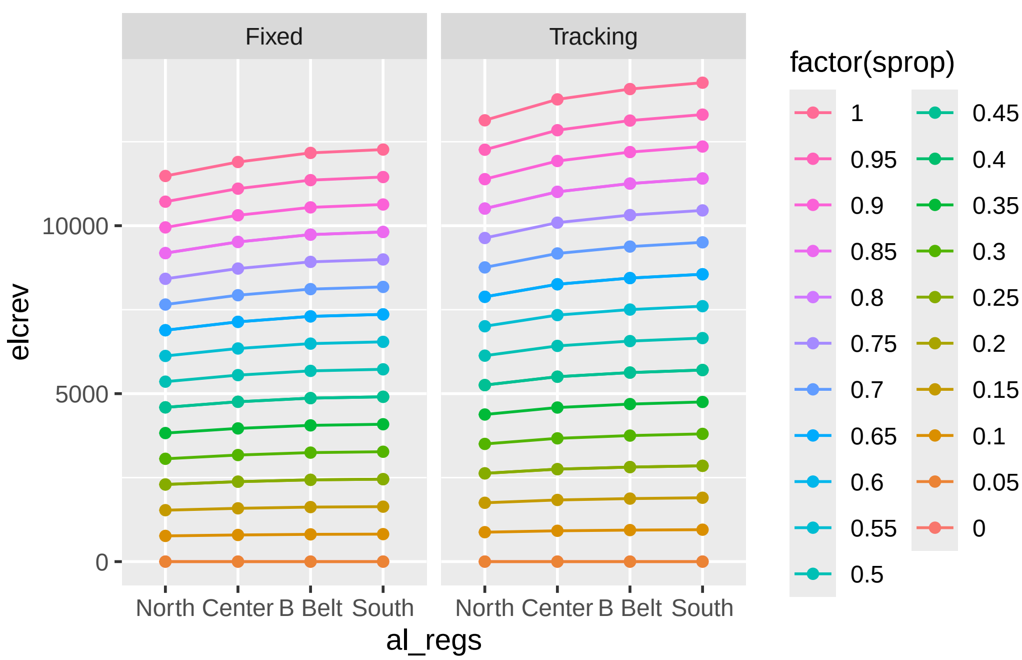
```
Electricity Price =  0.01
```



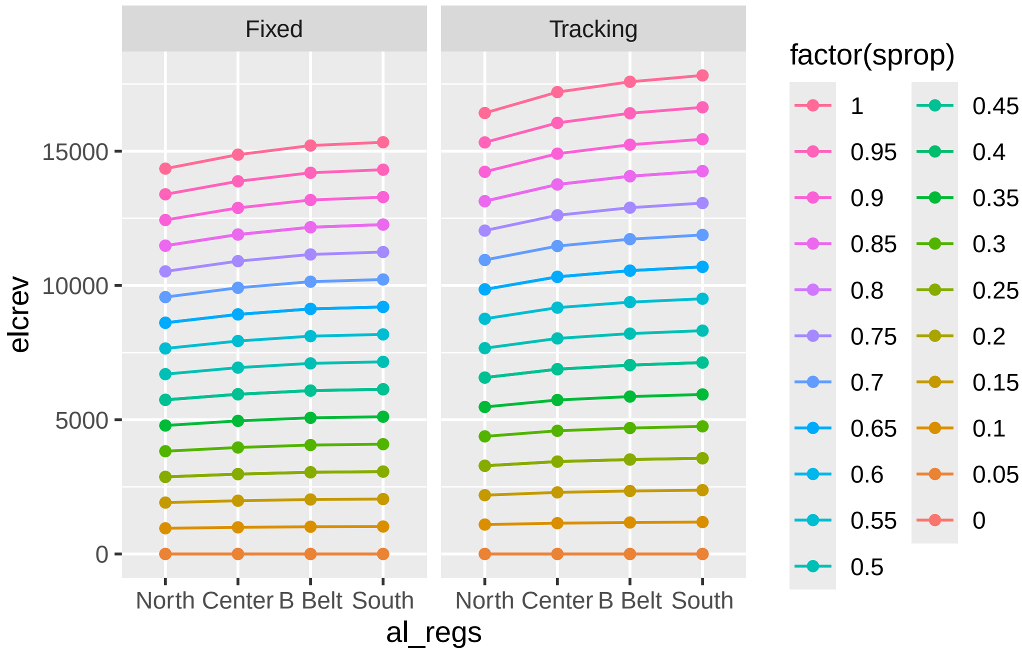

```
Electricity Price =  0.015
```



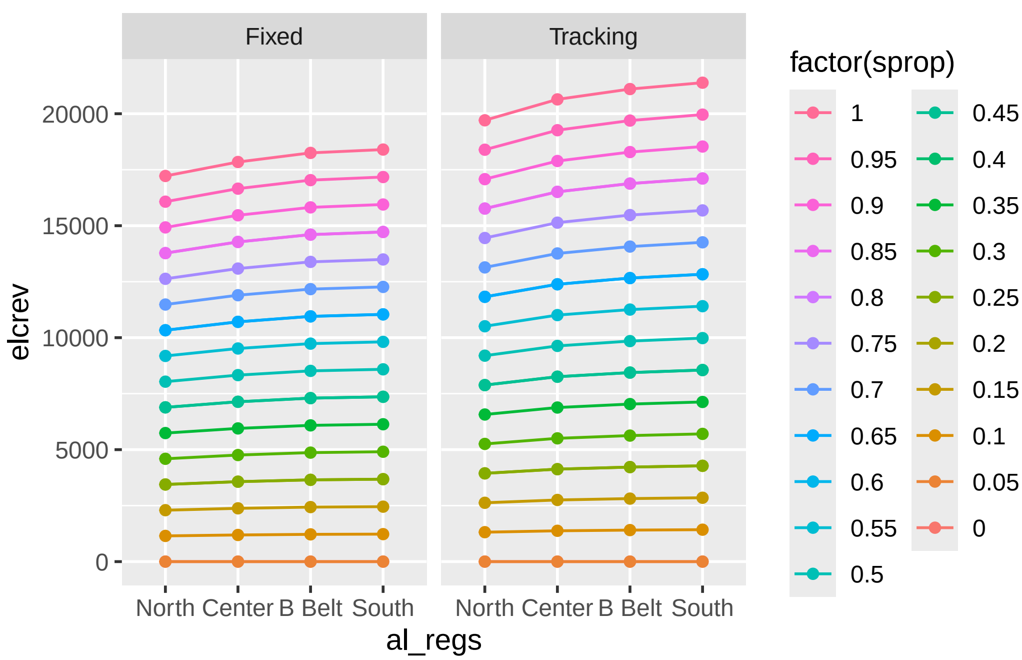

```
Electricity Price =  0.02
```



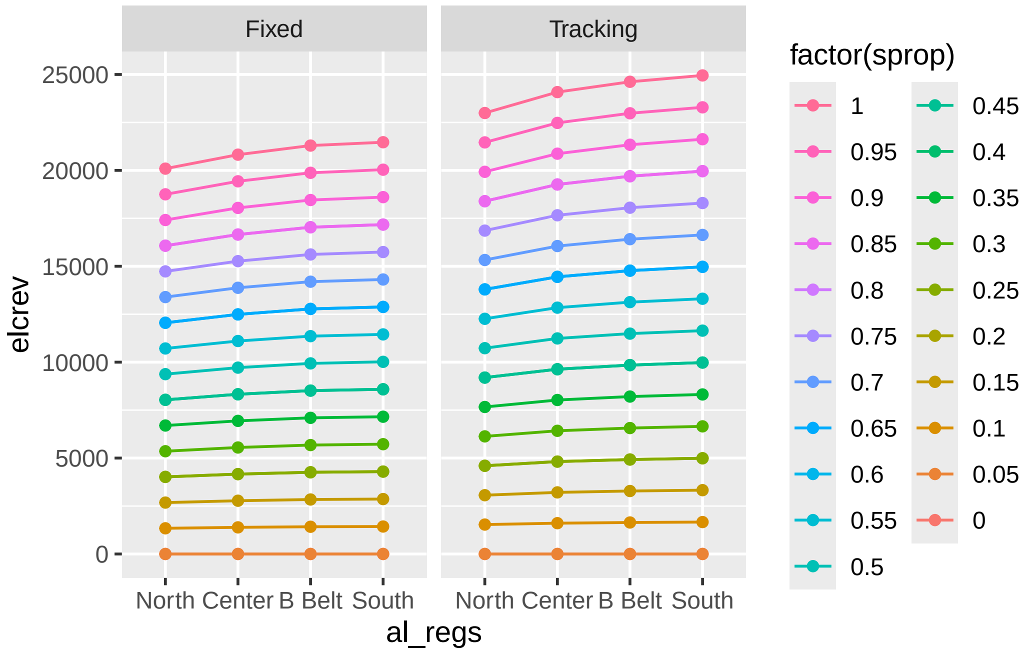

```
Electricity Price =  0.025
```



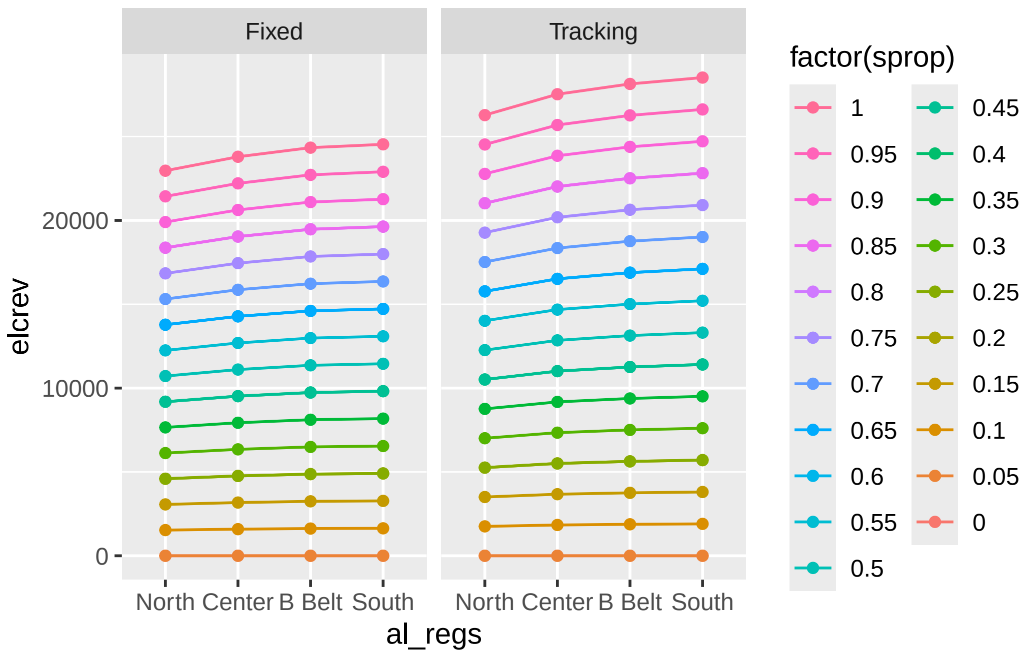

```
Electricity Price =  0.03
```



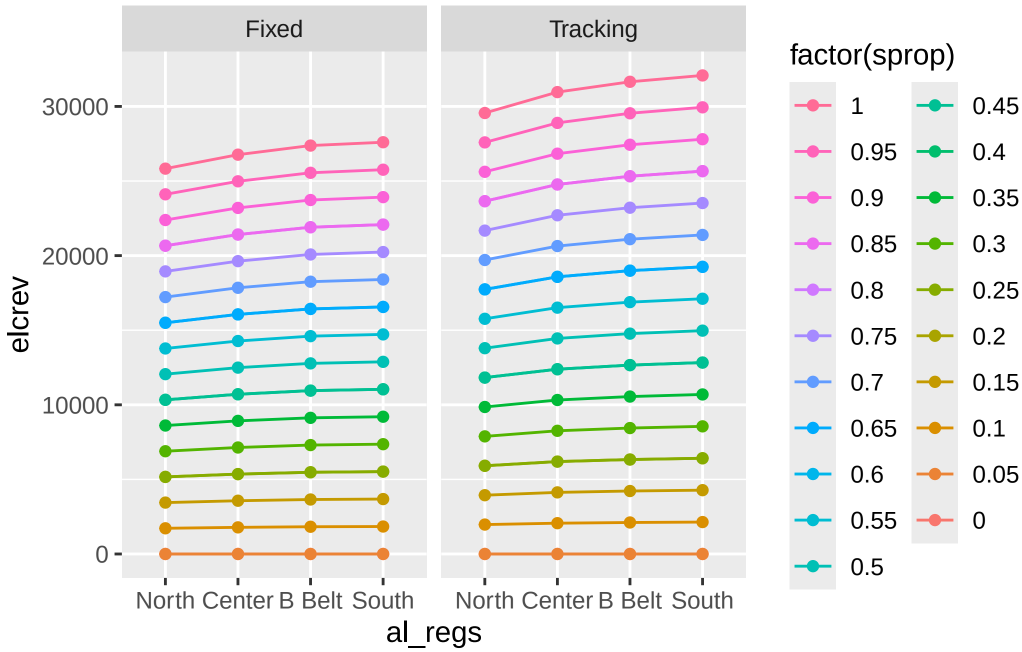

```
Electricity Price =  0.035
```



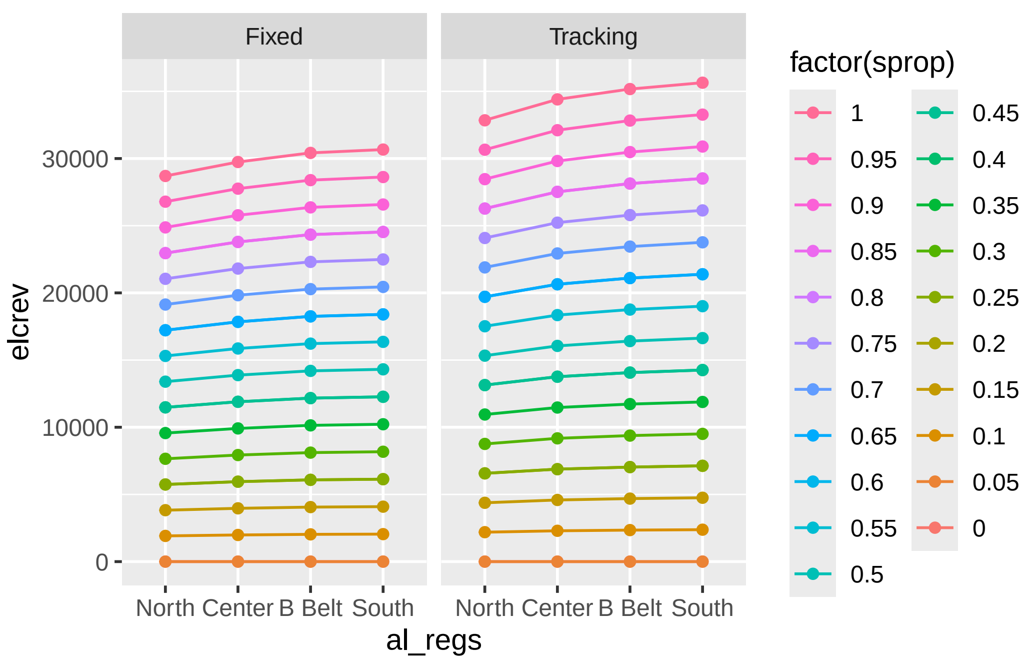

```
Electricity Price =  0.04
```



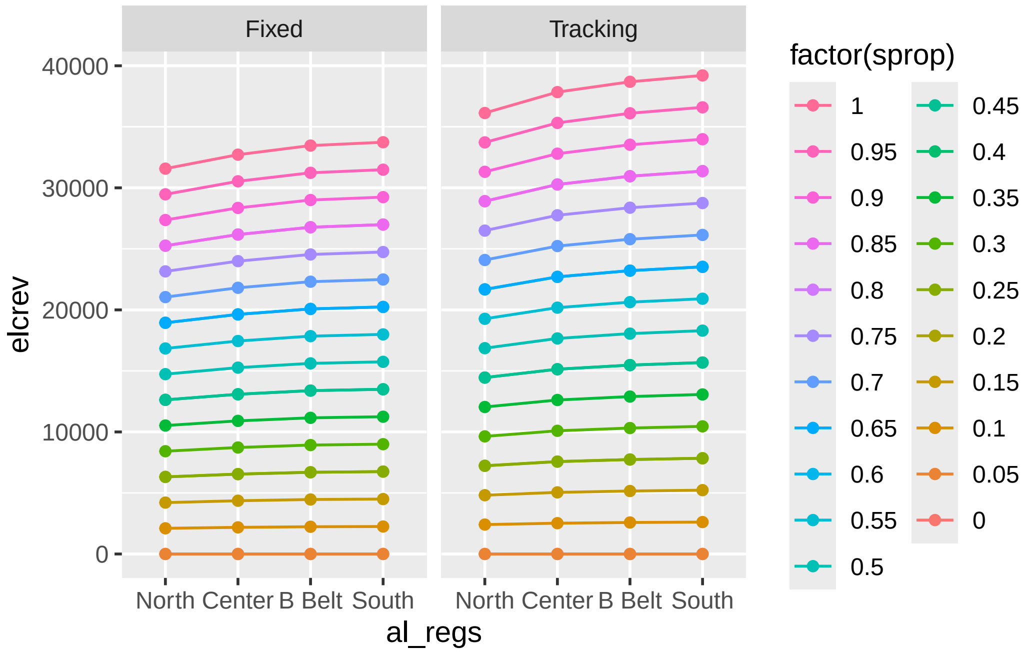

```
Electricity Price =  0.045
```



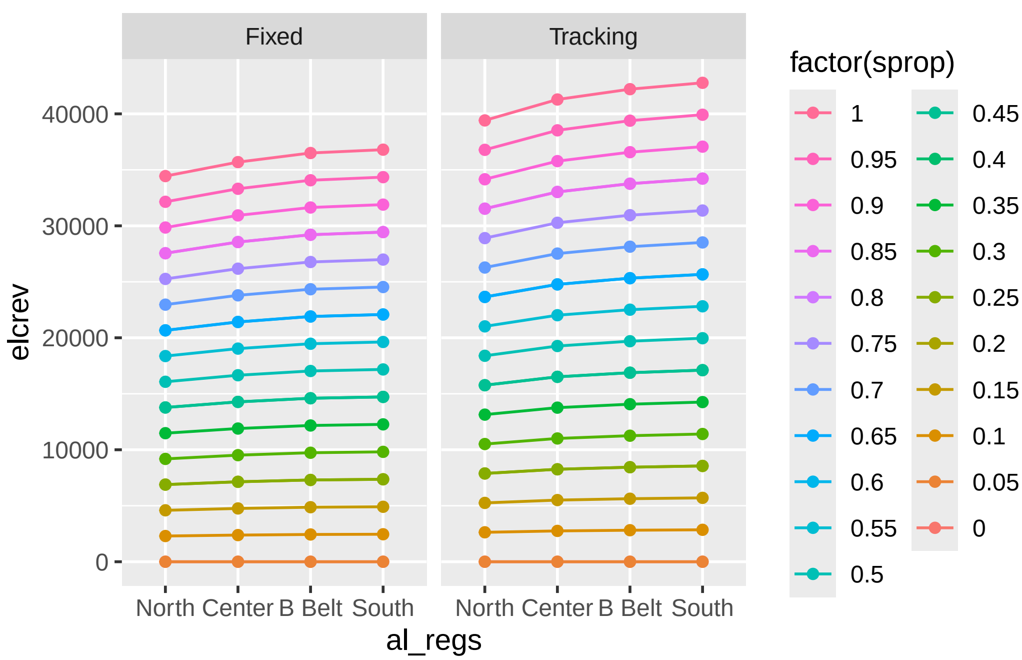

```
Electricity Price =  0.05
```




```
Electricity Price =  0.055
```




```
Electricity Price =  0.06
```



### 3.4 Cost and Profit from solar

- Cost of solar energy system in agrivoltaic setting.
- I used energy output per 7.75 ft.*3.5 ft. panel (545 w), capex ($/w), and total number of panels to get total cost for each height and panel tracking system.
- height = height of solar panels; see capex dataset for details.
- capex = capex from capex table; see capex dataset for details.
- opex = Operational cost ($15/kW/Year) Source: Ramasamy, 2022. PV Cost Benchmark (This is revised to 3% of annual capex based on Dennis Brother's suggestion).
- ttlcost = Total cost for given DC system size.
- anncost = Annual payment to repay loan ($P_{ann}$) = $\frac{P_o(i(1+i)^t)}{(1+i)^t-1)}$ , where $P_o$ = CAPEX loan burrowed to repay in $t$ years; $t = 25$, and $i$ = annual interest rate at 5%.
- moncost = Monthly payment to repay loan ($P_{mon}$) = $\frac{P_o((i/12)(1+(i/12))^{t*12})}{(1+(i/12))^{t*12}-1)}$, where $P_o$ = CAPEX loan burrowed to repay in $t$ years; $t = 25$, and $i$ = annual interest rate at 5%.
- reap = Rural Energy for America Program reimburses 50% of capex (ttlcost) upfront. The waiting time for reimbursement is about 6 months. So, 50% of ttlcost acquire simple interest for six months.
- inscst = insurance cost. $5 per $1000 capex.
- taxcredit = 30% tax credit of annual cost covered through federal tax exemption.
- eprofit = profit from electricity after subtracting total cost (ttlcost) from total revenue (elcrev).
- eannprof = annual profit from solar after subtracting annual loan repayment distributed over 25 years.
- emonprof = monthly profit from solar after subtracting monthly loan repayment distributed over 25 years.
- eannprofworeap = annual profit without REAP benefit.
- eannprofwoincentives = Annual profit without incentives.

```
i = 0.07 # Discount/interest Rate
n = 25 # Life Span of solar panels (Years)
reapprop = 25/100  # Percentage of CAPEX covered by REAP program.

expanded_data <- energy_revenue %>%
  slice(rep(1:n(),
```

```
            each = 3))
capex_height <- rep(unique(capex$height),
                    length.out = nrow(energy_revenue))

energy_cost = cbind(expanded_data, capex_height) %>%
  rename(height = capex_height)

energy_cost <- left_join(energy_cost,
                         capex,
                         by = c("array", "height")) %>%
  mutate(
    # 7.75*3.5 sq.ft. panel energy output = 545 W.
    # Operational cost (OPEX) = $15/kW-yr; 1 kW = 1,000W.
    # Opex = 545*15/1000*panels,

    # Land lease cost Per acre.
    landlease = 1000,

    # Total Capex
    ttlcost = capex*545*panels,

    # Cost of Insurance = $5/$1000/Yr Total capex
    inscst = ttlcost*5/1000, #Cost

    # Renewable energy credit 6.60 $/MWh
    recredit = 6.60/1000*energy, #Return

    # REAP Program = 50% of Capex - Simple interest rmbrst delay
    reap = reapprop*ttlcost - (reapprop*ttlcost)*i*0.5/100, #Return

    # Annualized cost - reap:
    annlzcost = (ttlcost - reap)*(i*(1+i)^n)/((1+i)^n-1),

    # Annualized Cost of total cost:
    annoftotcost = ttlcost*(i*(1+i)^n)/((1+i)^n-1),

    # Monthalized using monthly discount rate:
    monthlycost = ttlcost*
      ((i/12)*(1+(i/n))^(n*12))/((1+(i/12))^(n*12)-1),

    # Operational cost = 3% of annualized total capex
    opex = 3*annoftotcost/100, #Cost
```

```
    # Tax credit = 30% of annualized capex
    taxcr = 30*annoftotcost/100, #Return

    # Annualized using annual discount rate:
    anncost = annlzcost + opex
    )

solar_profit <- energy_cost %>%
  mutate(
    # Annualized Profit
    eannprof = elcrev + recredit + taxcr - anncost,

    eannprofworeap = elcrev + recredit + taxcr - annoftotcost,
    eannprofwoincentives = elcrev - annoftotcost
    )

write_xlsx(file = "Results/Solar Profit.xlsx",
           x = solar_profit,
           overwrite = TRUE)
str(solar_profit)
```

```
'data.frame':   5544 obs. of  24 variables:
 $ sprop              : num  0 0 0 0 0 0 0 0 0 0 ...
 $ al_regs            : chr  "Black Belt" "Black Belt" "Black Belt" "Black Belt" ...
 $ array              : chr  "Fixed" "Fixed" "Fixed" "Tracking" ...
 $ dc_kw              : num  0 0 0 0 0 0 0 0 0 0 ...
 $ panels             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ energy             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ elcprc             : num  0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 ...
 $ elcrev             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ height             : num  4.6 6.4 8.2 4.6 6.4 8.2 4.6 6.4 8.2 4.6 ...
 $ capex              : num  1.59 1.85 2.33 1.73 1.92 ...
 $ landlease          : num  1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 ...
 $ ttlcost            : num  0 0 0 0 0 0 0 0 0 0 ...
 $ inscst             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ recredit           : num  0 0 0 0 0 0 0 0 0 0 ...
 $ reap               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ annlzcost          : num  0 0 0 0 0 0 0 0 0 0 ...
 $ annoftotcost       : num  0 0 0 0 0 0 0 0 0 0 ...
 $ monthlycost        : num  0 0 0 0 0 0 0 0 0 0 ...
 $ opex               : num  0 0 0 0 0 0 0 0 0 0 ...
```

```
 $ taxcr               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ anncost             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprof            : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprofworeap      : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprofwoincentives: num  0 0 0 0 0 0 0 0 0 0 ...
```

```
head(solar_profit); tail(solar_profit)
```

```
  sprop    al_regs    array dc_kw panels energy elcprc elcrev height    capex
1     0 Black Belt    Fixed     0      0      0   0.01      0    4.6 1.593333
2     0 Black Belt    Fixed     0      0      0   0.01      0    6.4 1.850000
3     0 Black Belt    Fixed     0      0      0   0.01      0    8.2 2.330000
4     0 Black Belt Tracking     0      0      0   0.01      0    4.6 1.733333
5     0 Black Belt Tracking     0      0      0   0.01      0    6.4 1.921667
6     0 Black Belt Tracking     0      0      0   0.01      0    8.2 2.110000
  landlease ttlcost inscst recredit reap annlzcost annoftotcost monthlycost
1      1000       0      0        0    0         0            0           0
2      1000       0      0        0    0         0            0           0
3      1000       0      0        0    0         0            0           0
4      1000       0      0        0    0         0            0           0
5      1000       0      0        0    0         0            0           0
6      1000       0      0        0    0         0            0           0
  opex taxcr anncost eannprof eannprofworeap eannprofwoincentives
1    0     0       0        0              0                    0
2    0     0       0        0              0                    0
3    0     0       0        0              0                    0
4    0     0       0        0              0                    0
5    0     0       0        0              0                    0
6    0     0       0        0              0                    0
```

```
     sprop  al_regs    array  dc_kw panels energy elcprc   elcrev height
5539     1 Southern    Fixed 423.74    885 613342   0.06 36800.52    4.6
5540     1 Southern    Fixed 423.74    885 613342   0.06 36800.52    6.4
5541     1 Southern    Fixed 423.74    885 613342   0.06 36800.52    8.2
5542     1 Southern Tracking 423.74    885 712873   0.06 42772.38    4.6
5543     1 Southern Tracking 423.74    885 712873   0.06 42772.38    6.4
5544     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
        capex landlease   ttlcost   inscst recredit     reap annlzcost
5539 1.593333      1000  768504.5 3842.523 4048.057 192058.9  49465.10
5540 1.850000      1000  892301.2 4461.506 4048.057 222997.2  57433.32
5541 2.330000      1000 1123817.3 5619.086 4048.057 280856.0  72334.94
5542 1.733333      1000  836030.0 4180.150 4704.962 208934.3  53811.40
```

```
5543 1.921667      1000  926867.9 4634.339 4704.962 231635.9  59658.22
5544 2.110000      1000 1017705.8 5088.529 4704.962 254337.4  65505.03
     annoftotcost monthlycost     opex    taxcr  anncost  eannprof
5539     65945.77    2194.929 1978.373 19783.73 51443.47  9188.838
5540     76568.83    2548.506 2297.065 22970.65 59730.39  4088.838
5541     96435.34    3209.740 2893.060 28930.60 75228.00 -5448.824
5542     71740.17    2387.789 2152.205 21522.05 55963.61 13035.785
5543     79535.01    2647.232 2386.050 23860.50 62044.27  9293.577
5544     87329.86    2906.674 2619.896 26198.96 68124.93  5551.369
     eannprofworeap eannprofwoincentives
5539      -5313.461            -29145.25
5540     -12749.605            -39768.31
5541     -26656.160            -59634.82
5542      -2740.775            -28967.79
5543      -8197.166            -36762.63
5544     -13653.558            -44557.48
```

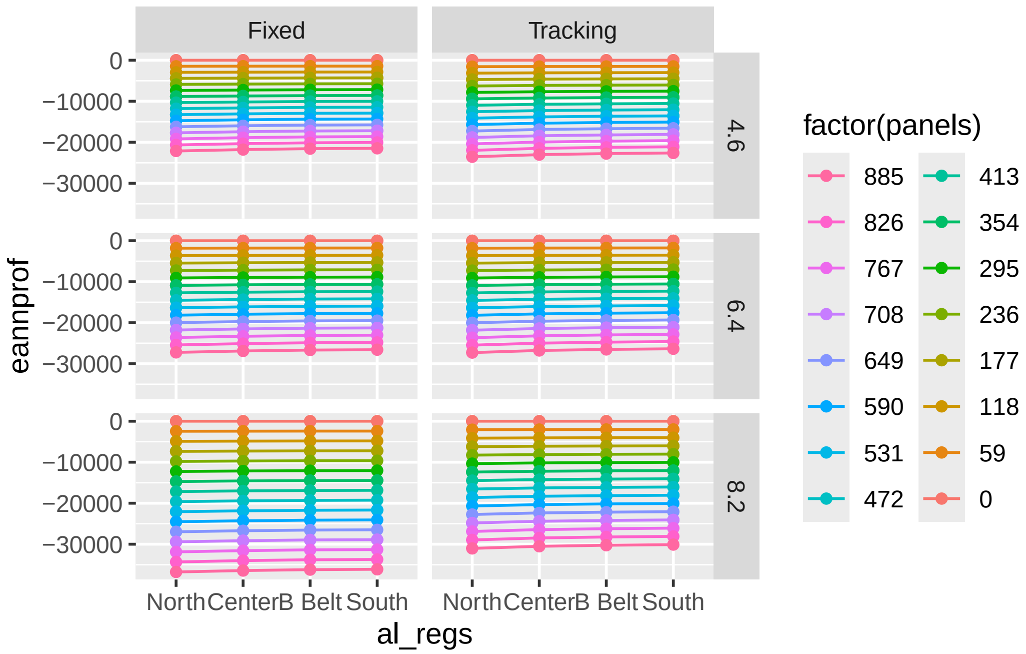
### 3.4.1 Plot Solar profit

Solar annual profit by number of solar panels

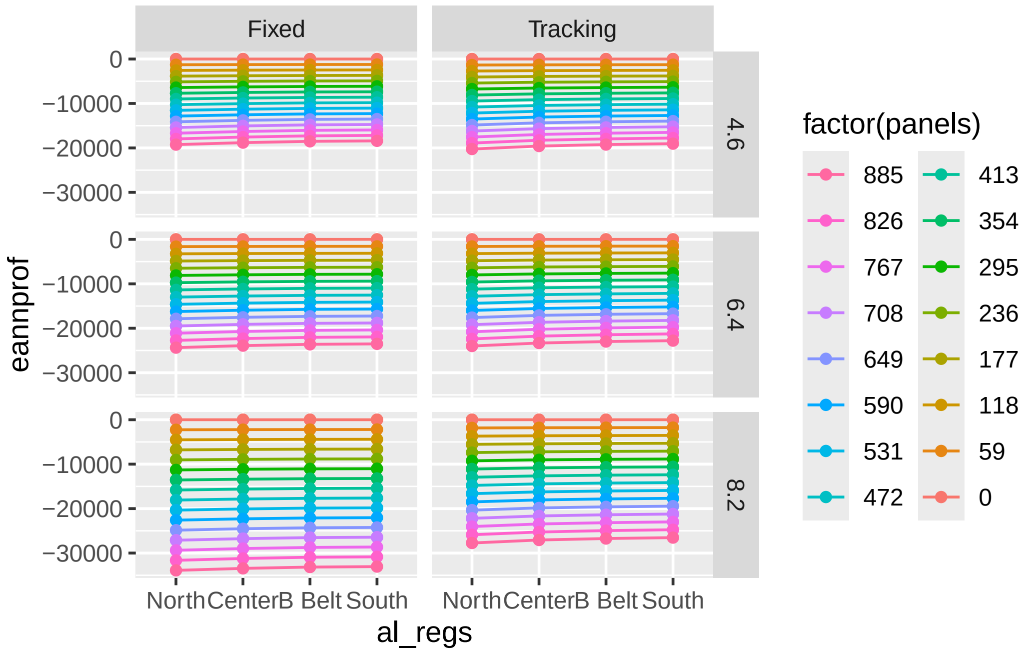
```
lox <- c("Northern", "Central", "Black Belt", "Southern")
array_levs = c("Single Axis Rotation", "Fixed Open Rack")
datalot_levs = c("Location 1", "Location 2")
  for (i in unique(solar_profit$elcprc)) {
    b = ggplot(
      data = (solar_profit %>%
                dplyr::filter(elcprc == i)),
      mapping = aes(
        x = al_regs,
        y = eannprof, #Annual Profit
        #fill = energy,
        color = factor(panels),
        group = factor(panels)
      )
    ) +
      geom_line() +
      geom_point() +
      facet_grid(height ~ array) +
      scale_x_discrete(limits = lox,
                       labels = c("North", "Center",
                                  "B Belt", "South")) +
```

```r
    guides(color = guide_legend(ncol = 2,
                                reverse = TRUE))
  cat("Electricity Price = ", i)
  print(b)
}
```

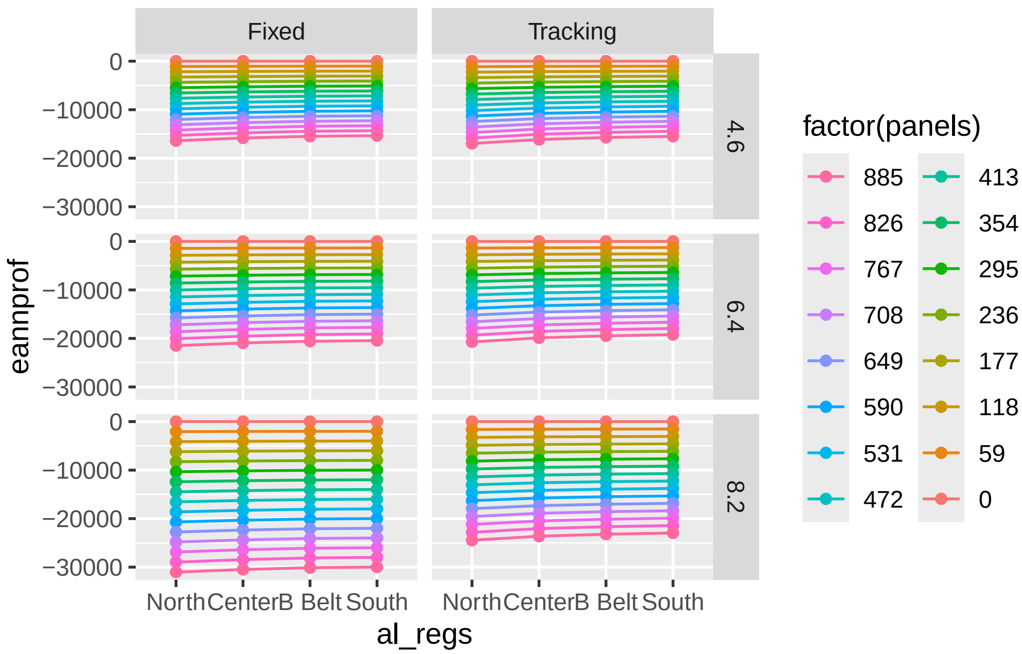
```
Electricity Price =  0.01
```



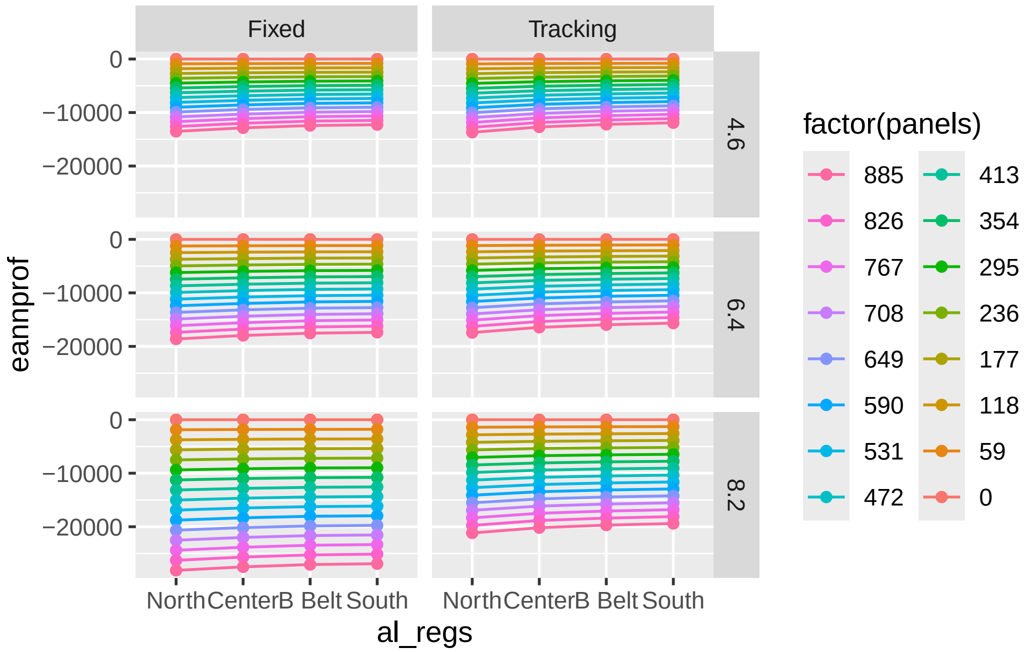

```
Electricity Price =  0.015
```



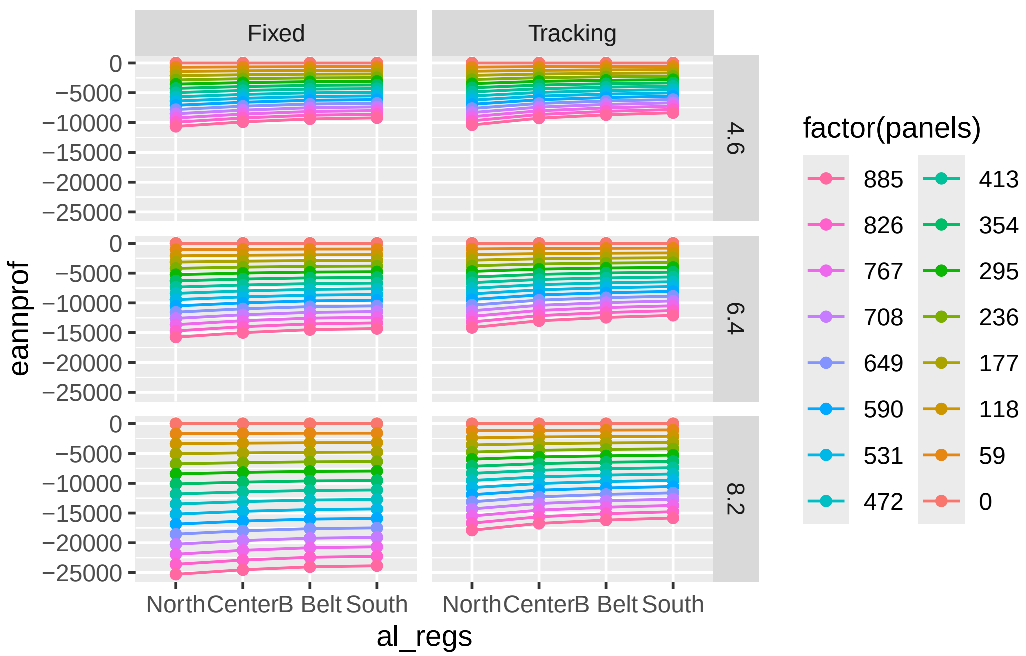

```
Electricity Price =  0.02
```



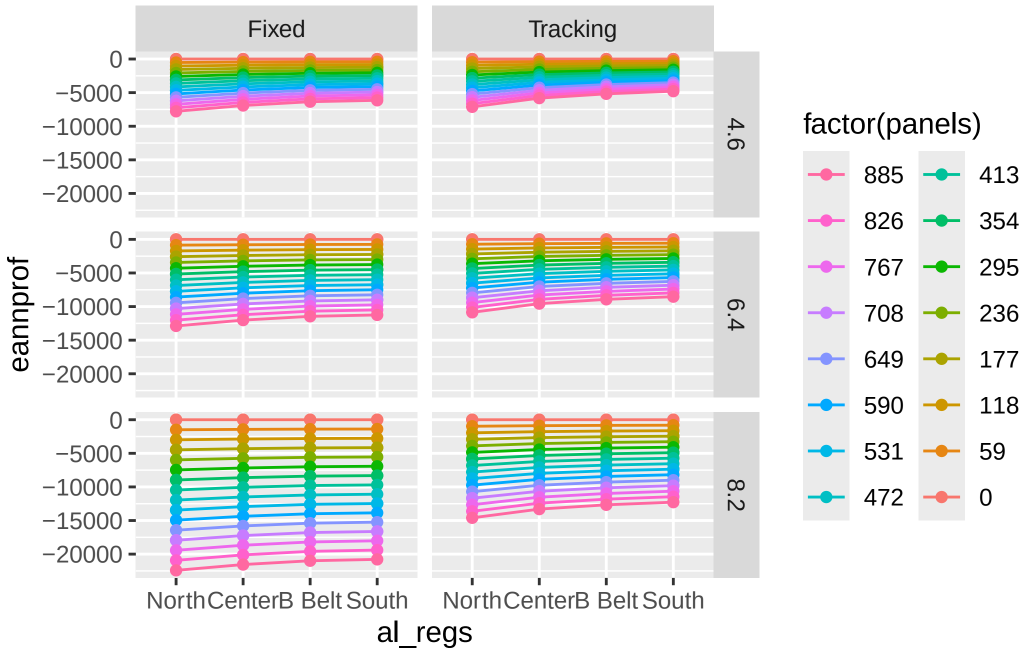

```
Electricity Price =  0.025
```



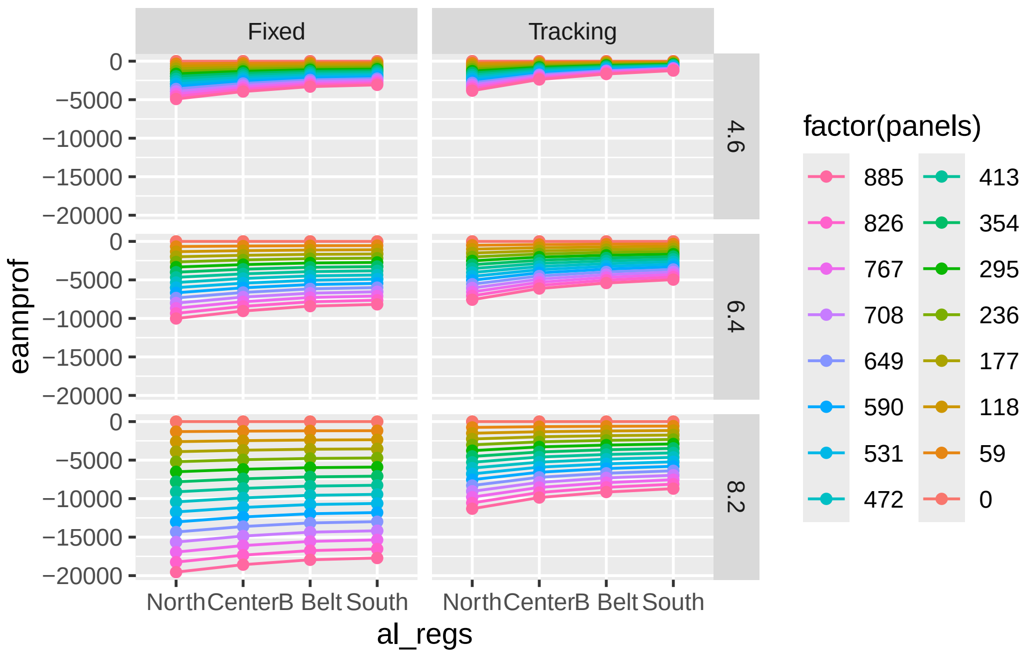

```
Electricity Price =  0.03
```



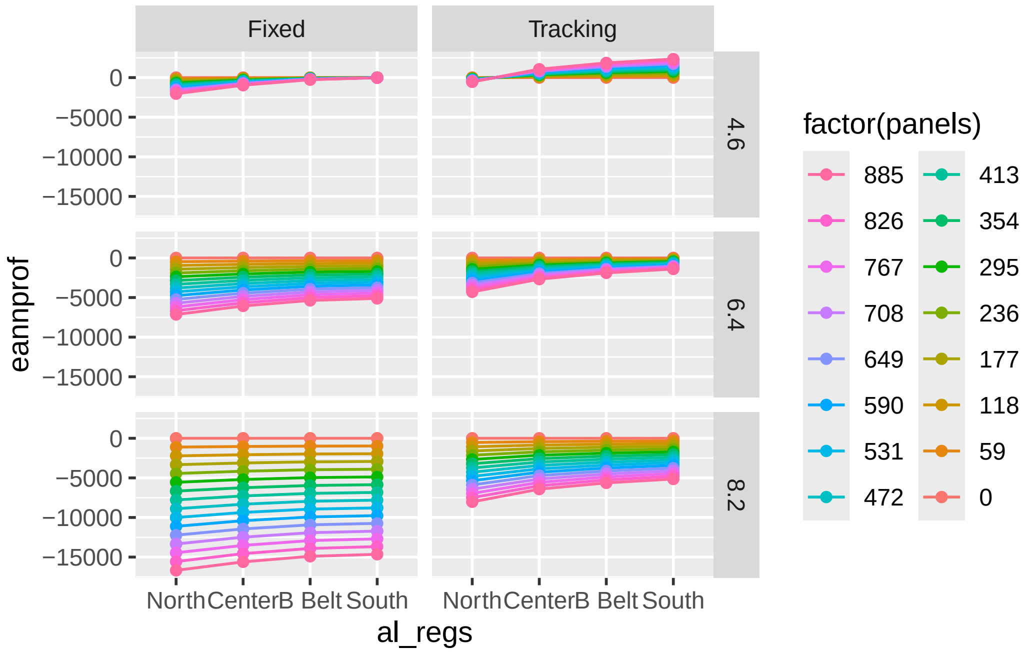

```
Electricity Price =  0.035
```



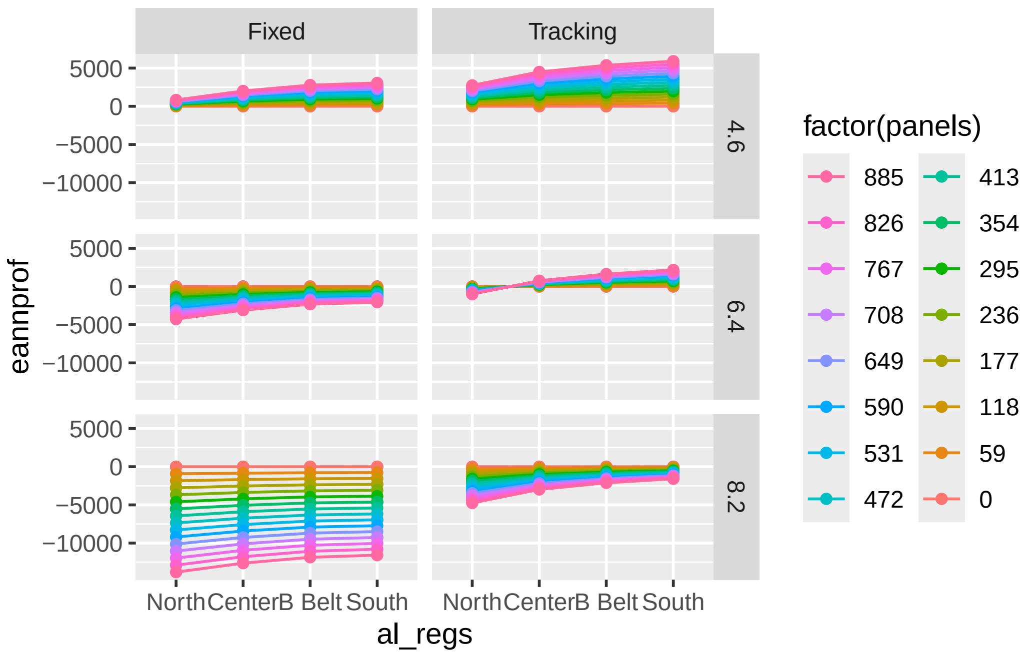

Electricity Price =  0.04



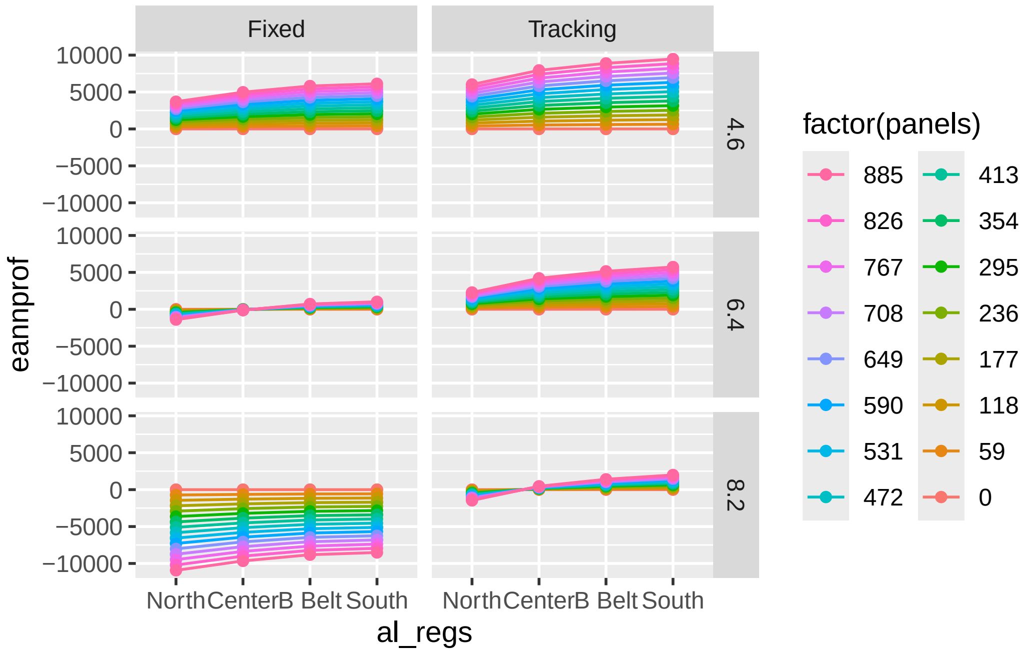

Electricity Price =  0.045



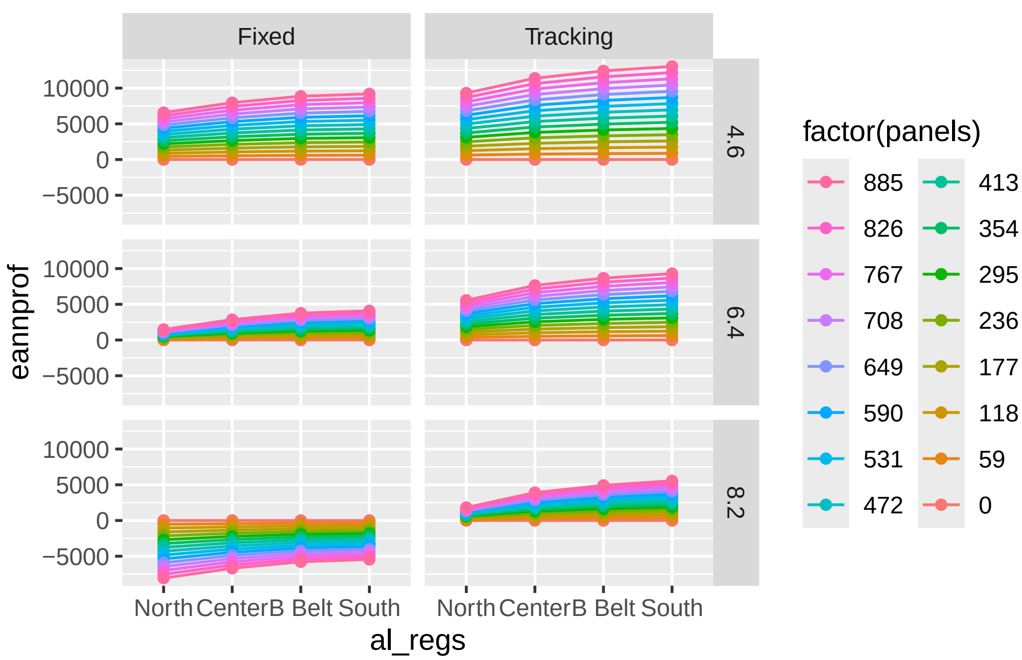

```
Electricity Price =  0.05
```




```
Electricity Price =  0.055
```




Electricity Price =  0.06



# 4 Profit from crops

## 4.1 Tomato

Filter return to operator, land and capital profit from Tomato:

```
tomato_profit = tomato %>%
  select(yldvar, yield,
         rolac17, rolac18, rolac19, rolac20,
         rolac21, rolac22, rolac23)
dim(tomato_profit)
```

```
[1] 21  9
```

```
tomato_profit
```

```
   yldvar yield     rolac17     rolac18     rolac19     rolac20     rolac21
3     2.0  2720  21679.3826  24399.3826  27119.3826  29839.3826  32559.3826
4     1.9  2584  20065.3826  22649.3826  25233.3826  27817.3826  30401.3826
5     1.8  2448  18451.3826  20899.3826  23347.3826  25795.3826  28243.3826
6     1.7  2312  16837.3826  19149.3826  21461.3826  23773.3826  26085.3826
7     1.6  2176  15223.3826  17399.3826  19575.3826  21751.3826  23927.3826
8     1.5  2040  13609.3826  15649.3826  17689.3826  19729.3826  21769.3826
9     1.4  1904  11995.3826  13899.3826  15803.3826  17707.3826  19611.3826
10    1.3  1768  10381.3826  12149.3826  13917.3826  15685.3826  17453.3826
11    1.2  1632   8767.3826  10399.3826  12031.3826  13663.3826  15295.3826
12    1.1  1496   7153.3826   8649.3826  10145.3826  11641.3826  13137.3826
13    1.0  1360   5539.3826   6899.3826   8259.3826   9619.3826  10979.3826
14    0.9  1224   3925.3826   5149.3826   6373.3826   7597.3826   8821.3826
15    0.8  1088   2311.3826   3399.3826   4487.3826   5575.3826   6663.3826
16    0.7   952    697.3826   1649.3826   2601.3826   3553.3826   4505.3826
17    0.6   816   -916.6174   -100.6174    715.3826   1531.3826   2347.3826
18    0.5   680  -2530.6174  -1850.6174  -1170.6174   -490.6174    189.3826
19    0.4   544  -4144.6174  -3600.6174  -3056.6174  -2512.6174  -1968.6174
20    0.3   408  -5758.6174  -5350.6174  -4942.6174  -4534.6174  -4126.6174
21    0.2   272  -7372.6174  -7100.6174  -6828.6174  -6556.6174  -6284.6174
22    0.1   136  -8986.6174  -8850.6174  -8714.6174  -8578.6174  -8442.6174
23    0.0     0 -10600.6174 -10600.6174 -10600.6174 -10600.6174 -10600.6174
       rolac22     rolac23
3   35279.3826  37999.3826
4   32985.3826  35569.3826
```

```
5    30691.3826   33139.3826
6    28397.3826   30709.3826
7    26103.3826   28279.3826
8    23809.3826   25849.3826
9    21515.3826   23419.3826
10   19221.3826   20989.3826
11   16927.3826   18559.3826
12   14633.3826   16129.3826
13   12339.3826   13699.3826
14   10045.3826   11269.3826
15    7751.3826    8839.3826
16    5457.3826    6409.3826
17    3163.3826    3979.3826
18     869.3826    1549.3826
19   -1424.6174    -880.6174
20   -3718.6174   -3310.6174
21   -6012.6174   -5740.6174
22   -8306.6174   -8170.6174
23 -10600.6174 -10600.6174
```

Convert data to long format:

```r
# Assign column names for clarity
colnames(tomato_profit) <- c("yldvar", "yield",
                  "rolac17", "rolac18", "rolac19",
                  "rolac20", "rolac21", "rolac22",
                  "rolac23")

# Reshape the data frame from wide to long format
tomato_long <- melt(tomato_profit,
                id.vars = c("yldvar", "yield"),
                measure.vars = c("rolac17", "rolac18", "rolac19",
                                 "rolac20", "rolac21", "rolac22",
                                 "rolac23"),
                variable.name = "price",
                value.name = "profit")

# Convert the 'Price' column to numeric by extracting the number
tomato_long$price <- as.numeric(gsub("rolac", "", tomato_long$price))
str(tomato_long)
```

```
'data.frame':   147 obs. of  4 variables:
```

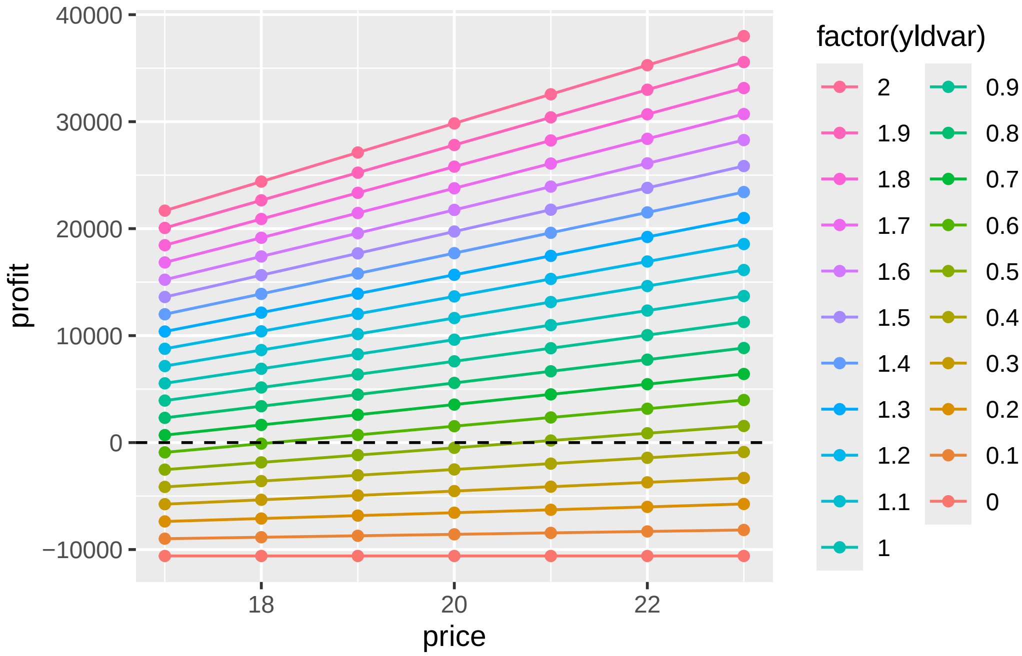
```
 $ yldvar: num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield : num  2720 2584 2448 2312 2176 ...
 $ price : num  17 17 17 17 17 17 17 17 17 17 ...
 $ profit: num  21679 20065 18451 16837 15223 ...
```

```
head(tomato_long); tail(tomato_long)
```

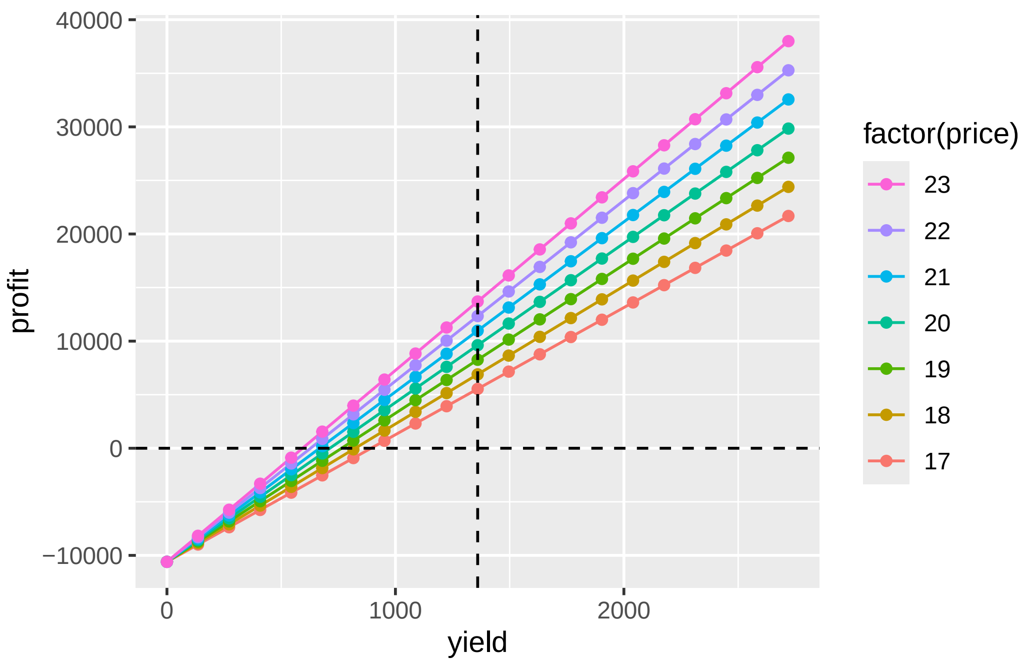
```
  yldvar yield price   profit
1    2.0  2720    17 21679.38
2    1.9  2584    17 20065.38
3    1.8  2448    17 18451.38
4    1.7  2312    17 16837.38
5    1.6  2176    17 15223.38
6    1.5  2040    17 13609.38

    yldvar yield price      profit
142    0.5   680    23   1549.3826
143    0.4   544    23   -880.6174
144    0.3   408    23  -3310.6174
145    0.2   272    23  -5740.6174
146    0.1   136    23  -8170.6174
147    0.0     0    23 -10600.6174
```

### 4.1.1 Plot Tomato Profit

```
ggplot(data = tomato_long,
       mapping = aes(x = price,
                     y = profit,
                     color = factor(yldvar),
                     group = factor(yield))) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = 0,
             linetype = "dashed",
             color = "black") +
  guides(color = guide_legend(ncol = 2,
                              reverse = TRUE))
```




```r
ggplot(data = tomato_long,
       mapping = aes(x = yield,
                     y = profit,
                     #fill = yield,
                     color = factor(price),
                     group = factor(price))) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = 0,
             linetype = "dashed",
             color = "black") +
  # Vertical dashed line is 100% yield
  geom_vline(xintercept = tomato_long$yield[11],
             linetype = "dashed",
             color = "black") +
guides(color = guide_legend(reverse = TRUE))
```




## 4.2 Strawberry

Filter return to operator, land and capital profit from strawberry

```
strawberry_profit = strawberry %>%
  select(yldvar, yield,
         rolac3, rolac4, rolac5, rolac6,
         rolac7, rolac8, rolac9)
str(strawberry_profit)
```

```
'data.frame':   21 obs. of  9 variables:
 $ yldvar: num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield : num  6150 5842 5535 5228 4920 ...
 $ rolac3: num  -1740 -2317 -2894 -3471 -4048 ...
 $ rolac4: num  4410 3525 2641 1756 872 ...
 $ rolac5: num  10560 9368 8176 6984 5792 ...
 $ rolac6: num  16710 15210 13711 12211 10712 ...
 $ rolac7: num  22860 21053 19246 17439 15632 ...
 $ rolac8: num  29010 26895 24781 22666 20552 ...
 $ rolac9: num  35160 32738 30316 27894 25472 ...
```

```
strawberry_profit
```

```
   yldvar  yield     rolac3       rolac4     rolac5     rolac6     rolac7
3     2.0 6150.0  -1740.495   4409.50503  10559.505  16709.505  22859.505
4     1.9 5842.5  -2317.350   3525.15003   9367.650  15210.150  21052.650
5     1.8 5535.0  -2894.205   2640.79503   8175.795  13710.795  19245.795
6     1.7 5227.5  -3471.060   1756.44003   6983.940  12211.440  17438.940
7     1.6 4920.0  -4047.915    872.08503   5792.085  10712.085  15632.085
8     1.5 4612.5  -4624.770    -12.26997   4600.230   9212.730  13825.230
9     1.4 4305.0  -5201.625   -896.62497   3408.375   7713.375  12018.375
10    1.3 3997.5  -5778.480  -1780.97997   2216.520   6214.020  10211.520
11    1.2 3690.0  -6355.335  -2665.33497   1024.665   4714.665   8404.665
12    1.1 3382.5  -6932.190  -3549.68997   -167.190   3215.310   6597.810
13    1.0 3075.0  -7509.045  -4434.04497  -1359.045   1715.955   4790.955
14    0.9 2767.5  -8085.900  -5318.39997  -2550.900    216.600   2984.100
15    0.8 2460.0  -8662.755  -6202.75497  -3742.755  -1282.755   1177.245
16    0.7 2152.5  -9239.610  -7087.10997  -4934.610  -2782.110   -629.610
17    0.6 1845.0  -9816.465  -7971.46497  -6126.465  -4281.465  -2436.465
18    0.5 1537.5 -10393.320  -8855.81997  -7318.320  -5780.820  -4243.320
19    0.4 1230.0 -10970.175  -9740.17497  -8510.175  -7280.175  -6050.175
20    0.3  922.5 -11547.030 -10624.52997  -9702.030  -8779.530  -7857.030
21    0.2  615.0 -12123.885 -11508.88497 -10893.885 -10278.885  -9663.885
22    0.1  307.5 -12700.740 -12393.23997 -12085.740 -11778.240 -11470.740
23    0.0    0.0 -13277.595 -13277.59497 -13277.595 -13277.595 -13277.595
       rolac8     rolac9
3   29009.505  35159.505
4   26895.150  32737.650
5   24780.795  30315.795
6   22666.440  27893.940
7   20552.085  25472.085
8   18437.730  23050.230
9   16323.375  20628.375
10  14209.020  18206.520
11  12094.665  15784.665
12   9980.310  13362.810
13   7865.955  10940.955
14   5751.600   8519.100
15   3637.245   6097.245
16   1522.890   3675.390
17   -591.465   1253.535
18  -2705.820  -1168.320
19  -4820.175  -3590.175
```

```
20  -6934.530  -6012.030
21  -9048.885  -8433.885
22 -11163.240 -10855.740
23 -13277.595 -13277.595
```

Convert data to long format:

```
# Assign column names for clarity
colnames(strawberry_profit) <- c("yldvar", "yield",
                  "rolac3", "rolac4", "rolac5",
                  "rolac6", "rolac7", "rolac8",
                  "rolac9")
# Reshape the data frame from wide to long format
stberry_long <- melt(strawberry_profit,
                id.vars = c("yldvar", "yield"),
                measure.vars = c("rolac3", "rolac4", "rolac5",
                                 "rolac6", "rolac7", "rolac8",
                                 "rolac9"),
                variable.name = "price",
                value.name = "profit")

# Convert the 'Price' column to numeric by extracting the number
stberry_long$price <- as.numeric(gsub("rolac", "", stberry_long$price))
str(stberry_long)
```

```
'data.frame':   147 obs. of  4 variables:
 $ yldvar: num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield : num  6150 5842 5535 5228 4920 ...
 $ price : num  3 3 3 3 3 3 3 3 3 3 ...
 $ profit: num  -1740 -2317 -2894 -3471 -4048 ...
```

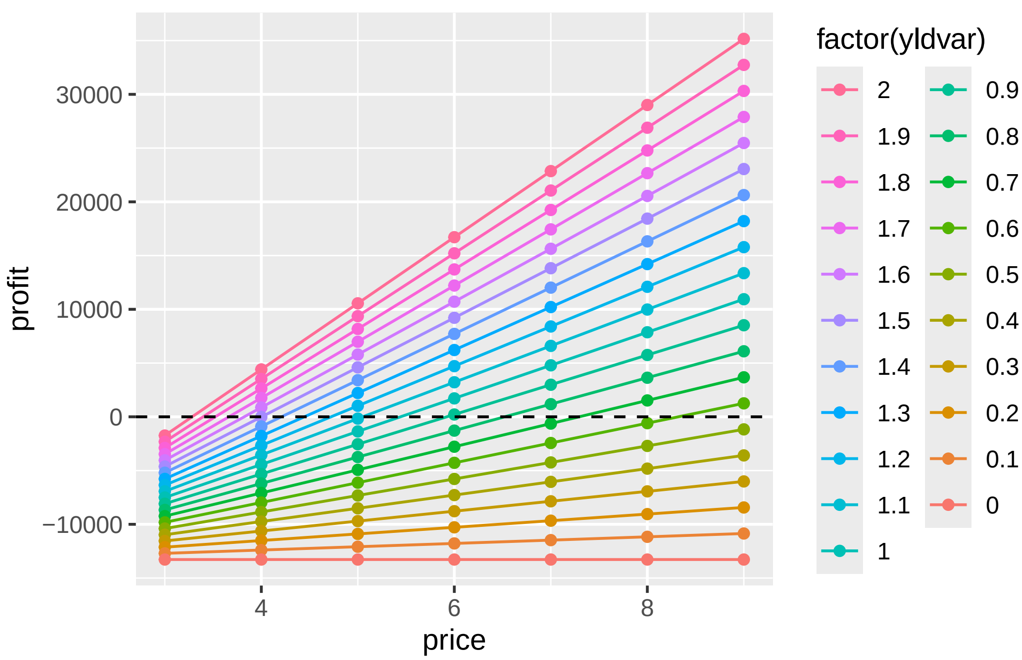
```
head(stberry_long); tail(stberry_long)
```

```
  yldvar  yield price    profit
1    2.0 6150.0     3 -1740.495
2    1.9 5842.5     3 -2317.350
3    1.8 5535.0     3 -2894.205
4    1.7 5227.5     3 -3471.060
5    1.6 4920.0     3 -4047.915
6    1.5 4612.5     3 -4624.770
```

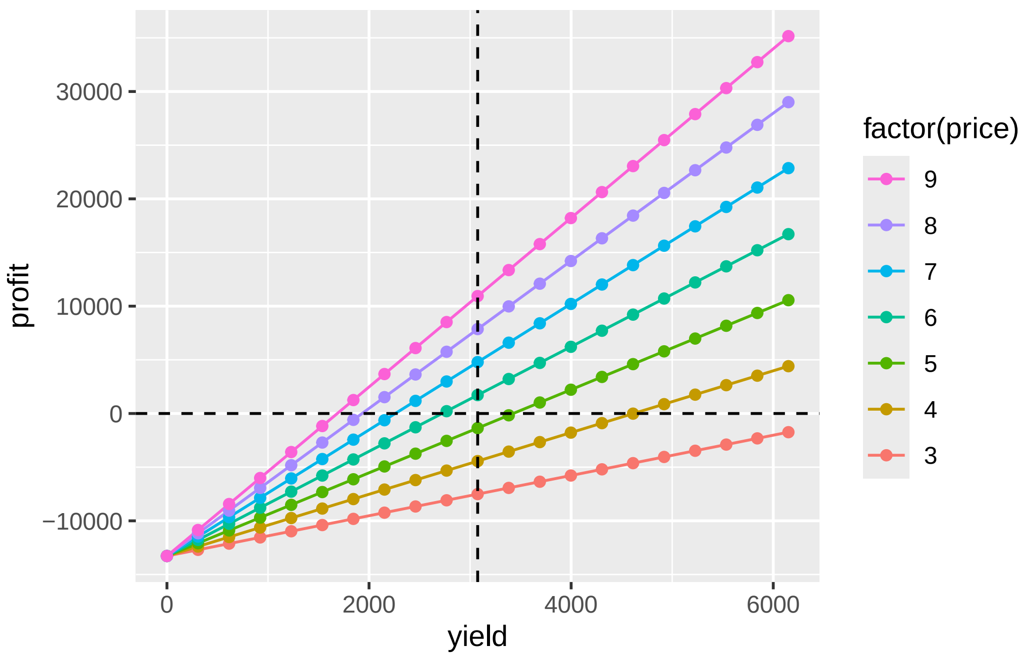
```
    yldvar  yield price     profit
142    0.5 1537.5     9  -1168.320
143    0.4 1230.0     9  -3590.175
144    0.3  922.5     9  -6012.030
145    0.2  615.0     9  -8433.885
146    0.1  307.5     9 -10855.740
147    0.0    0.0     9 -13277.595
```

### 4.2.1 Plot Strawberry Profit

```
ggplot(data = stberry_long,
       mapping = aes(x = price,
                     y = profit,
                     color = factor(yldvar),
                     group = factor(yield))) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = 0,
             linetype = "dashed",
             color = "black") +
  guides(color = guide_legend(ncol = 2,
                              reverse = TRUE))
```



```
ggplot(data = stberry_long,
       mapping = aes(x = yield,
                     y = profit,
                     color = factor(price),
                     group = factor(price))) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = 0,
             linetype = "dashed",
             color = "black") +
  #Vertical dashed line is 100% yield
  geom_vline(xintercept = stberry_long$yield[11],
             linetype = "dashed",
             color = "black") +
  guides(color = guide_legend(reverse = TRUE))
```




### 4.3 Squash

Filter return to operator, land and capital profit from squash

```
squash_profit = squash %>%
  select(yldvar, yield,
         rolac11, rolac12, rolac13, rolac14,
         rolac15, rolac16, rolac17)
squash_profit
```

Convert data to long format:

```
# Assign column names for clarity
colnames(squash_profit) <- c("yldvar", "yield",
                  "rolac11", "rolac12", "rolac13",
                  "rolac14", "rolac15", "rolac16",
                  "rolac17")

# Reshape the data frame from wide to long format
squash_long <- melt(squash_profit,
                id.vars = c("yldvar", "yield"),
                measure.vars = c("rolac11", "rolac12", "rolac13",
                                 "rolac14", "rolac15", "rolac16",
                                 "rolac17"),
                variable.name = "price",
                value.name = "profit")

# Convert the 'Price' column to numeric by extracting the number
squash_long$price <- as.numeric(gsub("rolac", "", squash_long$price))
str(squash_long)
head(squash_long); tail(squash_long)
```

#### 4.3.1 Profit from squash:

```
ggplot(data = squash_long,
       mapping = aes(x = price,
                     y = profit,
                     color = factor(yldvar),
                     group = factor(yield))) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = 0,
             linetype = "dashed",
             color = "black") +
```

```
  guides(color = guide_legend(ncol = 2,
                              reverse = TRUE))
```

```
ggplot(data = squash_long,
       mapping = aes(x = yield,
                     y = profit,
                     color = factor(price),
                     group = factor(price))) +
  geom_line() +
  geom_point() +
  geom_hline(yintercept = 0,
             linetype = "dashed",
             color = "black") +
  # Vertical dashed line is 100% yield
    geom_vline(xintercept = squash_long$yield[11],
             linetype = "dashed",
             color = "black") +
  guides(color = guide_legend(reverse = TRUE))
```

# 5 Profit from agrivoltaics

Total profit from solar and crops for all combinations of AVs simulated.

## 5.1 Profit from tomato agrivoltaic system

- Joint profit from tomato (tomato_long) and solar energy production (solar_profit) from 1 acre of land.
- The last variable (tav_profit) is the final profit from tomato agrivoltaic system which is the result of our interest.

```
# Calculate all combinations of rows from both matrices in a vectorized way
solar_expanded <- solar_profit[rep(1:nrow(solar_profit),
                                   each = nrow(tomato_long)), ]
tomato_expanded <- tomato_long[rep(1:nrow(tomato_long),
                                   times = nrow(solar_profit)), ]

# Calculate the new column for tav_profit directly
tav_profit_values <- solar_expanded$eannprof + tomato_expanded$profit
```

```r
# Combine the matrices and the calculated tav_profit column
tav_profit <- cbind(solar_expanded,
                    tomato_expanded,
                    tav_profit = tav_profit_values)

# Convert to a data frame and ensure the correct format
tav_profit <- as.data.frame(tav_profit)
tav_profit <- data.frame(lapply(tav_profit, unlist))
str(tav_profit)
```

```
'data.frame':   814968 obs. of  29 variables:
 $ sprop                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ al_regs              : chr  "Black Belt" "Black Belt" "Black Belt" "Black Belt" ...
 $ array                : chr  "Fixed" "Fixed" "Fixed" "Fixed" ...
 $ dc_kw                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ panels               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ energy               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ elcprc               : num  0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 ...
 $ elcrev               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ height               : num  4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 ...
 $ capex                : num  1.59 1.59 1.59 1.59 1.59 ...
 $ landlease            : num  1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 ...
 $ ttlcost              : num  0 0 0 0 0 0 0 0 0 0 ...
 $ inscst               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ recredit             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ reap                 : num  0 0 0 0 0 0 0 0 0 0 ...
 $ annlzcost            : num  0 0 0 0 0 0 0 0 0 0 ...
 $ annoftotcost         : num  0 0 0 0 0 0 0 0 0 0 ...
 $ monthlycost          : num  0 0 0 0 0 0 0 0 0 0 ...
 $ opex                 : num  0 0 0 0 0 0 0 0 0 0 ...
 $ taxcr                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ anncost              : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprof             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprofworeap       : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprofwoincentives: num  0 0 0 0 0 0 0 0 0 0 ...
 $ yldvar               : num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield                : num  2720 2584 2448 2312 2176 ...
 $ price                : num  17 17 17 17 17 17 17 17 17 17 ...
 $ profit               : num  21679 20065 18451 16837 15223 ...
 $ tav_profit           : num  21679 20065 18451 16837 15223 ...
```

```r
head(tav_profit); tail(tav_profit)
```

```
  sprop    al_regs array dc_kw panels energy elcprc elcrev height    capex
1     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
2     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
3     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
4     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
5     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
6     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
  landlease ttlcost inscst recredit reap annlzcost annoftotcost monthlycost
1      1000       0      0        0    0         0            0           0
2      1000       0      0        0    0         0            0           0
3      1000       0      0        0    0         0            0           0
4      1000       0      0        0    0         0            0           0
5      1000       0      0        0    0         0            0           0
6      1000       0      0        0    0         0            0           0
  opex taxcr anncost eannprof eannprofworeap eannprofwoincentives yldvar yield
1    0     0       0        0              0                    0    2.0  2720
2    0     0       0        0              0                    0    1.9  2584
3    0     0       0        0              0                    0    1.8  2448
4    0     0       0        0              0                    0    1.7  2312
5    0     0       0        0              0                    0    1.6  2176
6    0     0       0        0              0                    0    1.5  2040
  price   profit tav_profit
1    17 21679.38   21679.38
2    17 20065.38   20065.38
3    17 18451.38   18451.38
4    17 16837.38   16837.38
5    17 15223.38   15223.38
6    17 13609.38   13609.38
```

```
       sprop  al_regs    array  dc_kw panels energy elcprc   elcrev height
814963     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814964     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814965     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814966     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814967     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814968     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
       capex landlease ttlcost   inscst recredit     reap annlzcost
814963  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814964  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
```

```
814965  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814966  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814967  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814968  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
       annoftotcost monthlycost     opex    taxcr  anncost eannprof
814963     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814964     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814965     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814966     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814967     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814968     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
       eannprofworeap eannprofwoincentives yldvar yield price      profit
814963      -13653.56            -44557.48    0.5   680    23   1549.3826
814964      -13653.56            -44557.48    0.4   544    23   -880.6174
814965      -13653.56            -44557.48    0.3   408    23  -3310.6174
814966      -13653.56            -44557.48    0.2   272    23  -5740.6174
814967      -13653.56            -44557.48    0.1   136    23  -8170.6174
814968      -13653.56            -44557.48    0.0     0    23 -10600.6174
       tav_profit
814963  7100.7518
814964  4670.7518
814965  2240.7518
814966  -189.2482
814967 -2619.2482
814968 -5049.2482
```

### 5.1.1 Saving results locally

```r
#write_csv(tav_profit, "tav_profit.csv")
write_feather(tav_profit,
  sink = "Data/tav_profit.feather",
  version = 2,
  chunk_size = 65536L,
  compression = c("default"),
  #compression = c("default", "lz4", "lz4_frame", "uncompressed", "zstd"),
  compression_level = NULL
)
```

## 5.2 Profit from strawberry agrivoltaic system

- Joint profit from strawberry (stberry_long) and solar energy production (solar_profit) from 1 acre of land.
- The last variable (sbav_profit) is the final profit from strawberry agrivoltaic system which is the result of our interest.

```r
# Generate all combinations of rows from both matrices in a vectorized way
solar_expanded <- solar_profit[rep(1:nrow(solar_profit),
                                   each = nrow(stberry_long)), ]
stberry_expanded <- stberry_long[rep(1:nrow(stberry_long),
                                     times = nrow(solar_profit)), ]

# Calculate the new column for sbav_profit directly
sbav_profit_values <- solar_expanded$eannprof + stberry_expanded$profit

# Combine the matrices and the calculated sbav_profit column
sbav_profit <- cbind(solar_expanded,
                     stberry_expanded,
                     sbav_profit = sbav_profit_values)

# Convert to a data frame and ensure the correct format
sbav_profit <- as.data.frame(sbav_profit)
sbav_profit <- data.frame(lapply(sbav_profit, unlist))
str(sbav_profit)
```

```
'data.frame':   814968 obs. of  29 variables:
 $ sprop                 : num  0 0 0 0 0 0 0 0 0 0 ...
 $ al_regs               : chr  "Black Belt" "Black Belt" "Black Belt" "Black Belt" ...
 $ array                 : chr  "Fixed" "Fixed" "Fixed" "Fixed" ...
 $ dc_kw                 : num  0 0 0 0 0 0 0 0 0 0 ...
 $ panels                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ energy                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ elcprc                : num  0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 ...
 $ elcrev                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ height                : num  4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 4.6 ...
 $ capex                 : num  1.59 1.59 1.59 1.59 1.59 ...
 $ landlease             : num  1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 ...
 $ ttlcost               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ inscst                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ recredit              : num  0 0 0 0 0 0 0 0 0 0 ...
 $ reap                  : num  0 0 0 0 0 0 0 0 0 0 ...
```

```
 $ annlzcost           : num  0 0 0 0 0 0 0 0 0 0 ...
 $ annoftotcost        : num  0 0 0 0 0 0 0 0 0 0 ...
 $ monthlycost         : num  0 0 0 0 0 0 0 0 0 0 ...
 $ opex                : num  0 0 0 0 0 0 0 0 0 0 ...
 $ taxcr               : num  0 0 0 0 0 0 0 0 0 0 ...
 $ anncost             : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprof            : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprofworeap      : num  0 0 0 0 0 0 0 0 0 0 ...
 $ eannprofwoincentives: num  0 0 0 0 0 0 0 0 0 0 ...
 $ yldvar              : num  2 1.9 1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 ...
 $ yield               : num  6150 5842 5535 5228 4920 ...
 $ price               : num  3 3 3 3 3 3 3 3 3 3 ...
 $ profit              : num  -1740 -2317 -2894 -3471 -4048 ...
 $ sbav_profit         : num  -1740 -2317 -2894 -3471 -4048 ...
```

```
head(sbav_profit); tail(sbav_profit)
```

```
  sprop    al_regs array dc_kw panels energy elcprc elcrev height    capex
1     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
2     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
3     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
4     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
5     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
6     0 Black Belt Fixed     0      0      0   0.01      0    4.6 1.593333
  landlease ttlcost inscst recredit reap annlzcost annoftotcost monthlycost
1      1000       0      0        0    0         0            0           0
2      1000       0      0        0    0         0            0           0
3      1000       0      0        0    0         0            0           0
4      1000       0      0        0    0         0            0           0
5      1000       0      0        0    0         0            0           0
6      1000       0      0        0    0         0            0           0
  opex taxcr anncost eannprof eannprofworeap eannprofwoincentives yldvar  yield
1    0     0       0        0              0                    0    2.0 6150.0
2    0     0       0        0              0                    0    1.9 5842.5
3    0     0       0        0              0                    0    1.8 5535.0
4    0     0       0        0              0                    0    1.7 5227.5
5    0     0       0        0              0                    0    1.6 4920.0
6    0     0       0        0              0                    0    1.5 4612.5
  price    profit sbav_profit
1     3 -1740.495   -1740.495
2     3 -2317.350   -2317.350
3     3 -2894.205   -2894.205
```

```
4      3 -3471.060   -3471.060
5      3 -4047.915   -4047.915
6      3 -4624.770   -4624.770

       sprop  al_regs    array  dc_kw panels energy elcprc   elcrev height
814963     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814964     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814965     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814966     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814967     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
814968     1 Southern Tracking 423.74    885 712873   0.06 42772.38    8.2
       capex landlease ttlcost   inscst recredit     reap annlzcost
814963  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814964  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814965  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814966  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814967  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
814968  2.11      1000 1017706 5088.529 4704.962 254337.4  65505.03
       annoftotcost monthlycost     opex    taxcr  anncost eannprof
814963     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814964     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814965     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814966     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814967     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
814968     87329.86    2906.674 2619.896 26198.96 68124.93 5551.369
       eannprofworeap eannprofwoincentives yldvar  yield price     profit
814963      -13653.56            -44557.48    0.5 1537.5     9  -1168.320
814964      -13653.56            -44557.48    0.4 1230.0     9  -3590.175
814965      -13653.56            -44557.48    0.3  922.5     9  -6012.030
814966      -13653.56            -44557.48    0.2  615.0     9  -8433.885
814967      -13653.56            -44557.48    0.1  307.5     9 -10855.740
814968      -13653.56            -44557.48    0.0    0.0     9 -13277.595
       sbav_profit
814963   4383.0492
814964   1961.1942
814965   -460.6608
814966  -2882.5158
814967  -5304.3708
814968  -7726.2258
```

### 5.2.1 Saving results locally

```r
#write_csv(sbav_profit, "tav_profit.csv")
write_feather(sbav_profit,
  sink = "Data/sbav_profit.feather",
  version = 2,
  chunk_size = 65536L,
  compression = c("default"),
  #compression = c("default", "lz4", "lz4_frame", "uncompressed", "zstd"),
  compression_level = NULL
)
```

## 5.3 Profit from squash agrivoltaic system

- Joint profit from squash (squash_long) and solar energy production (solar_profit) from 1 acre of land.
- The last variable (sqav_profit) is the final profit from squash agrivoltaic system which is the result of our interest.

```r
# Efficient calculation of all combinations of rows from both matrices
solar_expanded <- solar_profit[rep(1:nrow(solar_profit),
                                   each = nrow(squash_long)), ]
squash_expanded <- squash_long[rep(1:nrow(squash_long),
                                   times = nrow(solar_profit)), ]

# Calculate the new column for sqav_profit directly
sqav_profit_values <- solar_expanded$eannprof + squash_expanded$profit

# Combine the matrices and the calculated sqav_profit column
sqav_profit <- cbind(solar_expanded,
                     squash_expanded,
                     sqav_profit = sqav_profit_values)

# Convert to a data frame and ensure the correct format
sqav_profit <- as.data.frame(sqav_profit)
sqav_profit <- data.frame(lapply(sqav_profit, unlist))
str(sqav_profit)
head(sqav_profit); tail(sqav_profit)
```

### 5.3.1 Saving results locally

```r
#write_csv(sqav_profit, "tav_profit.csv")
write_feather(sqav_profit,
  sink = "Data/sqav_profit.feather",
  version = 2,
  chunk_size = 65536L,
  compression = c("default"),
  #compression = c("default", "lz4", "lz4_frame", "uncompressed", "zstd"),
  compression_level = NULL
)
```