Using R to Understand Alberta's Solar Resource: Presentation to the Calgary RUG

21 April 2021

My target audience

You can't please all of the people all the time

- R users curious about solar energy
- Solar/renewables professionals looking for a new tool
- Concerned Albertans
- People on a lark

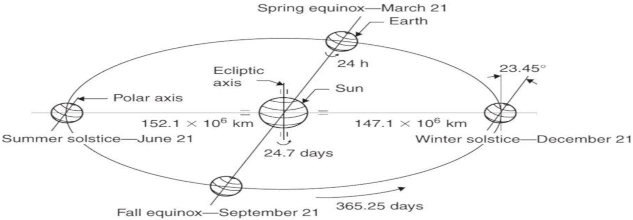
Prerequisites: numeracy/scientific literacy; bit of computer coding

About this talk: What I hope to achieve

- Explain the worldwide solar resource and its relationship to geography
- Explain the photovoltaic effect
- Explain how analysing data can be used to build understanding of this
- Do a practice run with some data based in Alberta
- Talk about R and solar data in general
- Have some fun!

N.B.: There is no way I could cover all of this in an hour; I will try not to tell lies, but I cannot tell you the whole truth

The sun and us



The sun: a point source (?!)

- We can think of the sun as a point source of radiation, roughly 150 million kms away
- By the time the sun's rays hit the earth, we are bombarded with 1.7 * 10ˆ17 Joules of energy per second
- That works out as 340 W per mˆ2 (Don't believe me? Do the math!)
- How much is that anyway?

Deloreans?

Going from 1985 to 1955 roughly 1.42 million times

Quick review . . .

Power vs energy

- $$1J = 1kg * 1 * \frac{m}{s^2}$$
- $$1W = 1\frac{J}{s}$$
  (1 J*Hz)
- Or: increasing the potential energy of $6 * 10^{18}$ electrons by 1 V

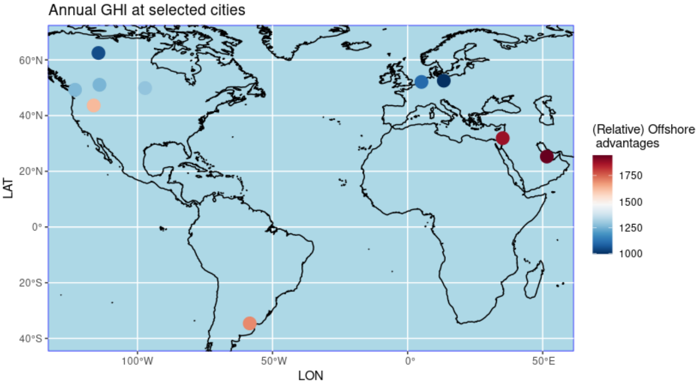
What this means for us

- Heating one cup of coffee requires ~300,000 Joules
- Electricity is often usually measured in kWh (check your electric bill)
- Regularly charging your smartphone might take between 2 and 6 kWh yearly
- An Albertan household might use 7,200 kWh of electricity in a typical year

In practical terms: cities we know

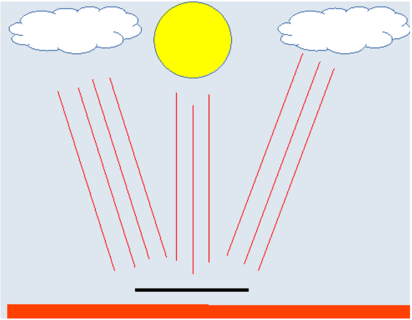
```
##                      LON       LAT Annual GHI
## Calgary       -114.06259  51.05342    1251.95
## Vancouver     -123.11395  49.26087    1259.25
## Edmonton      -113.50800  53.53541    1197.20
## Yellowknife   -114.43849  62.47094    1047.55
## Winnipeg       -97.16858  49.88402    1284.80
## Utrecht          5.12768  52.08095    1102.30
## Buenos Aires   -58.43708 -34.60756    1697.25
## Ramallah        35.19517  31.90308    1879.75
## Doha            51.52642  25.28563    1945.45
## Berlin          13.38886  52.51704     996.45
```

A picture = 1*10^3 words



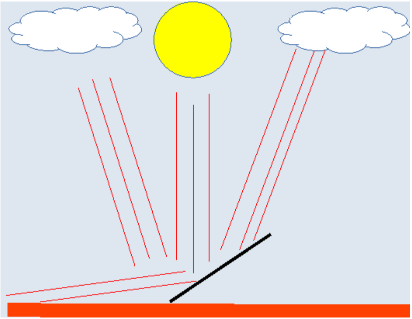
GHI: a TLA explained

- If the sun were a point source directly above, then only "DNR" applies
- GHI takes into account the "diffuse" irradiation bouncing off, eg, clouds
- In Edmonton, diffuse irradiation might be cf. for DNR



From GHI to POA

- We can tilt the panels to catch more sunshine
- Amount of tilt varies by latitude
- The change now is the ground reflected component



Albedo, Diffuse radiation: geography

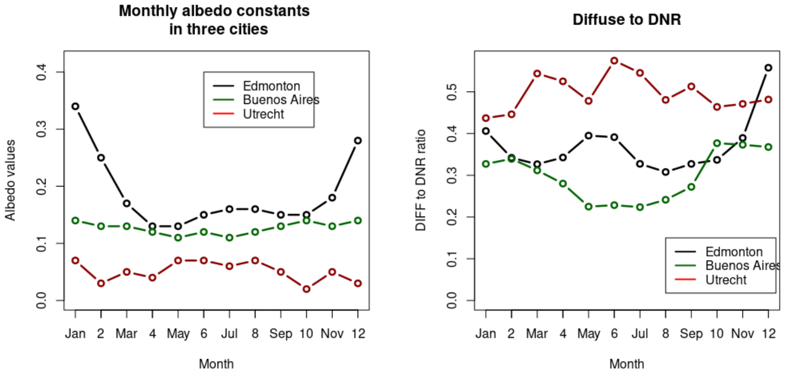
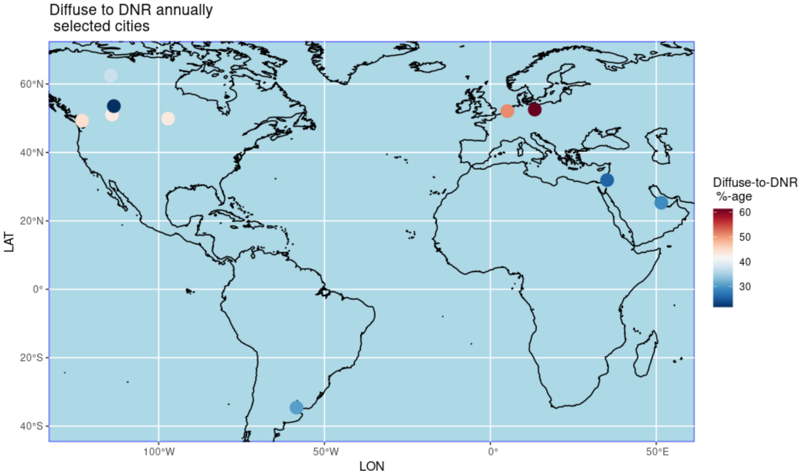


Figure 1: Geography plays a role in determining composition of solar radiation

Diffuse to DNR: cities across the world

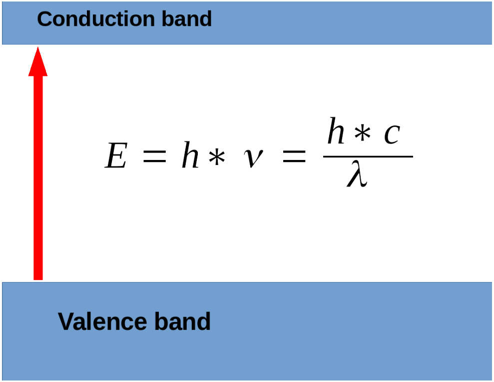


Part 1: Prizes to take home

- We get a lot of solar radiation from the sun
- It falls unequally on different parts of the globe
- The relationship between solar radiation, meteorology and geography is complex
- The different components of solar radiation are significant, especially for tilted panels

The photovoltaic effect

- Photons hit electrons in the valence band of a semi-conductor
- The electrons can now move up to the conduction band
- We can optimise this process by tweaking the semiconductors into “p-n junctions”



$$E = h * \nu = \frac{h * c}{\lambda}$$

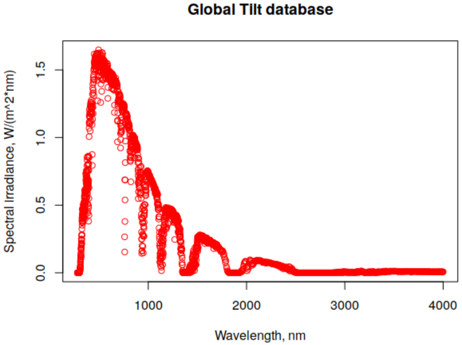
If you are a solid state physicist or electrical engineer

. . . but wait, I said semiconductors

- CdTe and CIGS PV cells are good examples of “thin film” technologies
- There are good reasons why they are not terribly widepsread . . .
- Silicon (not a-Si) technologies account for 95% of global installation
- Don’t forget: the LCOE (more later)

The photovoltaic effect: constraints

- Transmittivity of the covers always imperfect (see below)
- Take a Silicon band gap of 1.3 eV: some photons are below the threshold
- For a photon with $E_{photon} >= E_{gap}$, all excess energy is lost
- We can optimise this process by tweaking the semiconductors into “p-n junctions”



Efficiency and yield

- On a global level, 504 GW (417 DL) of PV capacity generated 585 TWh of electricity, a “CF” of 13.25%
- This should improve with time, but there are limits
- Conversion efficiency drops with operating cell temperature

$$Yield = \eta * H$$

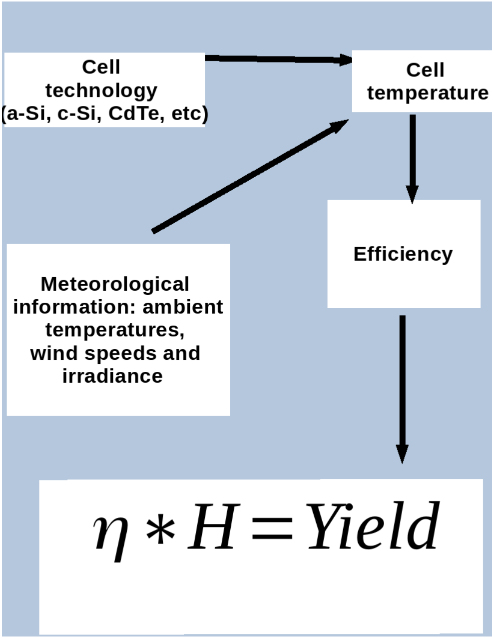
$$\eta = \eta_{stc} * [(1 - \beta_R * T'_{cell}) + \gamma * log_{10}(I)]$$

$$T_{cell} = T_{amb} + \frac{I}{U_0 + U_1 + v_{wind}}$$

Do not confuse STC, NOTC. I is for irradiance (= insolation per unit time).

Why solar data is not an "OKCupid" Phenomenon

- Consider hourly data for solar PV yield
- We need observations on wind speed, ambient temperature and irradiance and insolation
- With all parameters decided, we need ~500,000 30-second readings (rows) of three variables (columns) per year
-



The decision variable: LCOE, or "Should I buy solar panels?"

- Look at your electric bill
- Land is a major factor for the cost of solar PV farms
- "NPV" is a fancy way of saying "take time into account"

$$LCOE = \sum \frac{NPV(Costs : O\&M, fuel, investments, land(solar))}{NPV(Electricity/Yields)}$$

Part 2: Prizes to take home

- Cell operating temperature inversely corresponds to efficiency of PV yield
- Cell operating temperature is a function of the technology used but also the ambient conditions
- We can simplify a physics, engineering and meteorology issue to a number crunching exercise
- Knowing how much yield we get from panels allows us to calculate how economically feasible solar panels are

You can do this at home, kids

	mSi	pSi	aSi	microSi	CdTe
T_NOCT	45.00	46.00	46.00	45.00	45.00
eta_STC	18.40	14.10	6.00	9.50	10.70
beta_STC	-0.38	-0.45	-0.19	-0.24	-0.25
U_0	30.02	30.02	25.73	30.02	23.37
U_1	6.28	6.28	10.67	6.28	5.44

Table 1: See Schwingschackl et al, 2018, for details of these data which can be used to model PV panel operations.

Okay, I should have said

```
#We want to make some maps
#in the end
library(rgeos)
library(maptools)
library(ggmap)
library(ggplot2)
library(sp)
library(rgdal)
library(raster)

#...and we also need
library(nasapower)
#for solar data
```

Write functions, trust me

```
#A function to return a multi-year value of cell temperatures
koehl_model_monthly_cell_temperatures <-function
(ambients_df, irradiances_df, windspeeds_df, techno_specification)
{
  selected_technology =
      dplyr::select(koehl_table,
                    techno_specification)

  u_0 = selected_technology[4,]
   u_1 = selected_technology[5,]
  #This function will return the
  #monthly cell temperatures

   monthly_cell_temperatures =
    matrix(0, nrow = nrow(ambients_df), ncol = 12)

  for(i in 1:nrow(windspeeds_df))
  {
    for(j in 1:12)
    {
      monthly_cell_temperatures[i,j] =  ambients_df[i,j] +
        (irradiances_df[i,j])/
        (windspeeds_df[i,j] + u_0 + u_1)
    }
  }

  return(monthly_cell_temperatures)
}
```

See the script for a fuller definition

```
create_monthly_etas <- function(cell_temperatures_df, irradiances_df)
{
  eta_STC = 0.154
  pv_gamma_ref = 0.12
  beta_ref = 0.0045
  eta_cellsDF = data.frame(matrix(0, nrow = nrow(irradiances_df), ncol = 12), s

  for(i in 1:nrow(irradiances_df))
  {
    for(j in 1:12)
    {
      temp_prime = cell_temperatures_df[i,j] - 25
      eta_cellsDF[i,j] = eta_STC*(1 - beta_ref*(temp_prime)) + eta_STC*pv_gamma
    }
  }
  return(eta_cellsDF)
}
```

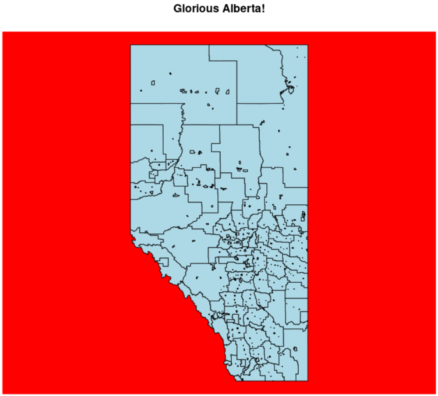
Ambient temperatures, irradiances

- We will increase the monthly average temperature by 40%: PV cells only working during daylight
- Irradiances is simply assumed to be

$$I = \frac{G}{D}$$

where D is the amount of daylight hours per month

All dressed up . . . where do we go?



We want data to work with

	LON	LAT	GHI	POA_enhancement
Medicine Hat	-110.79	49.83	1343.20	9.40
Lethbridge	-111.69	53.37	1193.55	16.70
Claresholm	-114.07	53.33	1182.60	17.60
Hanna	-111.38	54.76	1153.40	17.90
Strathmore	-114.20	54.37	1149.75	18.80
Calgary	-117.14	53.49	1157.05	19.60
Wainwright	-116.39	51.76	1233.70	15.20
Red Deer	-111.92	58.10	1105.95	16.30
Rocky Mountain House	-116.44	57.45	1131.50	15.00
Lloydminster	-118.10	54.58	1135.15	19.90
Edmonton	-118.66	55.67	1168.00	14.90
Cold Lake	-112.15	49.99	1332.25	9.90
White Court	-113.58	49.56	1332.25	10.60
Hinton	-111.02	51.43	1266.55	13.30
Canmore	-112.96	51.08	1262.90	14.00
Fort McMurray	-114.13	51.18	1251.95	14.70
Slave Lake	-111.50	52.48	1222.75	15.00
Grande Cache	-113.81	52.39	1222.75	15.20
Grande Prairie	-115.66	52.31	1219.10	15.70

How we use the data

```
#...build a data frame to hold the results first, "our_df"

for(i in 1:nrow(alberta_coordinates))
{
calgary.rug.request = nasapower::get_power(community = "SSE", pars = c("T2M",
         lonlat = c(alberta_coordinates$LON[i], alberta_coordinates$LAT[i]),
                                   temporal_average = "CLIMATOLOGY")
our_df[i,] = data.frame(calgary.rug.request[,4:16])
#We want 13 columns: one for each month + Annual average
}
```

Disecting a nasapower request

- Longitude and latitude
- We have to give a "temporal" average AND dates in general
- We have to let NASA know what we want

- Numeric pair in order of "longitude, latitude"
- Using "climatology" gives you a 30-year average with values in months + annual average (if applicable)
- We use parameters ("pars"). For example, "ALL-SKY_SFC_SW_DWN" is the equivalent of GHI

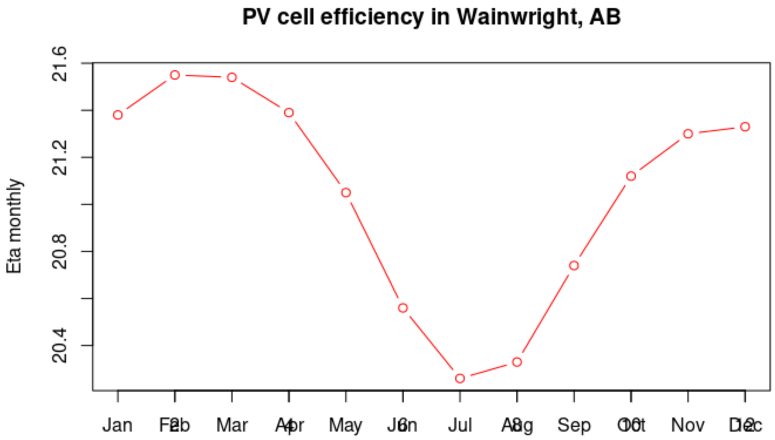
NB: See my blog about hourly requests; avoid maximum radiation parameter at high latitudes

In case you're wondering . . .

% latex table generated in R 3.6.3 by xtable 1.8-4 package % Wed Apr 21 16:07:00 2021

	LON	LAT	PARAMETER	JAN	FEB	MAR	APR	MAY	JUN	JUL
1	-110.79	49.83	ALLSKY_SFC_SW_DWN	1.18	2.11	3.27	4.83	5.70	6.16	6.58
2	-110.79	49.83	T2M	-7.75	-5.08	0.25	6.02	11.99	16.69	20.61
3	-110.79	49.83	SG_DAY_HOUR_AVG	8.65	10.17	11.88	13.73	15.37	16.27	15.87

How did we do?


PV cell efficiency in Wainwright, AB
Eta monthly
21.6
21.2
20.8
20.4
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2
4
6
8
10
12

Elephants

From here on out, all slides are added after the presentation on 21 April.

Alberta-wide, monthly PV efficiency in %-age

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Medicine Hat	21.20	21.30	21.10	20.60	20.10	19.60	19.20	19.30	19.90	20.50	21.00	21.10
Lethbridge	21.30	21.40	21.30	20.80	20.20	19.70	19.50	19.60	20.10	20.70	21.00	21.00
Claresholm	21.20	21.30	21.30	20.80	20.20	19.80	19.60	19.60	20.10	20.70	21.00	20.90
Hanna	21.30	21.50	21.40	20.90	20.20	19.70	19.50	19.60	20.10	20.70	21.00	21.00
Strathmore	21.20	21.40	21.30	20.80	20.20	19.80	19.50	19.60	20.10	20.70	21.00	20.80
Calgary	21.10	21.30	21.30	21.10	20.50	20.10	19.90	19.90	20.40	20.90	21.10	21.00
Wainwright	21.40	21.50	21.50	21.40	21.10	20.60	20.30	20.30	20.70	21.10	21.30	21.30
Red Deer	21.30	21.50	21.50	21.10	20.30	19.70	19.50	19.60	20.20	20.80	21.10	21.00
Rocky Mountain House	21.20	21.50	21.40	21.00	20.30	19.80	19.60	19.70	20.20	20.80	21.00	20.90
Lloydminster	21.10	21.30	21.20	20.80	20.30	19.80	19.60	19.70	20.10	20.70	21.00	20.90
Edmonton	21.10	21.30	21.40	20.90	20.30	19.90	19.60	19.70	20.20	20.70	21.00	20.90
Cold Lake	21.10	21.20	21.10	20.60	20.10	19.60	19.20	19.40	19.90	20.50	21.00	21.10
White Court	21.20	21.30	21.20	20.80	20.30	19.90	19.50	19.60	20.00	20.60	21.00	21.10
Hinton	21.20	21.30	21.20	20.70	20.10	19.60	19.30	19.40	19.90	20.60	21.00	21.10
Canmore	21.20	21.30	21.20	20.70	20.10	19.70	19.40	19.50	20.00	20.60	21.00	21.10
Fort McMurray	21.20	21.30	21.20	20.80	20.30	19.90	19.60	19.70	20.10	20.70	21.00	21.10
Slave Lake	21.20	21.30	21.20	20.70	20.10	19.70	19.40	19.50	20.00	20.60	21.00	21.00
Grande Cache	21.20	21.30	21.20	20.80	20.20	19.80	19.60	19.60	20.10	20.70	21.00	21.00
Grande Prairie	21.20	21.30	21.30	21.10	20.60	20.20	19.90	20.00	20.40	20.90	21.10	21.10

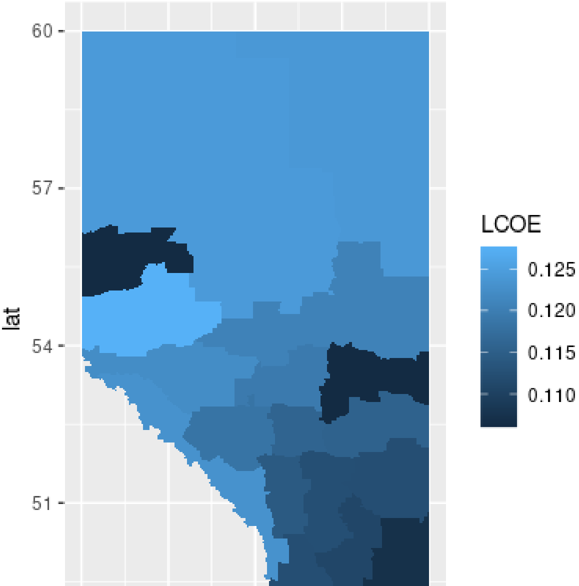
(Assuming) Yield = Efficiency X Insolation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Medicine Hat	37.90	61.50	104.90	146.40	173.60	177.40	192.00	158.50	115.50	78.80	43.40	32.30
Lethbridge	29.00	53.10	103.70	140.20	165.30	164.60	170.90	144.30	98.10	62.70	33.60	18.80
Claresholm	29.90	54.10	104.50	138.10	160.50	160.00	167.30	142.70	99.10	64.90	34.80	18.70
Hanna	26.20	50.40	102.90	138.70	163.20	160.90	162.70	141.20	94.00	59.20	31.20	16.30
Strathmore	26.40	51.30	101.80	136.10	157.60	161.10	162.80	140.70	95.90	60.20	31.80	14.90
Calgary	29.80	52.50	103.40	138.00	158.60	157.40	162.10	139.50	99.60	65.20	35.20	21.00
Wainwright	36.60	59.90	109.80	145.10	172.80	170.80	170.60	149.30	109.30	69.20	41.00	29.80
Red Deer	16.20	36.90	85.80	137.50	172.70	173.50	167.90	135.30	88.50	50.50	22.60	10.80
Rocky Mountain House	18.00	41.20	94.70	142.00	169.00	174.40	167.30	139.90	92.90	53.00	23.70	12.10
Lloydminster	26.60	50.10	99.90	135.50	156.30	160.30	161.60	136.80	93.90	60.50	32.00	17.40
Edmonton	20.50	42.40	93.30	139.90	168.10	174.30	176.60	147.20	97.70	58.80	27.40	15.90
Cold Lake	39.50	62.30	107.30	143.20	169.80	171.40	188.90	158.80	113.90	77.70	44.30	33.60
White Court	39.50	62.40	107.70	144.50	171.50	173.40	191.20	160.50	114.70	78.20	44.40	33.60
Hinton	32.50	54.90	101.20	144.10	168.60	171.10	180.00	151.30	106.80	71.80	38.20	27.50
Canmore	33.70	56.00	104.20	142.60	167.00	168.10	180.10	150.30	106.90	72.80	39.40	28.40
Fort McMurray	36.60	59.80	109.50	141.40	164.80	165.00	171.20	148.30	107.90	72.50	41.40	30.10
Slave Lake	31.60	55.00	101.10	141.30	167.40	166.70	174.50	146.30	101.10	65.70	35.80	23.30
Grande Cache	31.50	54.30	103.70	140.10	165.40	165.90	175.10	147.80	102.40	67.40	36.70	23.90
Grande Prairie	33.40	56.90	107.30	142.60	165.50	165.00	171.70	146.50	104.70	70.40	38.00	25.90

Final considerations

- Tilted panels may use $\sim 1/3$ of site area for inter-row spacing
- Consider how much the value of land changes from one place to the next
- Generally, people assume Operations and Maintenance cost of 10% for PV
- Installation cost of 1 kWp of PV panels

I want to make a (contrived) map of LCOE in Alberta! Read the script.



R packages for solar energy data

	Developer	Release date	Information source
solaR	Oscar Perpinan Lamigueiro	Jan 2020	Calculated
sirad	Jedrzej Bojanowski	Oct 2016	Calculated
insol	Javier Corripio	Feb 2021	Calculated
SolarData	Dazhi Yang	2018/2021	Ground based satellites
SunsVoc	Oscar Burleyson	2019	NA
nasapower	Adam Sparks	Jan 2020	Space-based satellites

Table 2: No 6 is my favourite, but No 4 is also worth a look. No 5 is a bit more involved.

Big thanks/where to go next

- Thanks to all of you (Calgary RUG)
- PVeducation.org: a wonderful educational site
- Sun/earth system: Kaligarou, 2012 (a good book, very in-depth and covers everything)
- All other images: either mine or from Wikimedia
- Fraunhofer Institute, really good site for high level analyses
- PV Modeling Collective, Sandia Labs
- edX course on PV electricity by Arno Smets (fairly involved)
- Big thanks to Prof Wilfried van Sark and Dr Sara Mirbagheri-Golroodbari, Utrecht University