Data center solar modeling

This was originally written to study the ideal mix of solar and batteries for any kind of load in any kind of climate. This version has been localized on sun-abundant land (Texas) for AI training data centers (high capex, high uptime).
The general idea is to analyze revenue per unit capex (including the power system) as a function of solar array and battery size.

Casey Handmer 12/19/24

Download data

Download Texas data from https://www.nrel.gov/grid/solar-power-data.html

Data Methodologies

The Solar Power Data for Integration Studies consist of 1 year (2006) of 5-minute solar power and hourly day-ahead forecasts for approximately 6,000 simulated PV plants. Solar power plant locations were determined based on the capacity expansion plan for high-penetration renewables in Phase 2 of the Western Wind and Solar Integration Study and the Eastern Renewable Generation Integration Study.

NREL generated the 5-minute data set using the Sub-Hour Irradiance Algorithm. The day-ahead solar forecast data for locations in the western United States were generated by 3TIER based on numerical weather predication simulations for Phase 1 of the Western Wind and Solar Integration Study. NREL generated the day-ahead solar forecast data in eastern U.S. locations using the Weather Research and Forecasting model.

The data are for specific years and should not be assumed to be representative of typical radiation levels for a site. These data should not generally be used for site-specific project development work.

Naming Convention

The naming convention of the state-wise solar power data (.csv files) from the Solar Integration Studies is as follows.

Data Type_Latitude_Longitude_Weather Year_PV Type_CapacityMW_Time Interval _Min.csv

- Data Type
  - Actual: Real power output
  - DA: Day ahead forecast
  - HA4: 4 hour ahead forecast
- Weather Year: The PV data is based on the particular year's known weather condition.
- PV Type
  - UPV: Utility scale PV
  - DPV: Distributed PV

    Note: The practical difference between UPV and DPV is in the configurations (UPV has single axis tracking while DPV is fixed tilt equaling to latitude) and the smoothing (both are run through a low-pass filter, the DPV will have more of the high frequency variability smoothed out).
- Capacity: Installed capacity in MW
- Time Interval: PV generation data reading interval in minutes.

In[1097]:=

```
path = "/home/chandmer/Documents/Solar\ Modeling/Texas/";
```

Having downloaded the Texas zip from the NREL website (a whole bunch of data from 2006!), let's dump the file names and see what we have.

In[1201]:=

```
files = Import[path]
```

Out[1201]=

```
{Actual_32.05_-94.15_2006_UPV_95MW_5_Min.csv, Actual_32.05_-94.35_2006_UPV_27MW_5_Min.csv,
 Actual_32.35_-94.25_2006_UPV_122MW_5_Min.csv,
 Actual_32.45_-94.75_2006_DPV_35MW_5_Min.csv,
 Actual_32.45_-94.85_2006_DPV_35MW_5_Min.csv,
 Actual_32.55_-102.25_2006_UPV_118MW_5_Min.csv,
 Actual_32.55_-102.75_2006_UPV_118MW_5_Min.csv,
 Actual_32.55_-103.05_2006_UPV_118MW_5_Min.csv,
 Actual_32.55_-94.85_2006_DPV_35MW_5_Min.csv,
```

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Actual_32.65_-102.85_2006_UPV_118MW_5_Min.csv,
Actual_32.65_-102.95_2006_UPV_118MW_5_Min.csv,
Actual_32.65_-94.45_2006_UPV_54MW_5_Min.csv,
Actual_32.75_-102.45_2006_UPV_17MW_5_Min.csv,
Actual_32.85_-103.05_2006_UPV_84MW_5_Min.csv,
Actual_32.95_-102.95_2006_UPV_17MW_5_Min.csv,
Actual_32.95_-94.95_2006_UPV_27MW_5_Min.csv,
Actual_33.05_-102.95_2006_UPV_67MW_5_Min.csv,
Actual_33.05_-94.25_2006_UPV_54MW_5_Min.csv,
Actual_33.15_-102.25_2006_UPV_50MW_5_Min.csv,
Actual_33.15_-94.65_2006_UPV_14MW_5_Min.csv,
Actual_33.25_-102.65_2006_UPV_17MW_5_Min.csv,
Actual_33.35_-94.35_2006_UPV_95MW_5_Min.csv,
Actual_33.45_-101.75_2006_UPV_84MW_5_Min.csv,
Actual_33.45_-102.95_2006_UPV_151MW_5_Min.csv,
Actual_33.45_-94.35_2006_DPV_27MW_5_Min.csv,
Actual_33.45_-94.45_2006_DPV_27MW_5_Min.csv,
Actual_33.55_-101.85_2006_DPV_37MW_5_Min.csv,
Actual_33.55_-94.45_2006_DPV_27MW_5_Min.csv,
Actual_33.55_-94.65_2006_UPV_136MW_5_Min.csv,
Actual_33.65_-101.75_2006_DPV_37MW_5_Min.csv,
Actual_33.65_-101.85_2006_DPV_37MW_5_Min.csv,
Actual_33.65_-101.95_2006_DPV_37MW_5_Min.csv,
Actual_33.65_-102.05_2006_UPV_34MW_5_Min.csv,
Actual_33.65_-102.45_2006_UPV_168MW_5_Min.csv,
Actual_33.75_-101.85_2006_DPV_37MW_5_Min.csv,
Actual_33.75_-101.95_2006_UPV_101MW_5_Min.csv,
Actual_33.75_-102.95_2006_UPV_50MW_5_Min.csv,
Actual_34.05_-102.05_2006_UPV_151MW_5_Min.csv,
Actual_34.15_-101.65_2006_UPV_151MW_5_Min.csv,
Actual_34.35_-102.95_2006_UPV_50MW_5_Min.csv,
Actual_34.55_-102.55_2006_UPV_168MW_5_Min.csv,
Actual_34.65_-102.85_2006_UPV_34MW_5_Min.csv,
Actual_34.95_-101.75_2006_DPV_27MW_5_Min.csv,
Actual_34.95_-101.85_2006_DPV_27MW_5_Min.csv,
Actual_34.95_-102.95_2006_UPV_67MW_5_Min.csv,
Actual_35.05_-101.85_2006_DPV_27MW_5_Min.csv,
Actual_35.15_-101.65_2006_UPV_101MW_5_Min.csv,
Actual_35.35_-101.75_2006_DPV_28MW_5_Min.csv,
Actual_35.35_-101.85_2006_DPV_28MW_5_Min.csv,
Actual_35.35_-101.95_2006_UPV_17MW_5_Min.csv,
Actual_35.35_-101.95_2006_UPV_67MW_5_Min.csv,
Actual_35.45_-101.85_2006_DPV_28MW_5_Min.csv,
Actual_35.75_-102.95_2006_UPV_151MW_5_Min.csv,
Actual_35.85_-102.85_2006_UPV_17MW_5_Min.csv,
Actual_36.05_-102.95_2006_UPV_17MW_5_Min.csv,
Actual_36.25_-102.95_2006_UPV_84MW_5_Min.csv,
DA_32.05_-94.15_2006_UPV_95MW_60_Min.csv, DA_32.05_-94.35_2006_UPV_27MW_60_Min.csv,
DA_32.35_-94.25_2006_UPV_122MW_60_Min.csv, DA_32.45_-94.75_2006_DPV_35MW_60_Min.csv,
DA_32.45_-94.85_2006_DPV_35MW_60_Min.csv, DA_32.55_-102.25_2006_UPV_118MW_60_Min.csv,
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DA_32.55_-102.75_2006_UPV_118MW_60_Min.csv, DA_32.55_-103.05_2006_UPV_118MW_60_Min.csv,
DA_32.55_-94.85_2006_DPV_35MW_60_Min.csv, DA_32.65_-102.85_2006_UPV_118MW_60_Min.csv,
DA_32.65_-102.95_2006_UPV_118MW_60_Min.csv, DA_32.65_-94.45_2006_UPV_54MW_60_Min.csv,
DA_32.75_-102.45_2006_UPV_17MW_60_Min.csv, DA_32.85_-103.05_2006_UPV_84MW_60_Min.csv,
DA_32.95_-102.95_2006_UPV_17MW_60_Min.csv, DA_32.95_-94.95_2006_UPV_27MW_60_Min.csv,
DA_33.05_-102.95_2006_UPV_67MW_60_Min.csv, DA_33.05_-94.25_2006_UPV_54MW_60_Min.csv,
DA_33.15_-102.25_2006_UPV_50MW_60_Min.csv, DA_33.15_-94.65_2006_UPV_14MW_60_Min.csv,
DA_33.25_-102.65_2006_UPV_17MW_60_Min.csv, DA_33.35_-94.35_2006_UPV_95MW_60_Min.csv,
DA_33.45_-101.75_2006_UPV_84MW_60_Min.csv, DA_33.45_-102.95_2006_UPV_151MW_60_Min.csv,
DA_33.45_-94.35_2006_DPV_27MW_60_Min.csv, DA_33.45_-94.45_2006_DPV_27MW_60_Min.csv,
DA_33.55_-101.85_2006_DPV_37MW_60_Min.csv, DA_33.55_-94.45_2006_DPV_27MW_60_Min.csv,
DA_33.55_-94.65_2006_UPV_136MW_60_Min.csv, DA_33.65_-101.75_2006_DPV_37MW_60_Min.csv,
DA_33.65_-101.85_2006_DPV_37MW_60_Min.csv, DA_33.65_-101.95_2006_DPV_37MW_60_Min.csv,
DA_33.65_-102.05_2006_UPV_34MW_60_Min.csv, DA_33.65_-102.45_2006_UPV_168MW_60_Min.csv,
DA_33.75_-101.85_2006_DPV_37MW_60_Min.csv, DA_33.75_-101.95_2006_UPV_101MW_60_Min.csv,
DA_33.75_-102.95_2006_UPV_50MW_60_Min.csv, DA_34.05_-102.05_2006_UPV_151MW_60_Min.csv,
DA_34.15_-101.65_2006_UPV_151MW_60_Min.csv, DA_34.35_-102.95_2006_UPV_50MW_60_Min.csv,
DA_34.55_-102.55_2006_UPV_168MW_60_Min.csv, DA_34.65_-102.85_2006_UPV_34MW_60_Min.csv,
DA_34.95_-101.75_2006_DPV_27MW_60_Min.csv, DA_34.95_-101.85_2006_DPV_27MW_60_Min.csv,
DA_34.95_-102.95_2006_UPV_67MW_60_Min.csv, DA_35.05_-101.85_2006_DPV_27MW_60_Min.csv,
DA_35.15_-101.65_2006_UPV_101MW_60_Min.csv, DA_35.35_-101.75_2006_DPV_28MW_60_Min.csv,
DA_35.35_-101.85_2006_DPV_28MW_60_Min.csv, DA_35.35_-101.95_2006_UPV_17MW_60_Min.csv,
DA_35.35_-101.95_2006_UPV_67MW_60_Min.csv, DA_35.45_-101.85_2006_DPV_28MW_60_Min.csv,
DA_35.75_-102.95_2006_UPV_151MW_60_Min.csv, DA_35.85_-102.85_2006_UPV_17MW_60_Min.csv,
DA_36.05_-102.95_2006_UPV_17MW_60_Min.csv, DA_36.25_-102.95_2006_UPV_84MW_60_Min.csv,
HA4_32.05_-94.15_2006_UPV_95MW_60_Min.csv, HA4_32.05_-94.35_2006_UPV_27MW_60_Min.csv,
HA4_32.35_-94.25_2006_UPV_122MW_60_Min.csv, HA4_32.45_-94.75_2006_DPV_35MW_60_Min.csv,
HA4_32.45_-94.85_2006_DPV_35MW_60_Min.csv, HA4_32.55_-102.25_2006_UPV_118MW_60_Min.csv,
HA4_32.55_-102.75_2006_UPV_118MW_60_Min.csv,
HA4_32.55_-103.05_2006_UPV_118MW_60_Min.csv,
HA4_32.55_-94.85_2006_DPV_35MW_60_Min.csv, HA4_32.65_-102.85_2006_UPV_118MW_60_Min.csv,
HA4_32.65_-102.95_2006_UPV_118MW_60_Min.csv, HA4_32.65_-94.45_2006_UPV_54MW_60_Min.csv,
HA4_32.75_-102.45_2006_UPV_17MW_60_Min.csv, HA4_32.85_-103.05_2006_UPV_84MW_60_Min.csv,
HA4_32.95_-102.95_2006_UPV_17MW_60_Min.csv, HA4_32.95_-94.95_2006_UPV_27MW_60_Min.csv,
HA4_33.05_-102.95_2006_UPV_67MW_60_Min.csv, HA4_33.05_-94.25_2006_UPV_54MW_60_Min.csv,
HA4_33.15_-102.25_2006_UPV_50MW_60_Min.csv, HA4_33.15_-94.65_2006_UPV_14MW_60_Min.csv,
HA4_33.25_-102.65_2006_UPV_17MW_60_Min.csv, HA4_33.35_-94.35_2006_UPV_95MW_60_Min.csv,
HA4_33.45_-101.75_2006_UPV_84MW_60_Min.csv, HA4_33.45_-102.95_2006_UPV_151MW_60_Min.csv,
HA4_33.45_-94.35_2006_DPV_27MW_60_Min.csv, HA4_33.45_-94.45_2006_DPV_27MW_60_Min.csv,
HA4_33.55_-101.85_2006_DPV_37MW_60_Min.csv, HA4_33.55_-94.45_2006_DPV_27MW_60_Min.csv,
HA4_33.55_-94.65_2006_UPV_136MW_60_Min.csv, HA4_33.65_-101.75_2006_DPV_37MW_60_Min.csv,
HA4_33.65_-101.85_2006_DPV_37MW_60_Min.csv, HA4_33.65_-101.95_2006_DPV_37MW_60_Min.csv,
HA4_33.65_-102.05_2006_UPV_34MW_60_Min.csv, HA4_33.65_-102.45_2006_UPV_168MW_60_Min.csv,
HA4_33.75_-101.85_2006_DPV_37MW_60_Min.csv, HA4_33.75_-101.95_2006_UPV_101MW_60_Min.csv,
HA4_33.75_-102.95_2006_UPV_50MW_60_Min.csv, HA4_34.05_-102.05_2006_UPV_151MW_60_Min.csv,
HA4_34.15_-101.65_2006_UPV_151MW_60_Min.csv, HA4_34.35_-102.95_2006_UPV_50MW_60_Min.csv,
HA4_34.55_-102.55_2006_UPV_168MW_60_Min.csv, HA4_34.65_-102.85_2006_UPV_34MW_60_Min.csv,
HA4_34.95_-101.75_2006_DPV_27MW_60_Min.csv, HA4_34.95_-101.85_2006_DPV_27MW_60_Min.csv,
HA4_34.95_-102.95_2006_UPV_67MW_60_Min.csv, HA4_35.05_-101.85_2006_DPV_27MW_60_Min.csv,
HA4_35.15_-101.65_2006_UPV_101MW_60_Min.csv, HA4_35.35_-101.75_2006_DPV_28MW_60_Min.csv,

HA4_35.35_-101.85_2006_DPV_28MW_60_Min.csv, HA4_35.35_-101.95_2006_UPV_17MW_60_Min.csv,
HA4_35.35_-101.95_2006_UPV_67MW_60_Min.csv, HA4_35.45_-101.85_2006_DPV_28MW_60_Min.csv,
HA4_35.75_-102.95_2006_UPV_151MW_60_Min.csv, HA4_35.85_-102.85_2006_UPV_17MW_60_Min.csv,
HA4_36.05_-102.95_2006_UPV_17MW_60_Min.csv, HA4_36.25_-102.95_2006_UPV_84MW_60_Min.csv}

Select just the files which correspond to actual arrays.

In[1248]:=
```
files = Select[files, StringTake[#, 6] == "Actual" &]
```

Out[1248]=
{Actual_32.05_-94.15_2006_UPV_95MW_5_Min.csv, Actual_32.05_-94.35_2006_UPV_27MW_5_Min.csv,
Actual_32.35_-94.25_2006_UPV_122MW_5_Min.csv,
Actual_32.45_-94.75_2006_DPV_35MW_5_Min.csv,
Actual_32.45_-94.85_2006_DPV_35MW_5_Min.csv,
Actual_32.55_-102.25_2006_UPV_118MW_5_Min.csv,
Actual_32.55_-102.75_2006_UPV_118MW_5_Min.csv,
Actual_32.55_-103.05_2006_UPV_118MW_5_Min.csv,
Actual_32.55_-94.85_2006_DPV_35MW_5_Min.csv,
Actual_32.65_-102.85_2006_UPV_118MW_5_Min.csv,
Actual_32.65_-102.95_2006_UPV_118MW_5_Min.csv,
Actual_32.65_-94.45_2006_UPV_54MW_5_Min.csv,
Actual_32.75_-102.45_2006_UPV_17MW_5_Min.csv,
Actual_32.85_-103.05_2006_UPV_84MW_5_Min.csv,
Actual_32.95_-102.95_2006_UPV_17MW_5_Min.csv,
Actual_32.95_-94.95_2006_UPV_27MW_5_Min.csv,
Actual_33.05_-102.95_2006_UPV_67MW_5_Min.csv,
Actual_33.05_-94.25_2006_UPV_54MW_5_Min.csv,
Actual_33.15_-102.25_2006_UPV_50MW_5_Min.csv,
Actual_33.15_-94.65_2006_UPV_14MW_5_Min.csv,
Actual_33.25_-102.65_2006_UPV_17MW_5_Min.csv,
Actual_33.35_-94.35_2006_UPV_95MW_5_Min.csv,
Actual_33.45_-101.75_2006_UPV_84MW_5_Min.csv,
Actual_33.45_-102.95_2006_UPV_151MW_5_Min.csv,
Actual_33.45_-94.35_2006_DPV_27MW_5_Min.csv,
Actual_33.45_-94.45_2006_DPV_27MW_5_Min.csv,
Actual_33.55_-101.85_2006_DPV_37MW_5_Min.csv,
Actual_33.55_-94.45_2006_DPV_27MW_5_Min.csv,
Actual_33.55_-94.65_2006_UPV_136MW_5_Min.csv,
Actual_33.65_-101.75_2006_DPV_37MW_5_Min.csv,
Actual_33.65_-101.85_2006_DPV_37MW_5_Min.csv,
Actual_33.65_-101.95_2006_DPV_37MW_5_Min.csv,
Actual_33.65_-102.05_2006_UPV_34MW_5_Min.csv,
Actual_33.65_-102.45_2006_UPV_168MW_5_Min.csv,
Actual_33.75_-101.85_2006_DPV_37MW_5_Min.csv,
Actual_33.75_-101.95_2006_UPV_101MW_5_Min.csv,
Actual_33.75_-102.95_2006_UPV_50MW_5_Min.csv,
Actual_34.05_-102.05_2006_UPV_151MW_5_Min.csv,
Actual_34.15_-101.65_2006_UPV_151MW_5_Min.csv,
Actual_34.35_-102.95_2006_UPV_50MW_5_Min.csv,
Actual_34.55_-102.55_2006_UPV_168MW_5_Min.csv,
Actual_34.65_-102.85_2006_UPV_34MW_5_Min.csv,

```
 Actual_34.95_-101.75_2006_DPV_27MW_5_Min.csv,
 Actual_34.95_-101.85_2006_DPV_27MW_5_Min.csv,
 Actual_34.95_-102.95_2006_UPV_67MW_5_Min.csv,
 Actual_35.05_-101.85_2006_DPV_27MW_5_Min.csv,
 Actual_35.15_-101.65_2006_UPV_101MW_5_Min.csv,
 Actual_35.35_-101.75_2006_DPV_28MW_5_Min.csv,
 Actual_35.35_-101.85_2006_DPV_28MW_5_Min.csv,
 Actual_35.35_-101.95_2006_UPV_17MW_5_Min.csv,
 Actual_35.35_-101.95_2006_UPV_67MW_5_Min.csv,
 Actual_35.45_-101.85_2006_DPV_28MW_5_Min.csv,
 Actual_35.75_-102.95_2006_UPV_151MW_5_Min.csv,
 Actual_35.85_-102.85_2006_UPV_17MW_5_Min.csv,
 Actual_36.05_-102.95_2006_UPV_17MW_5_Min.csv,
 Actual_36.25_-102.95_2006_UPV_84MW_5_Min.csv}
```

Make a quick map of where the arrays are in Texas.

In[1250]:=

```
arrLocs = Table[{ToExpression[StringTake[f, {8, 12}]],
   ToExpression[StringDelete[StringTake[f, {14, 20}], "_"]]}, {f, files}]
```

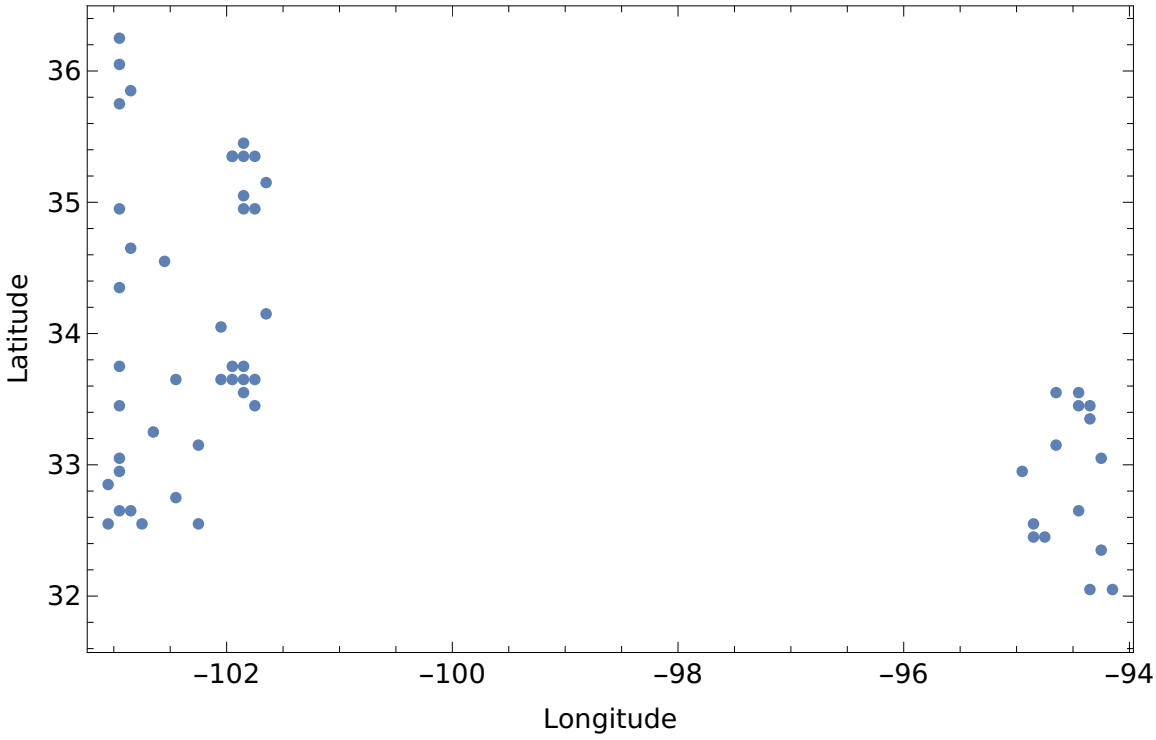
Out[1250]=

```
{{32.05, -94.15}, {32.05, -94.35}, {32.35, -94.25}, {32.45, -94.75}, {32.45, -94.85},
 {32.55, -102.25}, {32.55, -102.75}, {32.55, -103.05}, {32.55, -94.85}, {32.65, -102.85},
 {32.65, -102.95}, {32.65, -94.45}, {32.75, -102.45}, {32.85, -103.05}, {32.95, -102.95},
 {32.95, -94.95}, {33.05, -102.95}, {33.05, -94.25}, {33.15, -102.25}, {33.15, -94.65},
 {33.25, -102.65}, {33.35, -94.35}, {33.45, -101.75}, {33.45, -102.95}, {33.45, -94.35},
 {33.45, -94.45}, {33.55, -101.85}, {33.55, -94.45}, {33.55, -94.65}, {33.65, -101.75},
 {33.65, -101.85}, {33.65, -101.95}, {33.65, -102.05}, {33.65, -102.45}, {33.75, -101.85},
 {33.75, -101.95}, {33.75, -102.95}, {34.05, -102.05}, {34.15, -101.65},
 {34.35, -102.95}, {34.55, -102.55}, {34.65, -102.85}, {34.95, -101.75},
 {34.95, -101.85}, {34.95, -102.95}, {35.05, -101.85}, {35.15, -101.65},
 {35.35, -101.75}, {35.35, -101.85}, {35.35, -101.95}, {35.35, -101.95},
 {35.45, -101.85}, {35.75, -102.95}, {35.85, -102.85}, {36.05, -102.95}, {36.25, -102.95}}
```

In[1404]:=

```
ListPlot[arrLocs[[All, {2, 1}]], Frame → True, FrameLabel → {"Longitude", "Latitude"},
 FrameStyle → Directive[14, Black], ImageSize → 600]
```

Out[1404]=



Looks like the Mathematica geodata server is timing out :(

In[1396]:=

```
GeoListPlot[GeoPosition[arrLocs], GeoBackground → "Satellite", PlotMarkers → {Red, 10}]
```

GeoGraphics: Unable to download data for ranges {{−103.513, −93.6914}, {33.5962, 39.2212}} and zoom level 6 from the Wolfram geo server.

FilterRules: System`Private`SortOptions[$Failed] is not a valid replacement rule.

FilterRules:

System`Private`SortOptions[{FilterRules[System`Private`SortOptions[$Failed], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪28≫}], AlignmentPoint → Center, AspectRatio → Automatic, Axes → False, AxesLabel → None, AxesOrigin → Automatic, AxesStyle → {}, Background → None, BaselinePosition → Automatic, BaseStyle → {}, ≪45≫}] is not a valid replacement rule.

FilterRules:

FilterRules[System`Private`SortOptions[{FilterRules[System`Private`SortOptions[$Failed], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪28≫}], AlignmentPoint → Center, AspectRatio → Automatic, Axes → False, AxesLabel → None, AxesOrigin → Automatic, AxesStyle → {}, Background → None, BaselinePosition → Automatic, BaseStyle → {}, ≪45≫}], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪44≫}] is not a valid replacement rule.

General: Further output of FilterRules::rep will be suppressed during this calculation.

Lookup: The argument FilterRules[FilterRules[System`Private`SortOptions[{FilterRules[System`Private`SortOptions[$Failed], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪28≫}], AlignmentPoint → Center, AspectRatio → Automatic, Axes → False, AxesLabel → None, AxesOrigin → Automatic, AxesStyle → {}, Background → None, BaselinePosition → Automatic, BaseStyle → {}, ≪45≫}], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪44≫}], {ImageSize, AspectRatio}] is not a valid Association or a list of rules.

Lookup: The argument FilterRules[FilterRules[System`Private`SortOptions[{FilterRules[System`Private`SortOptions[$Failed], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪28≫}], AlignmentPoint → Center, AspectRatio → Automatic, Axes → False, AxesLabel → None, AxesOrigin → Automatic, AxesStyle → {}, Background → None, BaselinePosition → Automatic, BaseStyle → {}, ≪45≫}], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪44≫}], {ImageSize, AspectRatio}] is not a valid Association or a list of rules.

Lookup: The argument FilterRules[FilterRules[System`Private`SortOptions[{FilterRules[System`Private`SortOptions[$Failed], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪28≫}], AlignmentPoint → Center, AspectRatio → Automatic, Axes → False, AxesLabel → None, AxesOrigin → Automatic, AxesStyle → {}, Background → None, BaselinePosition → Automatic, BaseStyle → {}, ≪45≫}], {AlignmentPoint, AspectRatio, Axes, AxesLabel, AxesOrigin, AxesStyle, Background, BaselinePosition, BaseStyle, ColorOutput, ≪44≫}], {ImageSize, AspectRatio}] is not a valid Association or a list of rules.

General: Further output of Lookup::invrl will be suppressed during this calculation.

Reverse: Nonatomic expression expected at position 1 in Reverse[GeoRange].

URLFetch: A library error occurred. The raw details are: "libcurl error (28): Connection timeout after 3000 ms"

GeoServer: Cannot download vector style resources.

Out[1396]=

Unfortunately none near Van Horn, so we'll take one from the North

In[1112]:=

```
raw = Import[path <> files[[-1]], "Data"];
```

One day's worth of data points is 288 entries long.

In[1113]:=

```
day = 12 * 24;
```

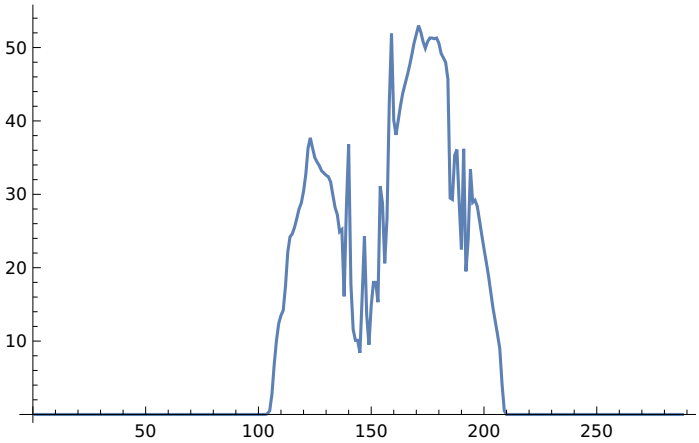
This is a whole year of data at 5 minute intervals!

Look at January 1

In[1115]:=

```
ListLinePlot[raw[[2 ;; day + 1, 2]], PlotRange → All]
```

Out[1115]=

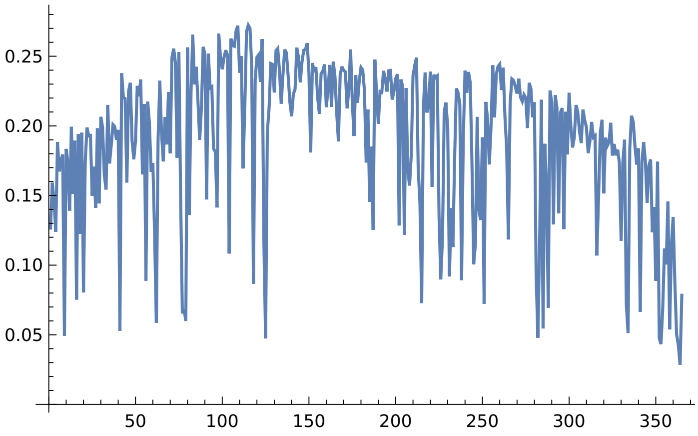


Average daily power generation

In[1192]:=

```
ListLinePlot[Total[Transpose[Partition[sol, day]] / day]]
```

Out[1192]=



Let’s clean it up a bit, standardize on a 1 MW equivalent array.

In[1119]:=

```
sol = raw[[2 ;; -1, 2]] / 84;
```

In[1121]:=

```
Clear[raw]
```

In[1266]:=

```
sol[[1 ;; 200]]
```

Out[1266]=

```
{0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.,
 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.,
 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.,
 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.,
 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0., 0.00119048,
 0.00595238, 0.0333333, 0.0809524, 0.120238, 0.147619, 0.160714, 0.169048,
 0.208333, 0.263095, 0.288095, 0.292857, 0.303571, 0.317857, 0.333333, 0.342857,
 0.361905, 0.389286, 0.432143, 0.44881, 0.432143, 0.416667, 0.409524, 0.403571,
 0.395238, 0.391667, 0.388095, 0.385714, 0.377381, 0.355952, 0.335714, 0.32381,
 0.296429, 0.3, 0.191667, 0.335714, 0.438095, 0.211905, 0.138095, 0.120238,
 0.120238, 0.1, 0.191667, 0.289286, 0.161905, 0.113095, 0.17619, 0.214286, 0.214286,
 0.182143, 0.370238, 0.342857, 0.245238, 0.317857, 0.502381, 0.617857, 0.477381,
 0.453571, 0.477381, 0.50119, 0.521429, 0.535714, 0.55, 0.565476, 0.583333,
 0.602381, 0.616667, 0.630952, 0.620238, 0.604762, 0.594048, 0.604762, 0.610714,
 0.610714, 0.609524, 0.610714, 0.602381, 0.585714, 0.578571, 0.571429, 0.544048,
 0.35119, 0.34881, 0.420238, 0.429762, 0.344048, 0.267857, 0.430952, 0.232143,
 0.284524, 0.397619, 0.344048, 0.347619, 0.338095, 0.315476, 0.291667, 0.269048}
```

Mean utilization

In[1122]:=

```
Total[sol] / Length[sol]
```

Out[1122]=

```
0.190943
```

Number of 5 minute intervals in a year.

In[1123]:=

```
Length[sol]
```

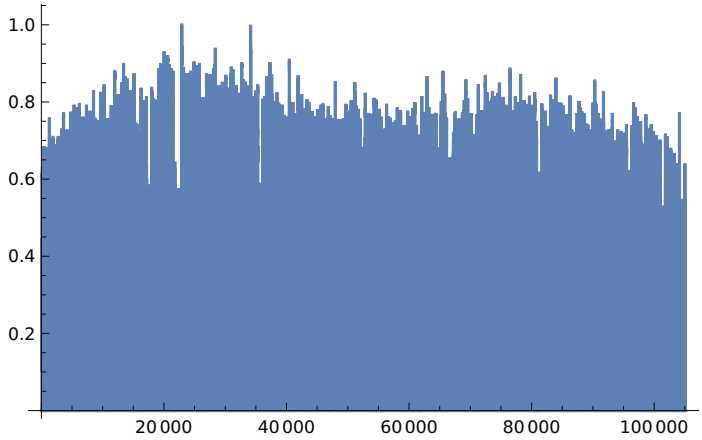
Out[1123]=

```
105 120
```

In[1124]:=

```
ListLinePlot[sol]
```

Out[1124]=

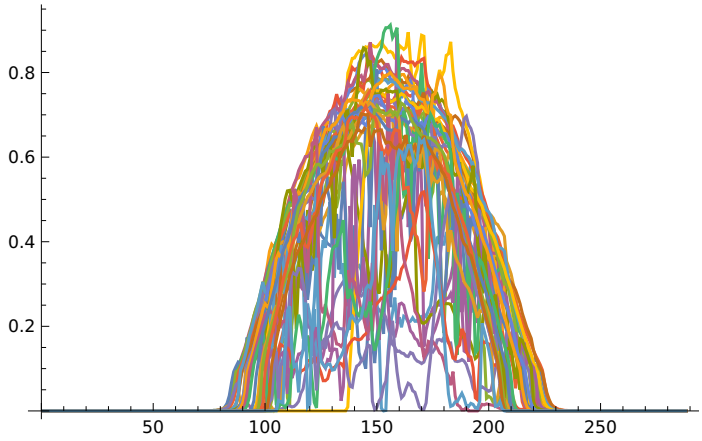


Every tenth day of the year.

In[1125]:=

```
ListLinePlot[Partition[sol, day][[1 ;; -1 ;; 10]]]
```

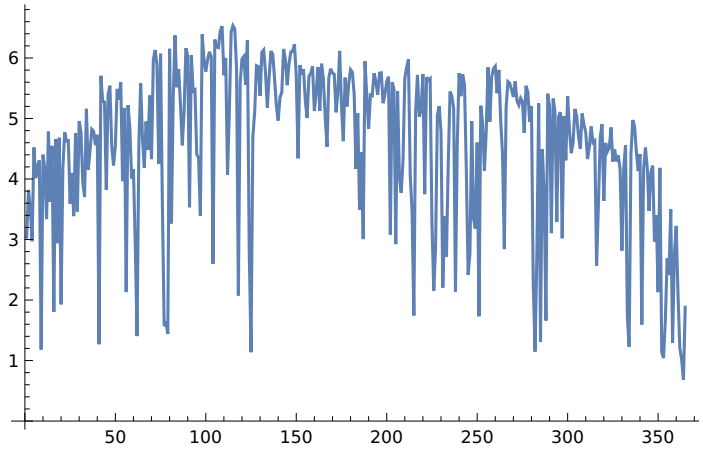
Out[1125]=



Power generated on any given day (MWh) for a 1 MW array.

In[1257]:=
```
ListLinePlot[Total[Transpose[Partition[sol, day]]] / 12]
```

Out[1257]=



Let's baseline to a 1 MW array. Then set up a numerical array with loads of different sizes, and batteries of various sizes. If the battery is empty, the load is off. If the battery is full, no further charging can occur. Everything on 5 minute intervals. Assume battery starts full on Jan 1.
Battery state is measured in MWh stored. So each 5 minute interval has to divide kWh or whatever by 12.

Time to run the sim

This function implements the above algorithm. It's also nicely vectorized so you can choose a bunch of battery sizes (in MWh), and a bunch of load sizes (in MW) to feed of a standard 1 MW array whose 5 minute power generation is given by the sol vector. The function is a bit slow because it literally runs multiple if-then conditionals every 5 minutes for a whole year. For vectorization, these ifs are expressed using masks (sundisc etc) calculated using the Sign function. Otherwise we'd be here all day. There are probably more efficient ways to run this algorithm - it enables me to run approximately 6000 different systems in parallel on about 100,000 sequential data points in about 2 hours on a consumer-grade laptop. Importantly, it is straight-forward enough that I can debug it.
It outputs a record of battery sizes, load sizes, a measure of battery state (roughly the fraction of the year it's not fully discharged) and the total utilization of the load over the course of the year, which includes an assumption that it can throttle if only partial power is available.

In[1127]:=
```
Uptime[caps_, loads_, sol_] := Catch[
    batt = Table[cap, {Length[sol]}, {cap, caps}, {Length[loads]}];
    util = 0 * batt;
    ts = 8760 / Length[sol]; (*hrs*)
    loadsmat = Table[loads, {Length[caps]}];
    capsmat = Transpose[Table[caps, {Length[loads]}]];

    Do[
     sundisc = 0.5 + 0.5 Sign[sol[[i]] - loadsmat];
     battdisc = 0.5 + 0.5 Sign[batt[[i]] - ts (loadsmat - sol[[i]])];
     capdisc = 0.5 + 0.5 Sign[batt[[i]] - capsmat];

     util[[i]] = sundisc + (1 - sundisc) battdisc +
       (1 - sundisc) (1 - battdisc) (sol[[i]] / loadsmat + batt[[i]] / (ts loadsmat));
     batt[[i + 1]] = sundisc (batt[[i]] + ts (sol[[i]] - loadsmat)) +
       (1 - sundisc) battdisc (batt[[i]] - ts (loadsmat - sol[[i]])) + (1 - sundisc) (1 - battdisc) * 0.;
     batt[[i + 1]] = capdisc capsmat + (1 - capdisc) batt[[i + 1]];

     , {i, 1, Length[sol] - 1}];
    Throw[Transpose[{capsmat, loadsmat,
       1 - Total[1. - Sign[batt]] / Length[batt], ts Total[util] / 8760.}, {3, 2, 1}]]];
```

What do we do with this?

While the Uptime function allows us to generally analyze the battery/solar system dynamics for any given solar resource (sol), in this case we're interested in a specific use case: hooking up a load with a given capex ($/MW) and maximizing productivity per dollar spent.

So we're going to wrap the Uptime function in a new function that produces the all in system cost for a given battery and array size and assumptions about the baseline cost of each of these subsystems. This is the function we're going to try to minimize.

In[1128]:=
```
AllInSystemCost[solarcost_, batterycost_, loadcost_, batterysize_, arraysize_, sol_] :=
 (#[[1]] * batterycost + solarcost + loadcost #[[2]]) / (#[[2]] × #[[4]]) &[
   Uptime[{batterysize / arraysize}, {1 / arraysize}, sol][1, 1]]
```

In[1129]:=
```
AllInSystemCost[200 000, 200 000, 5 000 000, 10, 5, sol]
```

Out[1129]=
$$1.0523 \times 10^{7}$$

To minimize this function, we calculate the cost under small variations to estimate the cost elasticity.

In[1130]:=

```
CostAndElasticity[solarcost_, batterycost_,
    loadcost_, batterysize_, arraysize_, sol_] := Catch[
    cost =
     AllInSystemCost[solarcost, batterycost, loadcost, batterysize, arraysize, sol];
    costb = AllInSystemCost[solarcost,
      batterycost, loadcost, 1.01 batterysize + 0.01, arraysize, sol];
    costa = AllInSystemCost[solarcost,
      batterycost, loadcost, batterysize, 1.01 arraysize + 0.01, sol];
    Throw[{cost, costb, costa, (cost - costb) / cost, (cost - costa) / cost}]];
```

In[1131]:=

```
cae = CostAndElasticity[200 000, 200 000, 5 000 000, 10, 5, sol]
```

Out[1131]=

$$\{1.0523 \times 10^7,\ 1.05017 \times 10^7,\ 1.0515 \times 10^7,\ 0.00202307,\ 0.000761787\}$$

Finally, we wrap the derivative function in a very crude gradient descent algorithm. It turns out that the underlying cost map is *just* regular enough that this approach is the best in terms of getting to a good enough answer with a minimum of brain sweat. I have a lot more experience with far more pathological cost functions in which we use the MCMC method, albeit at longer run time. For less pathological functions, Mathematica's inbuilt "FindMinimum" function works quite nicely. It has a few hacks to ensure convergence across a wide range of initial conditions.

Output is {{solarcost $/MW, battery cost $/MWh, loadcost $/MW}, {arraysize (MW), battery size (MWh), load size (1 MW by definition)}, {array cost $, battery cost $, load cost $ (all normalized to 1 MW)}, {total power system cost $, all in system cost $, all in system cost normalized by utilization $}, {output from Uptime function, which is battery size relative to 1 MW array, load size relative to 1 MW array, battery utilization, and system utilization}}

In[1365]:=

```
FindMinimumSystemCost[solarcost_, batterycost_, loadcost_, sol_] := Catch[
  bi = Min[10., 10. loadcost / 5 000 000];
  ai = Min[10., 1. + 9. loadcost / 5 000 000];
  (*could make these better based on loadcost priors*)
  amp = 100 + 700. (loadcost / 5 000 000)^1;
  steps = 10;
  (*This is some hacky nonsense that improves convergence in special cases.*)
  If[700 000 < loadcost < 1 300 000, amp *= 3];
  If[80 000 000 < loadcost, amp *= 0.5];
  costmin = 10^10;
  bimin = bi;
  aimin = ai;
  Do[
   cae = CostAndElasticity[batterycost, solarcost, loadcost, bi, ai, sol];
   If[cae[[1]] < costmin, aimin = ai; bimin = bi; costmin = cae[[1]];];
   If[True, Print[{cae, bi, ai}]];
   bi = Max[0., bi + amp RandomReal[{0.1, 1.}] × cae[[4]]];
   ai = Max[0.01, ai + amp RandomReal[{0.1, 1.}] × cae[[5]]];
   , {steps}];
  ut = Uptime[{bimin / aimin}, {1 / aimin}, sol][[1, 1]];
  Throw[{{solarcost, batterycost , loadcost},
    {aimin, bimin, 1.}, {solarcost aimin, batterycost bimin, loadcost},
    {solarcost aimin + batterycost bimin, solarcost aimin + batterycost bimin + loadcost,
     (solarcost aimin + batterycost bimin + loadcost) / ut[[-1]]}, ut}]]
```

In[1389]:=

```
FindMinimumSystemCost[200 000, 200 000, 100 000, sol]
```

$\{\{1.66859 \times 10^6, 1.67923 \times 10^6, 1.65736 \times 10^6, -0.0063749, 0.00672967\}, 0.2, 1.18\}$

$\{\{1.45358 \times 10^6, 1.45722 \times 10^6, 1.45688 \times 10^6, -0.00250686, -0.00227189\}, 0., 1.49534\}$

$\{\{1.46445 \times 10^6, 1.47164 \times 10^6, 1.4594 \times 10^6, -0.00490974, 0.00344715\}, 0., 1.27207\}$

$\{\{1.45281 \times 10^6, 1.45659 \times 10^6, 1.45593 \times 10^6, -0.00259921, -0.00214159\}, 0., 1.48859\}$

$\{\{1.44834 \times 10^6, 1.45323 \times 10^6, 1.44841 \times 10^6, -0.0033772, -0.0000483746\}, 0., 1.399\}$

$\{\{1.44845 \times 10^6, 1.45333 \times 10^6, 1.44831 \times 10^6, -0.00336945, 0.0000936224\}, 0., 1.39362\}$

$\{\{1.44836 \times 10^6, 1.45323 \times 10^6, 1.44839 \times 10^6, -0.00336213, -0.0000236344\}, 0., 1.39803\}$

$\{\{1.44838 \times 10^6, 1.45326 \times 10^6, 1.44837 \times 10^6, -0.00336949, 0.0000114355\}, 0., 1.39688\}$

$\{\{1.44838 \times 10^6, 1.45327 \times 10^6, 1.44837 \times 10^6, -0.00337567, 2.9087 \times 10^{-6}\}, 0., 1.39722\}$

$\{\{1.44838 \times 10^6, 1.45327 \times 10^6, 1.44837 \times 10^6, -0.00337574, 1.83186 \times 10^{-6}\}, 0., 1.39726\}$

Out[1389]=

$\{\{200\,000, 200\,000, 100\,000\}, \{1.399, 0., 1.\}, \{279\,801., 0., 100\,000\},$
$\{279\,801., 379\,801., 1.44834 \times 10^6\}, \{0., 0.714795, 0.034161, 0.262231\}\}$

While not strictly necessary to understand data centers, whose cost is around $50,000,000/MW, we'll find cost optimums across essentially the full range of potential load capexes, ranging from $10/kW (simple electric kettle) to $100,000/kW (state of the art supercomputer). What we will find is that for the lower capex loads, the optimal utilization is around 0.2, and

optimal utilization grows with load capex up to about 0.98 for data centers. It's surprising that it's not higher, but it turns out that marginal costs exceed marginal gains at some point!

For this exercise, I've baselined solar cost at $200,000/MW, which is consistent with cutting edge costs for fixed panel systems such as Jurchen, combined with the cheapest available solar modules. Similarly, while we've seen BESS systems come in under $100,000/MWh, in this model battery costs include all the non generative, non load electrical infrastructure: switching, power lines, BMS, and so on. So call it $200,000/MWh also - for now.

In[1292]:=
```
AbsoluteTiming[frontierTable =
   Table[FindMinimumSystemCost[200 000, 200 000, 10 000 * 10 ^ i, sol], {i, 0, 4, 0.1}];]
```

Out[1292]=
```
{6815.09, Null}
```

Export and save data

In[1293]:=
```
columnlabels = {"solar cost $/MW", "battery cost $/MWh",
   "load cost $/MW", "arraysize (MW)", "battery size (MWh)",
   "load size (1 MW by definition)", "array cost $", "battery cost $",
   "load cost $ (all normalized to 1 MW)", "total power system cost $",
   "total system cost $", "total system cost per utilization",
   "battery size relative to 1 MW array", "load size relative to 1 MW array",
   "annual battery utilization", "annual load utilization"};
```

In[1368]:=
```
Export["/home/chandmer/Documents/Solar Modeling/NorthTexas2.csv",
 Join[{columnlabels}, Table[Flatten[f], {f, frontierTable}]]]
```

Out[1368]=
```
/home/chandmer/Documents/Solar Modeling/NorthTexas2.csv
```

In[1415]:=
```
Join[{columnlabels}, Table[Flatten[f], {f, frontierTable}]]
```

Out[1415]=
```
{{solar cost $/MW, battery cost $/MWh, load cost $/MW,
   arraysize (MW), battery size (MWh), load size (1 MW by definition),
   array cost $, battery cost $, load cost $ (all normalized to 1 MW),
   total power system cost $, total system cost $, total system cost per utilization,
   battery size relative to 1 MW array, load size relative to 1 MW array,
   annual battery utilization, annual load utilization},
 {200 000, 200 000, 1000, 1.04325, 0., 1., 208 651., 0., 1000, 208 651.,
   209 651., 1.05247 × 10^6, 0., 0.958538, 0.0000475647, 0.199199},
 {200 000, 200 000, 10 000., 1.2133, 0., 1., 242 659., 0., 10 000., 242 659.,
   252 659., 1.09192 × 10^6, 0., 0.824202, 0.00410008, 0.231391},
 {200 000, 200 000, 12 589.3, 1.22932, 0., 1., 245 864., 0., 12 589.3,
   245 864., 258 453., 1.10294 × 10^6, 0., 0.813458, 0.00525114, 0.234331},
 {200 000, 200 000, 15 848.9, 1.24367, 0., 1., 248 734., 0., 15 848.9,
   248 734., 264 583., 1.11667 × 10^6, 0., 0.804073, 0.00651636, 0.23694},
 {200 000, 200 000, 19 952.6, 1.2633, 0., 1., 252 659., 0., 19 952.6,
   252 659., 272 612., 1.13371 × 10^6, 0., 0.791581, 0.00884703, 0.24046},
 {200 000, 200 000, 25 118.9, 1.28552, 0., 1., 257 104., 0., 25 118.9,
```

```
 257 104., 282 223., 1.15493 × 10^6, 0., 0.777896, 0.011406, 0.244363},
{200 000, 200 000, 31 622.8, 1.30012, 0., 1., 260 024., 0., 31 622.8,
 260 024., 291 647., 1.18137 × 10^6, 0., 0.76916, 0.0138128, 0.246871},
{200 000, 200 000, 39 810.7, 1.31318, 0., 1., 262 636., 0., 39 810.7,
 262 636., 302 447., 1.2143 × 10^6, 0., 0.761509, 0.01621, 0.249072},
{200 000, 200 000, 50 118.7, 1.32639, 0., 1., 265 278., 0., 50 118.7,
 265 278., 315 396., 1.25533 × 10^6, 0., 0.753927, 0.0189973, 0.251245},
{200 000, 200 000, 63 095.7, 1.35076, 0., 1., 270 151., 0., 63 095.7,
 270 151., 333 247., 1.30628 × 10^6, 0., 0.740326, 0.0245244, 0.255111},
{200 000, 200 000, 79 432.8, 1.37364, 0., 1., 274 729., 0., 79 432.8,
 274 729., 354 162., 1.36968 × 10^6, 0., 0.727991, 0.0292142, 0.258573},
{200 000, 200 000, 100 000., 1.40301, 0., 1., 280 601., 0., 100 000.,
 280 601., 380 601., 1.44829 × 10^6, 0., 0.712755, 0.0352264, 0.262794},
{200 000, 200 000, 125 893., 1.42784, 0., 1., 285 569., 0., 125 893.,
 285 569., 411 461., 1.54581 × 10^6, 0., 0.700357, 0.0400019, 0.266178},
{200 000, 200 000, 158 489., 1.46674, 0., 1., 293 348., 0., 158 489.,
 293 348., 451 838., 1.66646 × 10^6, 0., 0.681783, 0.0477549, 0.271137},
{200 000, 200 000, 199 526., 1.51868, 0., 1., 303 737., 0., 199 526.,
 303 737., 503 263., 1.81573 × 10^6, 0., 0.658465, 0.056992, 0.277168},
{200 000, 200 000, 251 189., 1.57328, 0., 1., 314 657., 0., 251 189.,
 314 657., 565 845., 2.00034 × 10^6, 0., 0.635613, 0.0652017, 0.282875},
{200 000, 200 000, 316 228., 1.62434, 0., 1., 324 869., 0., 316 228.,
 324 869., 641 097., 2.22787 × 10^6, 0., 0.615633, 0.0711948, 0.287762},
{200 000, 200 000, 398 107., 1.72009, 0., 1., 344 018., 0., 398 107.,
 344 018., 742 125., 2.50757 × 10^6, 0., 0.581364, 0.0814022, 0.295954},
{200 000, 200 000, 501 187., 1.8844, 0., 1., 376 879., 0., 501 187.,
 376 879., 878 067., 2.85294 × 10^6, 0., 0.530674, 0.0949772, 0.307776},
{200 000, 200 000, 630 957., 1.93413, 0.0133616, 1., 386 827., 2672.31, 630 957.,
 389 499., 1.02046 × 10^6, 3.26853 × 10^6, 0.0069083, 0.517027, 0.206364, 0.312207},
{200 000, 200 000, 794 328., 2.08694, 0., 1., 417 388., 0., 794 328.,
 417 388., 1.21172 × 10^6, 3.792 × 10^6, 0., 0.479171, 0.107667, 0.319545},
{200 000, 200 000, 1. × 10^6, 2.35316, 0.79068, 1., 470 632., 158 136., 1. × 10^6,
 628 768., 1.62877 × 10^6, 4.48503 × 10^6, 0.336007, 0.42496, 0.306383, 0.363157},
{200 000, 200 000, 1.25893 × 10^6, 2.72251, 1.47402, 1., 544 503., 294 805., 1.25893 × 10^6,
 839 308., 2.09823 × 10^6, 5.21209 × 10^6, 0.54142, 0.367308, 0.354243, 0.402571},
{200 000, 200 000, 1.58489 × 10^6, 3.26045, 3.38262, 1., 652 090., 676 523., 1.58489 × 10^6,
 1.32861 × 10^6, 2.91351 × 10^6, 5.98072 × 10^6, 1.03747, 0.306706, 0.445348, 0.48715},
{200 000, 200 000, 1.99526 × 10^6, 3.77113, 4.57001, 1., 754 226., 914 002., 1.99526 × 10^6,
 1.66823 × 10^6, 3.66349 × 10^6, 6.74085 × 10^6, 1.21184, 0.265173, 0.507021, 0.543476},
{200 000, 200 000, 2.51189 × 10^6, 4.33468, 7.64673, 1., 866 936., 1.52935 × 10^6, 2.51189 × 10^6,
 2.39628 × 10^6, 4.90817 × 10^6, 7.39835 × 10^6, 1.76408, 0.230697, 0.632163, 0.663414},
{200 000, 200 000, 3.16228 × 10^6, 5.20683, 10.812, 1., 1.04137 × 10^6, 2.16241 × 10^6,
 3.16228 × 10^6, 3.20377 × 10^6, 6.36605 × 10^6, 8.03002 × 10^6, 2.07651, 0.192055,
 0.767799, 0.792782}, {200 000, 200 000, 3.98107 × 10^6, 5.99079, 13.2821, 1.,
 1.19816 × 10^6, 2.65642 × 10^6, 3.98107 × 10^6, 3.85458 × 10^6, 7.83565 × 10^6, 8.788 × 10^6,
 2.21709, 0.166923, 0.875923, 0.891631}, {200 000, 200 000, 5.01187 × 10^6,
 6.65241, 13.6063, 1., 1.33048 × 10^6, 2.72125 × 10^6, 5.01187 × 10^6, 4.05173 × 10^6,
 9.06361 × 10^6, 9.92833 × 10^6, 2.04531, 0.150321, 0.901218, 0.912904},
```

```
{200 000, 200 000, 6.30957 × 10^6, 6.95193, 13.9357, 1., 1.39039 × 10^6,
  2.78714 × 10^6, 6.30957 × 10^6, 4.17753 × 10^6, 1.04871 × 10^7, 1.13415 × 10^7,
  2.00458, 0.143845, 0.915525, 0.924669}, {200 000, 200 000, 7.94328 × 10^6,
  7.22787, 14.2721, 1., 1.44557 × 10^6, 2.85441 × 10^6, 7.94328 × 10^6, 4.29999 × 10^6,
  1.22433 × 10^7, 1.30992 × 10^7, 1.97459, 0.138353, 0.927045, 0.934655},
{200 000, 200 000, 1. × 10^7, 7.51176, 14.5358, 1., 1.50235 × 10^6, 2.90717 × 10^6, 1. × 10^7,
  4.40952 × 10^6, 1.44095 × 10^7, 1.52878 × 10^7, 1.93508, 0.133125, 0.936339, 0.942548},
{200 000, 200 000, 1.25893 × 10^7, 7.9291, 14.7683, 1., 1.58582 × 10^6, 2.95366 × 10^6,
  1.25893 × 10^7, 4.53948 × 10^6, 1.71287 × 10^7, 1.80211 × 10^7, 1.86255, 0.126118,
  0.945424, 0.95048}, {200 000, 200 000, 1.58489 × 10^7, 8.20381, 14.9008,
  1., 1.64076 × 10^6, 2.98017 × 10^6, 1.58489 × 10^7, 4.62093 × 10^6, 2.04699 × 10^7,
  2.14384 × 10^7, 1.81633, 0.121895, 0.950381, 0.954823}, {200 000, 200 000,
  1.99526 × 10^7, 8.58735, 15.1189, 1., 1.71747 × 10^6, 3.02379 × 10^6, 1.99526 × 10^7,
  4.74126 × 10^6, 2.46939 × 10^7, 2.57177 × 10^7, 1.7606, 0.11645, 0.956982, 0.96019},
{200 000, 200 000, 2.51189 × 10^7, 9.36813, 15.4255, 1., 1.87363 × 10^6,
  3.08511 × 10^6, 2.51189 × 10^7, 4.95874 × 10^6, 3.00776 × 10^7, 3.10835 × 10^7, 1.6466,
  0.106745, 0.965753, 0.96764}, {200 000, 200 000, 3.16228 × 10^7, 10.2429,
  15.4811, 1., 2.04858 × 10^6, 3.09621 × 10^6, 3.16228 × 10^7, 5.14479 × 10^6,
  3.67676 × 10^7, 3.77895 × 10^7, 1.5114, 0.0976288, 0.97149, 0.972958},
{200 000, 200 000, 3.98107 × 10^7, 11.108, 15.4348, 1., 2.22159 × 10^6, 3.08697 × 10^6,
  3.98107 × 10^7, 5.30856 × 10^6, 4.51193 × 10^7, 4.61796 × 10^7, 1.38953,
  0.0900255, 0.975704, 0.977039}, {200 000, 200 000, 5.01187 × 10^7, 9.73758,
  18.4671, 1., 1.94752 × 10^6, 3.69343 × 10^6, 5.01187 × 10^7, 5.64094 × 10^6,
  5.57597 × 10^7, 5.70034 × 10^7, 1.89648, 0.102695, 0.977178, 0.978181},
{200 000, 200 000, 6.30957 × 10^7, 10.9891, 17.9765, 1., 2.19781 × 10^6,
  3.5953 × 10^6, 6.30957 × 10^7, 5.79311 × 10^6, 6.88888 × 10^7, 7.01193 × 10^7,
  1.63585, 0.0909995, 0.981716, 0.982452}, {200 000, 200 000, 7.94328 × 10^7,
  13.7464, 15.982, 1., 2.74929 × 10^6, 3.1964 × 10^6, 7.94328 × 10^7, 5.94569 × 10^6,
  8.53785 × 10^7, 8.64362 × 10^7, 1.16263, 0.0727461, 0.987081, 0.987764},
{200 000, 200 000, 1. × 10^8, 13.2239, 19.148, 1., 2.64479 × 10^6, 3.8296 × 10^6, 1. × 10^8,
  6.47438 × 10^6, 1.06474 × 10^8, 1.07455 × 10^8, 1.44798, 0.0756205, 0.990325, 0.990878}}
```

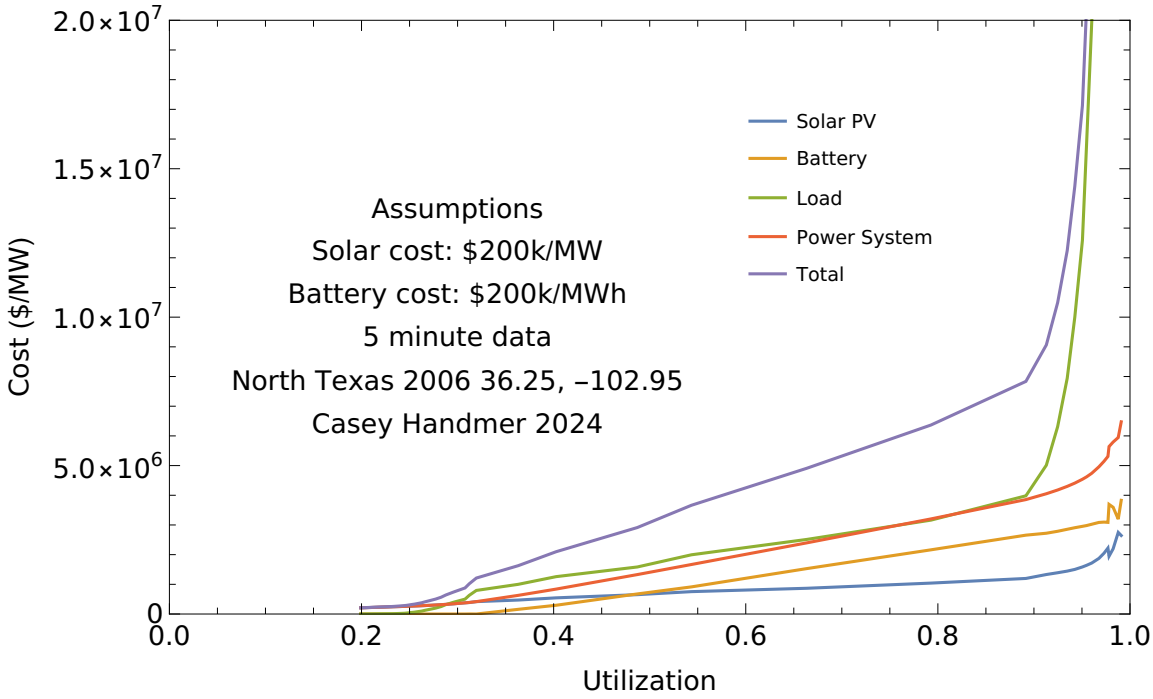
And now we do some plots, as a treat

This first plot shows how relative subsystems contribute to the overall cost, as a function of utilization. Utilization is not an independent variable, though, it's just a property of a given system with a given load capex. So, in Texas, for loads with ideal utilization over 90%, almost all the total system cost is driven by load, not power system - which is great! Most of the money is spent on the parts that are doing useful work.

In[1410]:=

```
ListLinePlot[{Transpose[{frontierTable[[All, -1, -1]], frontierTable[[All, 3, 1]]}],
  Transpose[{frontierTable[[All, -1, -1]], frontierTable[[All, 3, 2]]}],
  Transpose[{frontierTable[[All, -1, -1]], frontierTable[[All, 3, 3]]}],
  Transpose[{frontierTable[[All, -1, -1]], frontierTable[[All, 4, 1]]}],
  Transpose[{frontierTable[[All, -1, -1]], frontierTable[[All, 4, 2]]}]}, Frame → True,
 FrameStyle → Directive[14, Black], FrameLabel → {"Utilization", "Cost ($/MW)"},
 ImageSize → 600, PlotLegends → Placed[
   LineLegend[{"Solar PV", "Battery", "Load", "Power System", "Total"}], {0.7, 0.7}],
 PlotRange → {{0, 1}, {0 * 10 ^ 5, 2 * 10 ^ 7}}, ScalingFunctions → {"Linear", "Linear"},
 Epilog → Text[Rotate[Style["Assumptions\nSolar cost: $200k/MW\nBattery
       cost: $200k/MWh\n5 minute data\nNorth Texas 2006 36.25,
       -102.95\nCasey Handmer 2024", 14], 0], {0.3, 1. * 10 ^ 7}]]
```

Out[1410]=

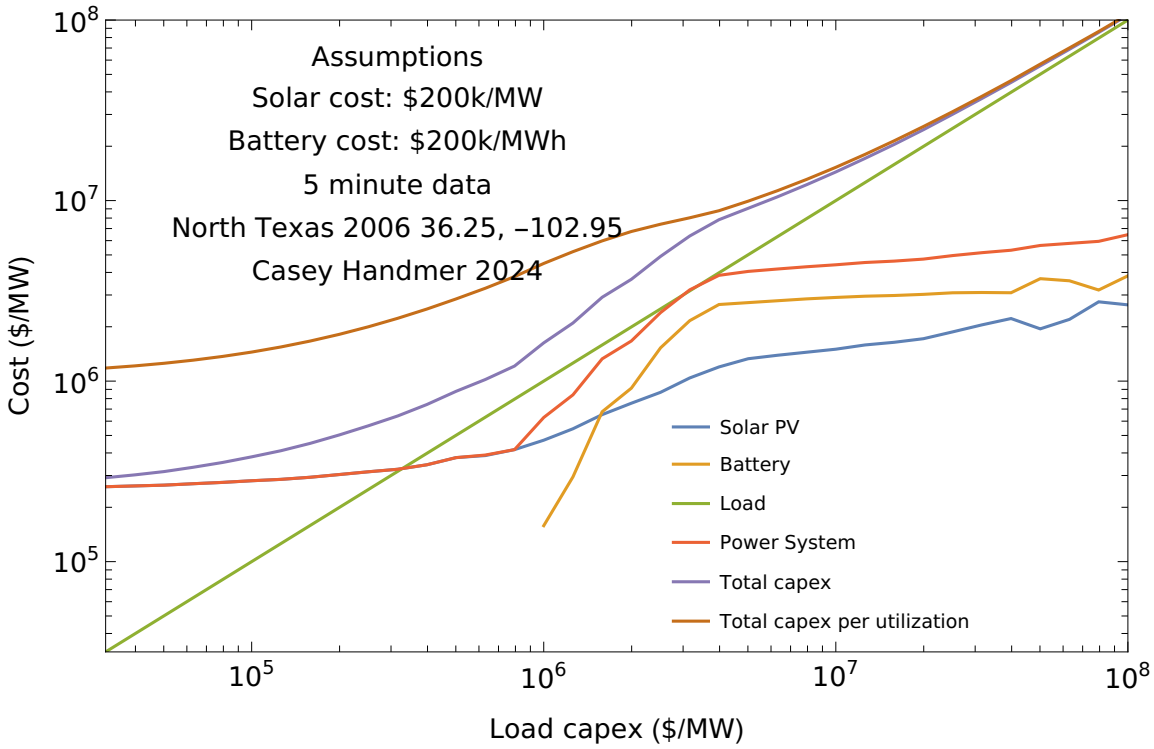


This chart shows how each of the various subcomponents' costs vary as a function of load capex. Note, in particular, a swift phase change around the crucial step of $1,000,000/MW. Below this level, we have lower utilization systems with almost no batteries. Above it, we use batteries to drive utilization up, amortization down, and overall value up.

In[1412]:=

```
ListLinePlot[{Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 3, 1]]}],
  Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 3, 2]]}],
  Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 3, 3]]}],
  Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 4, 1]]}],
  Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 4, 2]]}],
  Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 4, 3]]}]},
 Frame → True, FrameStyle → Directive[14, Black],
 FrameLabel → {"Load capex ($/MW)", "Cost ($/MW)"}, ImageSize → 600,
 PlotLegends → Placed[LineLegend[{"Solar PV", "Battery", "Load", "Power System",
     "Total capex", "Total capex per utilization"}], {0.7, 0.2}],
 ScalingFunctions → {"Log10", "Log10"}, PlotRange → {{10^4.5, 10^8}, {10^4.5, 10^8}},
 Epilog → Text[Rotate[Style["Assumptions\nSolar cost:
       $200k/MW\nBattery cost: $200k/MWh\n5 minute data\nNorth Texas
       2006 36.25, -102.95\nCasey Handmer 2024", 14], 0], {5.5, 7.2}]]
```

Out[1412]=

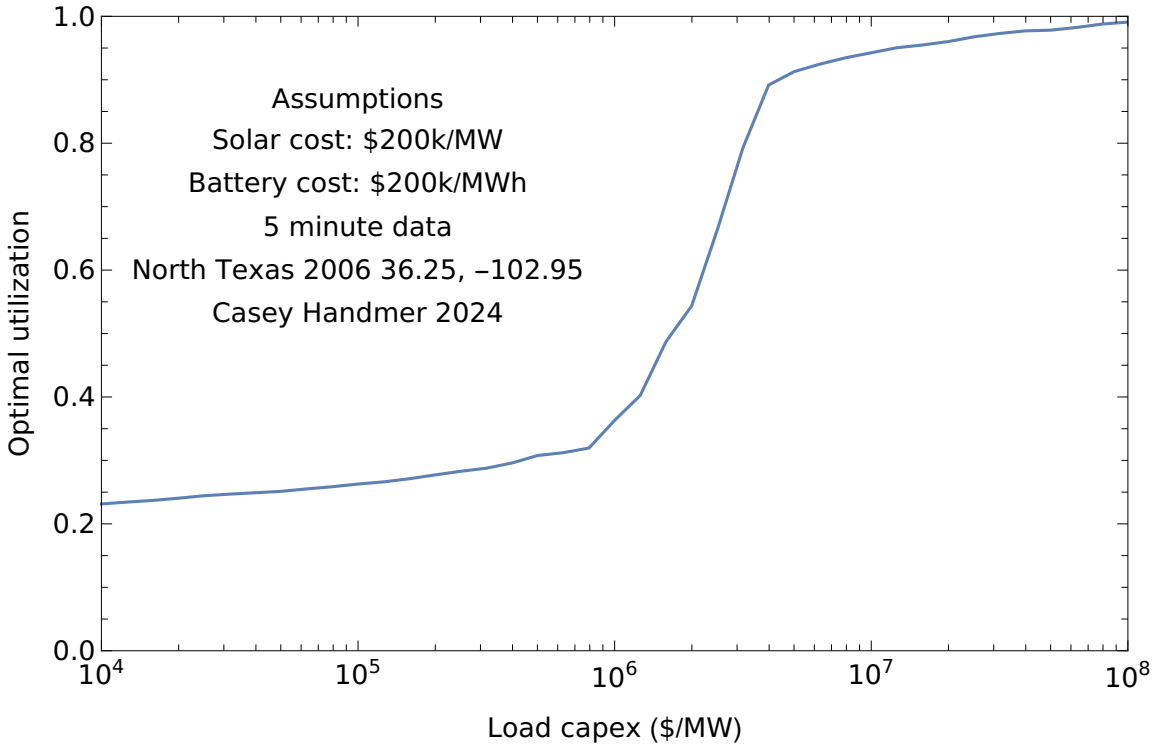


This chart makes the relationship between utilization and load capex even more explicit. Note, however, even for $100,000,000/MW systems, even for a place as sunny as Texas, optimal utilization is not 100%.

In[1407]:=

```
ListLinePlot[Transpose[{frontierTable[[All, 3, 3]], frontierTable[[All, 5, 4]]}],
 ScalingFunctions → {"Log10", "Linear"}, Frame → True, FrameStyle → Directive[14, Black],
 FrameLabel → {"Load capex ($/MW)", "Optimal utilization"},
 ImageSize → 600, PlotRange → {{10^4, 10^8}, {0, 1}},
 Epilog → Text[Rotate[Style["Assumptions\nSolar cost: $200k/MW\nBattery
       cost: $200k/MWh\n5 minute data\nNorth Texas 2006
       36.25, -102.95\nCasey Handmer 2024", 14], 0], {5, 0.7}]]
```

Out[1407]=

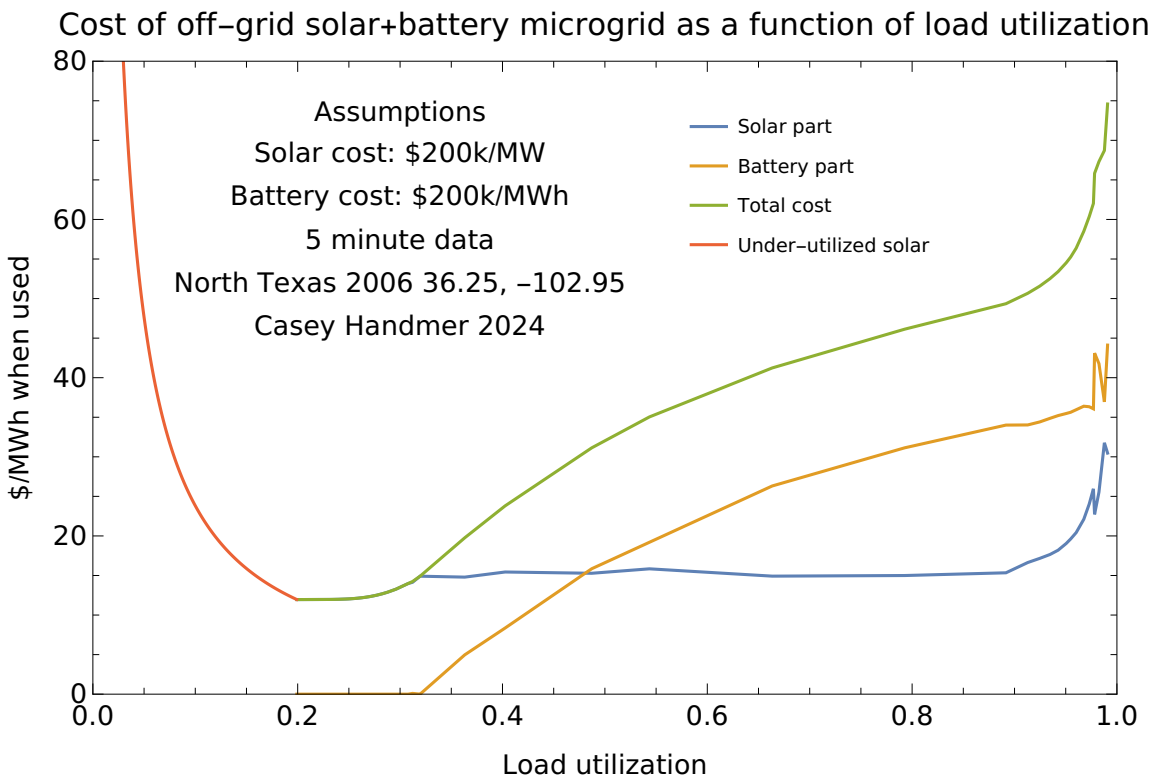


This is a fun chart. It shows the cumulative cost of the power side system as a functional of utilization. The key takeaways is that, for systems that can live with 25% utilization, power is *cheap*. For systems that can use 90% utilization, power is still cheap (about $50/MWh) but not as cheap as pure solar. But even pushing to 99% utilization, solar and battery costs don't go up all that much more. We're still below $80/MWh, which is competitive with any other power source. What happens here, to drive this last little bit, is an expansion of the solar PV system to ensure adequate power generation for the overnight batteries, even on very gloomy days. I also added a line corresponding the cost of not using available pure solar (no batteries) when available, for use cases with utilization even lower than raw power availability.

In[1408]:=

```
ListLinePlot[{Sort[Transpose[
      {frontierTable[[All, 5, 4]], (frontierTable[[All, 4, 1]] - frontierTable[[All, 3, 2]]) /
        (10 * 8760 * frontierTable[[All, 5, 4]])}][[1 ;; -1]],
  Sort[Transpose[{frontierTable[[All, 5, 4]], frontierTable[[All, 3, 2]] /
        (10 * 8760 * frontierTable[[All, 5, 4]])}][[1 ;; -1]],
  Sort[Transpose[{frontierTable[[All, 5, 4]], frontierTable[[All, 4, 1]] /
        (10 * 8760 * frontierTable[[All, 5, 4]])}][[1 ;; -1]],
  Table[{u, frontierTable[[1, 4, 1]] / (10 * 8760 * u)}, {u, 0.01, frontierTable[[1, 5, 4]], 0.001}]},
 ScalingFunctions → {"Linear", "Linear"},
 Frame → True,
 FrameStyle → Directive[14, Black],
 FrameLabel → {"Load utilization", "$/MWh when used"},
 ImageSize → 600,
 PlotRange → {{0, 1}, {0, 80}},
 Epilog → Text[
   Rotate[Style["Assumptions\nSolar cost: $200k/MW\nBattery cost: $200k/MWh\n5 minute
       data\nNorth Texas 2006 36.25, -102.95\nCasey Handmer 2024", 14], 0],
   {0.3, 60}], PlotLabel → Style["Cost of off-grid solar+battery microgrid
     as a function of load utilization", Black, 16],
 PlotLegends → Placed[LineLegend[{"Solar part", "Battery part",
     "Total cost", "Under-utilized solar"}], {0.7, 0.8}]]
```

Out[1408]=

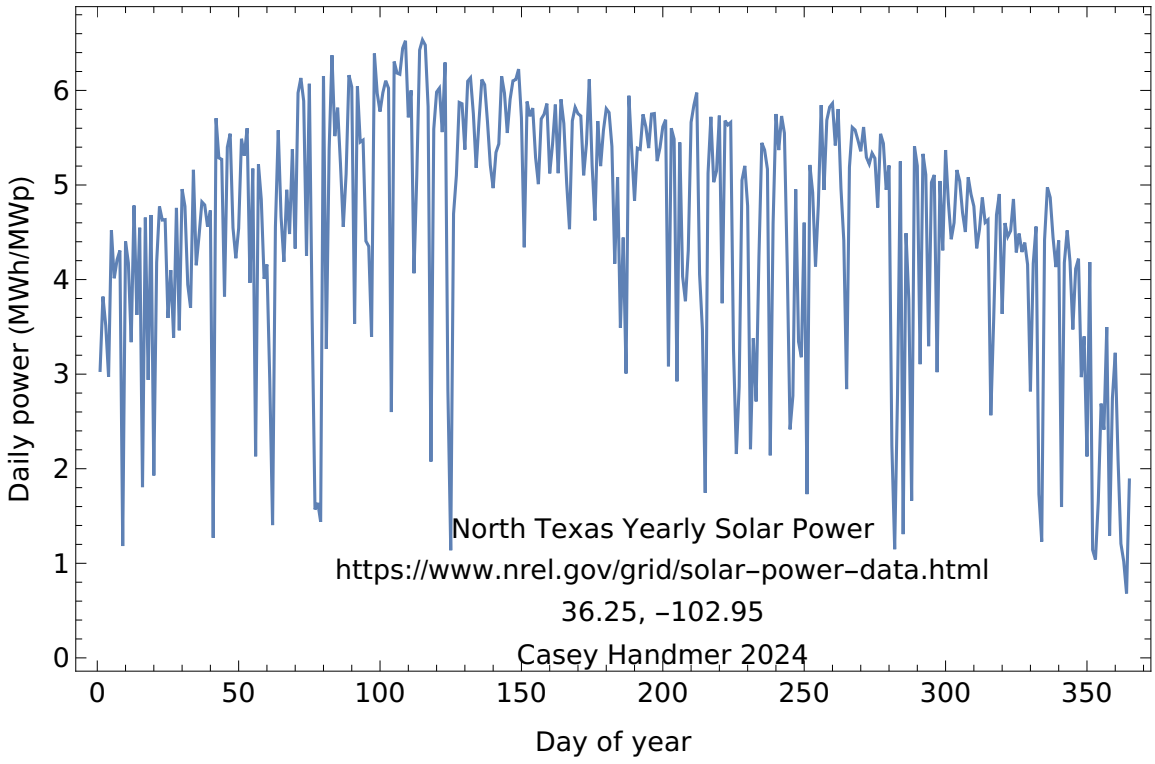


Finally, we repeat the power generation graph from above, for direct comparison and replication of this study.

In[1413]:=

```
ListLinePlot[24 Total[Transpose[Partition[sol, day]] / day], Frame → True,
 FrameStyle → Directive[14, Black], FrameLabel → {"Day of year", "Daily power (MWh/MWp)"},
 ImageSize → 600, PlotRange → All, Epilog → Text[Rotate[Style["North Texas Yearly Solar
       Power\nhttps://www.nrel.gov/grid/solar-power-data.html\n36.25,
       -102.95\nCasey Handmer 2024", 14], 0], {200, 0.7}]]
```

Out[1413]=



Conclusions

Off grid pure solar+batteries are cost competitive for a range of loads and desired utilizations, particularly in sunny places with good solar resources. There is no need for gas back up, grid connection, or auxiliary generators. All these options are higher cost and lower reliability than a distributed solar array with battery storage. Nor is it necessary to read a crystal ball here. For any given load in any given place, keep adding solar and batteries until the overall productivity per dollar spent reaches a peak, and we're done.