# Inexpensive, Firm PV Without Conventional Backup:
## The Role of Supply Shaping Through Curtailment

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*Clean Power Research*

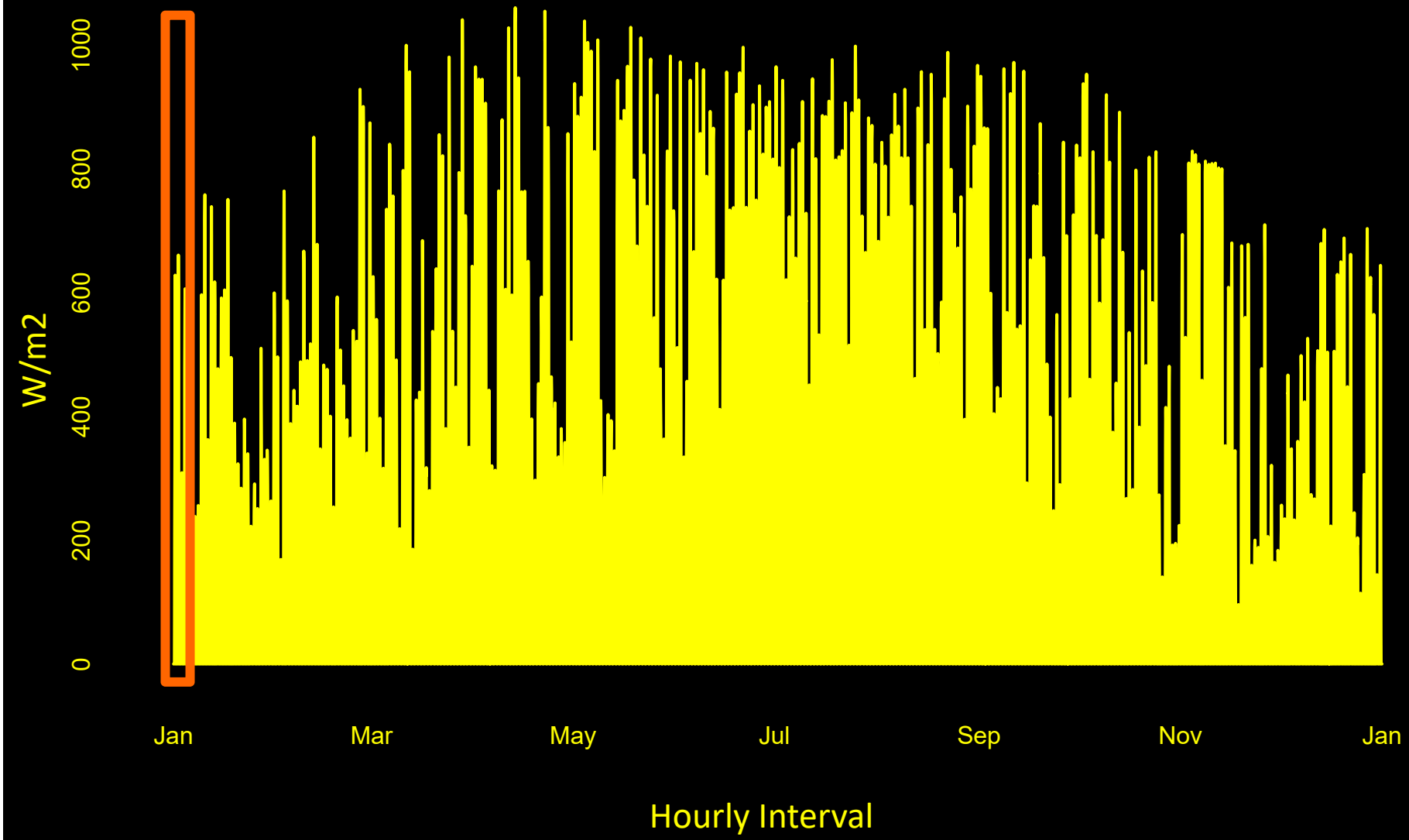
***For achieving high-penetration renewables!***

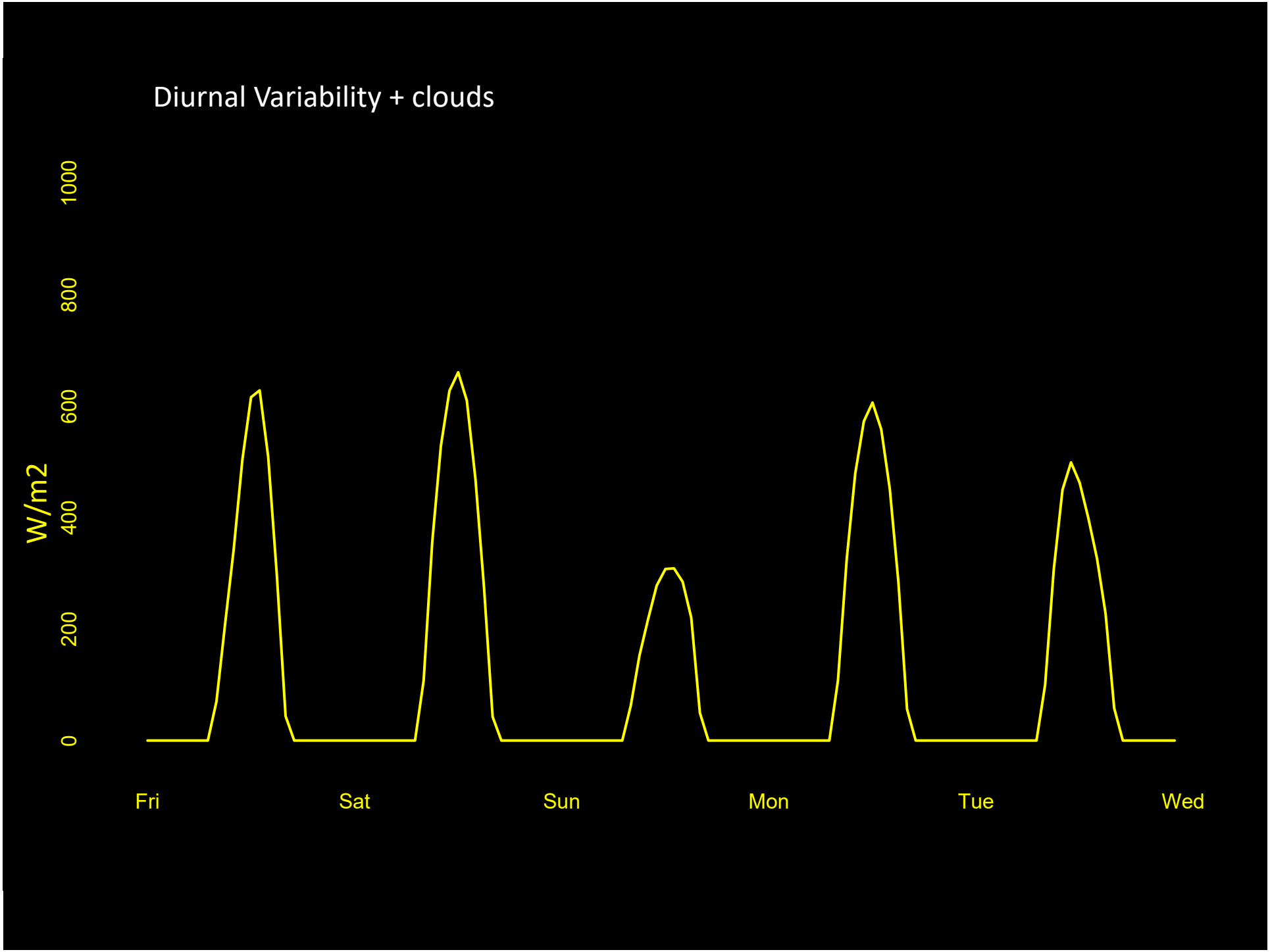
**This work is based upon work supported by:**
National Science Foundation GRF Grant No. DGE 1144155
DoE Sunshot Grant No. DE-EE0007669
Columbia University Center for Life Cycle Analysis
Clean Power Research

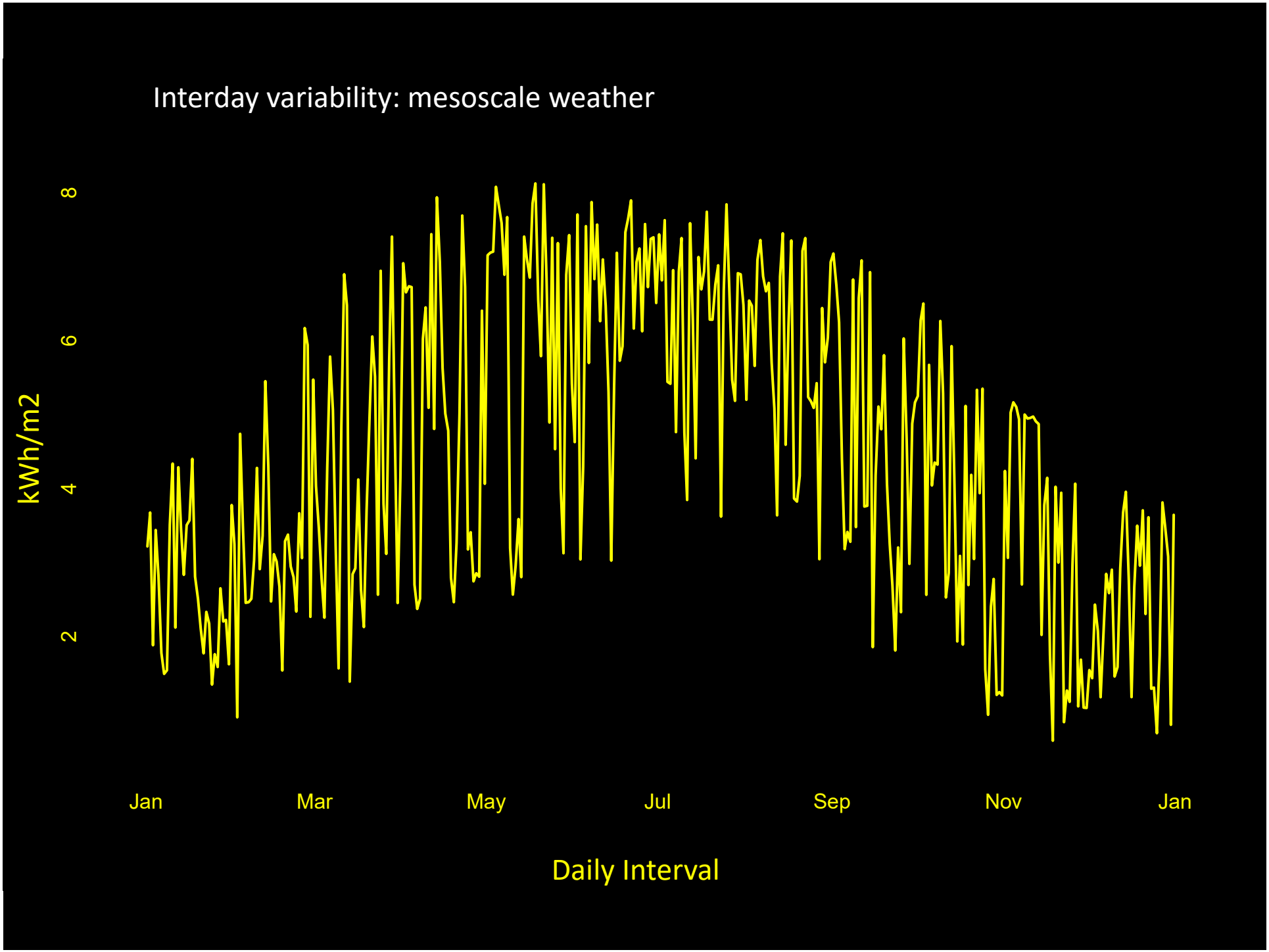
Why do we think we need backup to achieve high penetration?

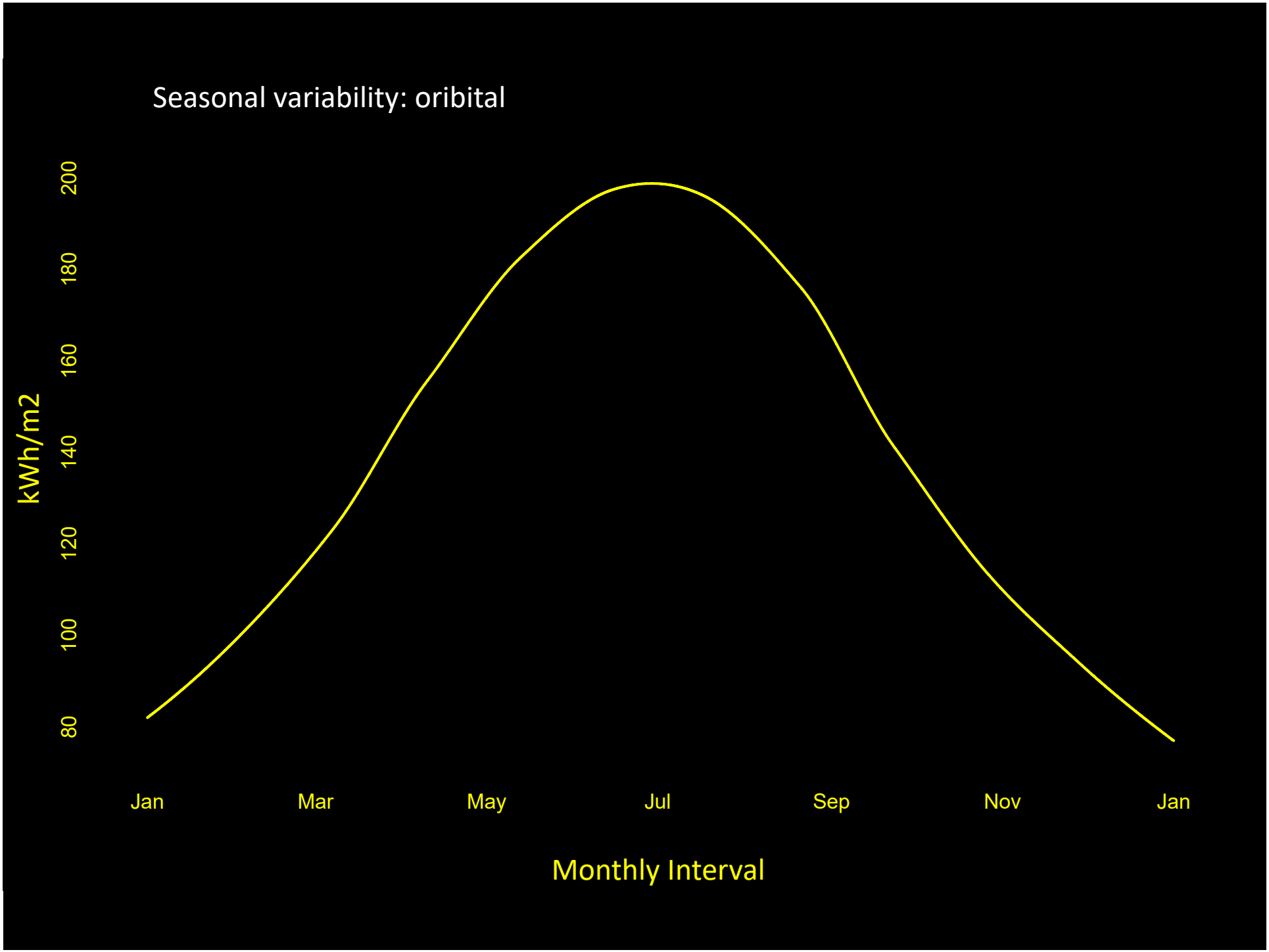
It’s because wind + solar are intermittent and what we really need is **firm power**
Storage is considered to be the keystone to mitigate variability on all timescales

Intraday Variability

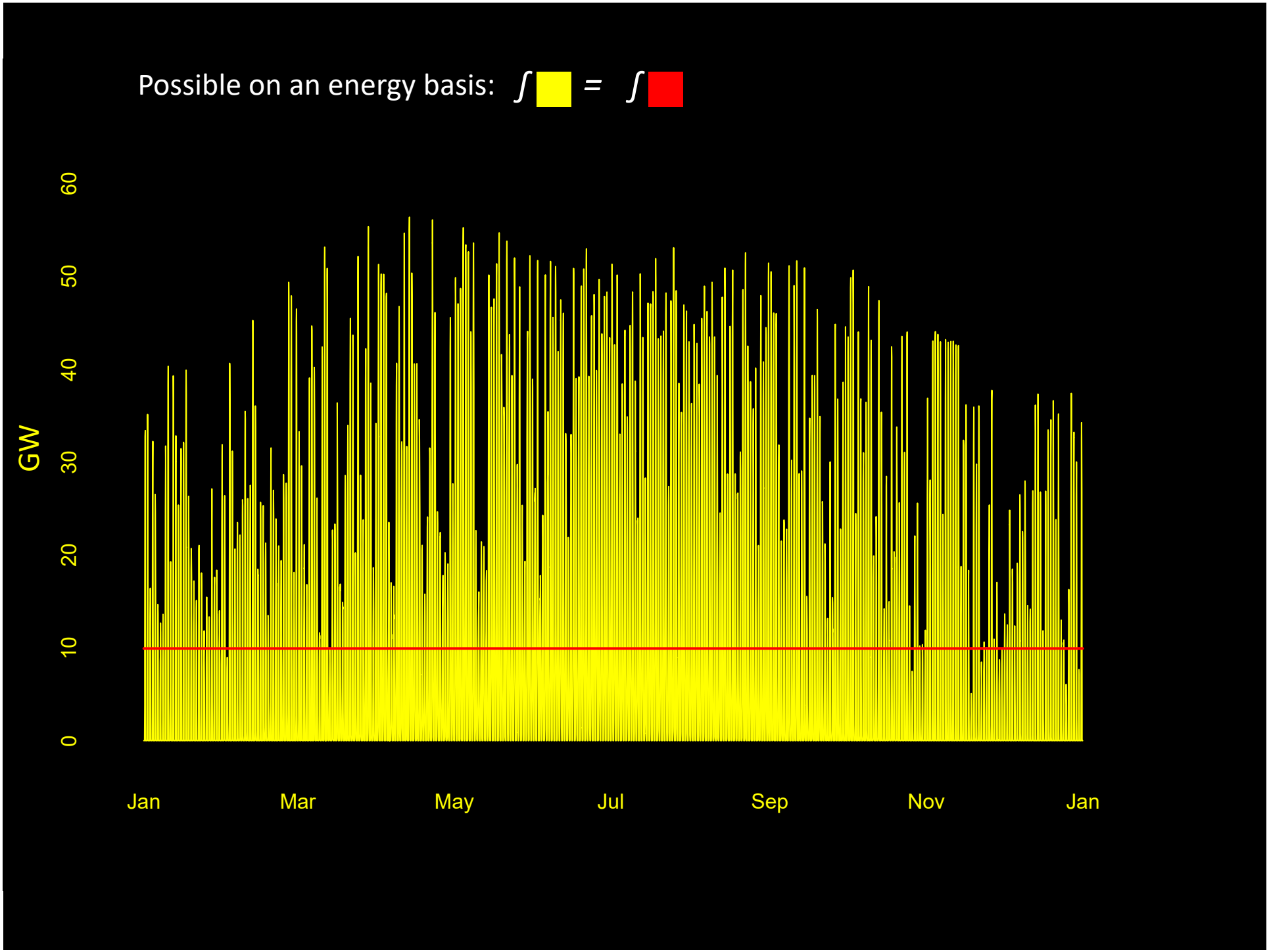



Diurnal Variability + clouds
W/m2
0
200
400
600
800
1000
Fri
Sat
Sun
Mon
Tue
Wed

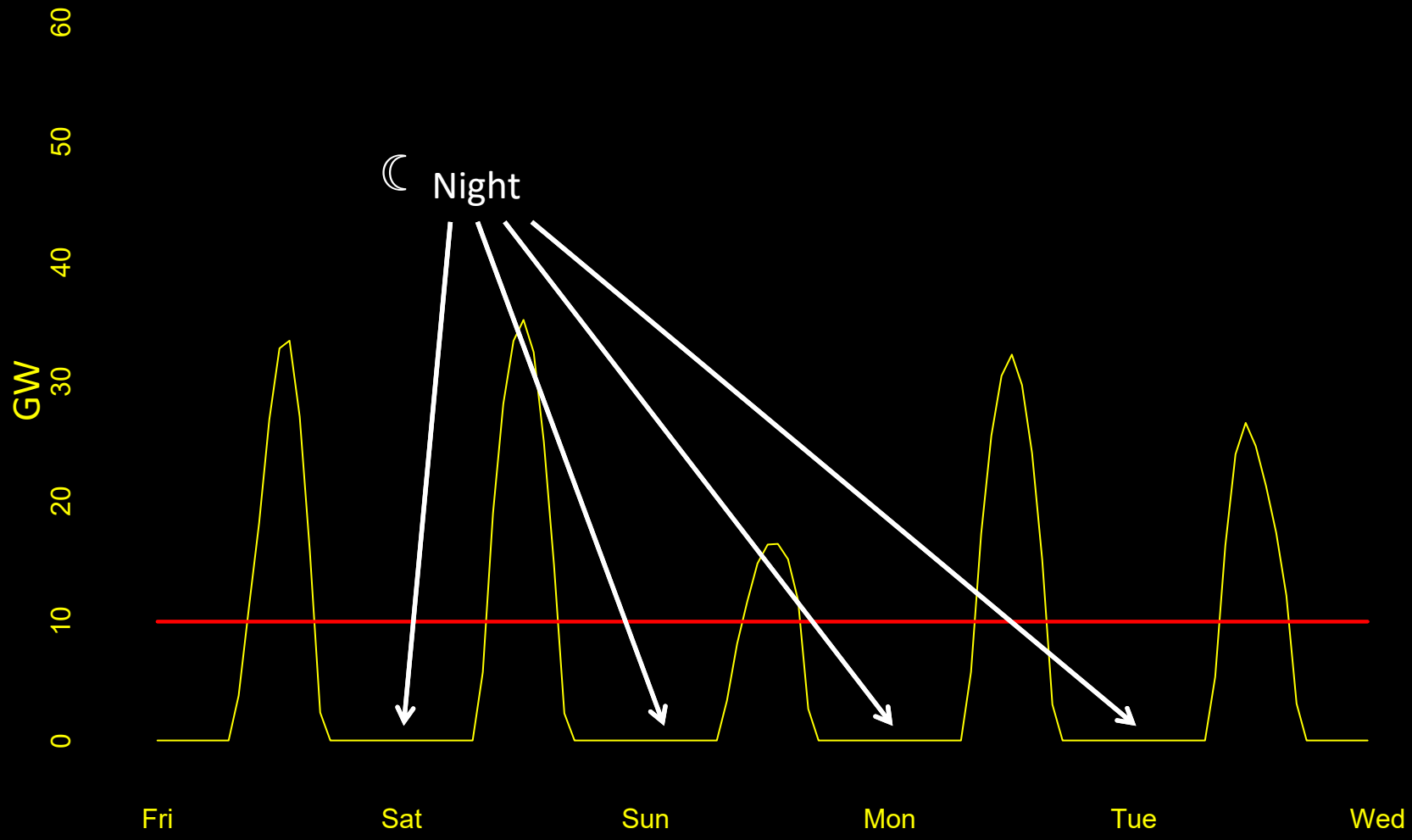

Interday variability: mesoscale weather
kWh/m2
2
4
6
8
Jan
Mar
May
Jul
Sep
Nov
Jan
Daily Interval

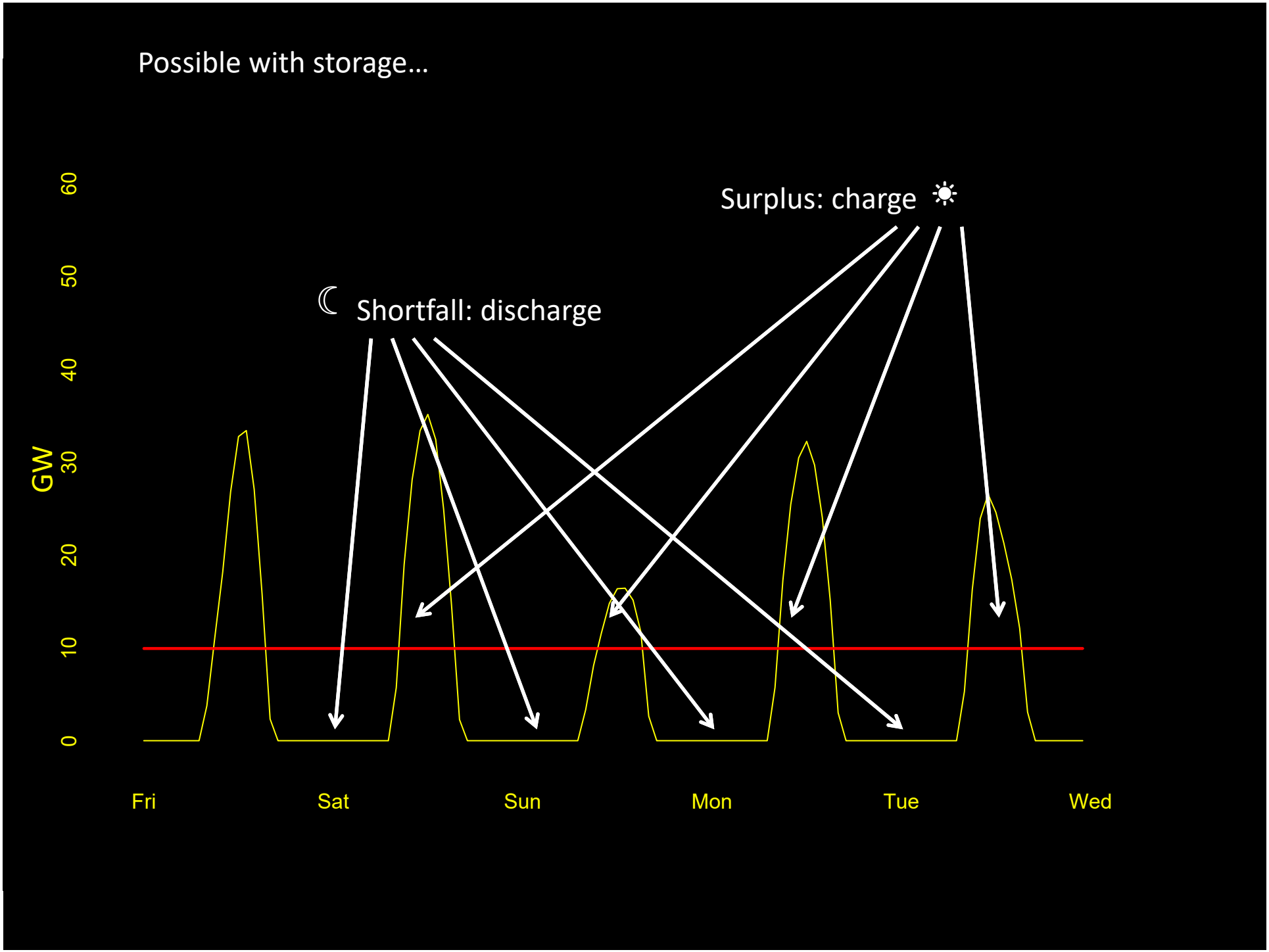

Seasonal variability: oribital
kWh/m2
200
180
160
140
120
100
80
Jan
Mar
May
Jul
Sep
Nov
Jan
Monthly Interval


GW
0
10
20
30
40
50
60
Say we want to produce baseload with PV
Jan
Mar
May
Jul
Sep
Nov
Jan

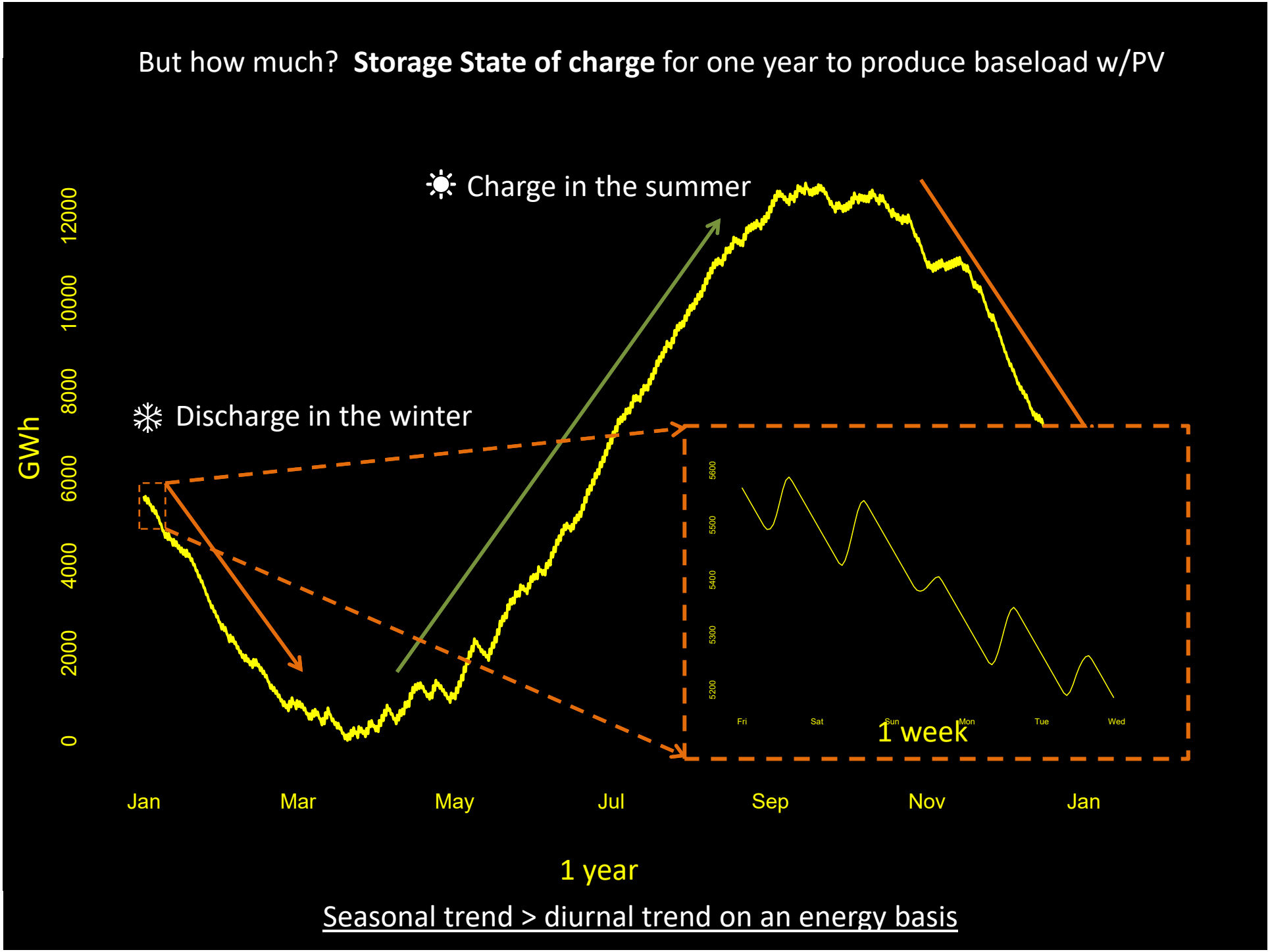

Possible on an energy basis: ∫ = ∫
GW
0
10
20
30
40
50
60
Jan
Mar
May
Jul
Sep
Nov
Jan

But impossible due to diurnal intermittency…

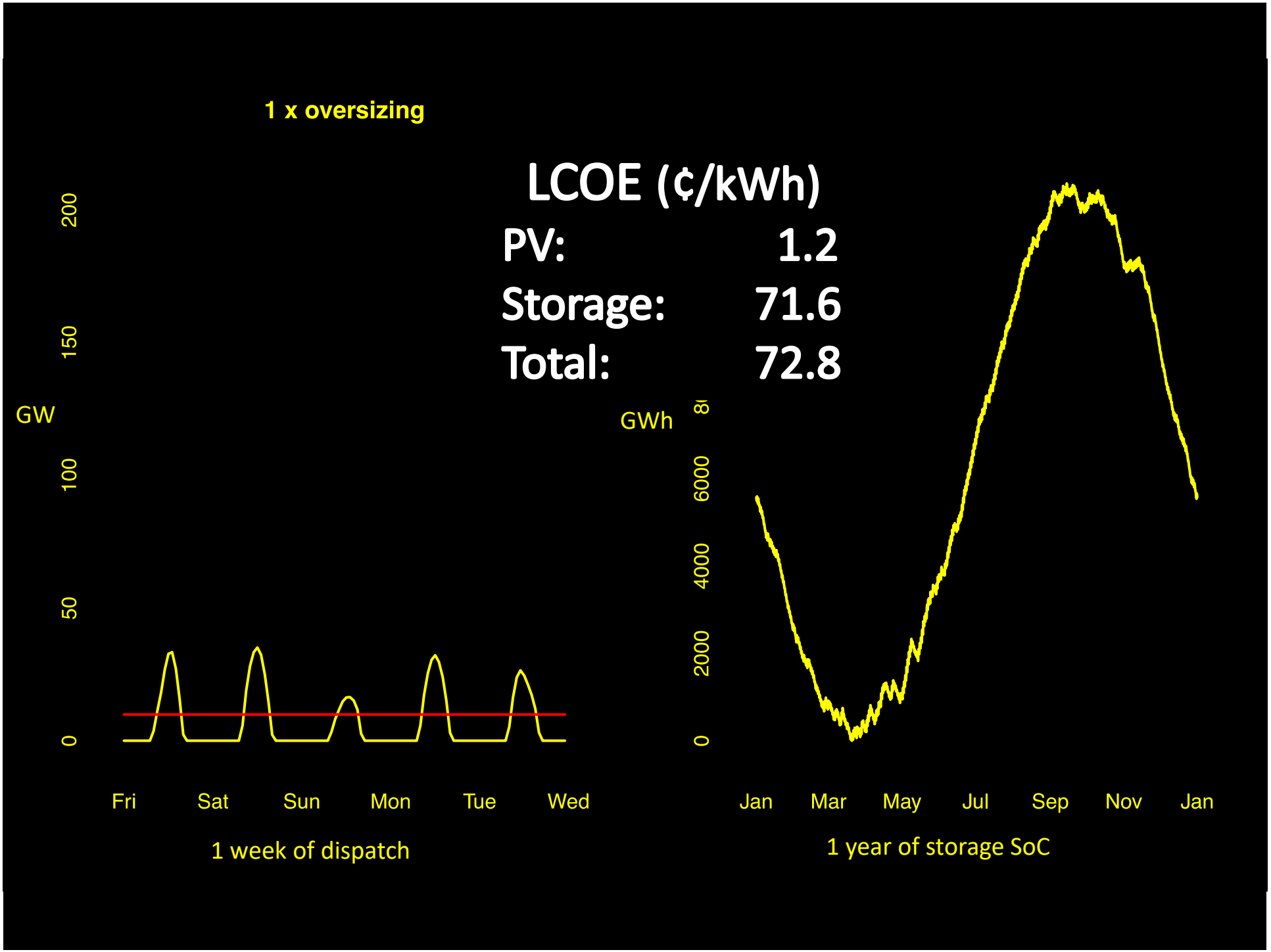



Possible with storage…
Surplus: charge
Shortfall: discharge
GW
60
50
40
30
20
10
0
Fri
Sat
Sun
Mon
Tue
Wed

But how much? **Storage State of charge** for one year to produce baseload w/PV




Seasonal trend > diurnal trend on an energy basis

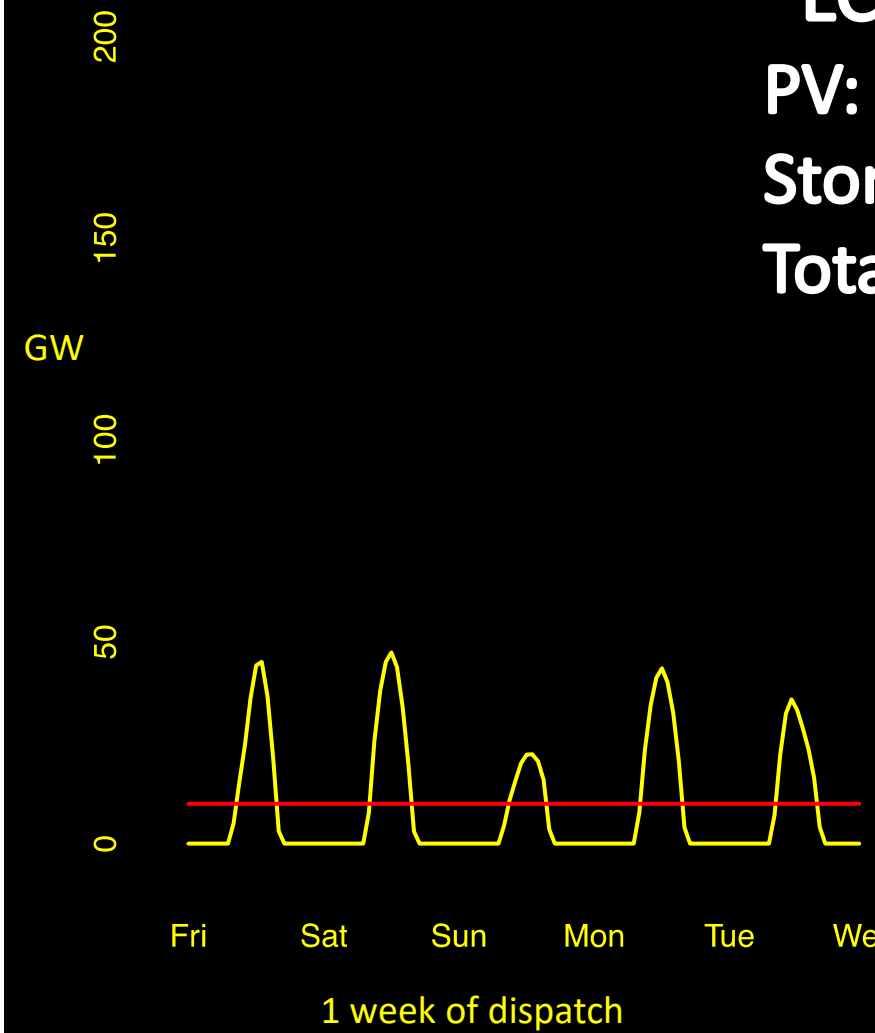

1 x oversizing
LCOE (¢/kWh)
PV: 1.2
Storage: 71.6
Total: 72.8
GW
200
150
100
50
0
Fri
Sat
Sun
Mon
Tue
Wed
1 week of dispatch
GWh
8
6000
4000
2000
0
Jan
Mar
May
Jul
Sep
Nov
Jan
1 year of storage SoC

1.3 x oversizing

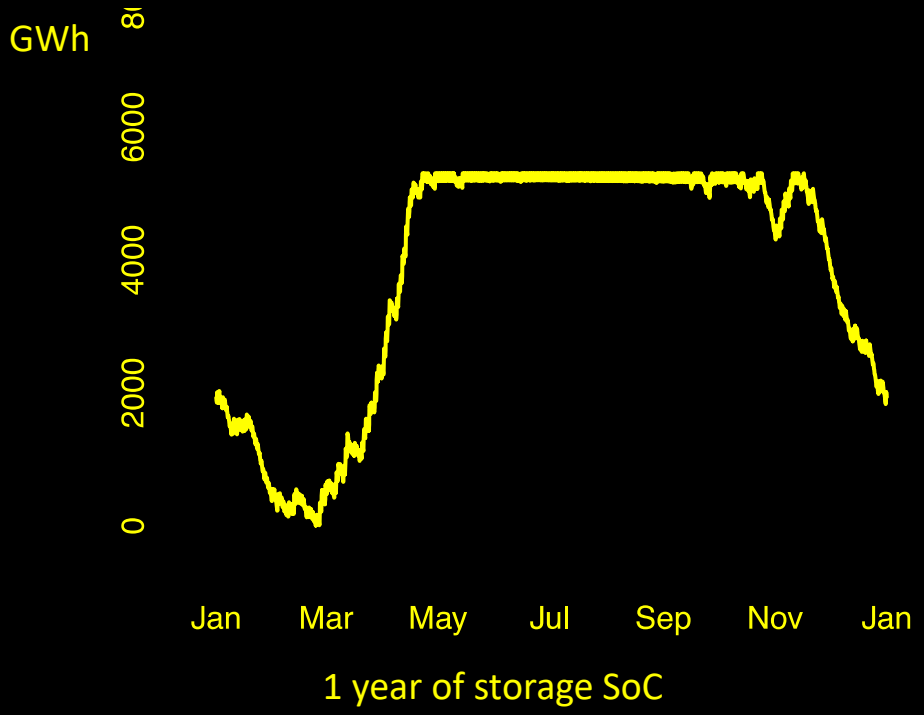
58.4 % reduction in storage

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 1.6 |
| Storage: | 30.1 |
| Total: | 31.7 |




1 week of dispatch



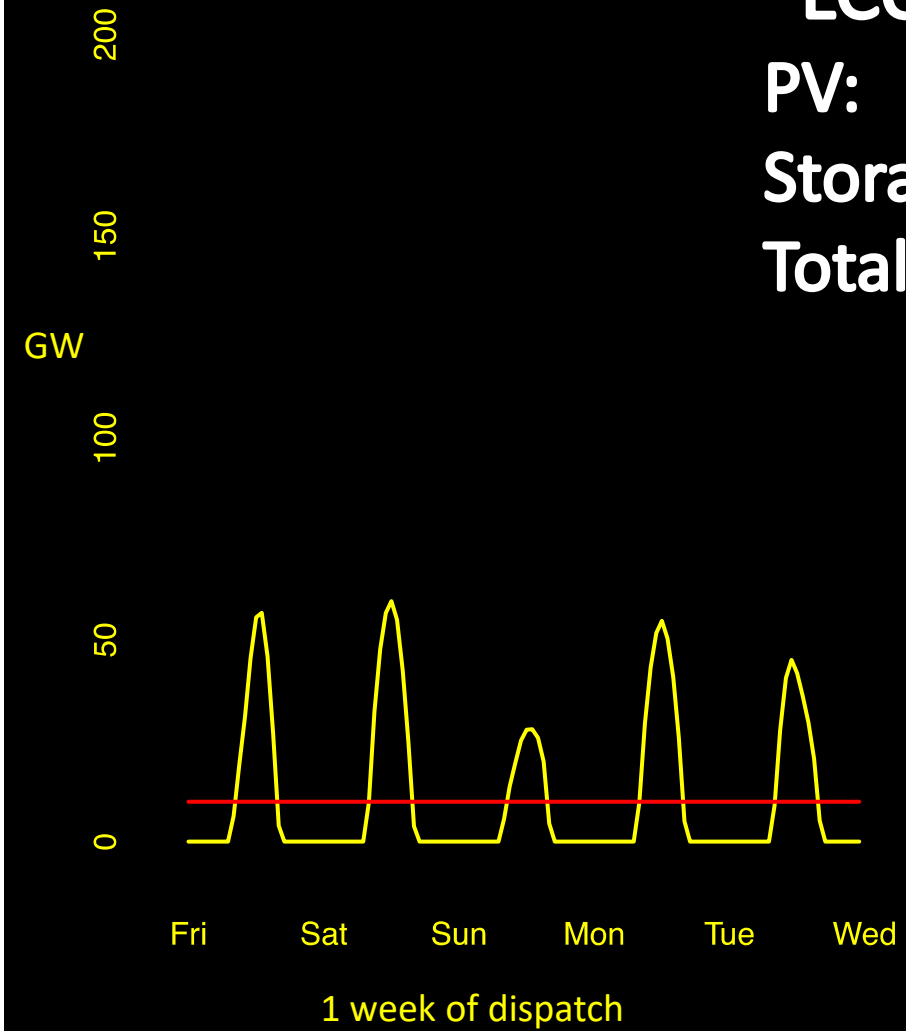

1 year of storage SoC

1.7 x oversizing

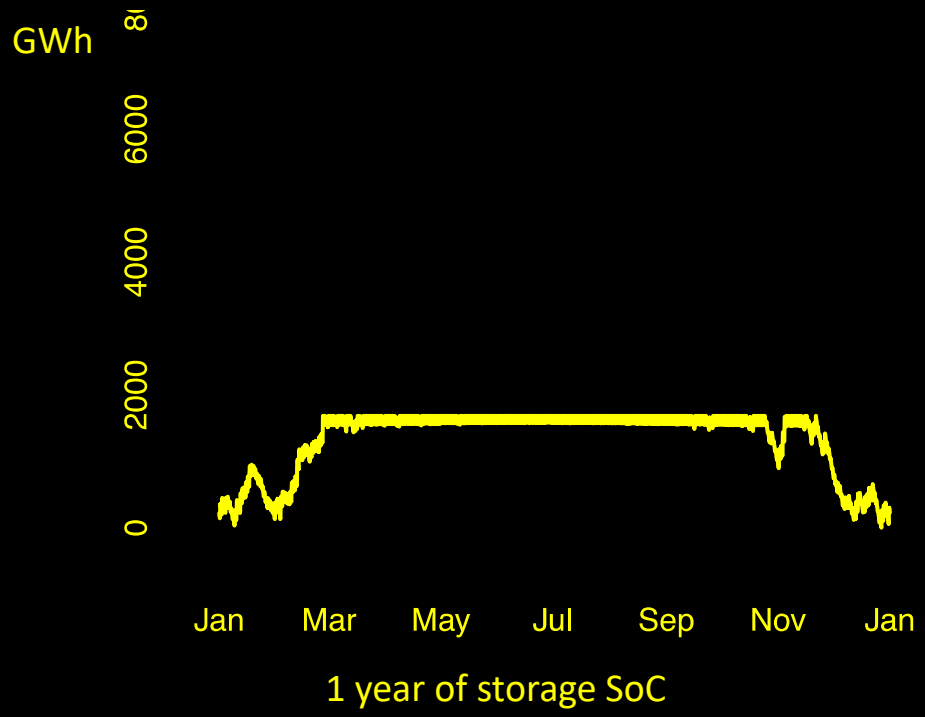
86.8 % reduction in storage

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 2.0 |
| Storage: | 9.9 |
| Total: | 12.0 |




1 week of dispatch



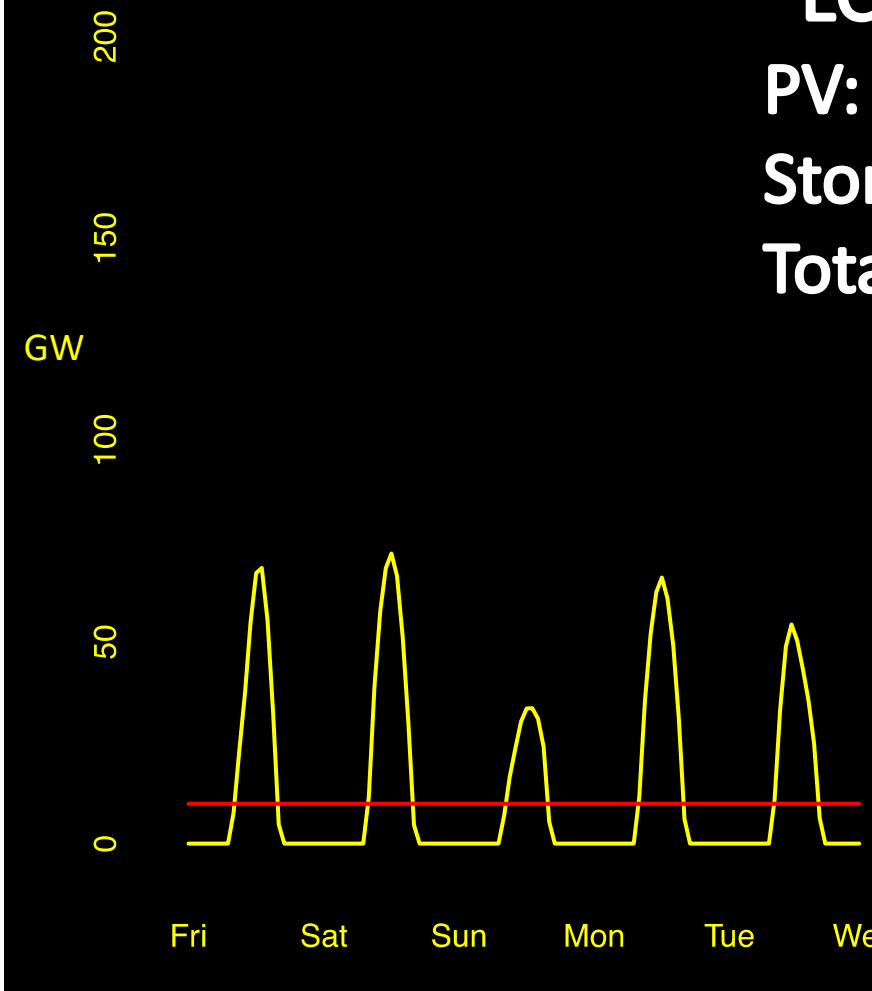

1 year of storage SoC

**2 x oversizing**

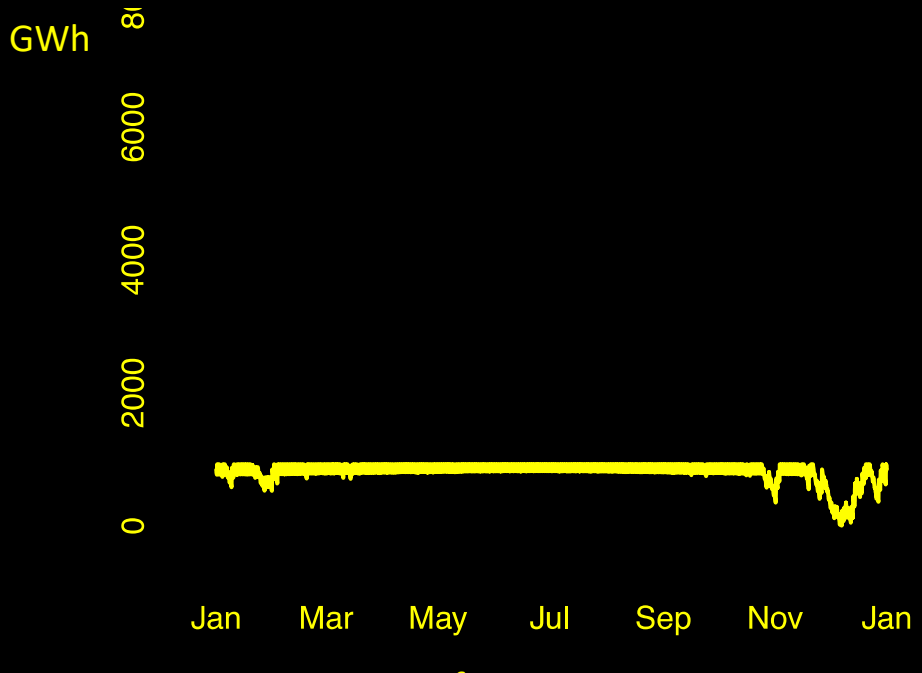
**92.8 % reduction in storage**

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 2.4 |
| Storage: | 5.7 |
| Total: | 8.1 |




1 week of dispatch



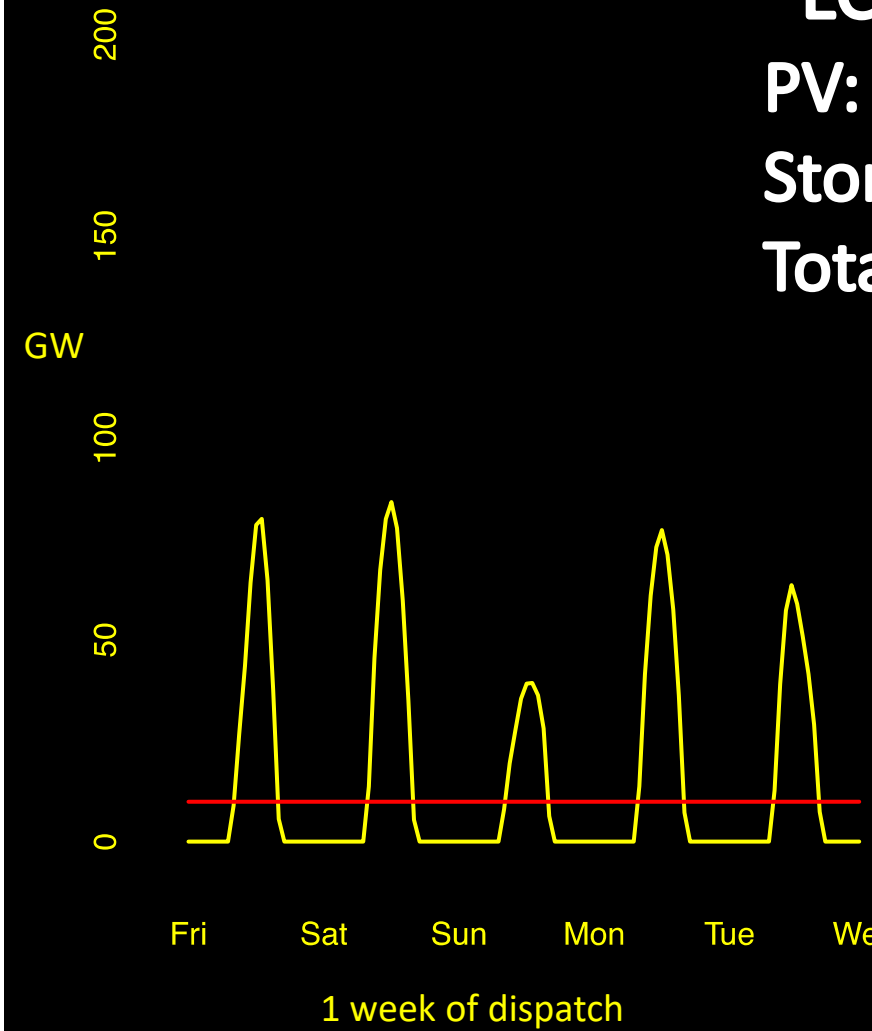

1 year of storage SoC

**2.4 x oversizing**

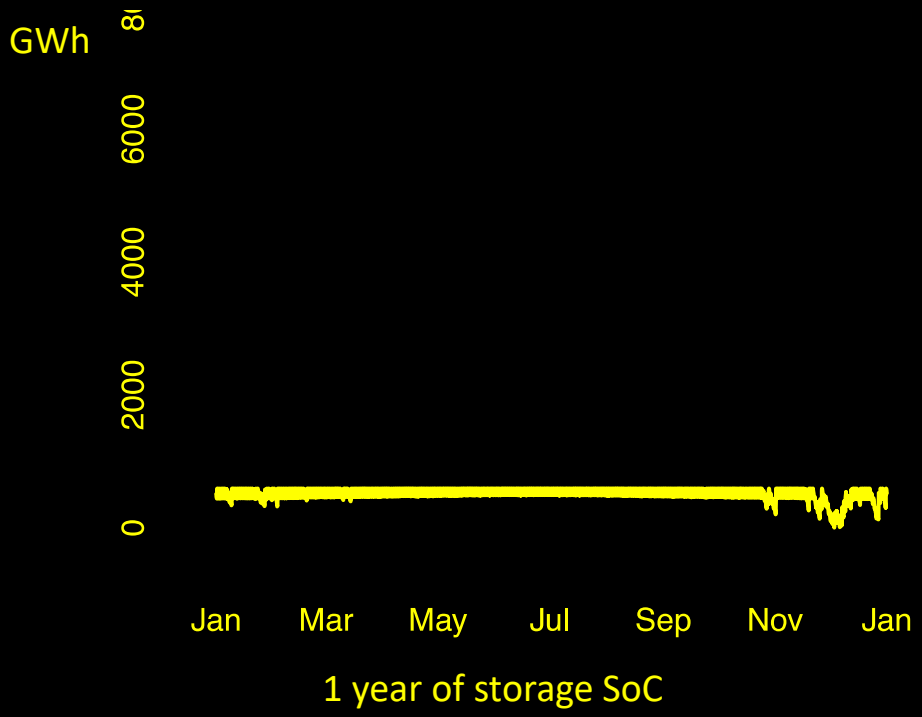
**95.4 % reduction in storage**

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 2.9 |
| Storage: | 3.9 |
| Total: | 6.7 |




1 week of dispatch



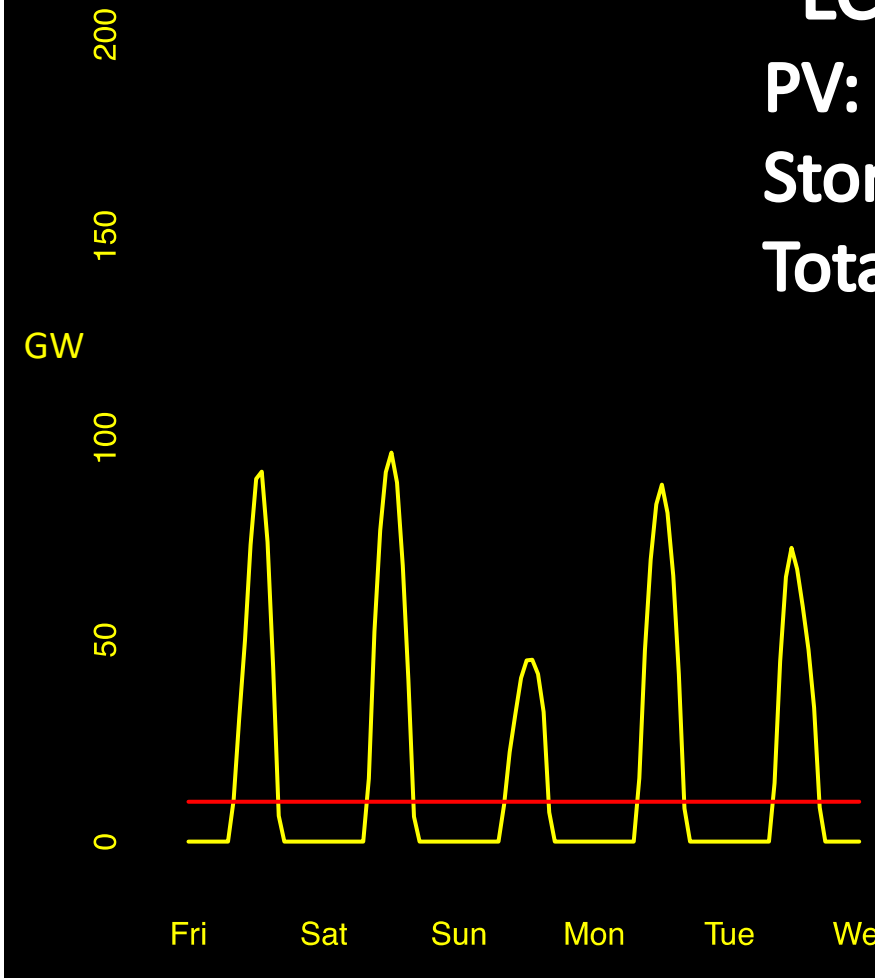

1 year of storage SoC

**2.7 x oversizing**

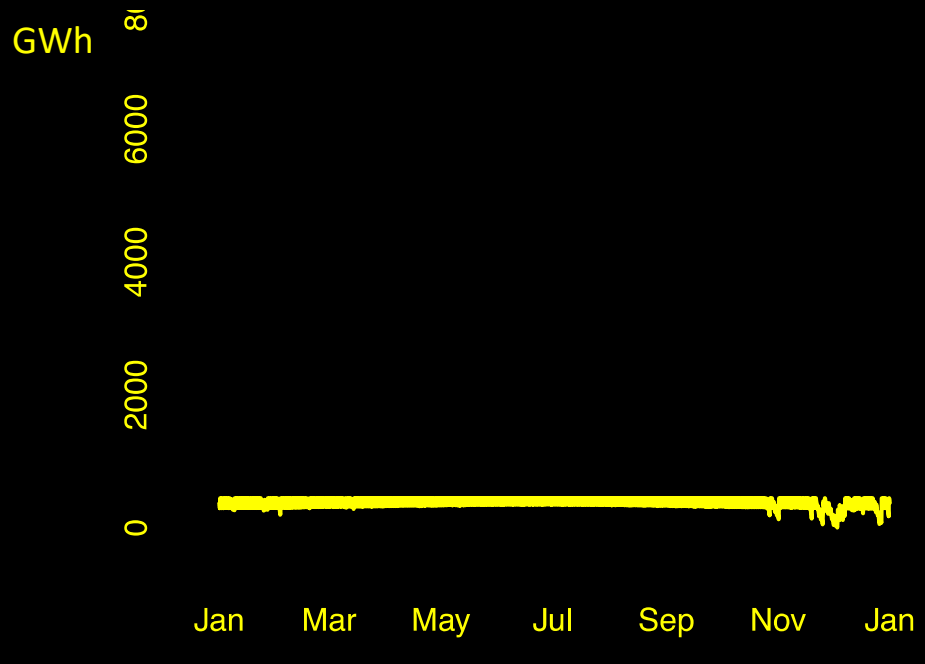
**96.5 % reduction in storage**

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 3.3 |
| Storage: | 3.0 |
| Total: | 6.3 |




1 week of dispatch



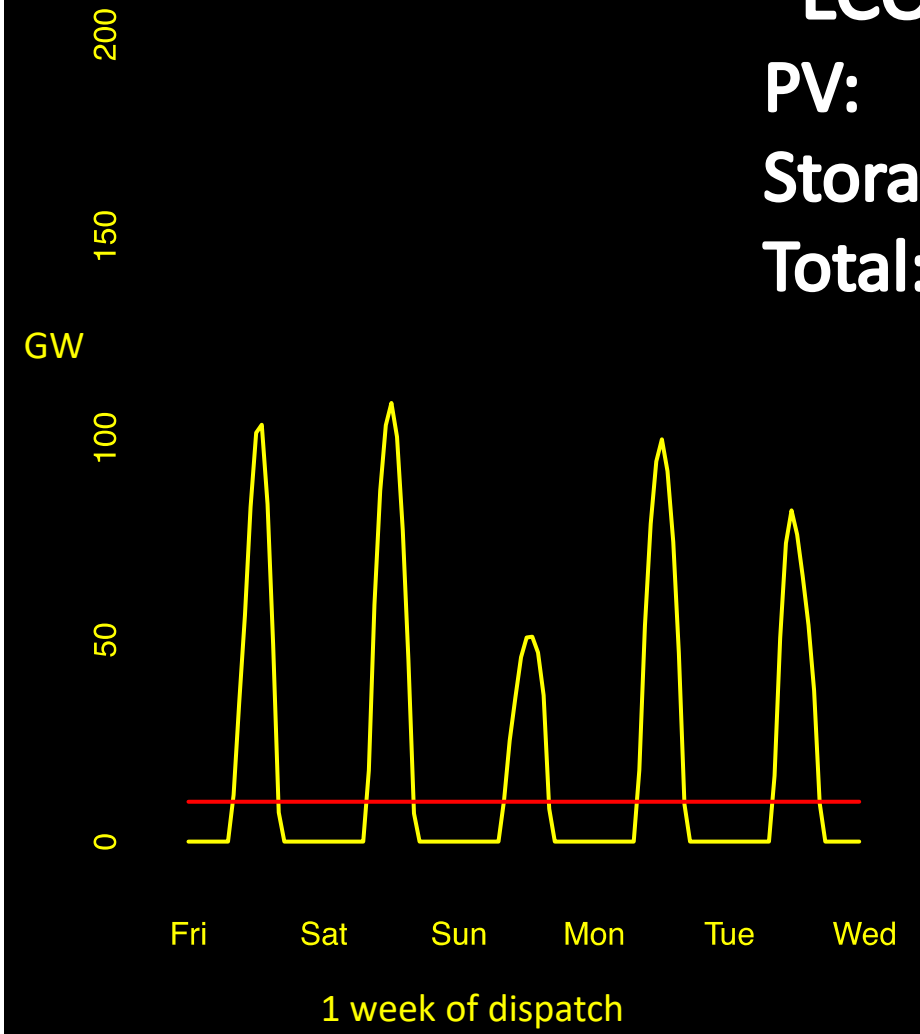

1 year of storage SoC

3.1 x oversizing

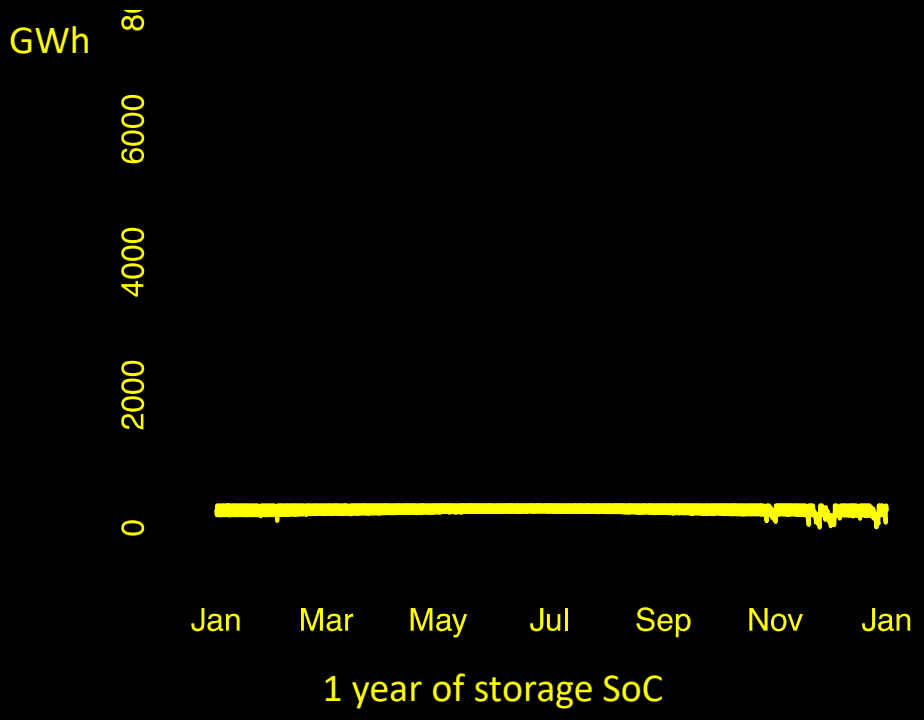
97.4 % reduction in storage

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 3.7 |
| Storage: | 2.4 |
| Total: | 6.1 |




1 week of dispatch



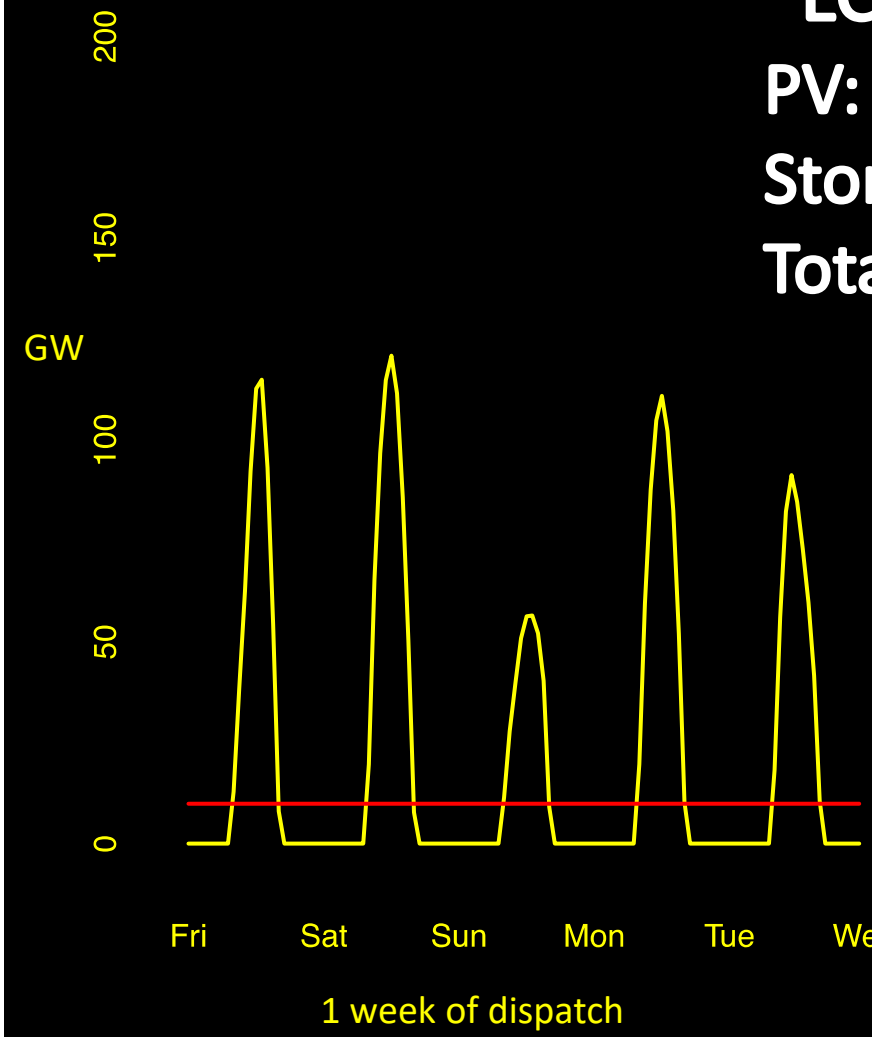

1 year of storage SoC

**3.4 x oversizing**

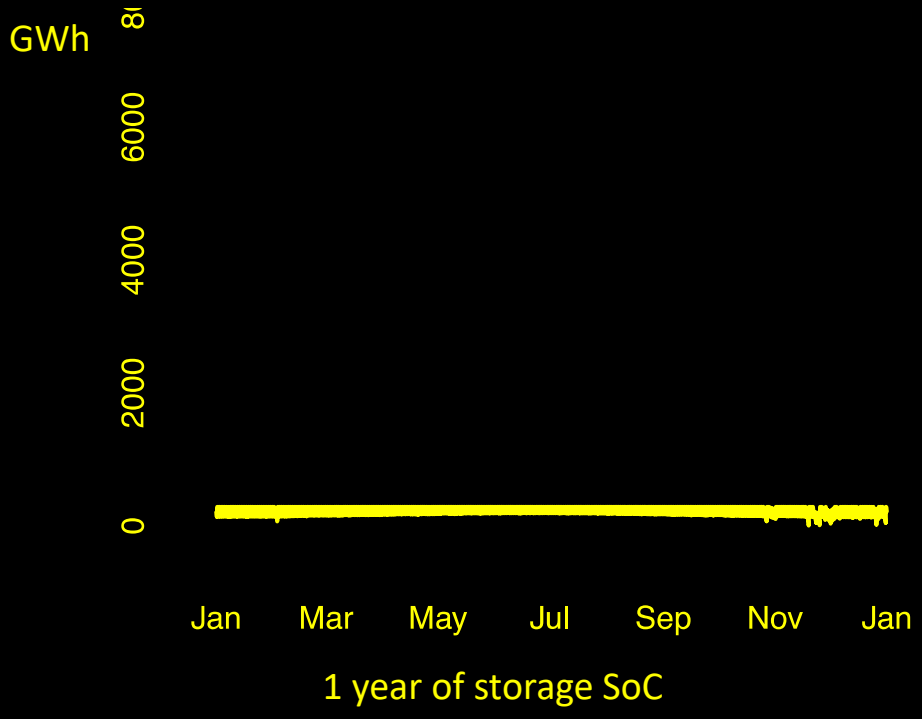
**97.8 % reduction in storage**

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 4.1 |
| Storage: | 2.1 |
| Total: | 6.2 |




1 week of dispatch



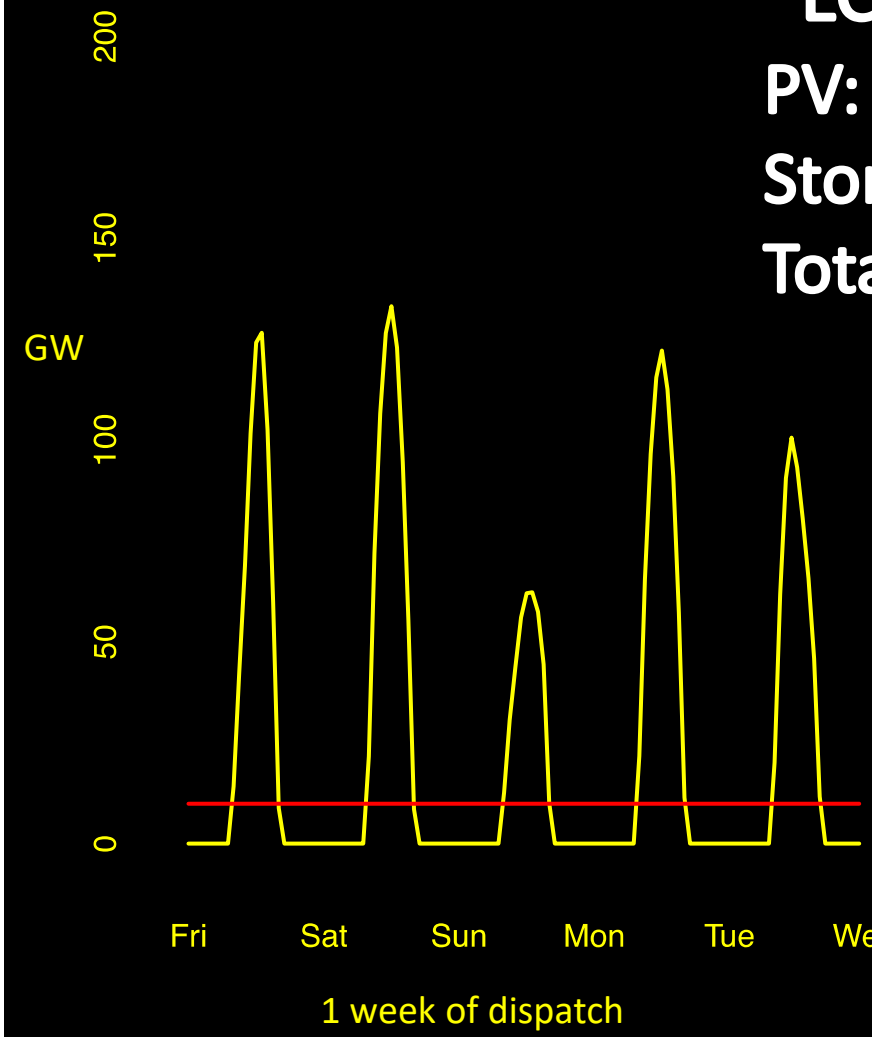

1 year of storage SoC

3.8 x oversizing

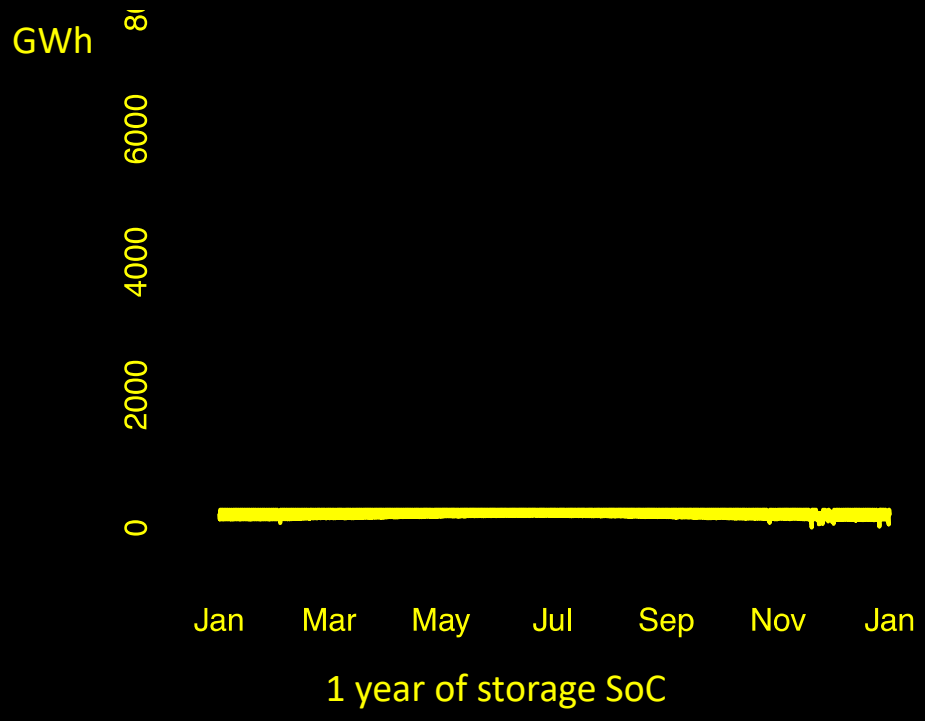
97.9 % reduction in storage

# LCOE (¢/kWh)

| | |
|---|---|
| PV: | 4.5 |
| Storage: | 2.1 |
| Total: | 6.6 |




1 week of dispatch



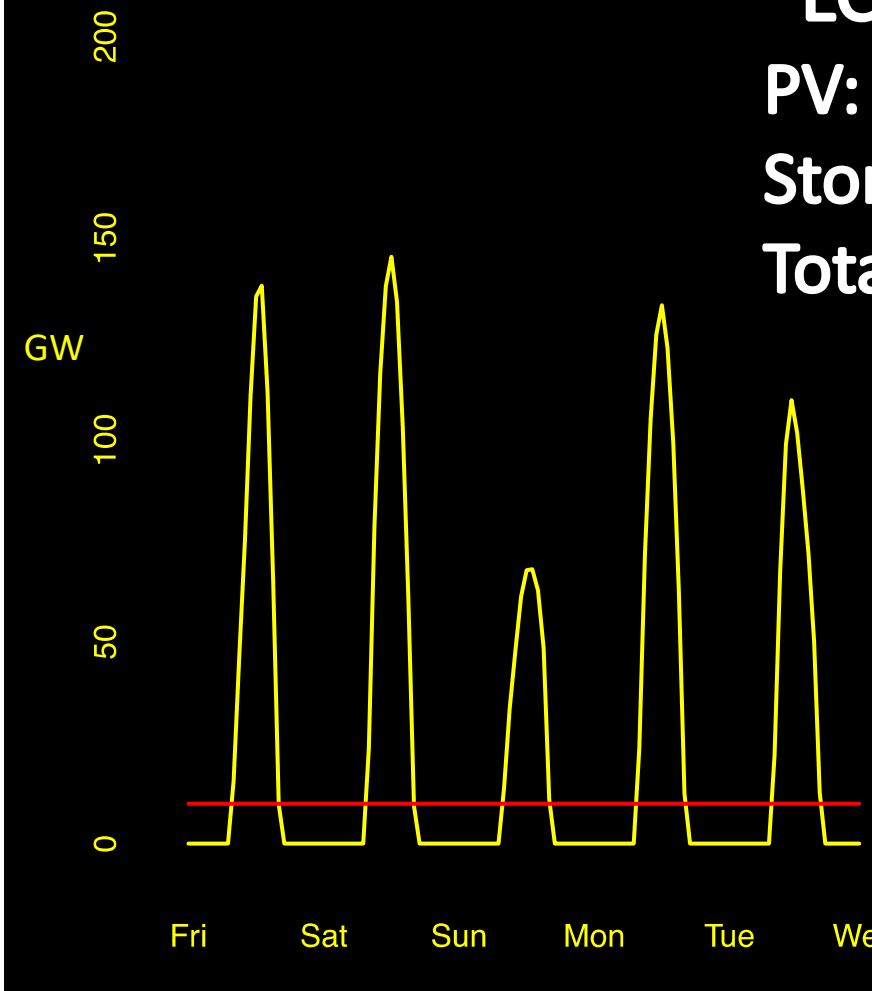

1 year of storage SoC

**4.1 x oversizing**

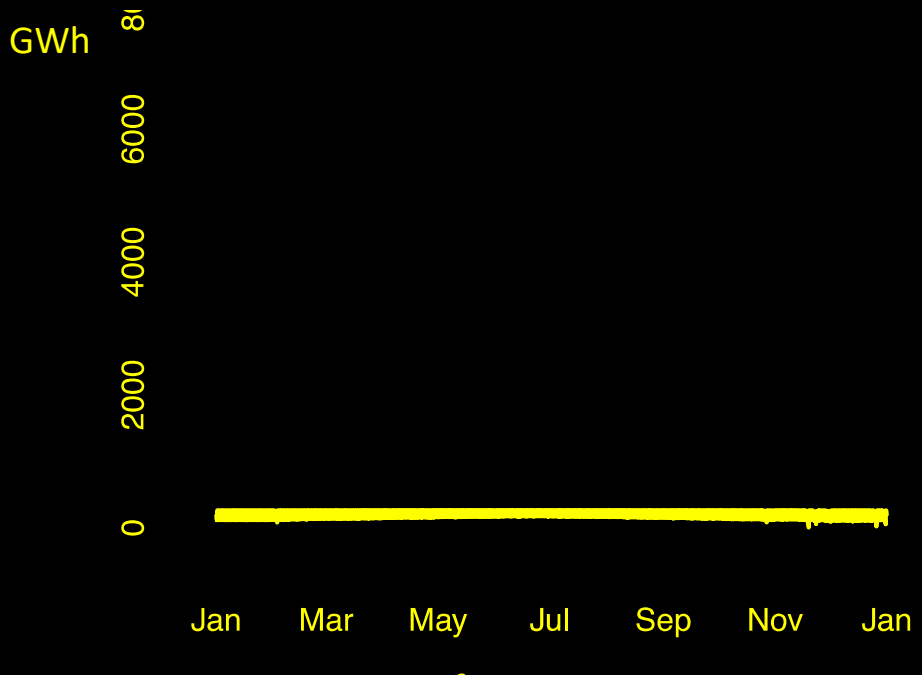
**97.9 % reduction in storage**

# LCOE (¢/kWh)

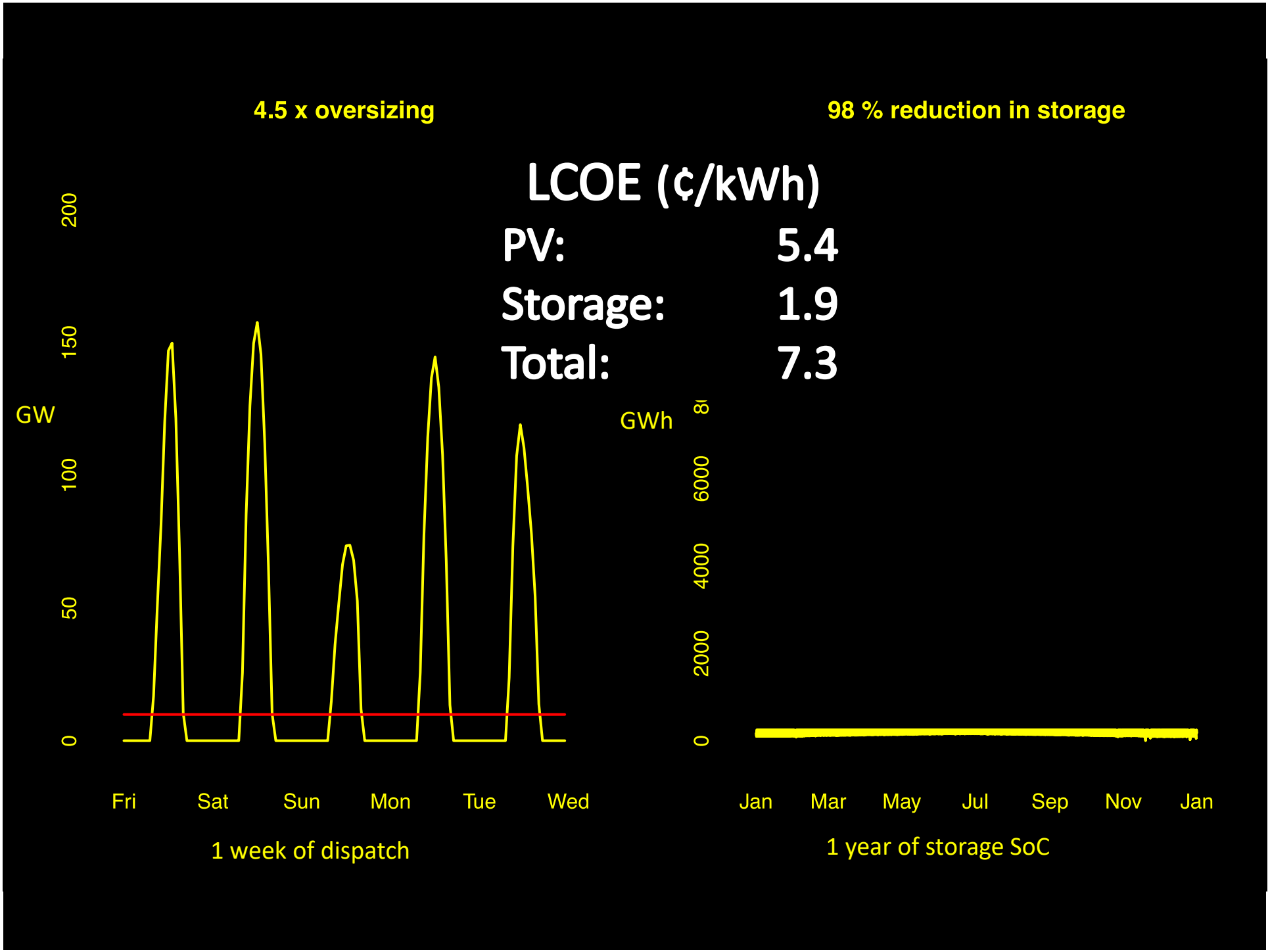
| | |
|---|---|
| PV: | 4.9 |
| Storage: | 2.0 |
| Total: | 6.9 |

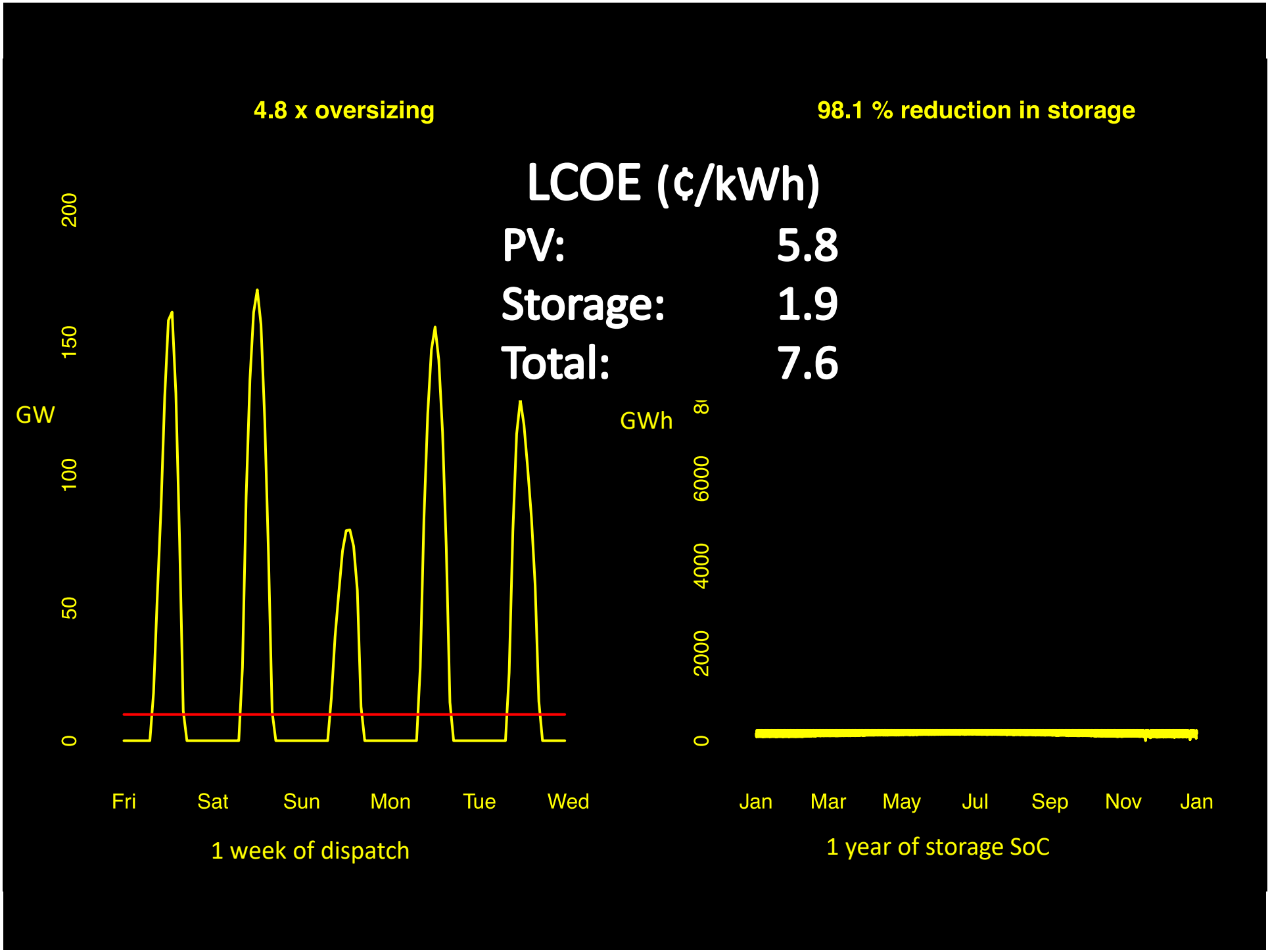


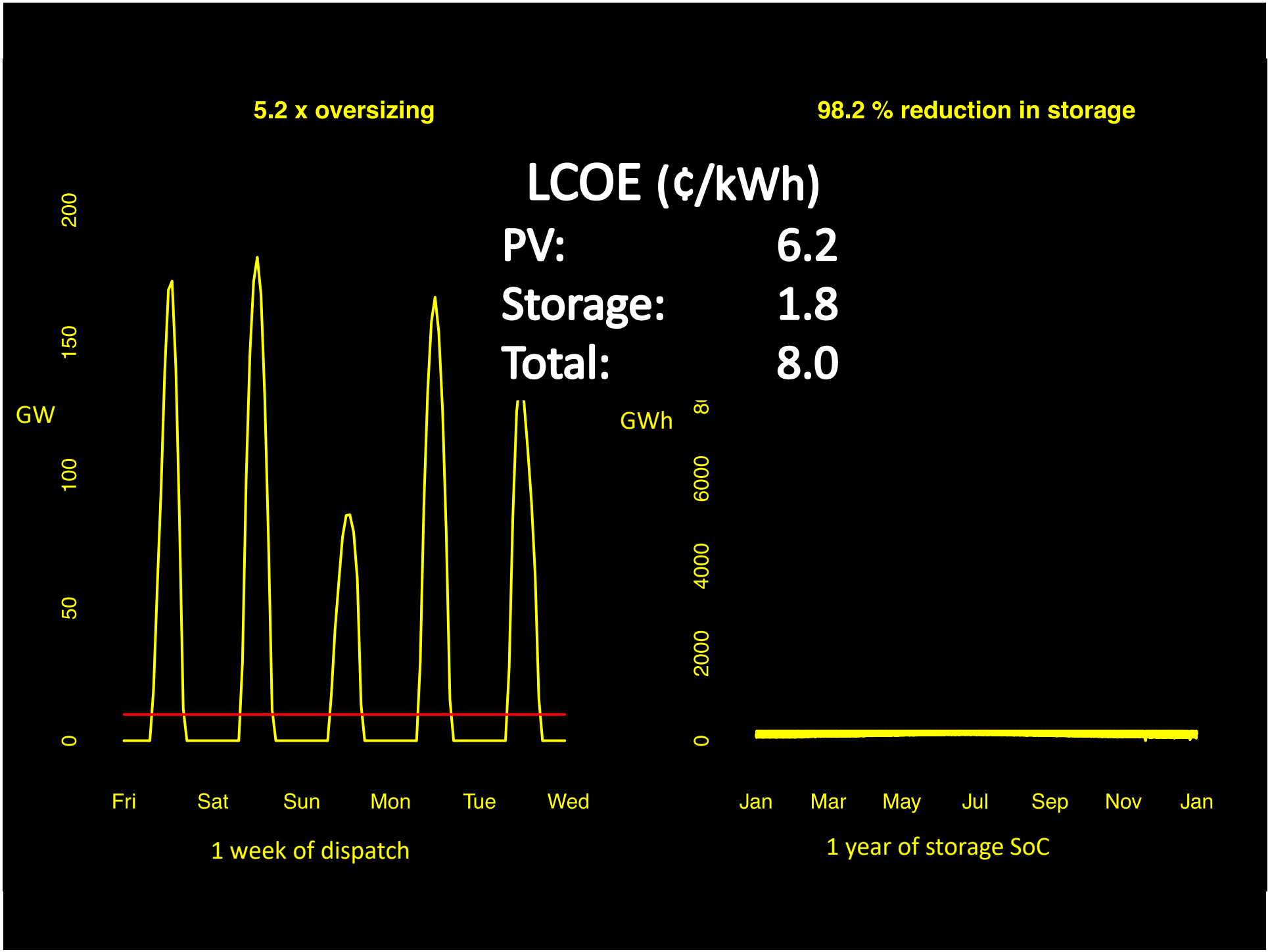

1 week of dispatch

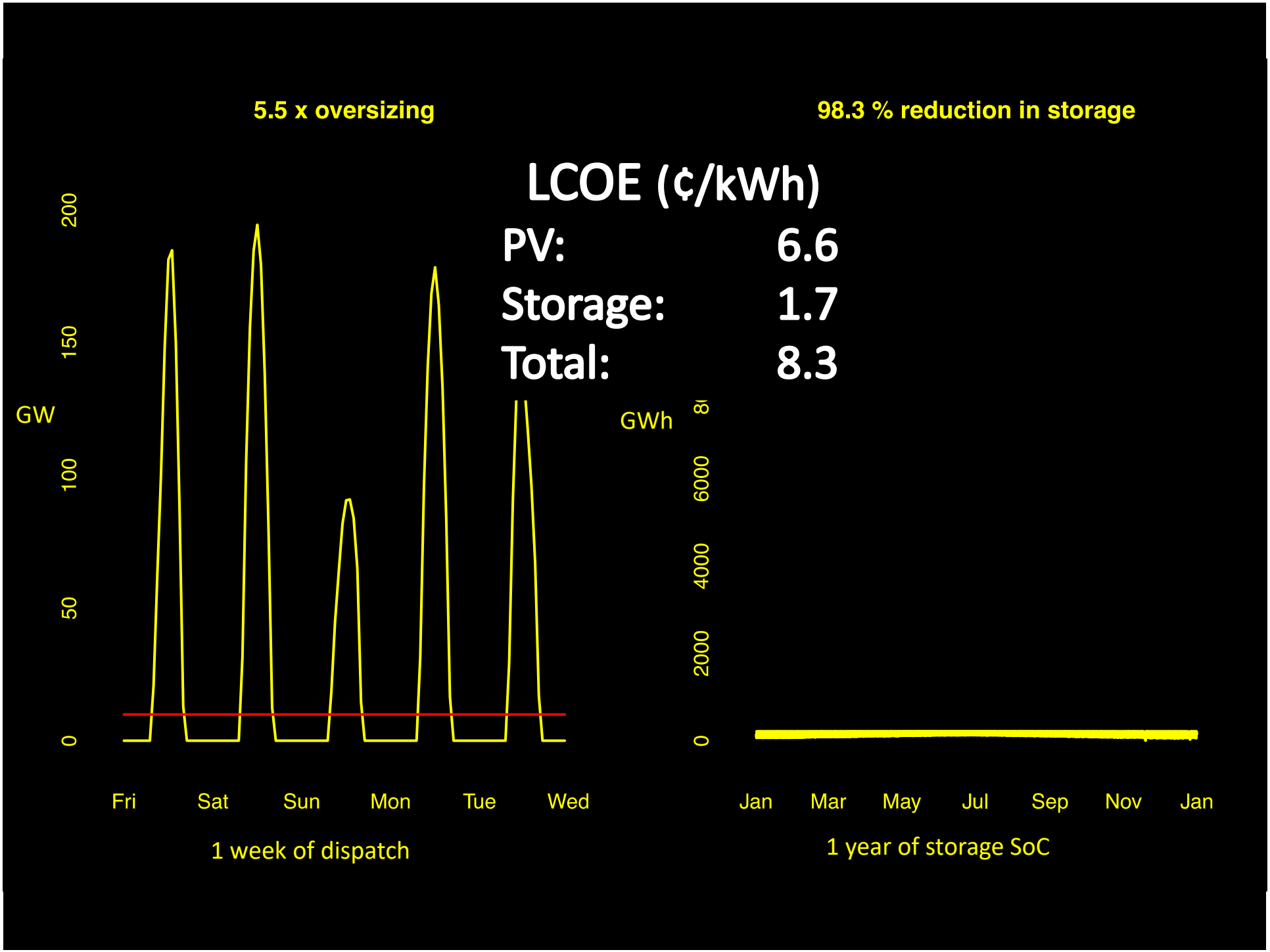


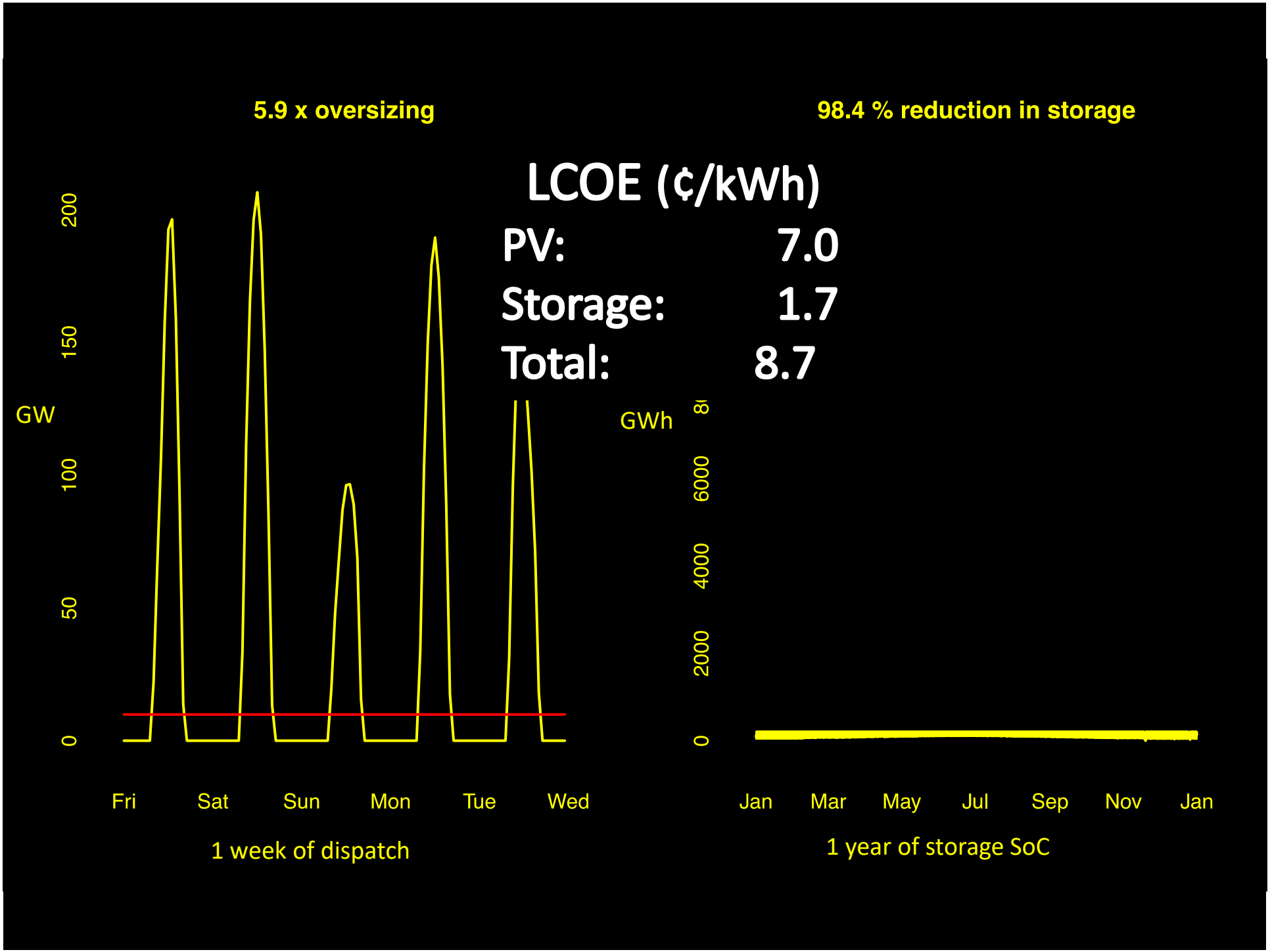

1 year of storage SoC

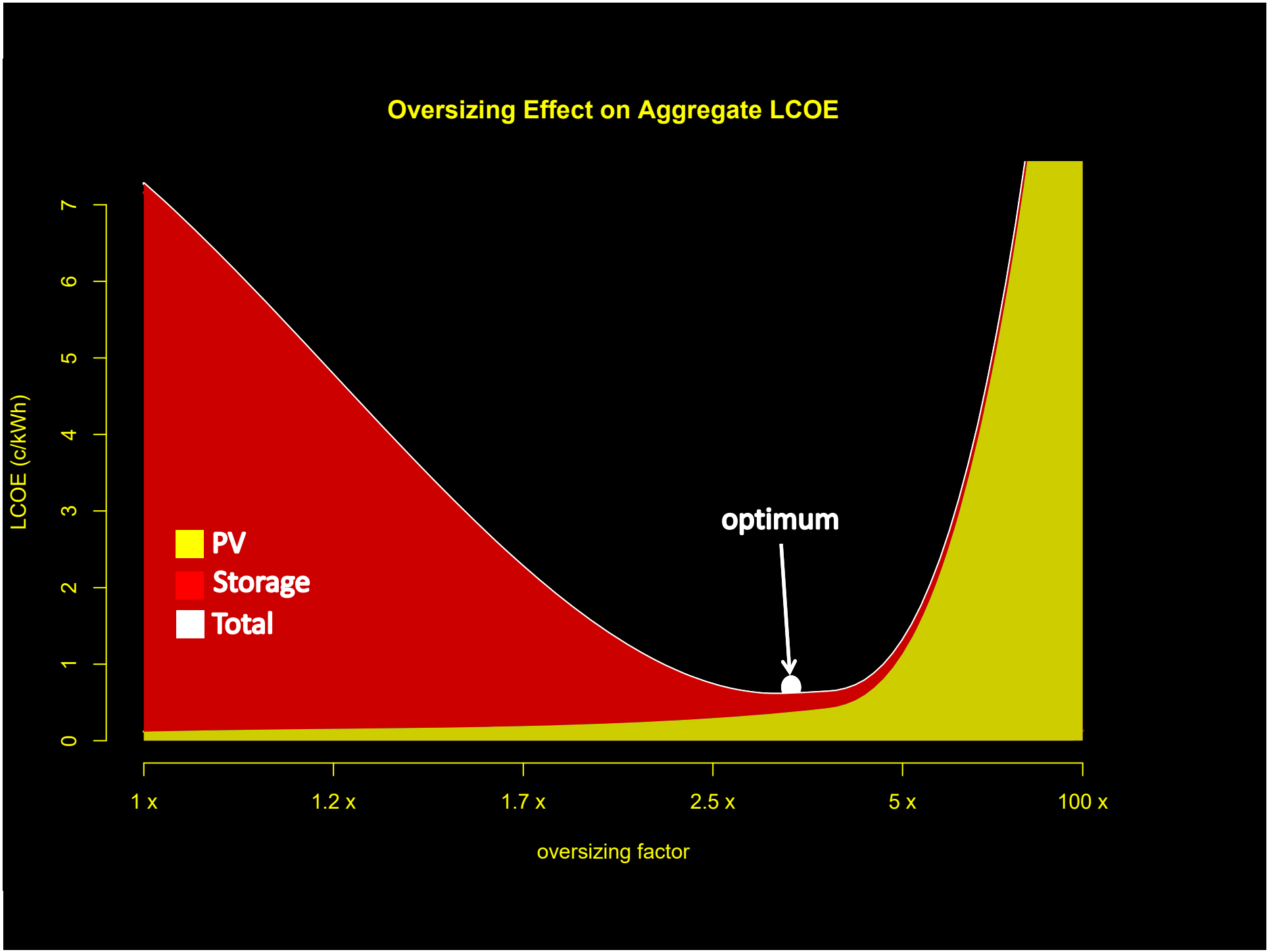

4.5 x oversizing
98 % reduction in storage
LCOE (¢/kWh)
PV: 5.4
Storage: 1.9
Total: 7.3
GW
0
50
100
150
200
Fri
Sat
Sun
Mon
Tue
Wed
1 week of dispatch
GWh
0
2000
4000
6000
8
Jan
Mar
May
Jul
Sep
Nov
Jan
1 year of storage SoC


4.8 x oversizing
98.1 % reduction in storage
LCOE (¢/kWh)
PV: 5.8
Storage: 1.9
Total: 7.6
GW
200
150
100
50
0
Fri
Sat
Sun
Mon
Tue
Wed
1 week of dispatch
GWh
8
6000
4000
2000
0
Jan
Mar
May
Jul
Sep
Nov
Jan
1 year of storage SoC

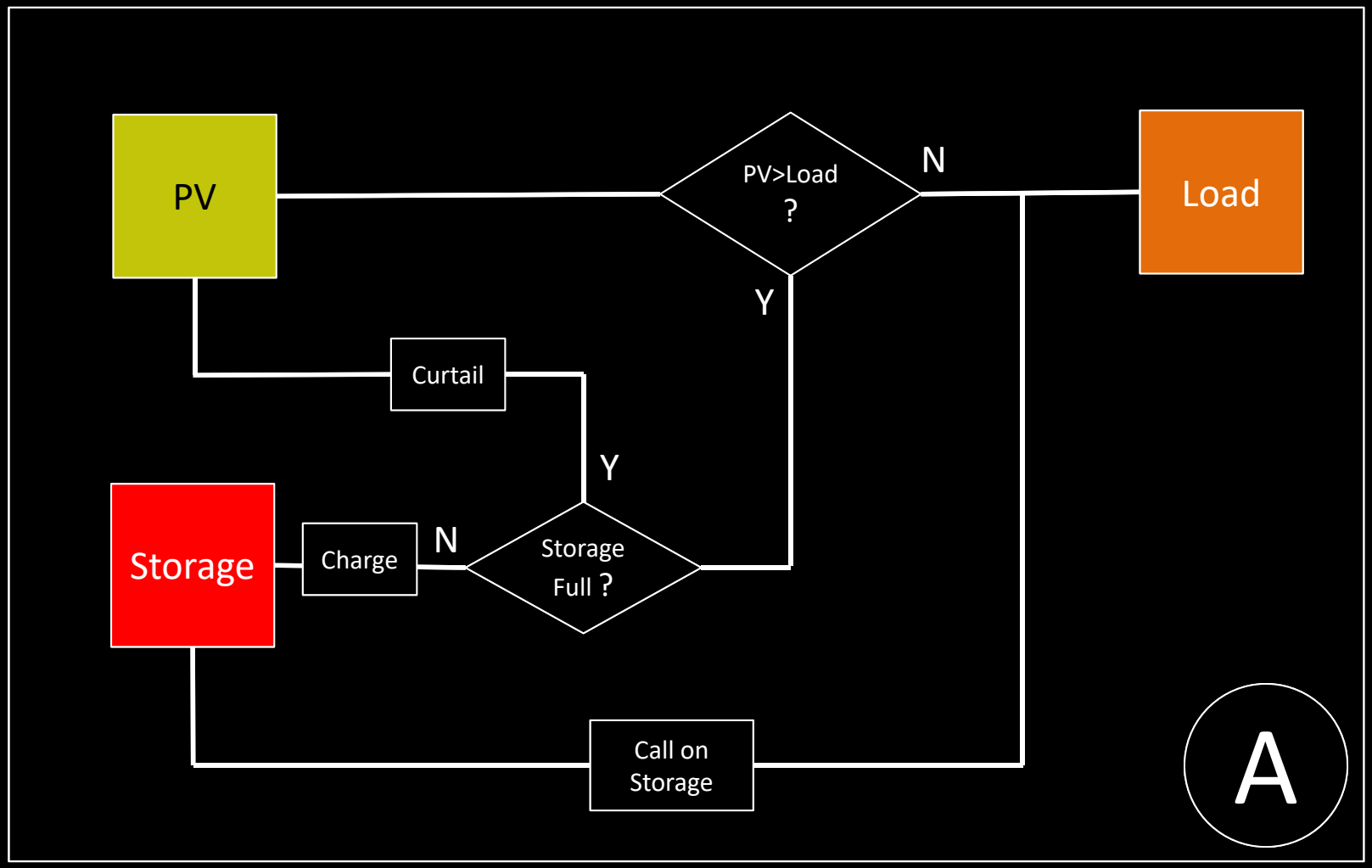

5.2 x oversizing
98.2 % reduction in storage
LCOE (¢/kWh)
PV: 6.2
Storage: 1.8
Total: 8.0
GW
200
150
100
50
0
Fri
Sat
Sun
Mon
Tue
Wed
1 week of dispatch
GWh
8
6000
4000
2000
0
Jan
Mar
May
Jul
Sep
Nov
Jan
1 year of storage SoC


5.5 x oversizing
98.3 % reduction in storage
LCOE (¢/kWh)
PV: 6.6
Storage: 1.7
Total: 8.3
GW
0
50
100
150
200
Fri
Sat
Sun
Mon
Tue
Wed
1 week of dispatch
GWh
0
2000
4000
6000
8
Jan
Mar
May
Jul
Sep
Nov
Jan
1 year of storage SoC

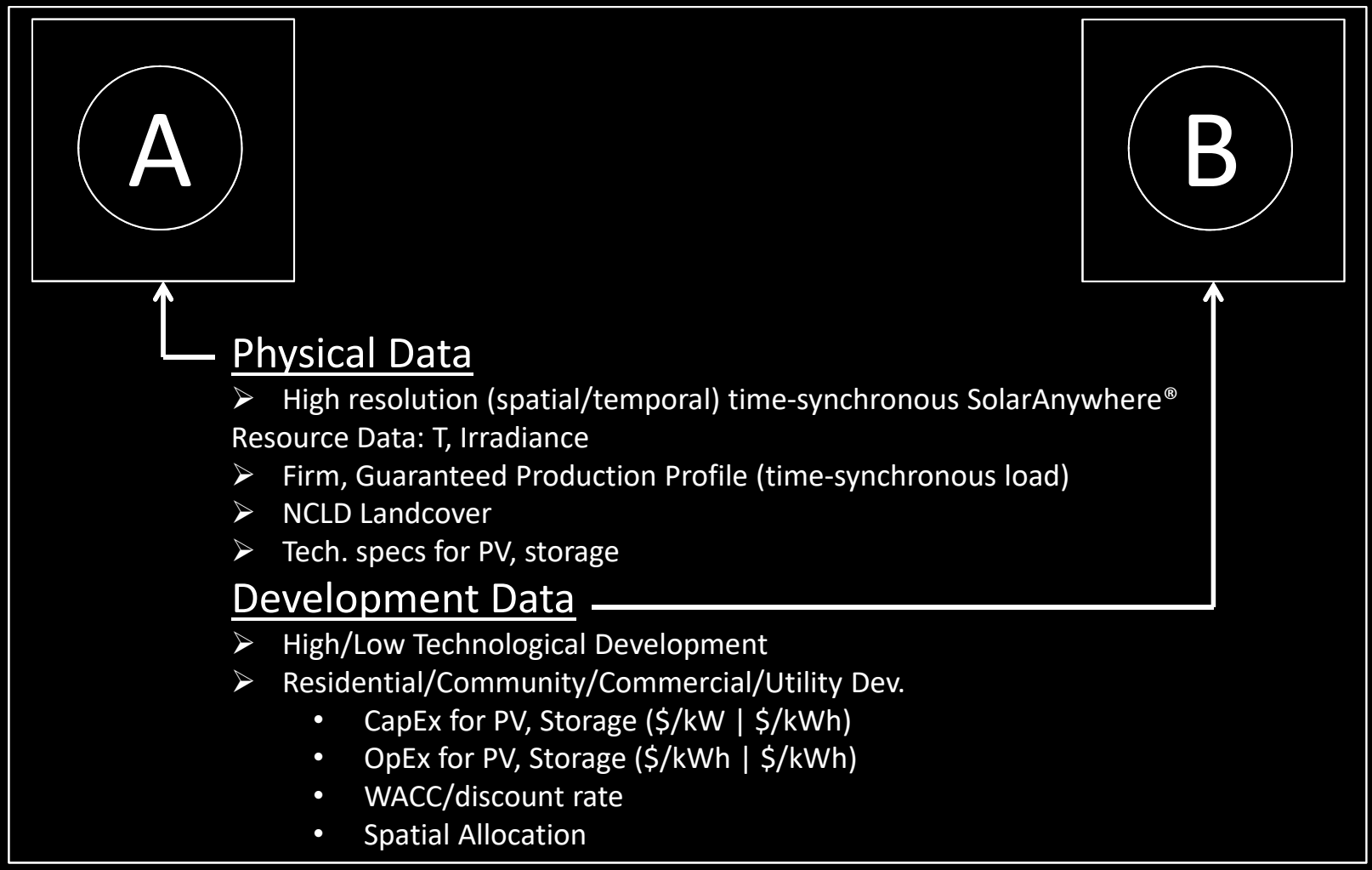

5.9 x oversizing
98.4 % reduction in storage
LCOE (¢/kWh)
PV: 7.0
Storage: 1.7
Total: 8.7
GW
0
50
100
150
200
Fri
Sat
Sun
Mon
Tue
Wed
1 week of dispatch
GWh
0
2000
4000
6000
Jan
Mar
May
Jul
Sep
Nov
Jan
1 year of storage SoC


Oversizing Effect on Aggregate LCOE
LCOE (c/kWh)
0
1
2
3
4
5
6
7
PV
Storage
Total
optimum
1 x
1.2 x
1.7 x
2.5 x
5 x
100 x
oversizing factor

# Simplified PV/Storage Dispatch Schema

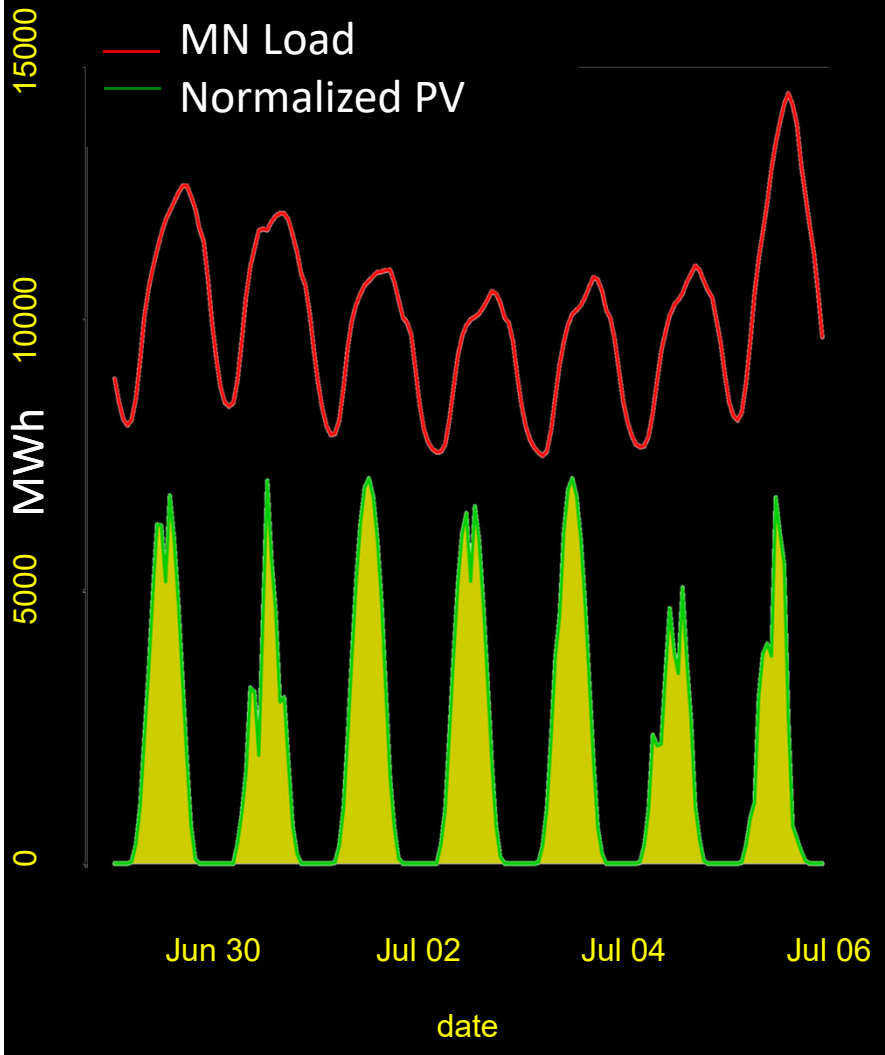


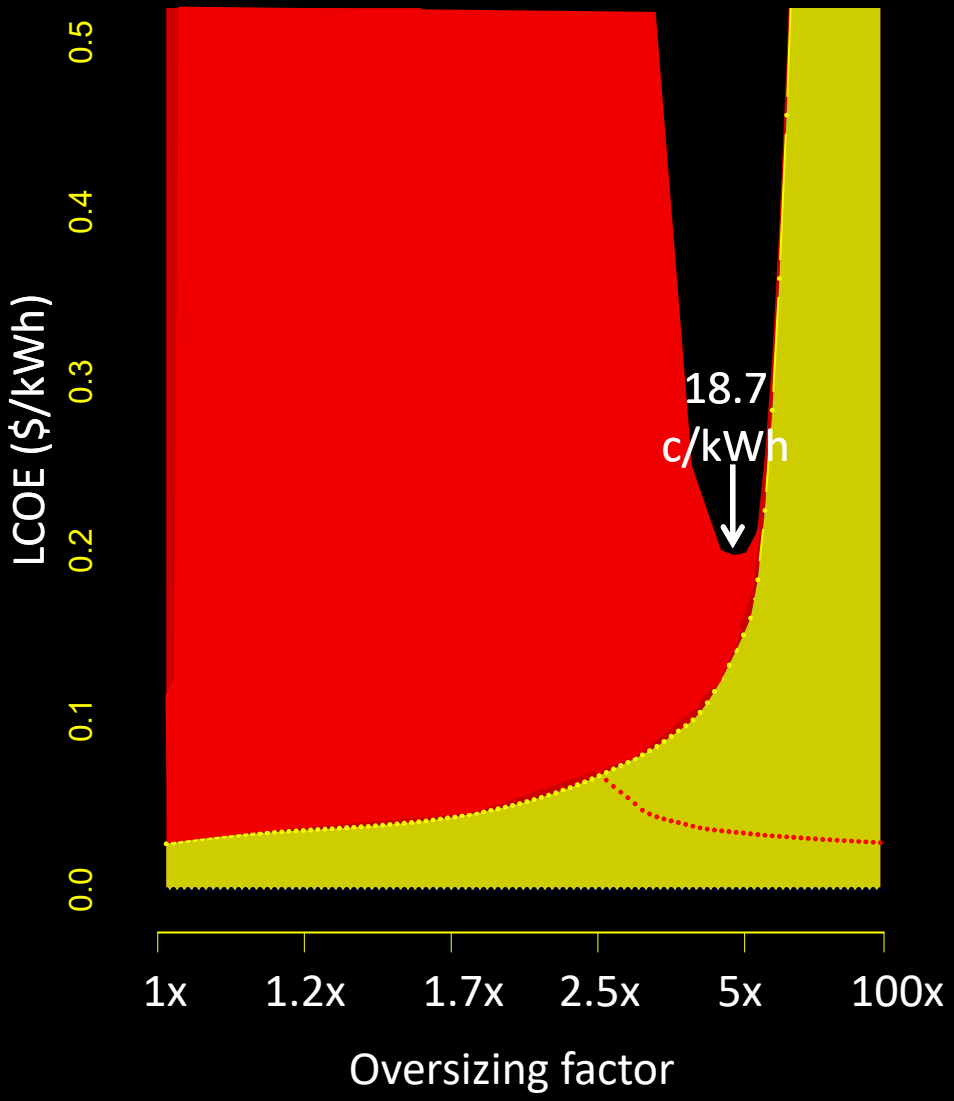
# Modeling Inputs




Boston Scientific
cee
Center for Energy and Environment
CUB
Citizens Utility Board
Empowering Minnesota Consumers
The City of Duluth Minnesota
Saint Paul
Clean Energy Resource Teams
Clean Grid Alliance
Delivering Midwest Renewable Energy
Clean Power Research
EPRI
Electric Power Research Institute
ESIG
Energy Systems Integration Group
Fresh Energy
IPS Solar
MN SOLAR PATHWAYS
illuminating pathways to 10% solar
LREC
Metropolitan Council
Alliance
MMUA
Minnesota Municipal Utilities Association
minnesota power
An Allete Company
MnSEIA
MISO
NREL
National Renewable Energy Laboratory
Otter Tail Power Company
res
power for good
rpu
we pledge, we deliver
smarter grid solutions
Target
Xcel Energy

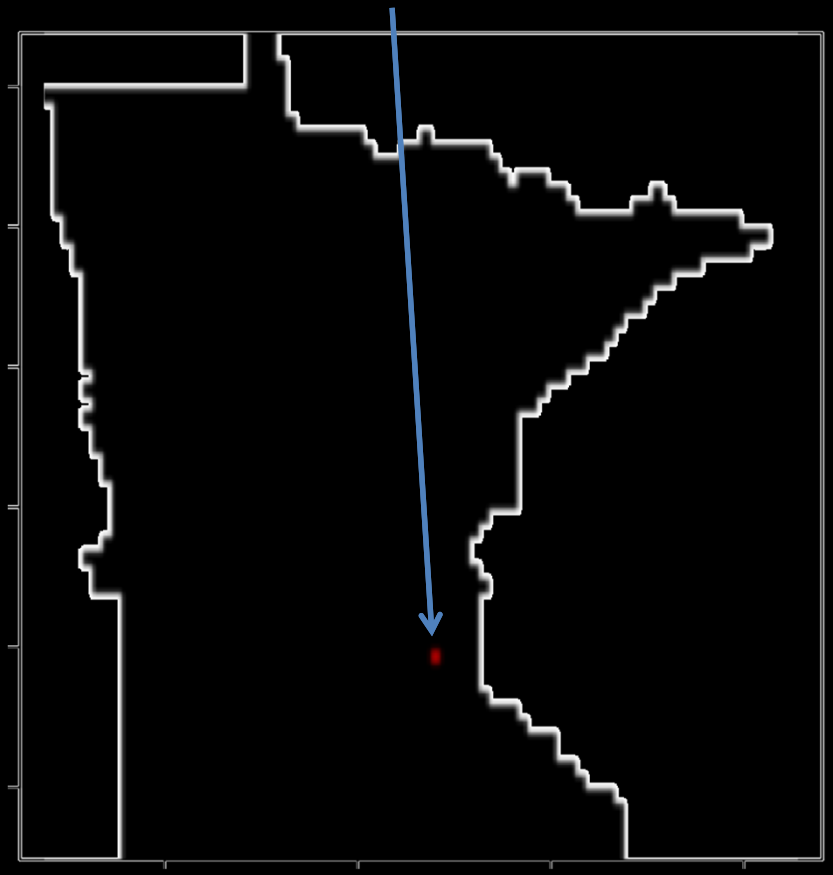
PV + Storage Meeting 100% of Hourly Load in MN, Utility-scale-led, Low Technological Development in 2050, WACC of 3% *single point*.



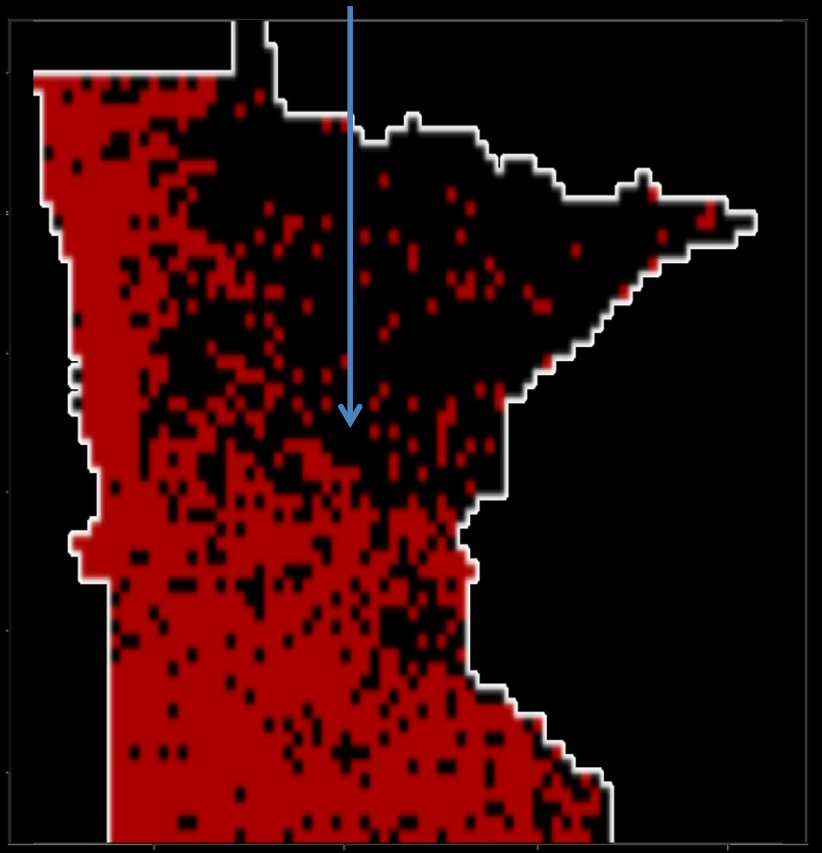




Non-official results

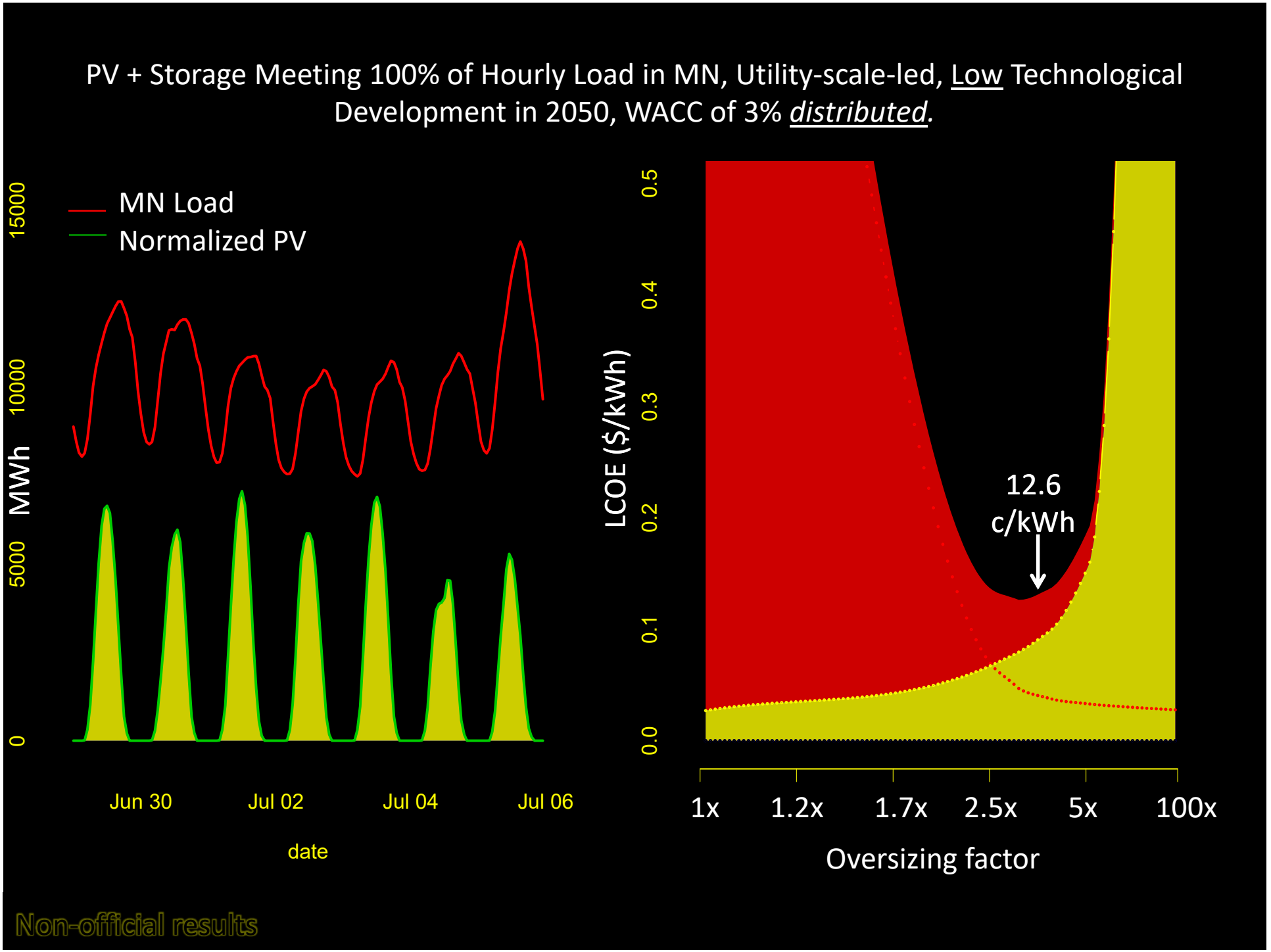
PV Allocated just in Minneapolis



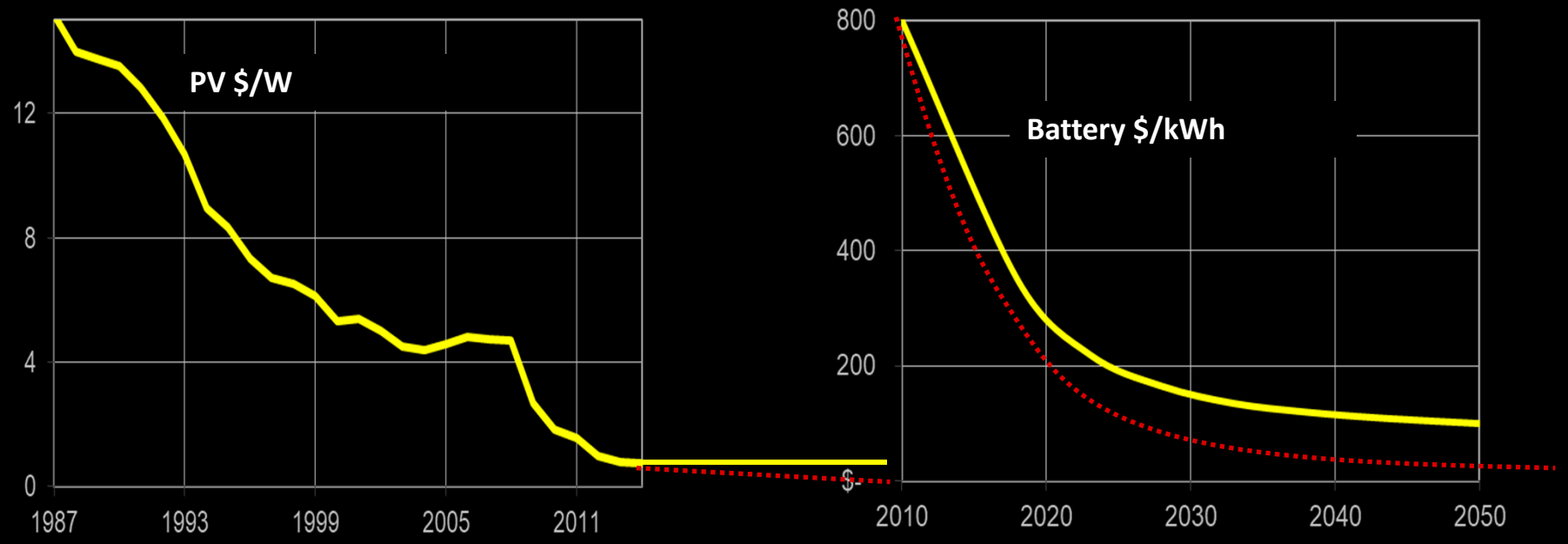
PV Spread more evenly (yet still Avoiding sensitive landcover)

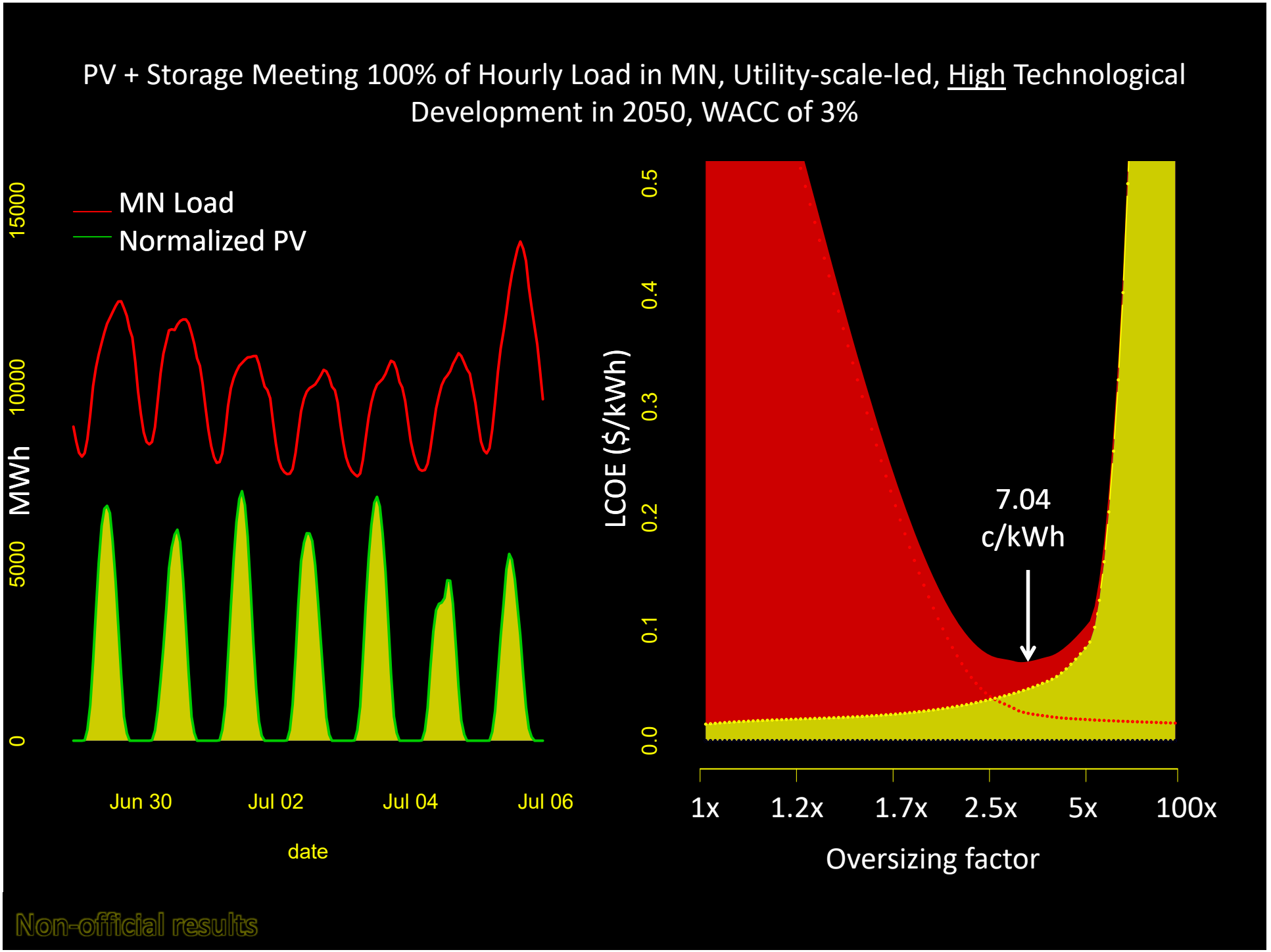


Geographic Dispersion Has an Effect on Cost

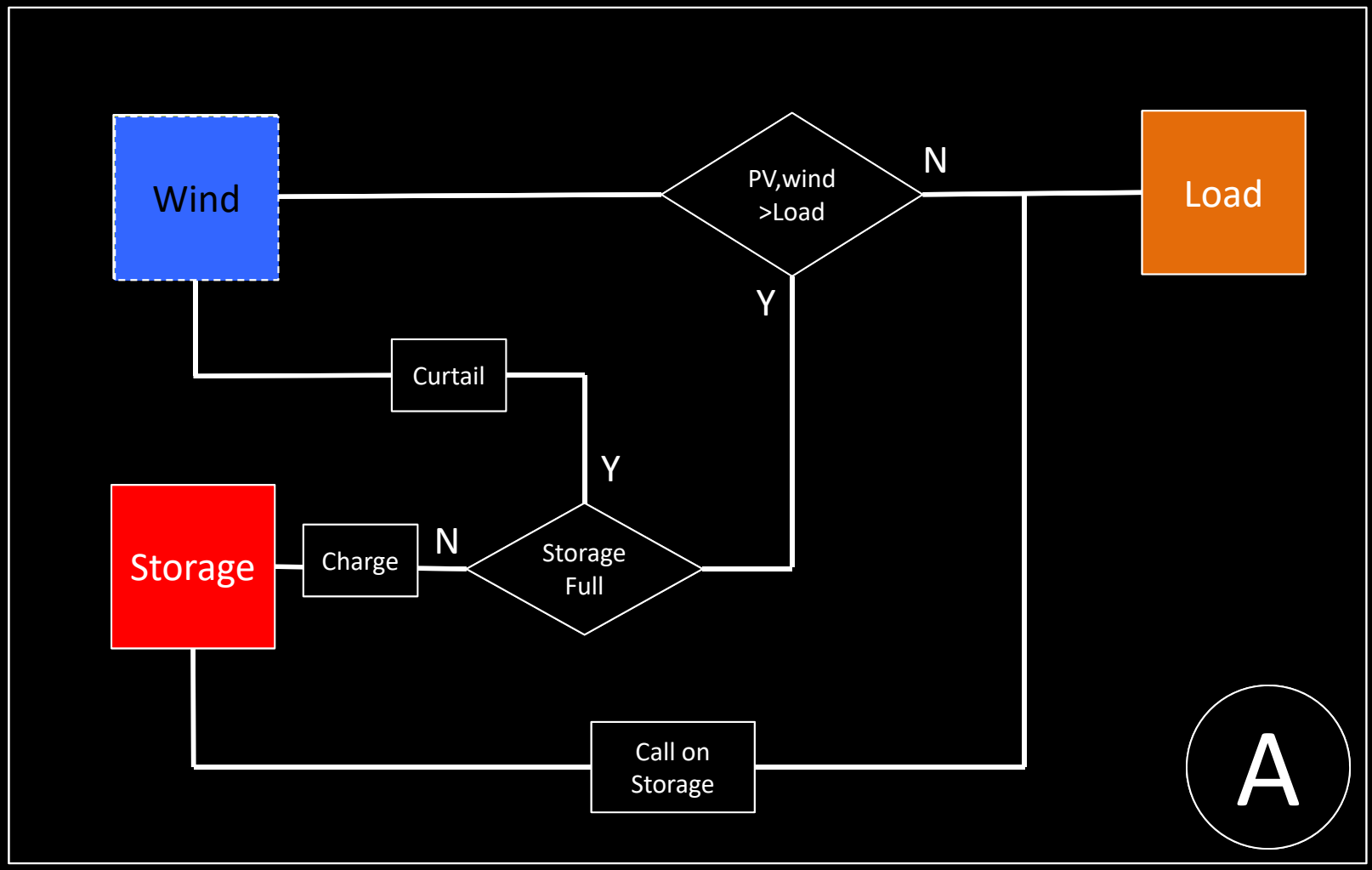

PV + Storage Meeting 100% of Hourly Load in MN, Utility-scale-led, Low Technological Development in 2050, WACC of 3% distributed.
MN Load
Normalized PV
15000
10000
5000
0
MWh
Jun 30
Jul 02
Jul 04
Jul 06
date
LCOE ($/kWh)
0.5
0.4
0.3
0.2
0.1
0.0
12.6
c/kWh
1x
1.2x
1.7x
2.5x
5x
100x
Oversizing factor
Non-official results

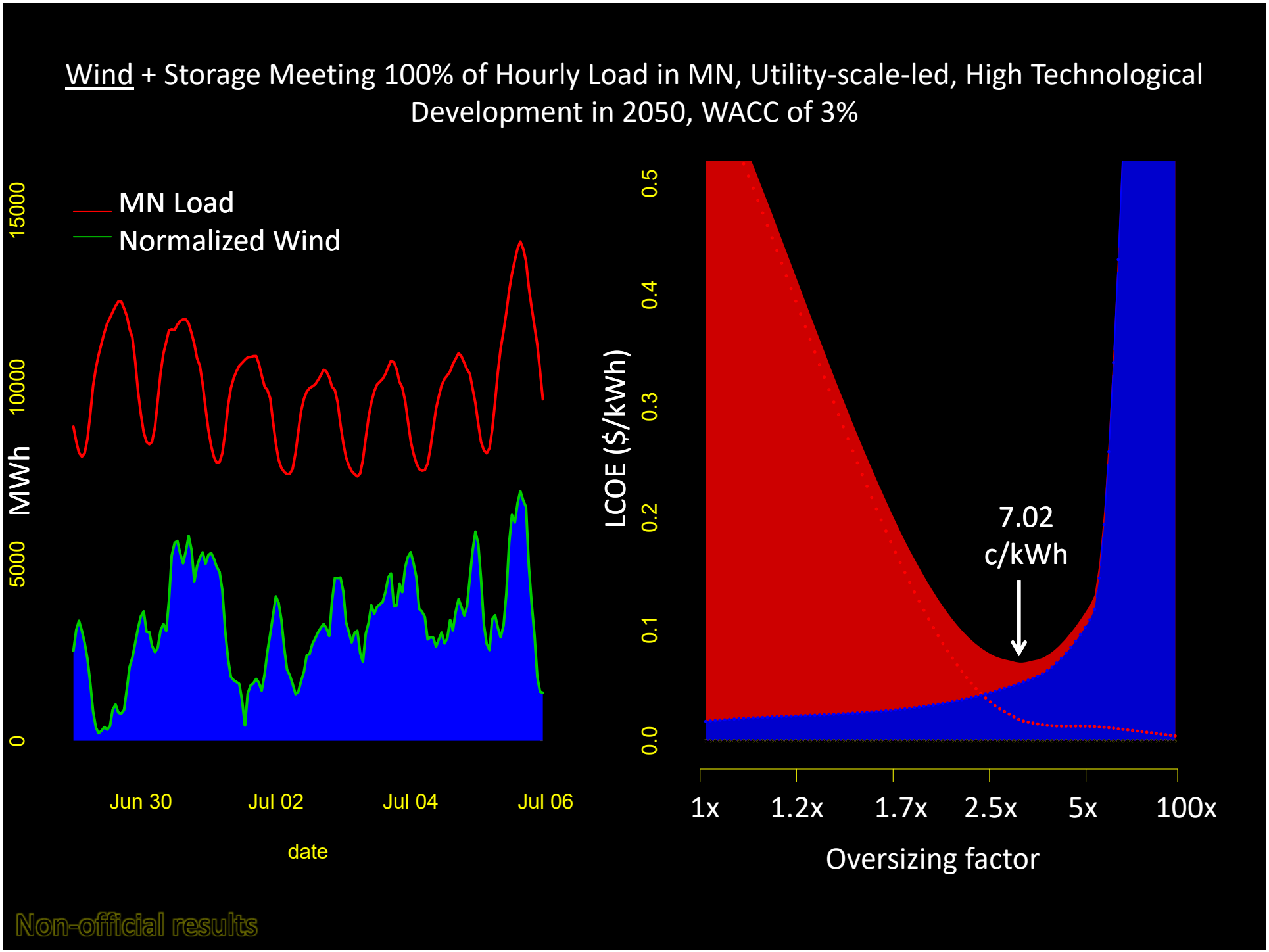
## …As the degree of technological development




PV + Storage Meeting 100% of Hourly Load in MN, Utility-scale-led, High Technological Development in 2050, WACC of 3%
MN Load
Normalized PV
MWh
15000
10000
5000
0
Jun 30
Jul 02
Jul 04
Jul 06
date
LCOE ($/kWh)
0.5
0.4
0.3
0.2
0.1
0.0
7.04
c/kWh
1x
1.2x
1.7x
2.5x
5x
100x
Oversizing factor
Non-official results

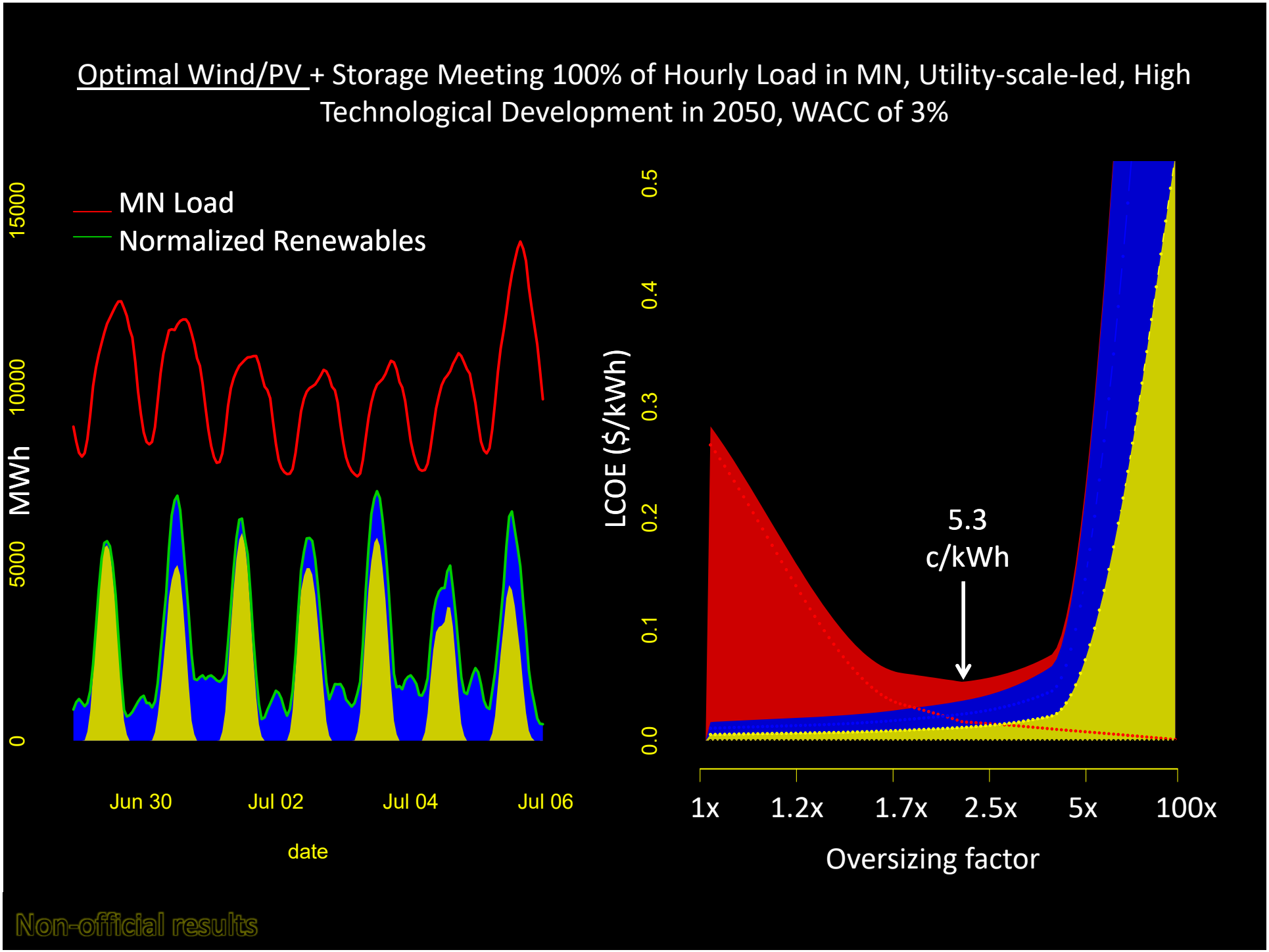
# Simplified PV/Storage Dispatch Schema



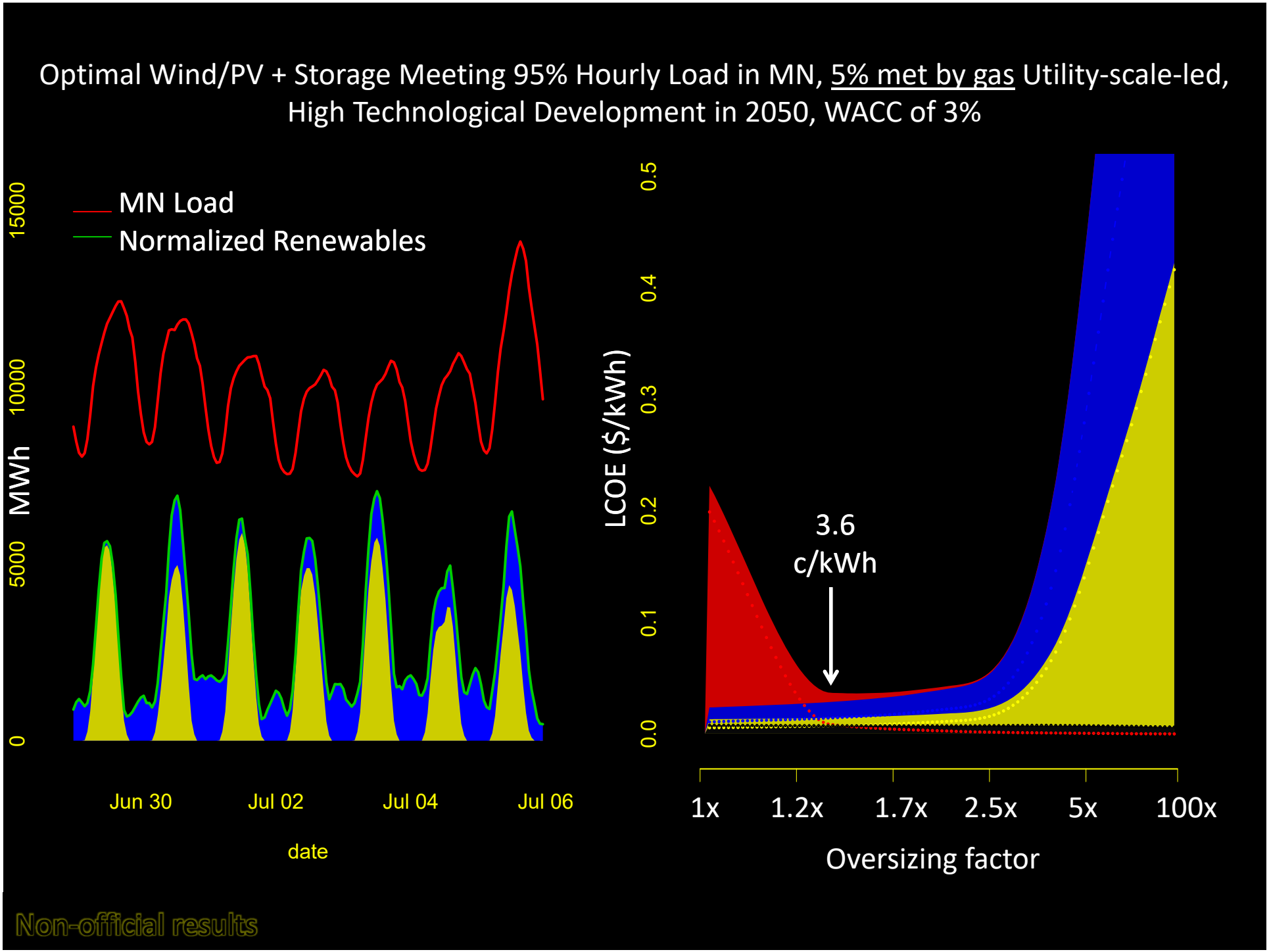

Wind + Storage Meeting 100% of Hourly Load in MN, Utility-scale-led, High Technological Development in 2050, WACC of 3%
MN Load
Normalized Wind
15000
10000
5000
0
MWh
Jun 30
Jul 02
Jul 04
Jul 06
date
LCOE ($/kWh)
0.5
0.4
0.3
0.2
0.1
0.0
7.02
c/kWh
1x
1.2x
1.7x
2.5x
5x
100x
Oversizing factor
Non-official results

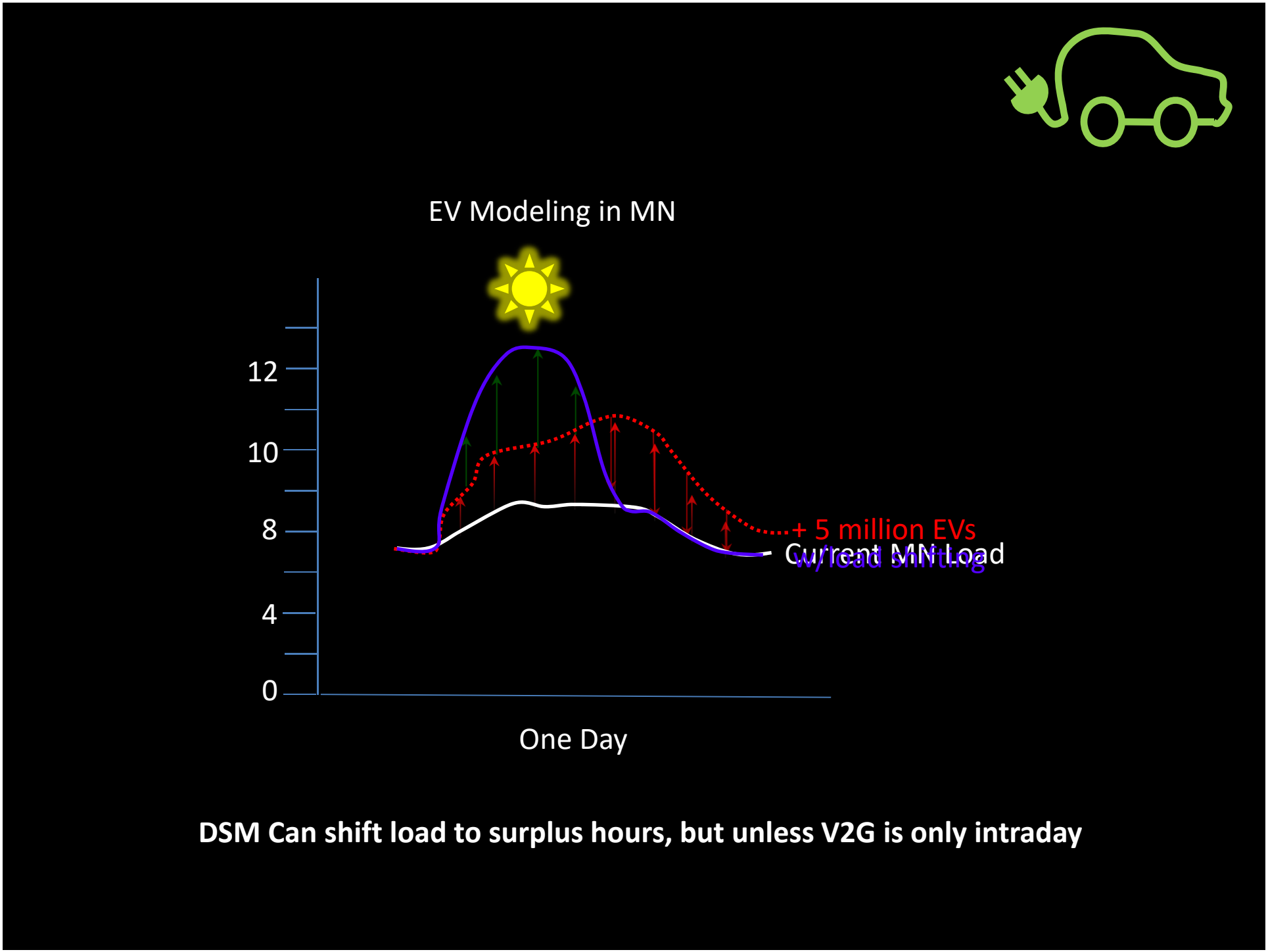
**Costs can be reduced further by blending the wind and solar resources**

**…where anticorrelated**


Optimal Wind/PV + Storage Meeting 100% of Hourly Load in MN, Utility-scale-led, High Technological Development in 2050, WACC of 3%
MN Load
Normalized Renewables
15000
10000
5000
0
MWh
Jun 30
Jul 02
Jul 04
Jul 06
date
LCOE ($/kWh)
0.5
0.4
0.3
0.2
0.1
0.0
5.3
c/kWh
1x
1.2x
1.7x
2.5x
5x
100x
Oversizing factor
Non-official results

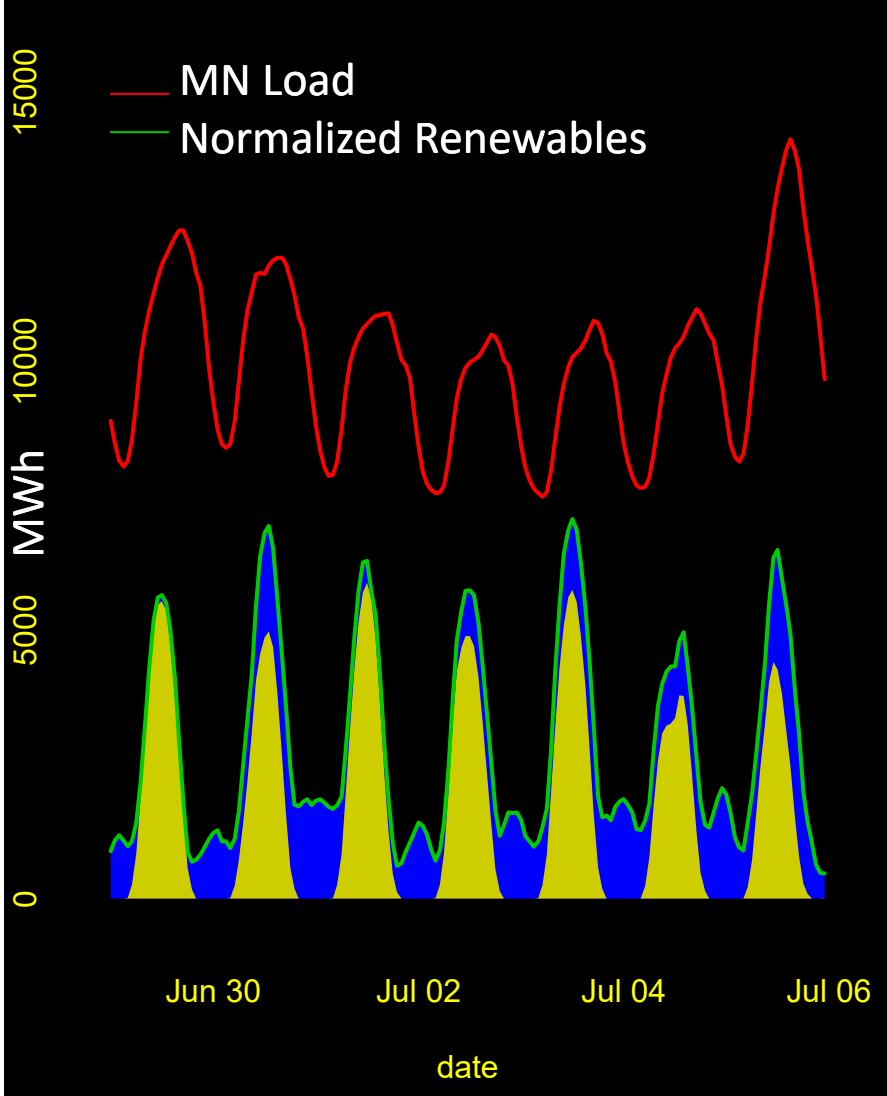
**Adding a small amount of conventional gas e.g. from stranded assets**

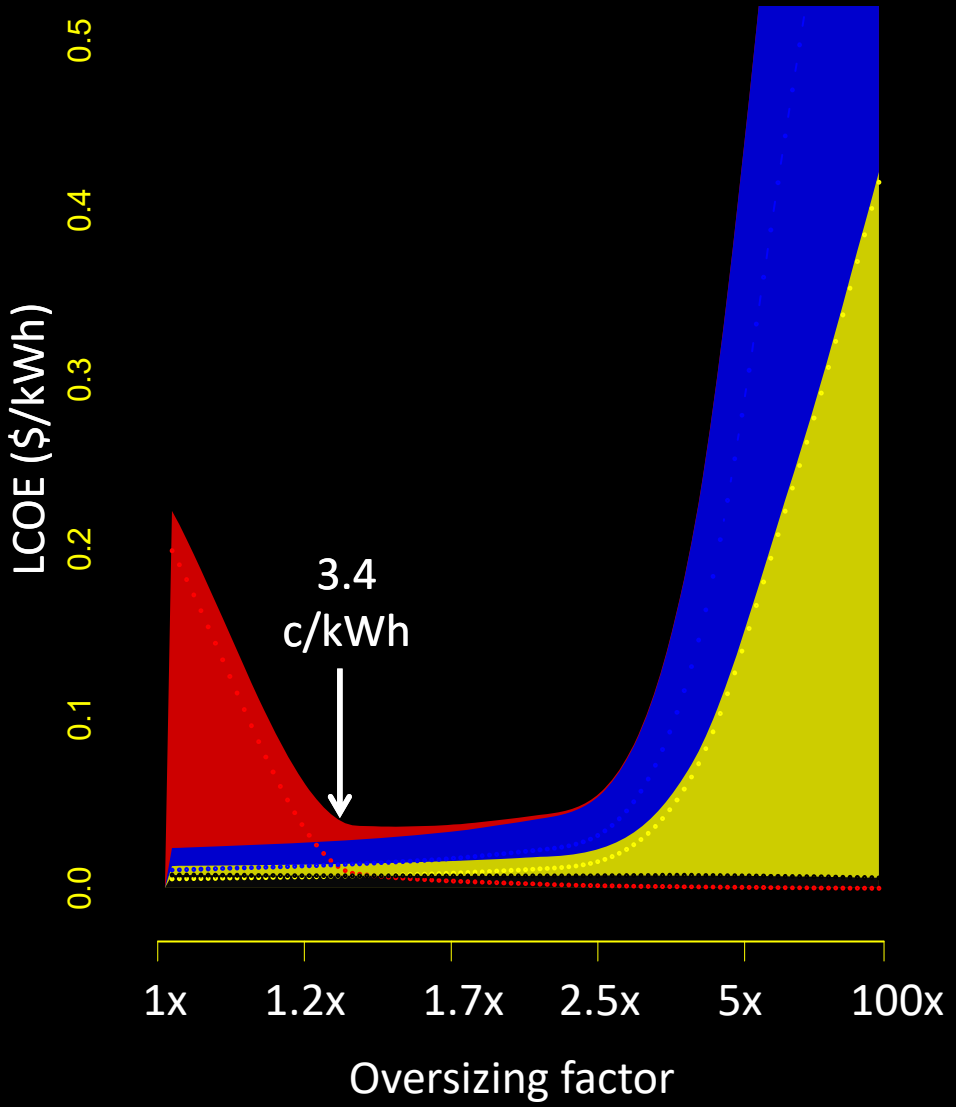

Optimal Wind/PV + Storage Meeting 95% Hourly Load in MN, 5% met by gas Utility-scale-led,
High Technological Development in 2050, WACC of 3%
MN Load
Normalized Renewables
15000
10000
5000
0
MWh
Jun 30
Jul 02
Jul 04
Jul 06
date
LCOE ($/kWh)
0.5
0.4
0.3
0.2
0.1
0.0
3.6
c/kWh
1x
1.2x
1.7x
2.5x
5x
100x
Oversizing factor
Non-official results




**DSM Can shift load to surplus hours, but unless V2G is only intraday**

Optimal Wind/PV + Storage Meeting 95% Hourly Load in MN, 5% met by gas Utility-scale-led, High Technological Development in 2050, WACC of 3% +EV electrification & load-shifting




Non-official results

## Key Takeaways

- Supply shaping via oversizing + curtailment has significant value for minimizing cost at high penetration
- Major cost reduction by optimizing relative penetration of PV + wind
- Major cost reduction by including minor amounts of gas backup at key times to minimize need for storage

**55% PV, 40% wind, 5% gas**

**3.6 c/kWh**

**Thanks!**

# Inexpensive, Firm PV Without Conventional Backup:
## The Role of Supply Shaping Through Curtailment

Marc Perez
*Clean Power Research*

***For achieving high-penetration renewables!***

**This work is based upon work supported by:**
National Science Foundation GRF Grant No. DGE 1144155
DoE Sunshot Grant No. DE-EE0007669
Columbia University Center for Life Cycle Analysis
Clean Power Research