REU - Electricity Infrastructure for Smart Cities

Optimization of Solar Battery and Panel System in Denver, Colorado

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Problem Statement

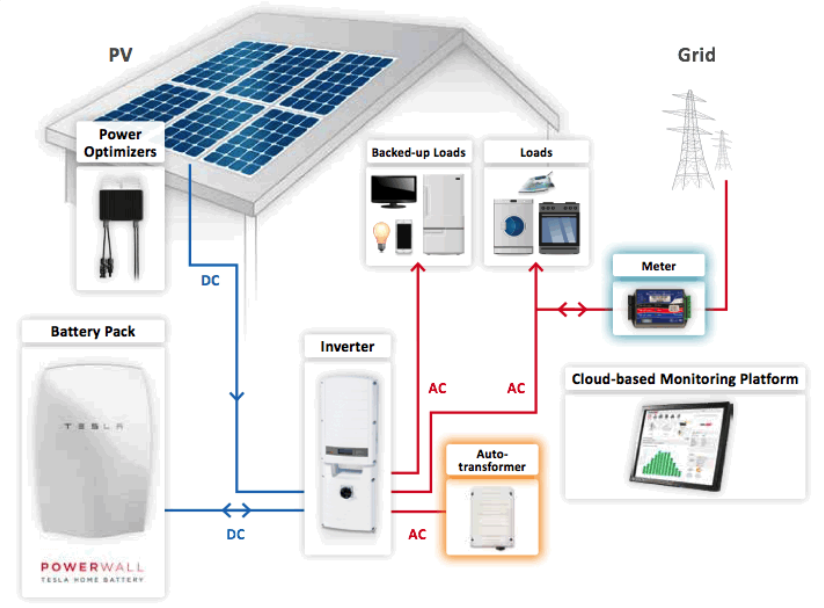


Fig. 1 Solar Panel and Battery System

- Problem: A person would like to go solar but does not know the cost.
- Solution: Optimize the size of a solar panel and battery to determine the most beneficial solution for a home.

Power and Energy Capacity

- Power=kW
  - Instantaneous output
  - Amount of electricity generated or discharged
- Energy=kWh
  - "volume of electricity"
  - Power over time
- Capacity
  - Measure of battery's potential to generate power and store energy
- Batteries intended to either maximize power or energy rating
- Examples
  - Primary use to regulate frequency (charge and discharge many times over short duration of time)
    - System designed with high power rating
  - Primary use to provide peak-shifting or backup power (discharge over long period of time)
    - System designed with high energy rating

Solar Capacity Factor

- Ratio of energy generated over time period divided by installed capacity
- Changes depending on location
- Colorado=high solar potential w/ 300+ days of sun
- Example:
  - System generates 20,500 kWh per year
  - Peak capacity=10kW
  - 24*365*10=87,600
  - Capacity factor=20,500/87,600*100=23%
- Ranges from 10-25%

Xcel Energy Rewards Program

- Small Rewards Program
  - 0.5kW-25kW systems
  - 2MW capacity allocated per month (24MW for year)
  - $0.005/kWh
    - $10 max paid back per month
    - $120 max per year
- Medium Rewards Program
  - 25.01kW-500kW systems
  - 6MW capacity allocated per quarter—3 months—(24MW for year)
  - $0.0375/kWh
    - $225 max paid back per quarter ($75 per month)
    - $900 max per year
- Large Rewards Program
  - 500kW+ systems
  - Accepting proposals
  - Capped at 120% of customer annual load
  - Up to 14MW
- All Payments made in REC
  - Renewable energy credit

Average Cost of Solar Panel Installation in Denver

System size*	Average cost per watt	Roof space required	Average cost (before tax credit)	Average cost (after tax credit)
4 kW	$4.18	267 sq/ft	$16,733	$11,713
5 kW	$4.06	333 sq/ft	$20,305	$14,214
6 kW	$3.90	400 sq/ft	$23,427	$16,399
8 kW	$3.87	533 sq/ft	$30,927	$21,649
10 kW	$3.79	667 sq/ft	$37,859	$26,502
12 kW	$3.66	800 sq/ft	$43,926	$30,748
20 kW	$3.48	1,333 sq/ft	$69,592	$48,714

Fig. 1 Differing Solar Panel System Size Installation Costs

Calculations

System Size (kW)		Average Cost After Tax Credit ($)
4		11,713
5	Typical	14,214
6		16,399
8		21,649
10		26,502
12		30,748
20		48,714

Xcel Energy Small Rewards ($/kWh)
0.005
Max ($/mo)
10
Max ($/yr)
120

Average Residential Electricity Rate ($/kWh)
11.46
Usage (kWh/month)
706
Electricity Bill ($)
81
5kW Solar System Covered Cost Monthly ($)
73.0002

Money earned monthly w/ 5kW ($)	Money Lost Monthly ($)	Payback Time (years)	Assumes 100% energy used is solar (5kW system)
3.53	6.47	14.0128	
Yearly	Yearly	If all storage used	
42.36	77.64	13.0165	

Money earned monthly w/ 5kW ($)	Out of Pocket Expense ($)	Payback Time (years)	Average 5kW Solar Generation Monthly (kWh)
3.185	7.9998	15.5476	637
Yearly	Yearly		Average 5kW Solar Generation Yearly (kWh)
38.22	95.9976		7639

Fig. 2 Payback Time in Years for Three Cases

Calculations

Money earned monthly w/ System ($)	System Size (kW)	Cost After Tax Credit ($)	Residential Electricity Rate ($/kWh)
0.45625	5	14,000	10
Yearly	Capacity Factor		Usage (kWh/month)
5.475	25%		750
	Solar Energy (kWh/year)		Electricity Bill ($)
	10950		75
	Solar Panel (kWh/month)		
	912.5		
	Solar Panel (kWh/day)		
	1.25		

5kW Solar Generation Monthly (kWh)	Price ($)	Payback Time (years)
1000	6700	21
5kW Solar System Covered Cost Monthly ($)	Supporting Hardware ($)	
91.25	1100	
	Installation Cost ($)	
	1000	
	Battery (kW)	
	15	
	Battery Energy (kWh/year)	
	21900	
	Solar Stored (kWh/year)	
	1950	

Fig. 3 Payback Time in Years Including Solar Battery

Sensitivity Analysis

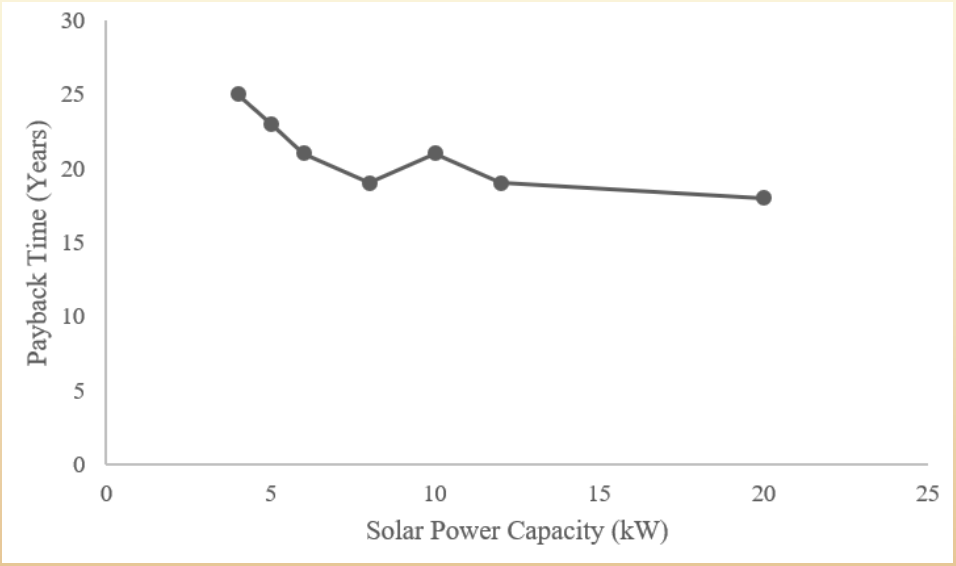


Fig. 4 Sensitivity analysis of payback time versus solar power capacity

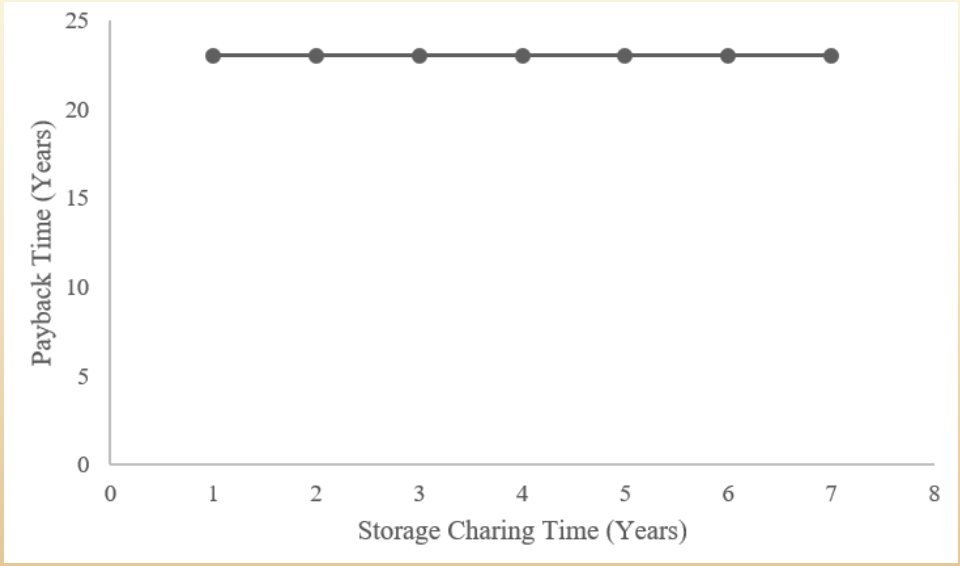


Fig. 5 Sensitivity analysis of payback time versus storage charging time

Sensitivity Analysis

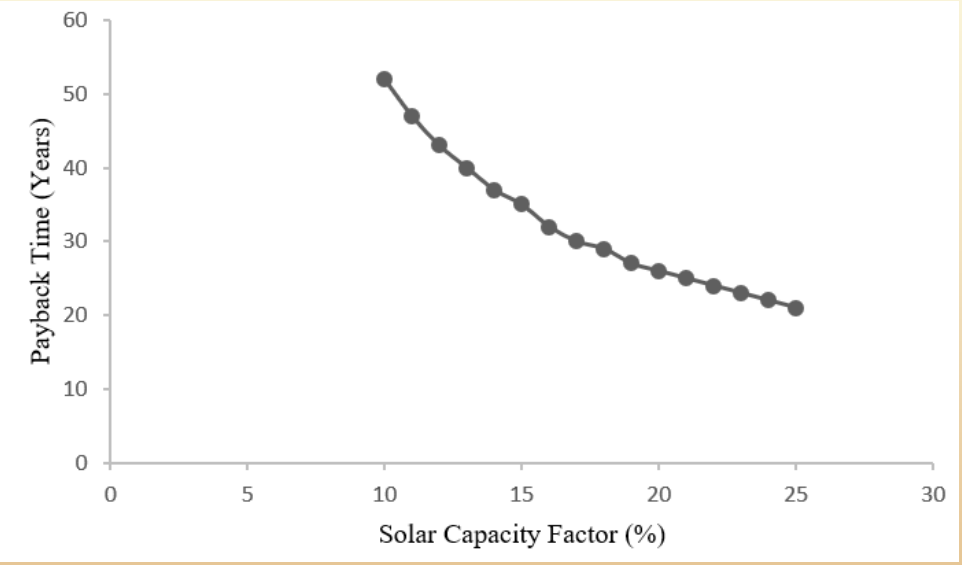


Fig. 6 Sensitivity analysis of payback time versus solar capacity factor

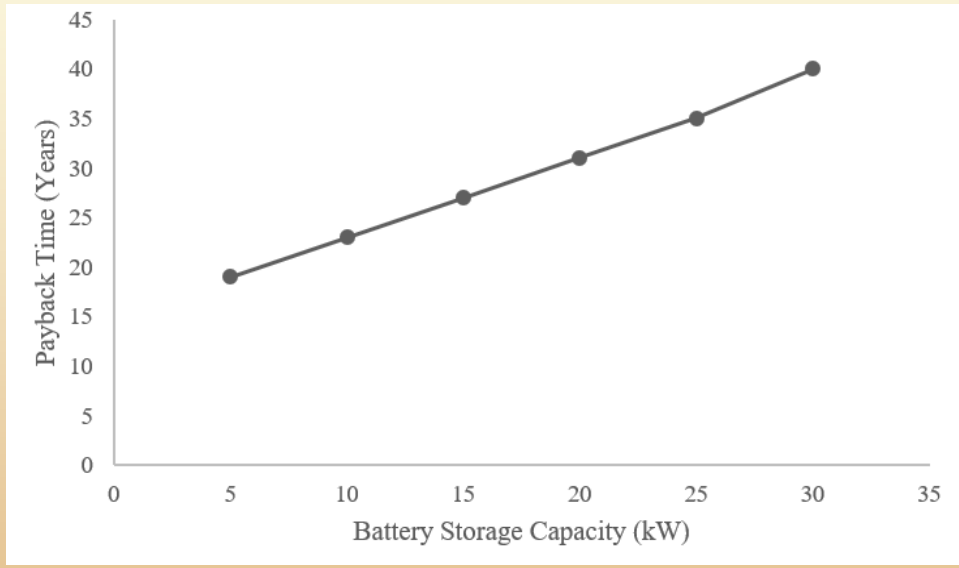


Fig. 7 Sensitivity analysis of payback time versus battery storage capacity

Variables

Table I Variable Constraints

Variable	Mathematical Notation	Lower Bound (lb)	Upper Bound (ub)
AC Size of PV System	S_{PV}	0	20kW
Power of PV	P_{PV}	0	Inf
PV Energy Produced	E_{PV}	0	39,770kWh
Battery System Size	S_B	0	7kW
Battery Energy Produced	E_B	-10,220kWh	10,220kWh
Grid Energy Bought	E_G	0	Inf
Money Earned	M	-inf	Inf
Cost of PV	C_{PV}	-inf	Inf
Cost of Battery	C_B	-inf	Inf
Cost of Grid	C_G	-inf	Inf

Parameters

Table II Parameter Constraints

Parameter	Mathematical Notation	Quantity	Units
Price of Electricity https://www.electricitylocal.com/states/colorado/	R	11.46	Cents per Kilowatt Hours (¢/kWh)
Efficiency of PV https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/	ε	19.41	Percent (%)
Capacity Factor https://euanmearns.com/solar-pv-capacity-factors-in-the-us-the-eia-data/	F	22.7	Percent (%)
Energy Consumed Monthly (Yearly) https://www.electricitylocal.com/states/colorado/	U	8472	Kilowatt Hours (kWh)
Hours of Battery Utilized https://www.voltaicsystems.com/blog/estimating-battery-charge-time-from-solar/	H	4	Hours (h)
Price of PV System http://www.freecleansolar.com/Panasonic-Solar-Panel-HIT-N320K-VBHN320KA03-p/vbhn320ka03.htm?gclid=CjwKCAjw67XpBRBqEiwA5RCocbjlKr9KEHjMMrQtd36tsanNZhU0MXo3p39EFZ2y5-g-Mp4e2dpDABoC2xwQAvD_BwE	R_{PV}	1090	Dollars per Kilowatt ($/kW)
Price of Battery https://www.tesla.com/powerwall	C_B	6700	Dollars ($)
Excel Energy Rewards https://www.xcelenergy.com/programs_and_rebates/residential_programs_and_rebates/renewable_energy_options_residential/solar/available_solar_options/on_your_home_or_in_your_yard/solar_rewards_for_residences	X	0.005	Dollars ($)

Mathematical Problem

Minimize Cpv+Cb+Cg-M

Subject to:

$$P_{PV} - F \cdot S_{PV} = 0$$

$$E_{PV} - P_{PV} \cdot 8760 = 0$$

$$E_{PV} + E_G + E_B = U$$

$$E_B - S_B \cdot H \cdot 365 = 0$$

$$C_G - R \cdot E_G = 0$$

$$M - E_{PV} \cdot X = 0$$

$$C_{PV} - R_{PV} * S_{PV} = 0$$

$$C_B - R_B * S_B = 0$$

x= [Spv
Ppv
Epv
Sb
Eb
Eg
M
Cpv
Cb
Cg]

$lb \leq x \leq ub$

*see table (slide 2)

Parameters

- Monthly Usage=706kWh
- Rpv=$1090/kW
- Rb=$957/kW

```
F=0.227;     %parameter inputs
R=0.1146;
U=8952;
H=4;
Rpv=1090;
Rb=957;
X=0.005;
```

Output

- Objective function
- Variable output
- Time in years

```
x=linprog(f,A,b,Aeq,beq,lb,ub);    %optimization

Spv=x(1)     %stating variables
Ppv=x(2)
Epv=x(3)
Sb=x(4)
Eb=x(5)
Eg=x(6)
M=x(7)
Cpv=x(8)
Cb=x(9)
Cg=x(10)

T=(Cb+Cg+Cpv+14214)/(M+R*Epv)    %payback time in years
```

Case 1

- Optimal Solution:
  - No solar panel or battery needed
  - Grid energy bought to fulfill load demand
- No bounds on grid energy bought
- No payback time in years b/c no solar panel or battery needed

```
Spv =
     0

Ppv =
     0

Epv =
     0

Sb =
     0

Eb =
     0
```

```
Eg =
   8.9520e+03

M =
     0

Cpv =
     0

Cb =
     0

Cg =
   1.0259e+03
```

```
T =
    Inf
```

```
lb=[0 0 0 0 -10220 0 -inf -inf -inf -inf].';

ub=[20 inf 39770 7 10220 inf inf inf inf inf].';
```

Case 2

- Optimal Solution:
  - Grid+Solar Panel System
  - 4kW Solar Panel System Size
- Constraints
  - $150 cap on grid energy bought
- ~20 years payback time

```
Spv =

    3.8436

Ppv =

    0.8725

Epv =

   7.6431e+03

Sb =

     0

Eb =

     0
```

```
Eg =

   1.3089e+03

M =

   38.2155

Cpv =

   4.1895e+03

Cb =

     0

Cg =

   150
```

```
T =

   20.2967
```

```
lb=[0 0 0 0 -10220 0 -inf -inf -inf 0].';

ub=[20 inf 39770 7 10220 inf inf inf inf 150].';
```

Case 3

- Optimal Solution:
  - Solar Panel+Battery
  - 4kW solar panel system size
  - 1kW solar battery size
- Constraints:
  - $0 bought from grid
  - Max 4kW solar panel system size
- ~20 years payback time

```
Spv =
    4.0000

Ppv =
    0.9080

Epv =
         7954

Sb =
    0.6836

Eb =
   998
```

```
Eg =
       0

M =
   39.7700

Cpv =
   4.3600e+03

Cb =
  654.1685

Cg =
       0
```

```
T =
   20.2125
```

```
lb=[0 0 0 0 -10220 0 -inf -inf -inf 0].';

ub=[4 inf 7954 7 10220 inf inf inf inf 0].';
```

Case 4

- Optimal Solution:
  - 5kW solar panel system size
- Constraints:
  - $0 bought from grid
- ~18 years payback time

```
Spv =
    4.5018

Ppv =
    1.0219

Epv =
         8952

Sb =
     0

Eb =
     0
```

```
Eg =
     0

M =
   44.7600

Cpv =
   4.9070e+03

Cb =
     0

Cg =
     0
```

```
T =
   17.8591
```

```
lb=[0 0 0 0 -10220 0 -inf -inf -inf 0].';

ub=[20 inf 39770 7 10220 inf inf inf inf 0].';
```

Case 4

- Optimal Solution:
  - 5kW solar panel system size
- Constraints:
  - $0 bought from grid
- ~18 years payback time

```
Spv =
    4.5018

Ppv =
    1.0219

Epv =
         8952

Sb =
     0

Eb =
     0
```

```
Eg =
     0

M =
   44.7600

Cpv =
   4.9070e+03

Cb =
     0

Cg =
     0
```

```
T =
   17.8591
```

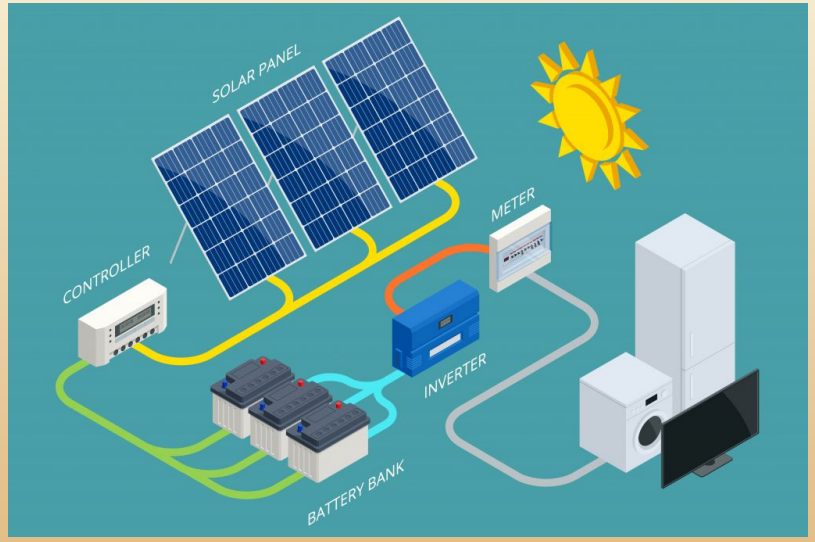
```
lb=[0 0 0 0 -10220 0 -inf -inf -inf 0].';

ub=[20 inf 39770 7 10220 inf inf inf inf 0].';
```

Conclusion

- If grid is included, 4kW solar panel system is the most practical
- A battery is not cost effective
- No 1kW solar battery
- In general, it is cheaper to buy from the grid b/c of the payback time required for the solar panel/battery

Future Research

- Types of solar battery storage
- Types of battery materials
- Climates around United States
- Large-scale use
  - Solar farms



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