Decarbonizing OCP

MSOM Practice-Based Research Competition Finalists Session

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Joint work with
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Acknowledgements:
Tarik Mortaji (OCP)
Yassine El Akel (OCP)
Kailyn Byrk (Dynamic Ideas LLC)

How This Project Came Together

12 December 2015: 196 countries met in Paris at COP-21

- Limit temperature rises to 2c, ideally 1.5c, of pre-industrial levels

“All the News That's Fit to Print”

The New York Times

Late Edition

Today, cloudy, warm for early December, high 63. **Tonight,** cloudy, drizzle, low 54. **Tomorrow,** rain becoming steady, high 63. Weather map is on SportsSunday, Page 12.

VOL. CLXV . . . No. 57,079 | ©2015 The New York Times | NEW YORK, SUNDAY, DECEMBER 13, 2015 | $6 beyond the greater New York metropolitan area. | $5.00

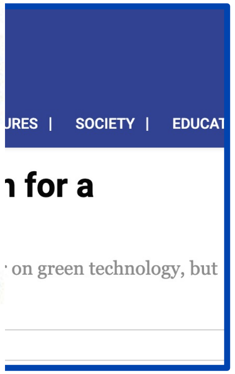
NATIONS APPROVE LANDMARK CLIMATE DEAL

In France, Consensus on a Need ... sions

2015-preser ... nate

“Climate (... *e. It is a harsh, unforgiving reality wl* ... *ng droughts”*

- **2021:** Mor



How This Project Came Together

2015-present: OCP, Morocco's largest company (5.6% of GDP), acts on climate change

- **2022:** Dr. Terrab, Chairman of OCP, pledges on national television, in front of King Mohammed IV, that OCP will invest $13 billion USD to (a) significantly decarbonize by 2027, (b) be carbon neutral by 2040

This project: invest ~$2 billion in solar panels and batteries, as part of decarbonizing by 2027

Collaboration with OCP

Our Team

OCP Governance

Former classmates, initiated collaboration to decarbonize OCP in 2021

Prof. Bertsimas
MIT PhD in OR '88

Dr. Terrab, OCP Chairman
MIT PhD in OR '90

Weekly Meetings

OCP Team

Ryan Cory-Wright

Vassilis Digalakis Jr.

Kailyn Byrk, Dynamic Ideas LLC

Tarik Mortaji, OCP

Yassine El Akel, OCP

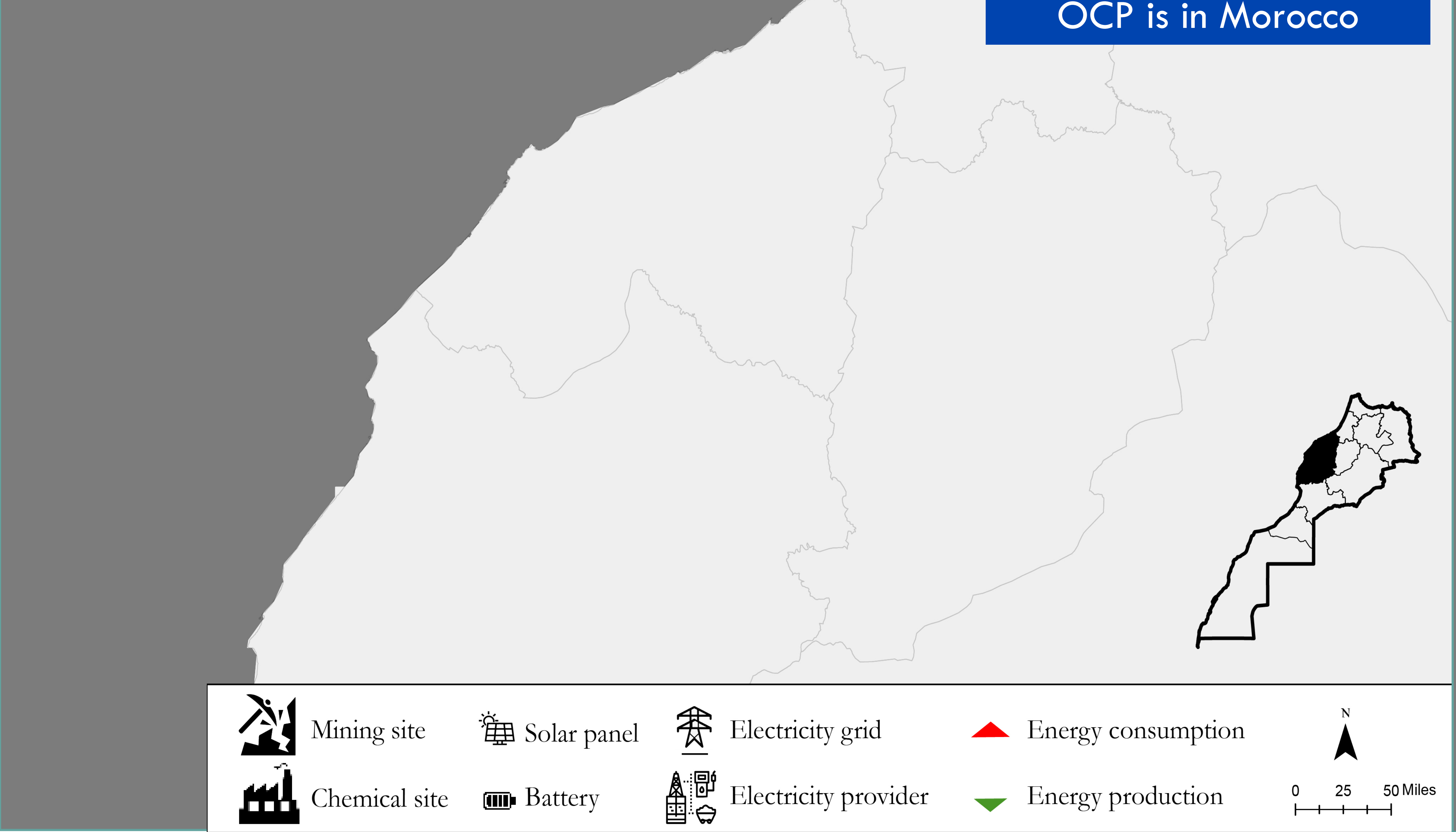
Agenda

1. OCP's Current Production Process

2. How to Decarbonize OCP Under a Budget

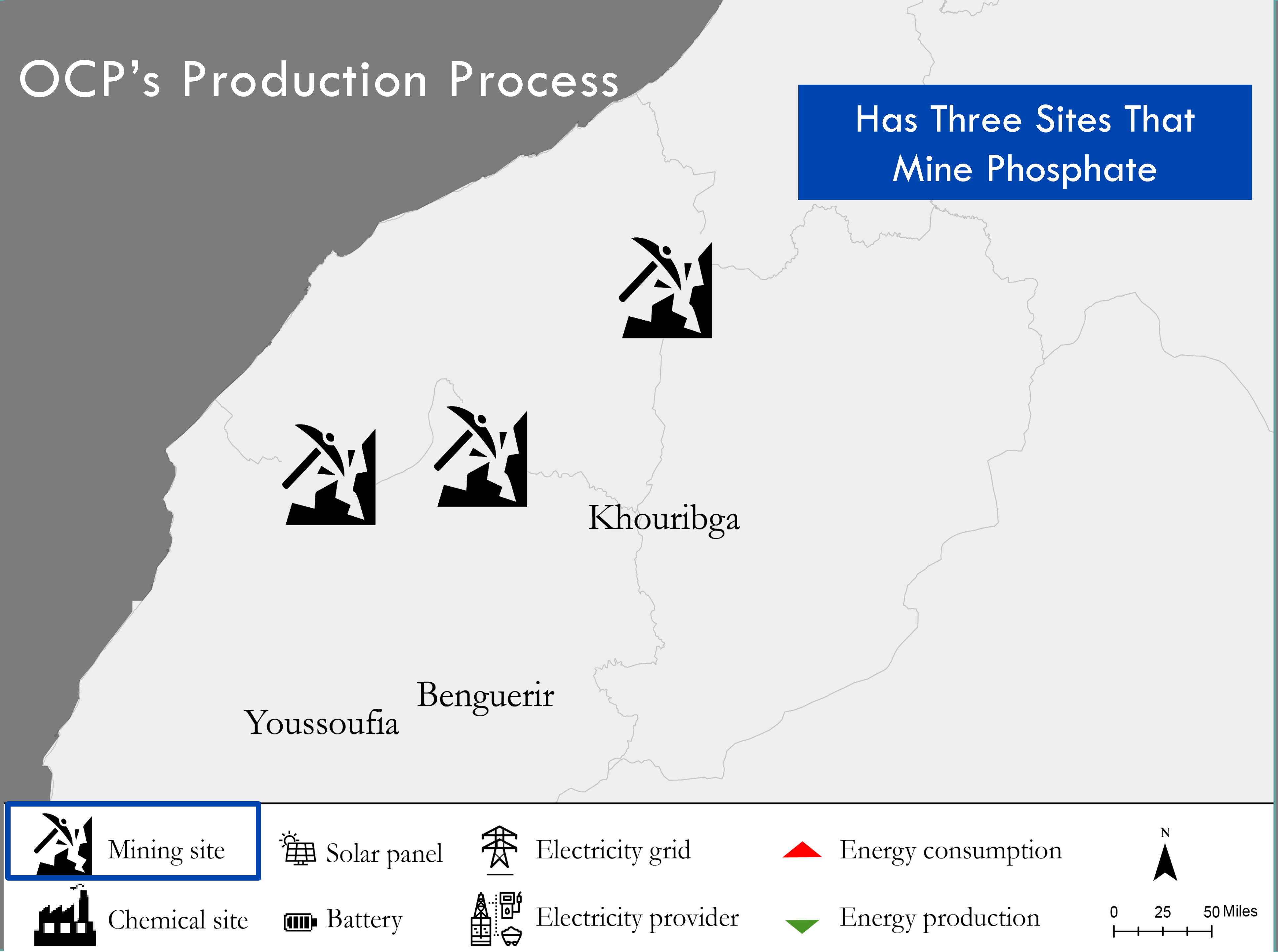
3. Impact on OCP's Operations

OCP's Production Process

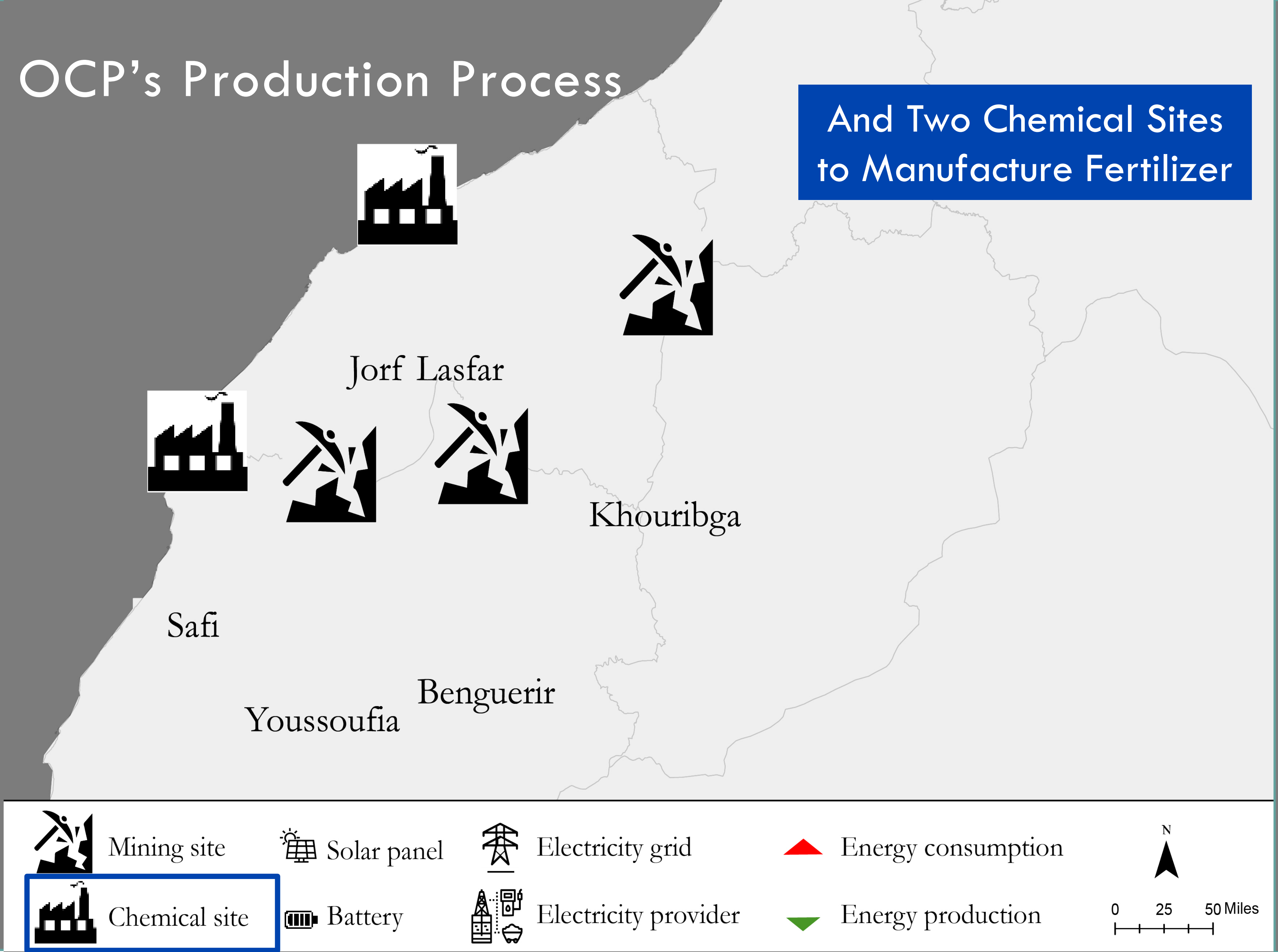


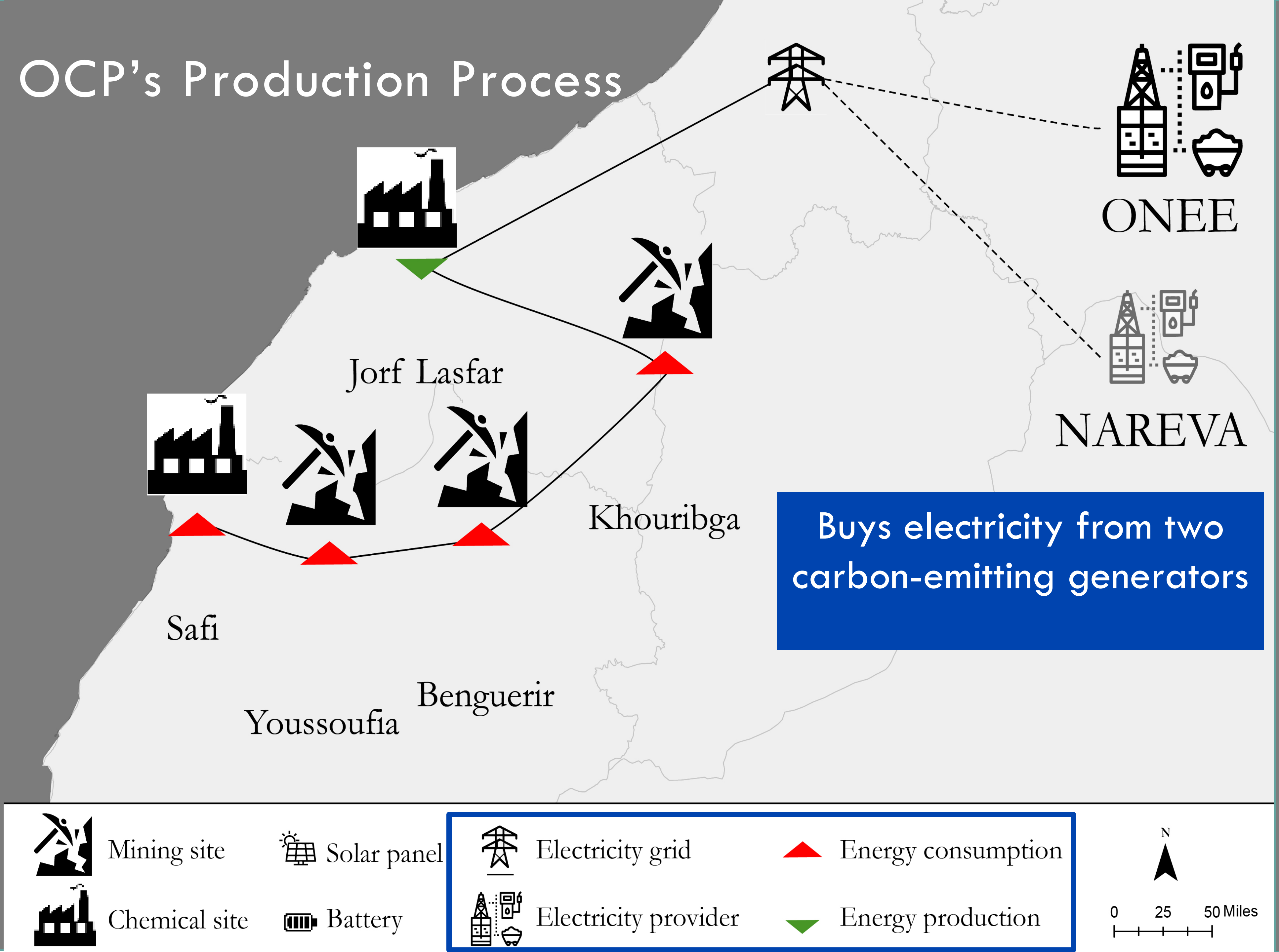
OCP's Production Process

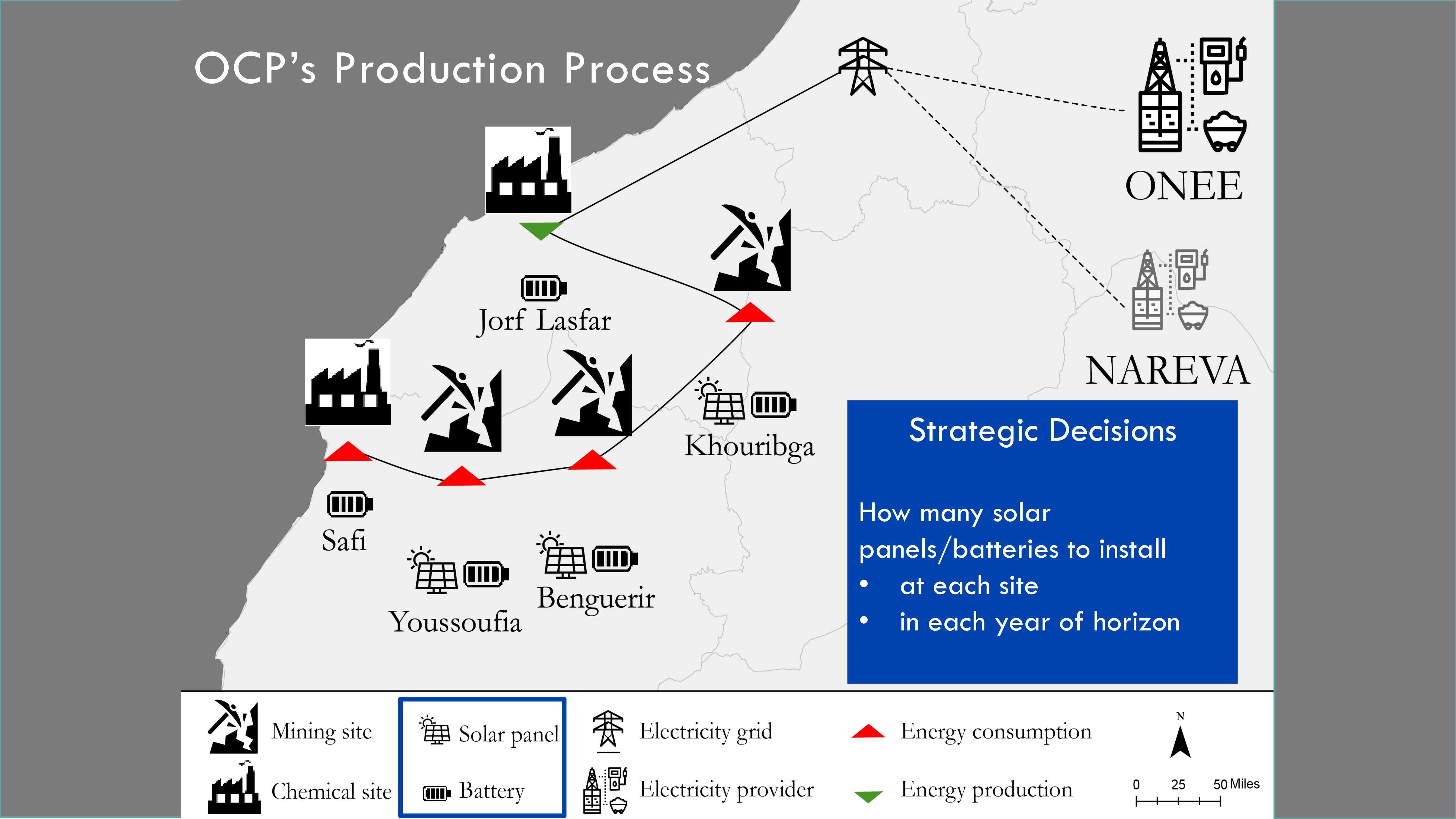
Has Three Sites That Mine Phosphate



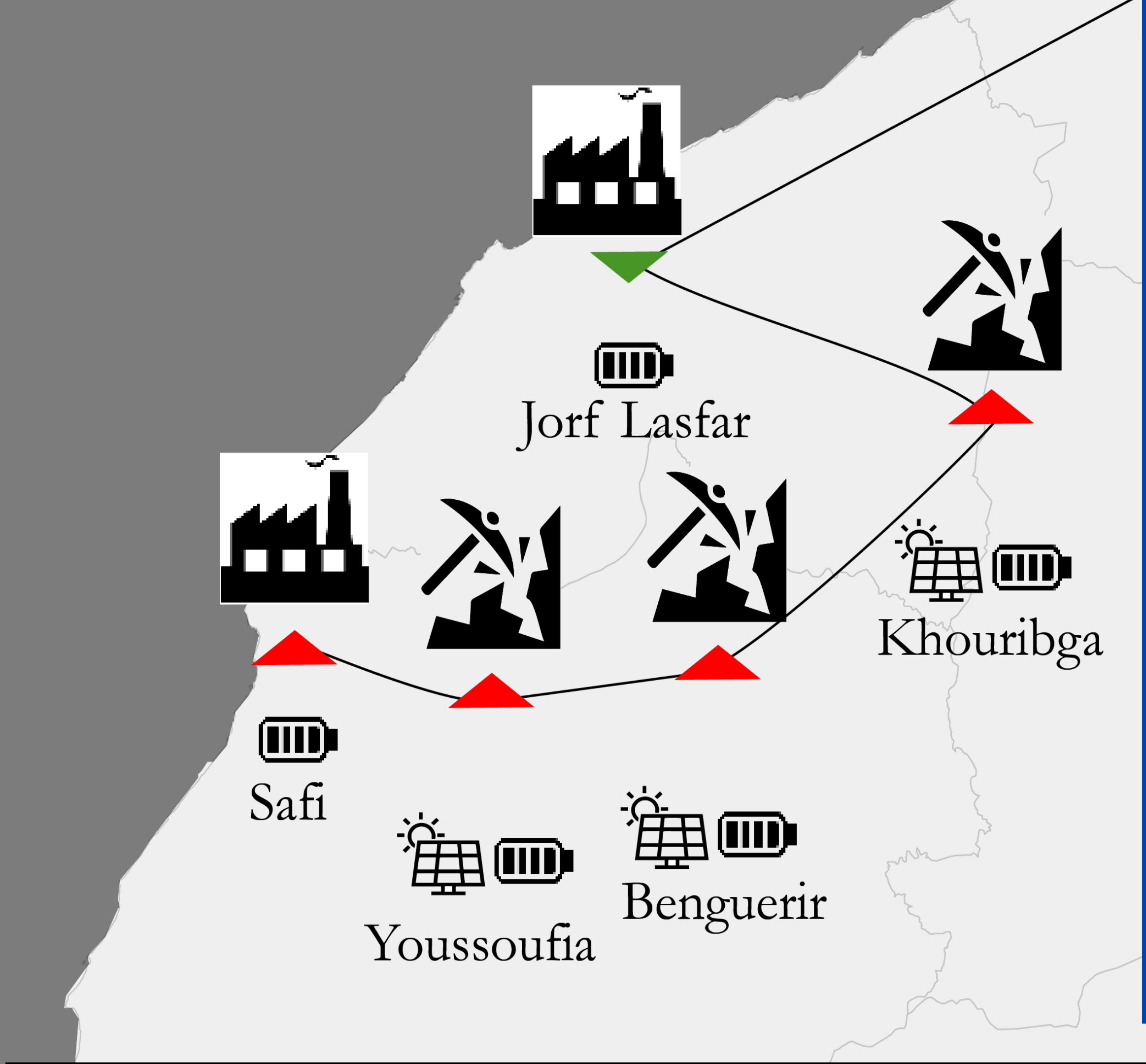
OCP's Production Process

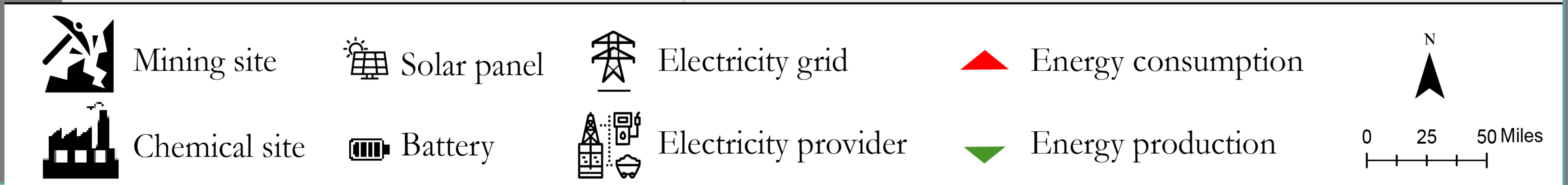



OCP's Production Process
ONEE
NAREVA
Jorf Lasfar
Khouribga
Safi
Benguerir
Youssoufia
Buys electricity from two carbon-emitting generators
Mining site
Chemical site
Solar panel
Battery
Electricity grid
Electricity provider
Energy consumption
Energy production
N
0
25
50 Miles


OCP's Production Process
ONEE
NAREVA
Jorf Lasfar
Khouribga
Safi
Youssoufia
Benguerir
Strategic Decisions
How many solar panels/batteries to install
• at each site
• in each year of horizon
Mining site
Chemical site
Solar panel
Battery
Electricity grid
Electricity provider
Energy consumption
Energy production
N
0
25
50 Miles

OCP's Production Process



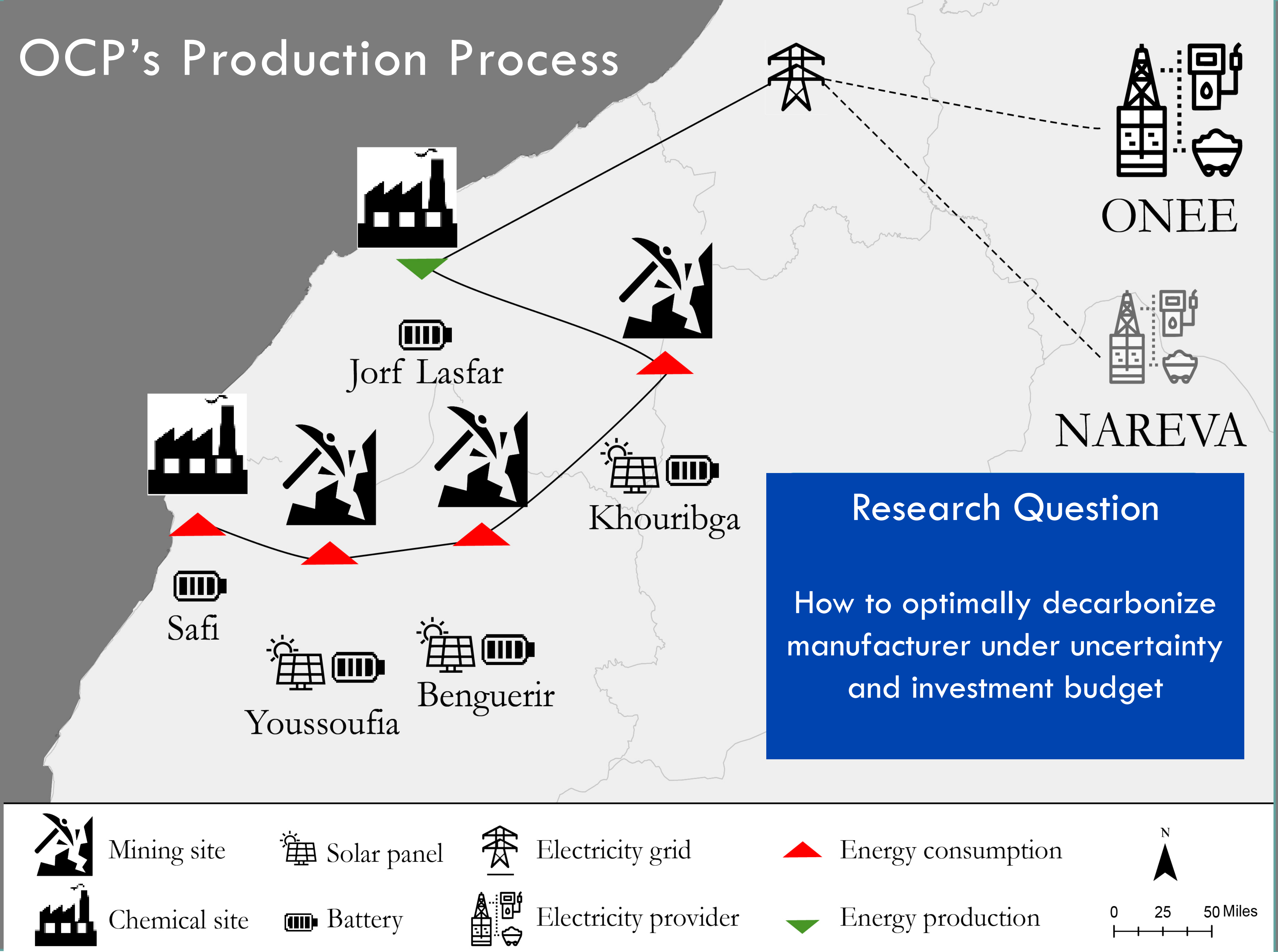


Operational Decisions

Operate system by hour, get most out of solar panels/batteries, with uncertainty in solar

- Store/release battery?
- Purchase from provider?
- Sell to provider?

OCP's Production Process



Research Question

How to optimally decarbonize manufacturer under uncertainty and investment budget

How to Decarbonize Under a Budget

Step 1: Modeling Uncertainty

- Discretize time into hours
- Decompose operational problem into 24-hour blocks
- Assume uncertainty fully revealed for 24-hour time period at start of period
- Assume battery level at end of each day same as start of day, but we get to pick level

Step 2: Simplifying the Problem

Ideally, minimize expected cost with sample-average approximation using historical data

Gives hour-by-hour problem over 20 years. Intractable 🚨

Scenario Reduction to the Rescue! Run k-means clustering on historical solar capacity factors:

1. Centroids of clusters -> reduced set of scenarios of hour-by-hour solar capacity factors
2. Number of points in each cluster -> mass on reduced scenarios

⚠️ SAA with small no. scenarios could overfit/disappoint out of sample ⚠️

Step 3: Guarding Against Overfitting

Robust and Distributionally Robust Optimization to the Rescue 🎉

- RO: make model robust to uncertainty in weather
- DRO: make model robust to uncertainty in climate

Exact convex reformulation via strong duality!

Conclusion: RO and DRO guard against overfitting. If we cross-validate size of uncertainty sets

Step 4: Cross-Validating Hyperparameters

Model has four hyperparameters due to uncertainty/ambiguity sets

Set hyperparameters using standard cross-validation techniques

With investment of $2 billion USD, compare robust solution against nominal solution (no robustness)

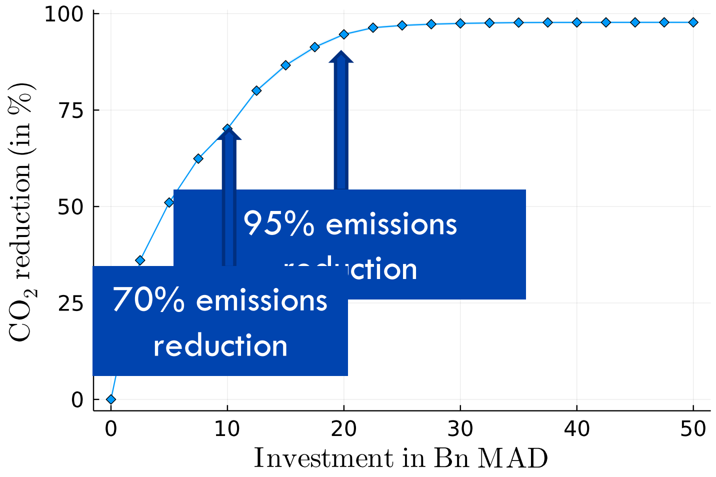
- Cross-validated cost over 20-year horizon 16.3% lower than no RO/DRO 🎉
- CO_2 emissions 3.5% lower than no RO/DRO 🎉

Managerial insight: accounting for uncertainty matters when decarbonizing

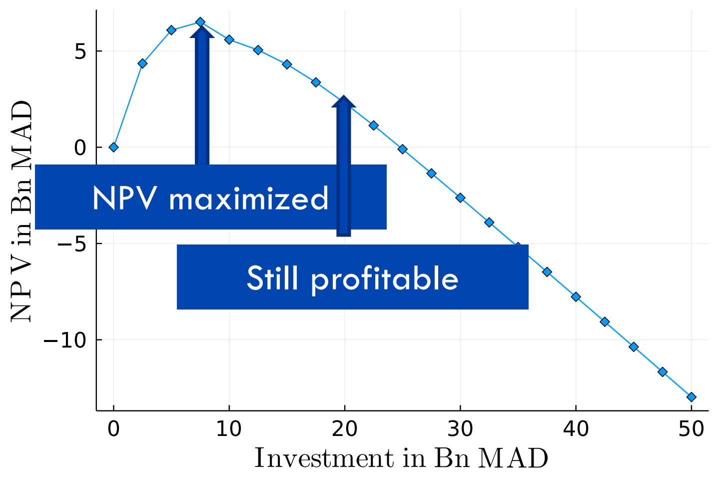
Making Optimal Strategic Decisions

Investment/Emissions Reduction by Budget

Fix cross-validated hyperparameters, vary budget (in MAD, divide by 10 for USD)



Emissions reduction by budget

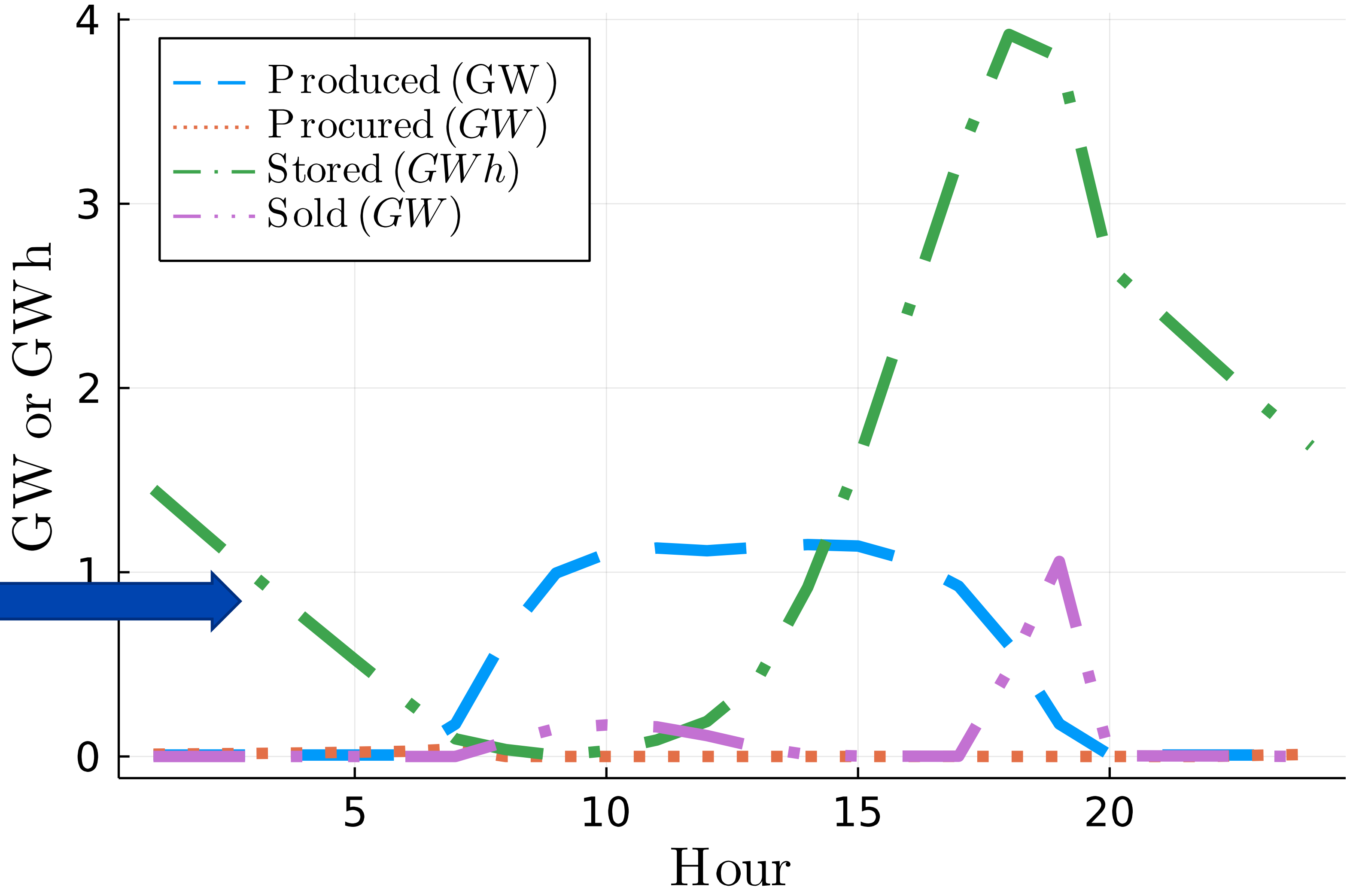


NPV by budget

- Solar/batteries reduce most emissions. Other technology better for last 5%
- Partly decarbonizing using solar/batteries is profitable. Fully decarbonizing is not

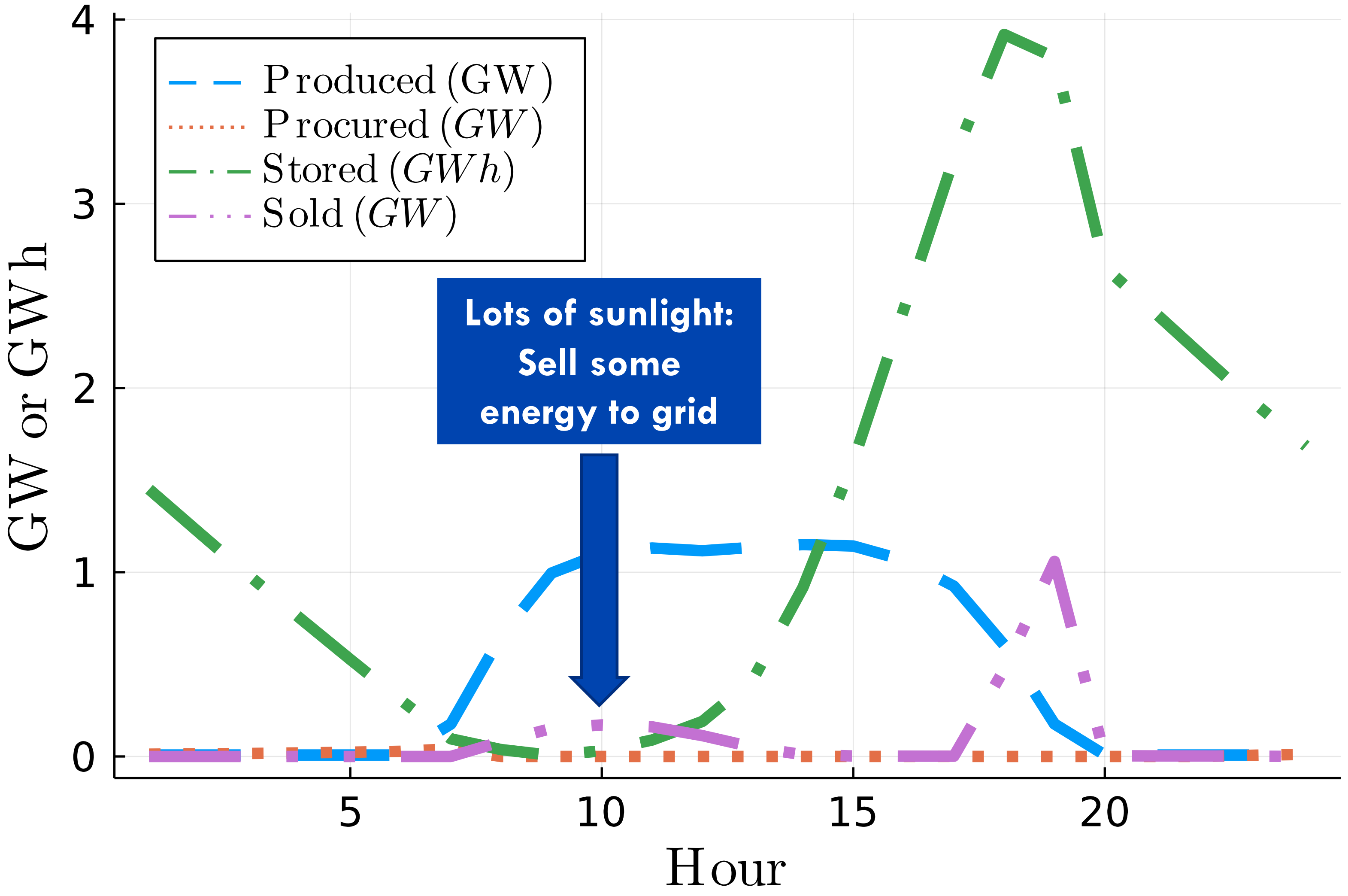
Impact on OCP's Operations

The Model in Action: A Sunny Day

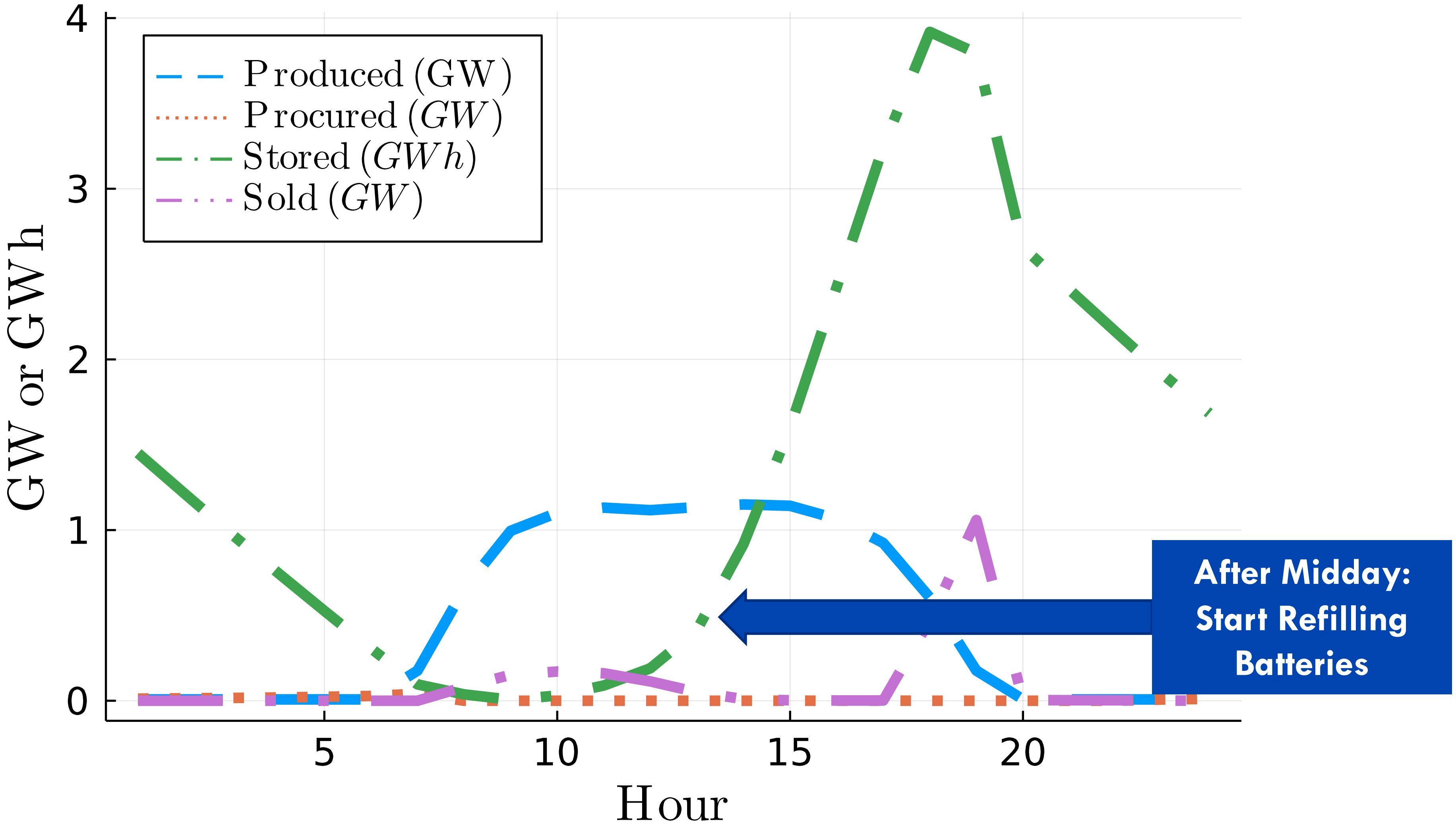


Good weather forecast: Preempt sun by draining batteries

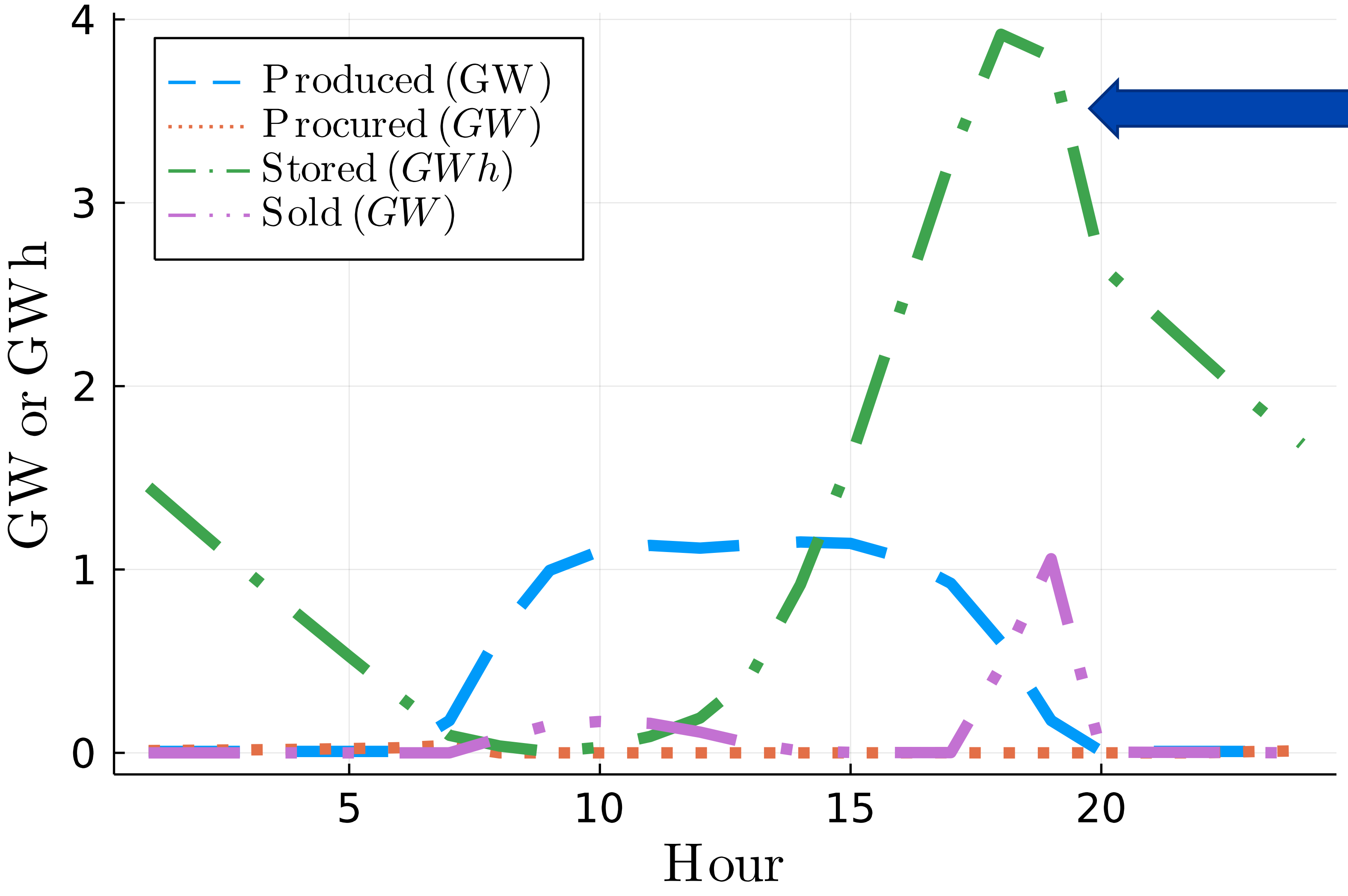
The Model in Action: A Sunny Day



The Model in Action: A Sunny Day



The Model in Action: A Sunny Day



Sun Setting: Run System Overnight Using Batteries

Summary

- Optimization methodology for partially decarbonizing OCP
  - Applicable in *any* system with significant energy needs
  - Profitability depends on local conditions, real interest rates

- Impact on OCP's operations
  - Implementation in progress, project will decarbonize majority of OCP's energy supply once implemented
  - Removes ~30% of OCP's total carbon emissions, first step toward OCP's pledge of decarbonizing by 2040
  - Fully decarbonizing involves other energy, like wind

    -> Work in progress

Thank you to the committee for organizing the competition!

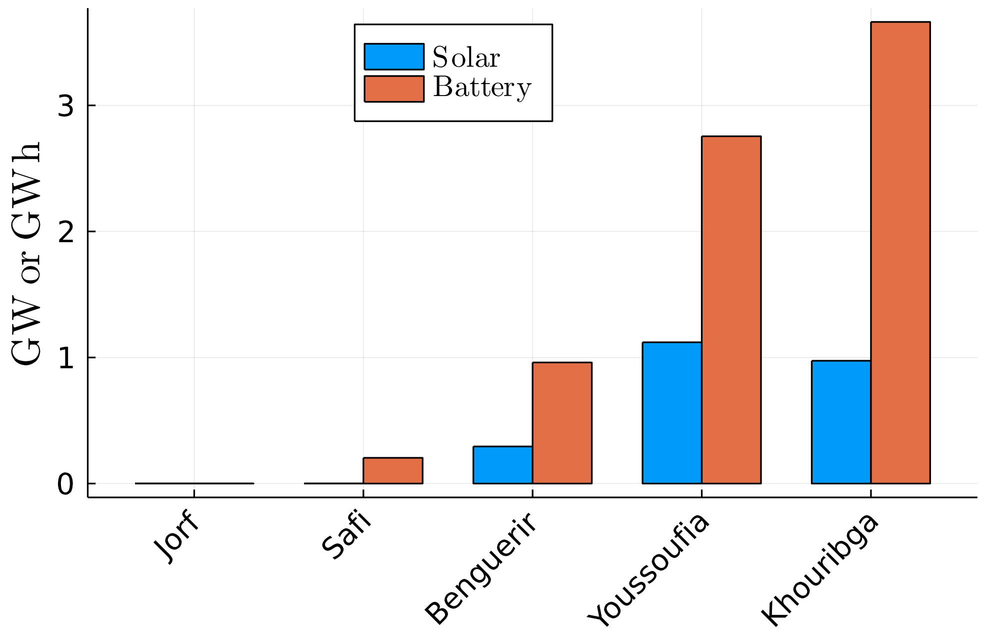
Questions?

Backup Slides

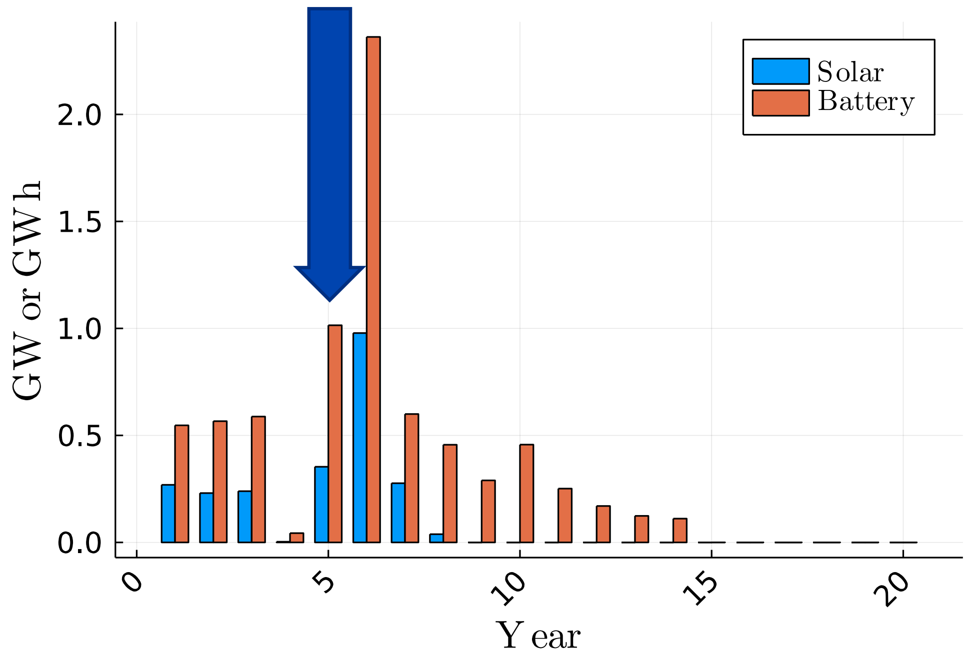
Strategic Decisions

Fix cross-validated hyperparameters, budget 2 Billion USD

Jorf Cogen closes 5 years into planning horizon; investment needed to compensate for closure



Investment by site, aggregated by year



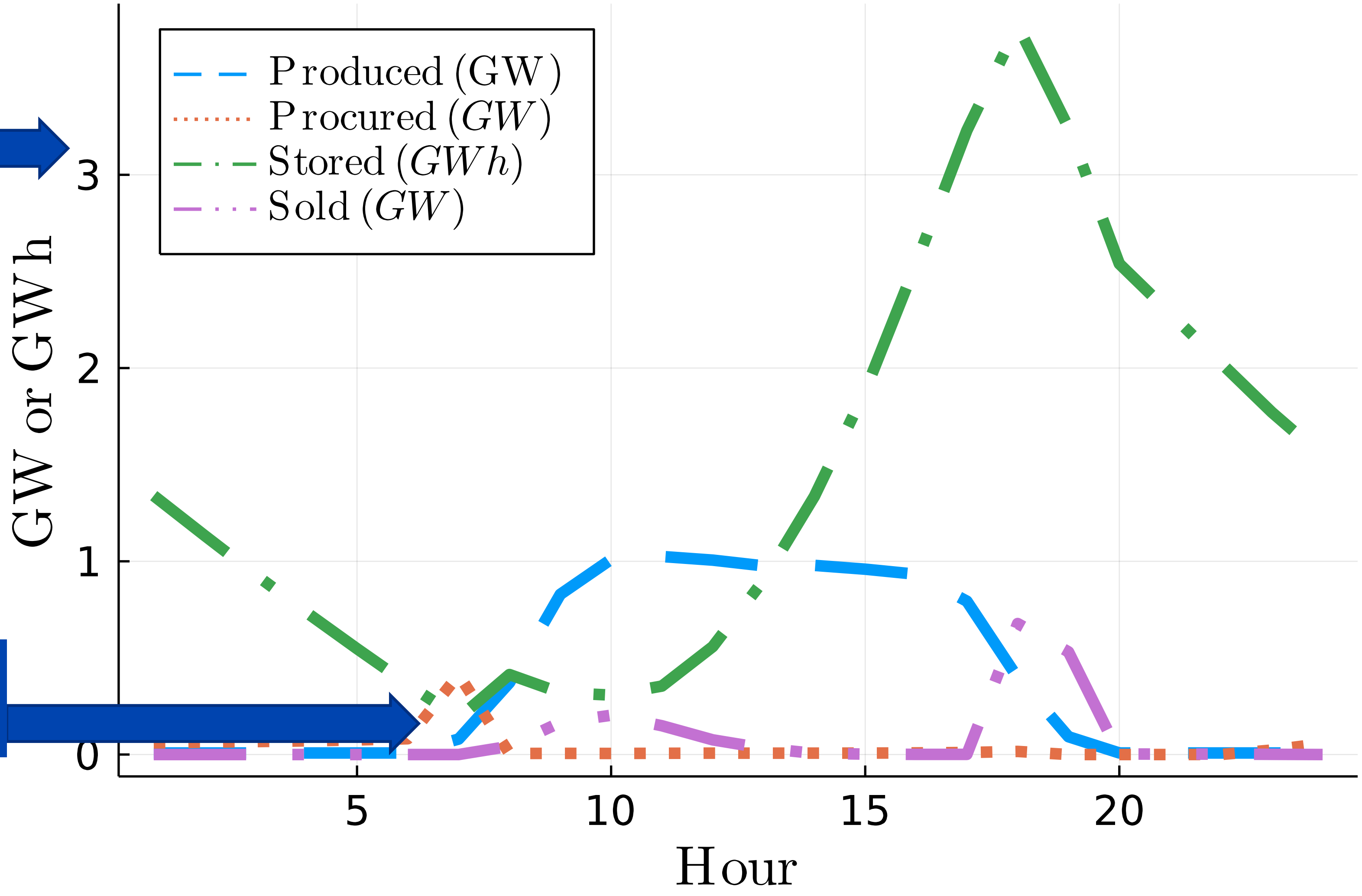
Investment by year, aggregated by site

Investing earlier means more cost savings

Model delays some investment, since OCP needs more energy later in horizon; solar degrades over time

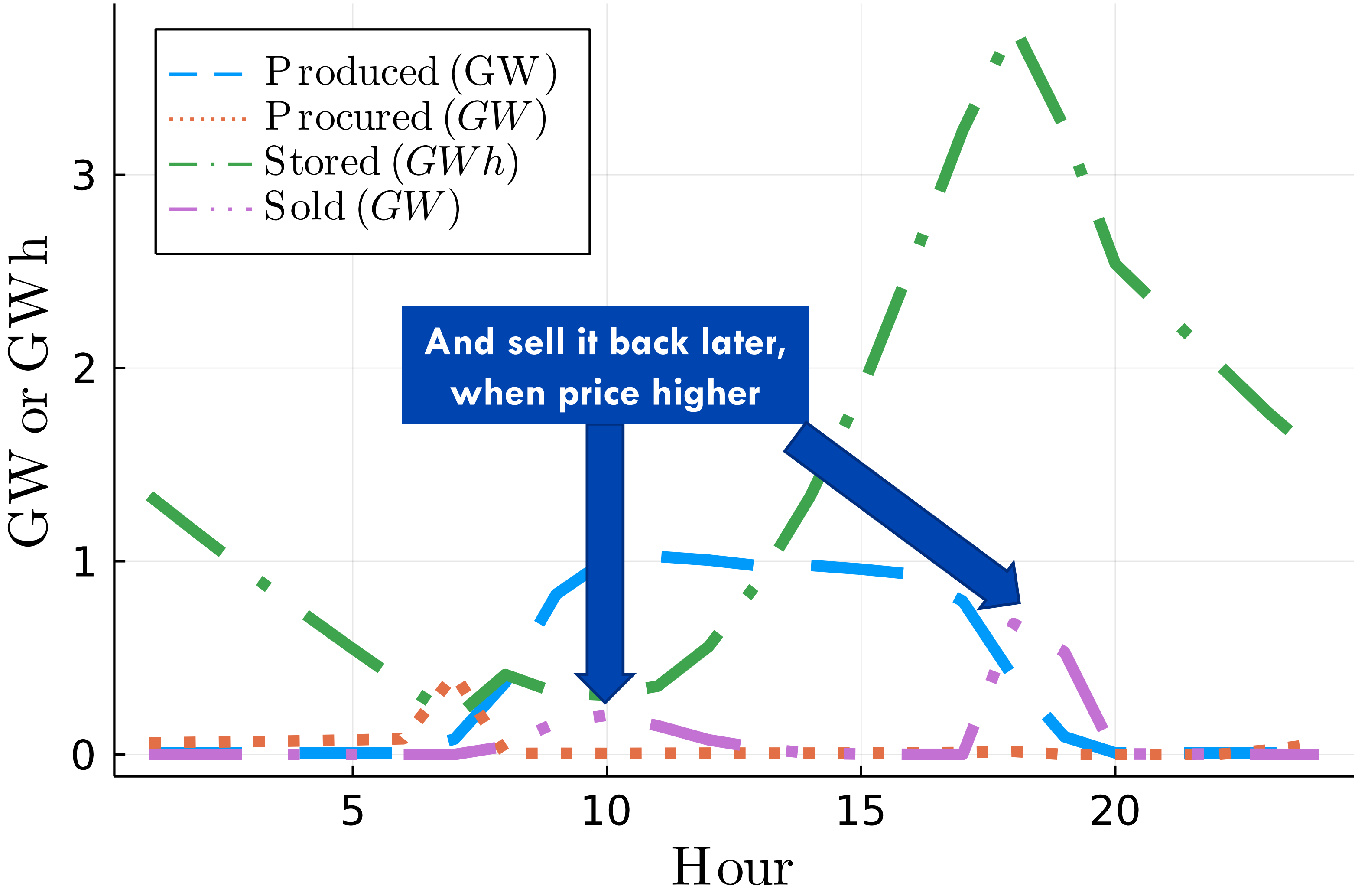
The Model in Action: A Less Sunny Day

Note: y-limit decreased from 4.5 to 3.5

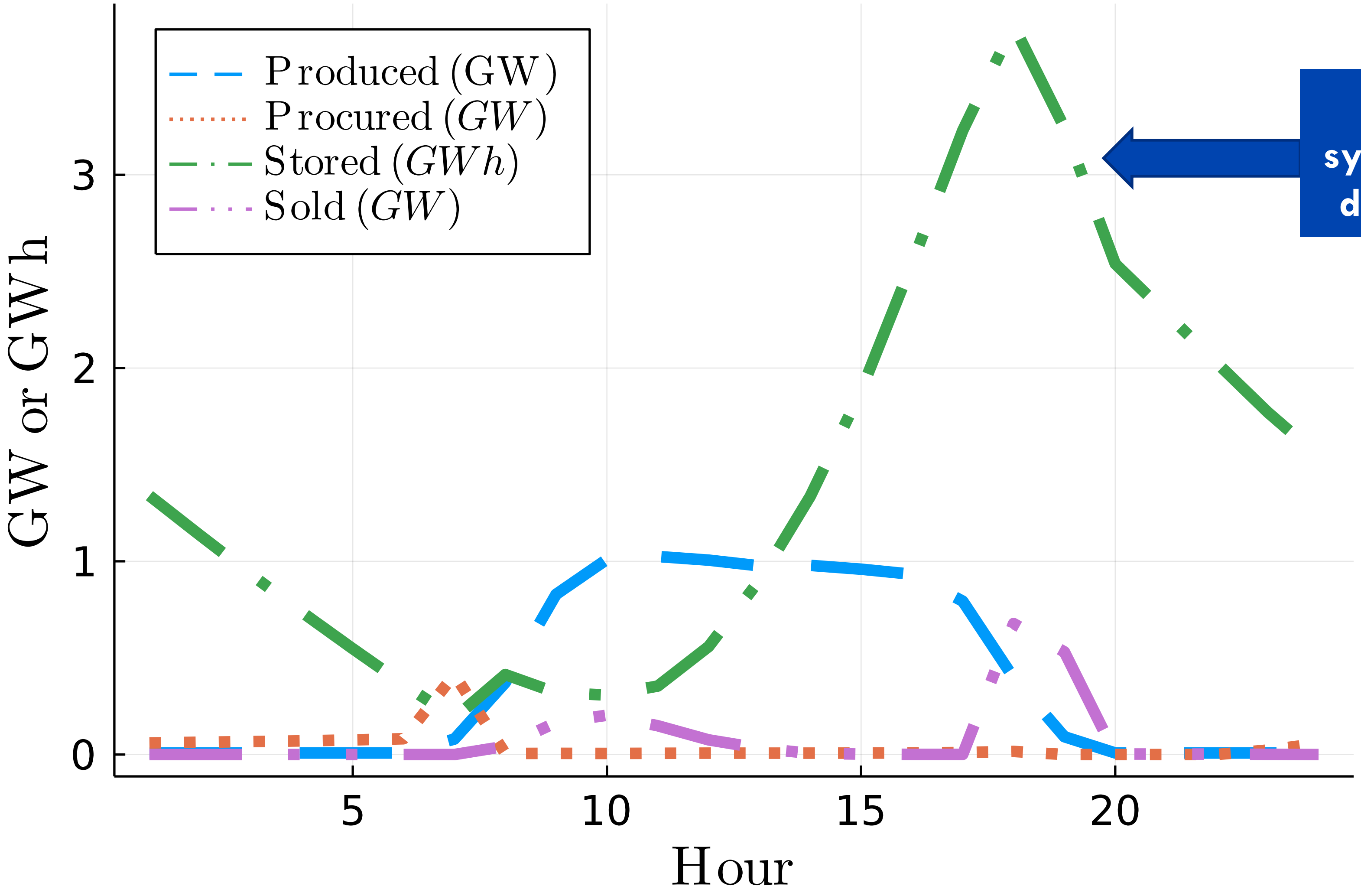


Buy some energy at night, while cheap

The Model in Action: A Less Sunny Day



The Model in Action: A Less Sunny Day



And still power system during whole day using batteries

Backup: Problem Data

Table 1 **Summary of notation. Calligraphic letters refer to sets, Roman/Greek letters refer to problem data. To preserve OCP's privacy, we do not disclose the data values not explicitly stated in this table.**

Symbol	Description
General Setting	
$\mathcal{H}$	Set of hours in each day, $\{1,\ldots,24\}$
$\mathcal{D}$	Set of reduced scenarios
$\mathcal{M}$	Set of months in a calendar year, $\{1,\ldots,12\}$
$\mathcal{Y}$	Set of years in OCP's planning horizon; i.e., $\{1,\ldots,20\}$
$\mathcal{N}$	Set of nodes in the network, i.e., {Jorf, Safi, Benguerir, Youssoufia, Khouribga}
$\mathcal{A}$	Set of all arcs in the network
$\mathrm{D}^{m,y}$	Number of days in month $m \in \mathcal{M}$ in year $y \in \mathcal{Y}$
$\mathrm{P}^{d,m,y}$	Probability of reduced scenarios of type $d \in \mathcal{D}$ in month $m \in \mathcal{M}$ in year $y \in \mathcal{Y}$
Investment Decisions	
B	Investment budget in MAD (Moroccan dirham)
ρ	Discount factor, i.e., 0.95
c_b^y	Cost of purchasing and installing one kWh of batteries in year $y \in \mathcal{Y}$
c_s^y	Cost of purchasing and installing one kW DC of solar panels in year $y \in \mathcal{Y}$
OCP Operations	
Operational Data	
R	Constant which converts energy released from batteries into a rate, i.e., 1
ξ	Annual rate of solar generation capacity degradation, i.e., 0.995
ν	Annual rate of battery storage degradation, i.e., 0.96
ψ	Proportion of energy stored in a battery available an hour later, i.e., 0.997
β	Fraction of daily amount of power produced by solar panels that may be sold, i.e., 0.2
$\mathcal{I}(n)$	Set of arcs $a=(i,n)$ flowing into node $n \in \mathcal{N}$
$\mathcal{O}(n)$	Set of arcs $a=(n,i)$ flowing out of node $n \in \mathcal{N}$
K_a	Capacity limit in kW on the flow through arc $a \in \mathcal{A}$
η_a	The transmission efficiency coefficient for arc $a \in \mathcal{A}$, i.e., $\eta = 0.99$
Time-Dependent Data	
G_o^h	ONEE generation capacity in kW at node $n \in \mathcal{N}$ in hour $h \in \mathcal{H}$
G_n^h	NAREVA generation capacity in kW at node $n \in \mathcal{N}$ in hour $h \in \mathcal{H}$
$\upsilon^{h,d}$	Capacity factor for a solar panel in hour $h \in \mathcal{H}$ of scenario $d \in \mathcal{D}$
$p_{O,n}^{h,m}$	Marginal cost of energy in MAD/kWh from ONEE at node $n \in \mathcal{N}$ at time $h \in \mathcal{H}$, $m \in \mathcal{M}$
$p_{N,n}^{h,m}$	Marginal cost of energy in MAD/kWh from NAREVA at node $n \in \mathcal{N}$ at time $h \in \mathcal{H}$, $m \in \mathcal{M}$
$p_{w,n}^{h,m}$	Marginal feed-in price in MAD/kWh for selling electricity at node $n \in \mathcal{N}$ at time $h \in \mathcal{H}$, $m \in \mathcal{M}$
$c_{r,a}^{h,m}$	Marginal cost in MAD/kWh of renting line $a \in \mathcal{A}$ at time $h \in \mathcal{H}$, $m \in \mathcal{M}$
$d_n^{h,m,y}$	Aggregate demand in kWh at node $n \in \mathcal{N}$ at time $h \in \mathcal{H}$, $m \in \mathcal{M}$, $y \in \mathcal{Y}$

Backup: SAA Model (Pre-robustifying)

$$\min \sum_{y\in\mathcal{Y}} \Bigg[\underbrace{\sum_{n\in\mathcal{N}} c_b^y((\rho)^y - (\rho)^{|\mathcal{Y}|}) b_n^y}_{\text{cost of batteries}} + \underbrace{\sum_{n\in\mathcal{N}} c_s^y((\rho)^y - (\rho)^{|\mathcal{Y}|}) z_n^y}_{\text{cost of solar}} + \underbrace{\sum_{a,m,d,h} (\rho)^y \mathrm{D}^{m,y} \mathrm{P}^{d,m,y} c_{r,a}^{h,m} |f_a^{h,d,m,y}|}_{\text{cost to rent lines}}$$

$$+ \underbrace{\sum_{n,m,d,h} (\rho)^y \mathrm{D}^{m,y} \mathrm{P}^{d,m,y} \left(p_{O,n}^{h,m} x_{O,n}^{h,d,m,y} + p_{N,n}^{h,m} x_{N,n}^{h,d,m,y} - p_{w,n}^{h,m} w_n^{h,d,m,y} \right)}_{\text{cost to procure and sell energy}} \Bigg] \tag{3a}$$

which is to be minimized subject to the following constraints:

$$\text{s.t.} \quad \sum_{n,y} c_b^y (\rho)^y b_n^y + c_s^y (\rho)^y z_n^y \le B, \tag{3b}$$

$$\sum_{a\in\mathcal{I}(n)} \tau_a(f_a^{h,d,m,y}) + \sum_{a\in\mathcal{O}(n)} \tau_a(-f_a^{h,d,m,y}) + R \cdot r_n^{h,d,m,y} + x_{O,n}^{h,d,m,y} + x_{N,n}^{h,d,m,y}$$

$$\ge d_n^{h,d,m,y} + w_n^{h,d,m,y} - v^{h,d} \left(\sum_{y'=1}^{y} \xi^{y-y'} z_n^{y'} \right), \tag{3c}$$

$$\sum_h w_n^{h,d,m,y} \le \beta \sum_h \left[v^{h,d} \left(\sum_{y'=1}^{y} \xi^{y-y'} z_n^{y'} \right) + \max\left\{0, -d_n^{h,m,y}\right\} \right], \tag{3d}$$

$$s_n^{h+1,d,m,y} = \psi s_n^{h,d,m,y} - r_n^{h,d,m,y}, \; s_n^{1,d,m,y} = \psi s_n^{24,d,m,y} - r_n^{24,d,m,y},$$

$$s_n^{h,d,m,y} \le \sum_{y'=1}^{y} \nu^{y-y'} b_n^{y'}, \tag{3e}$$

$$x_{O,n}^{h,d,m,y} \le G_o^h, \; x_{N,n}^{h,d,m,y} \le G_n^h, \tag{3f}$$

$$|f_a^{h,d,m,y}| \le K_a, \tag{3g}$$

$$s_n^{h,d,m,y}, x_{O,n}^{h,d,m,y}, x_{N,n}^{h,d,m,y}, w_n^{h,d,m,y}, b_n^y, z_n^y \ge 0,$$

$$z_n^y = 0 \text{ for } n \in \{\text{Jorf}, \text{Safi}\}.$$