Liabilities into Assets: Utilizing Legacy Mines for Pumped Storage

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Alfred P. Sloan Foundation

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PUSHing for Storage

A Case for Repurposing Decommissioned Mines for Pumped Underground Storage Hydro (PUSH) in the United States

Technical Report

October 2021

Roman Sidortsov, Shardul Tiwari, Timothy Scarlett, Ana Dyreson & David Watkins

KETL Keweenaw Energy Transition Lab at the Great Lakes Research Center | Michigan Technological University

The Energy Transition

Photo credit: Roman Sidortsov,

Storage must grow:

2020: 23.2 GW

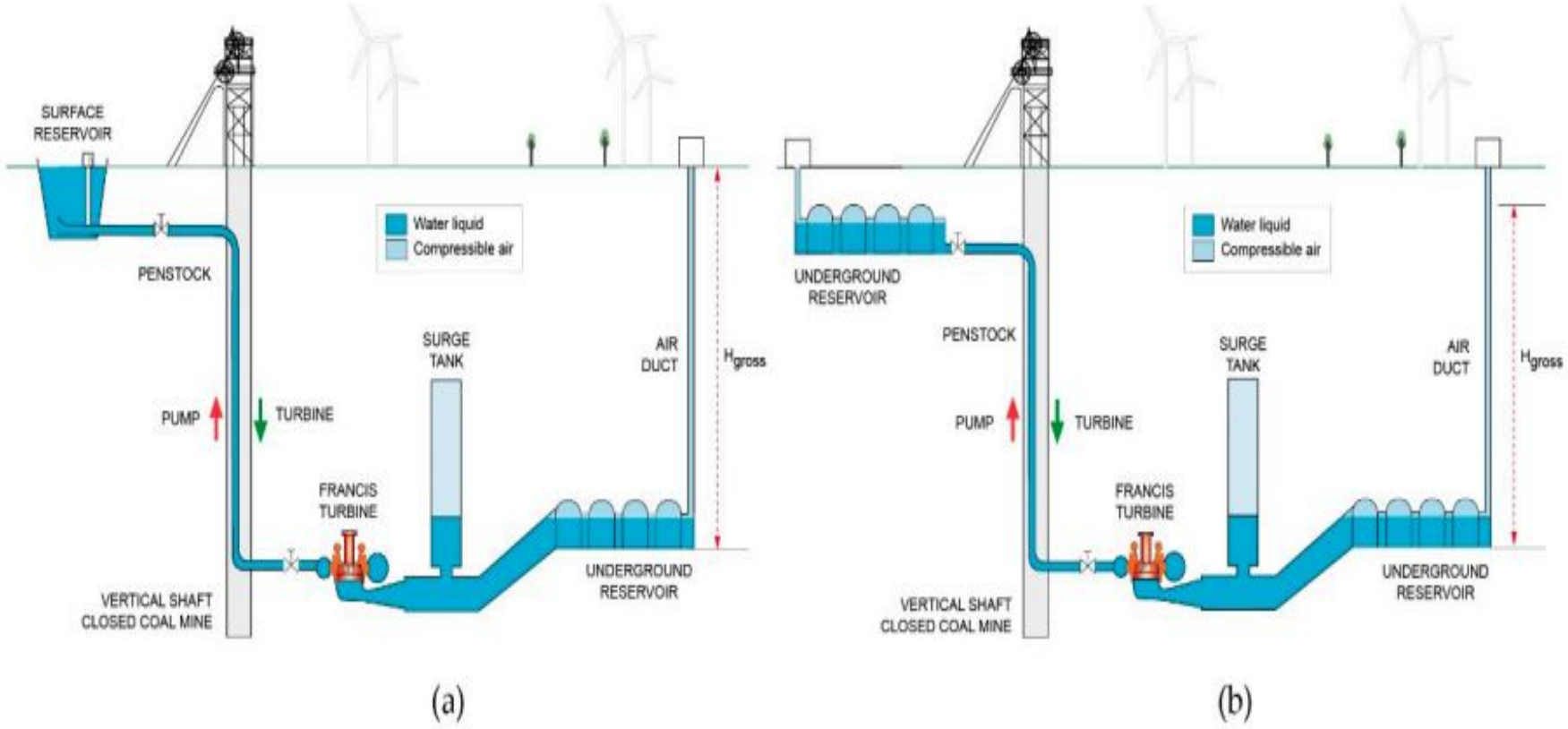
2050: 120 GW

Photo credit: MagicBones, London. https://www.picfair.com/pics/09434662-london-england-feb-22-2019-large-pile-of-old-used-corroded-batteries-at-a-uk-recycling-centre

Pump Storage Hydro: Ludington

Photo credit: Consumers Energy on Flikr:
https://www.flickr.com/photos/consumersenergy/28497624290

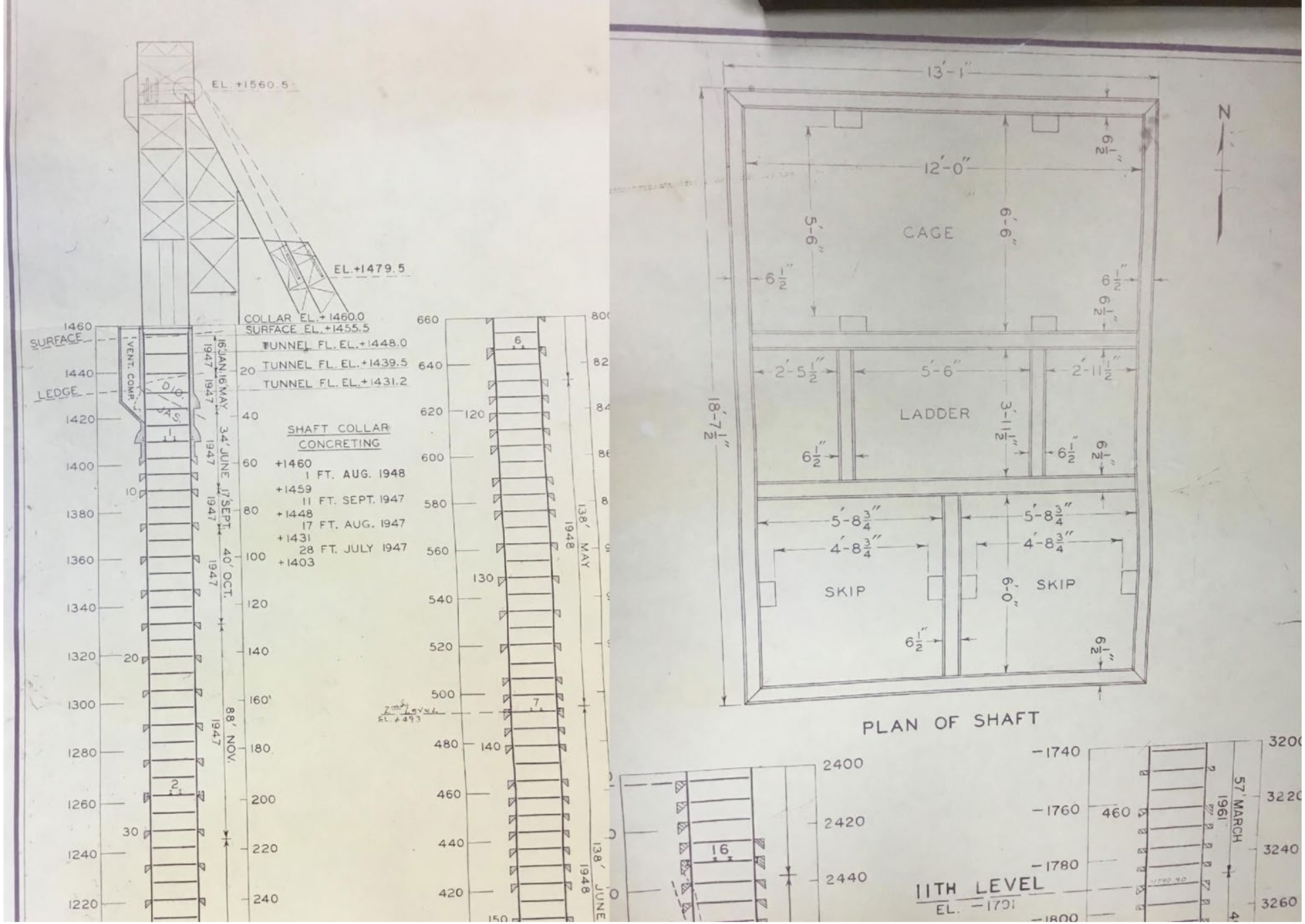
PUSH in a Nutshell

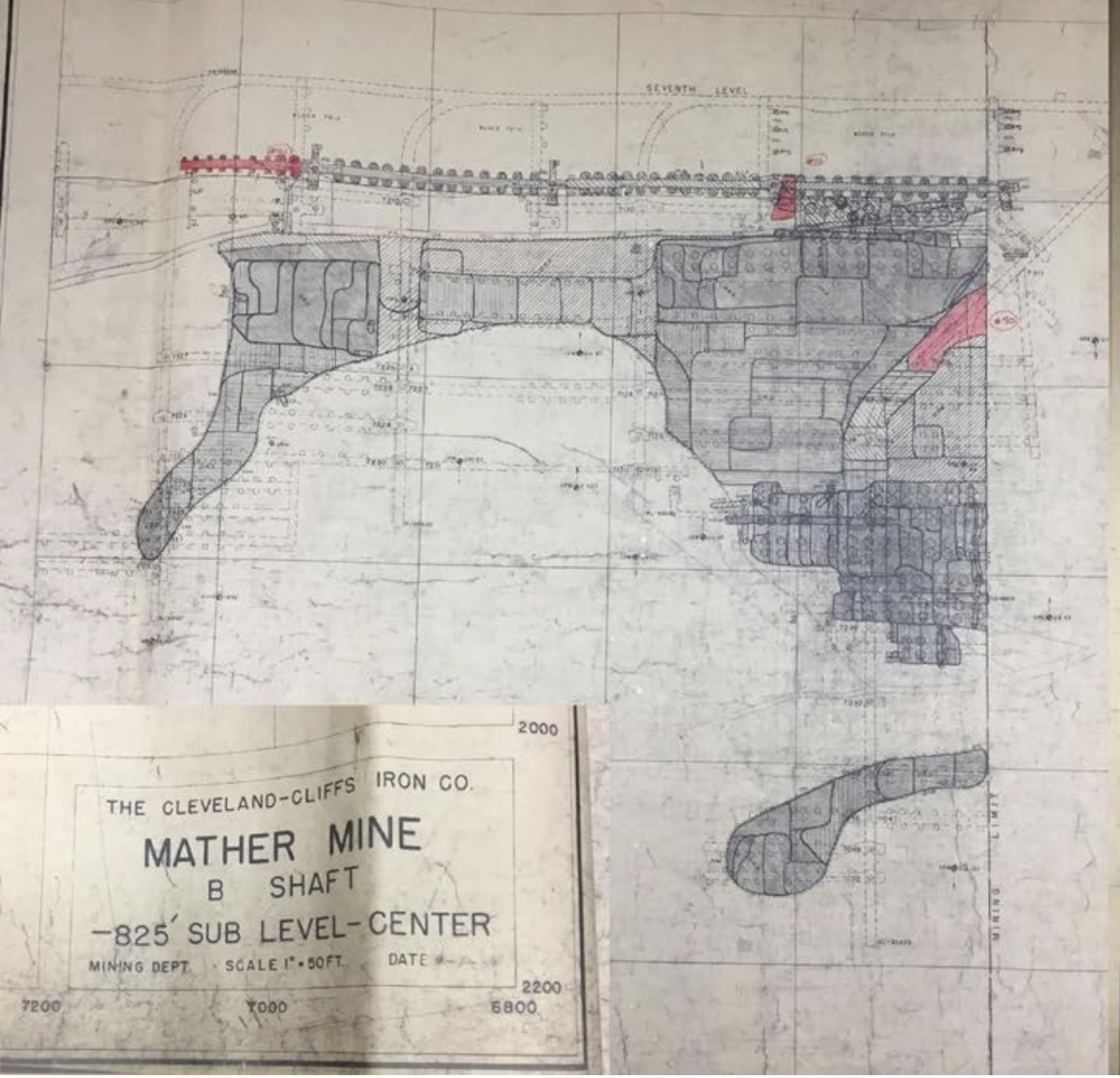


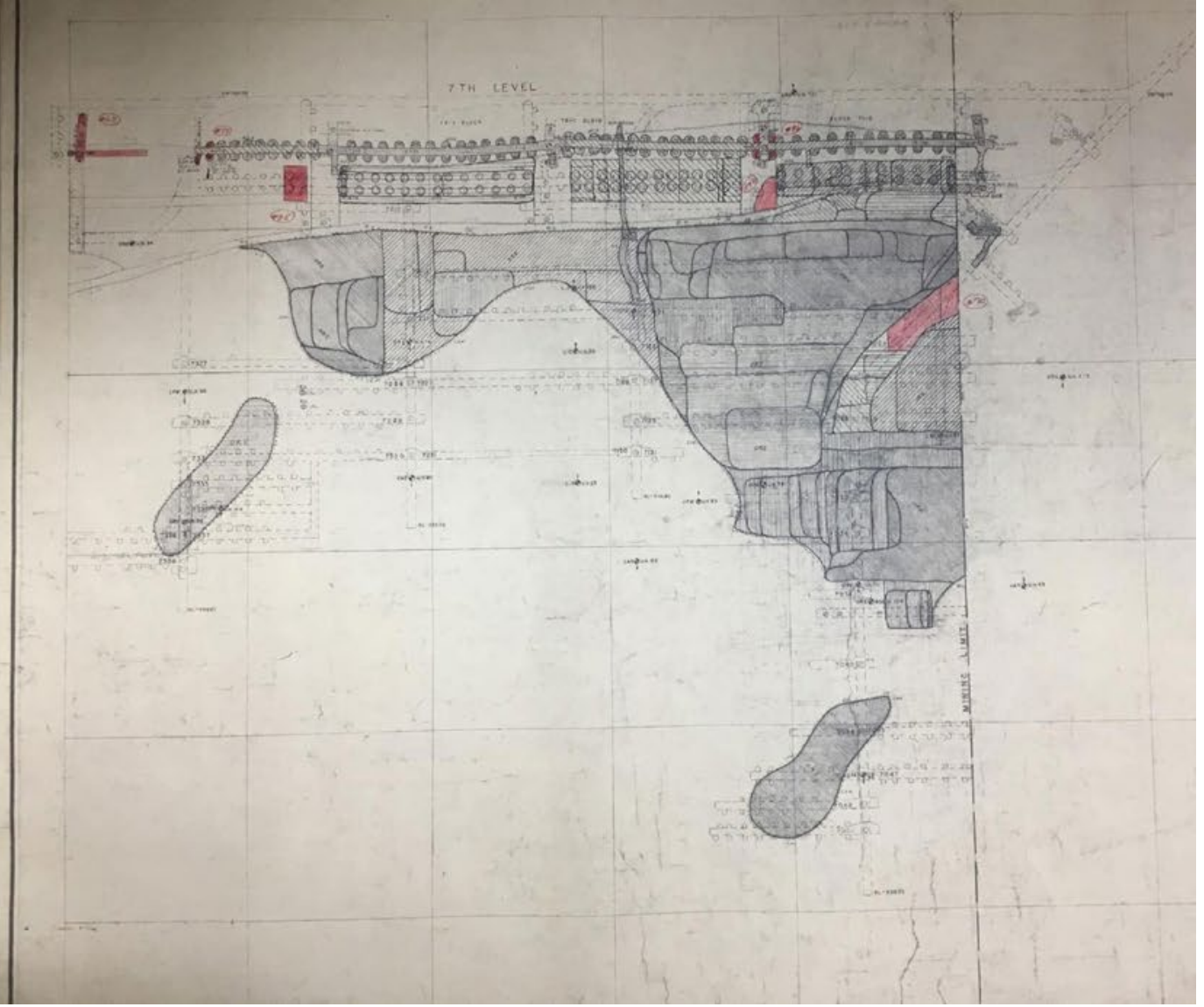
Source: Menéndez, J., Fernández-Oro, J. M., & Loredo, J., 2020

Photo credit: Paul Petosky, GeneologyTrails.com

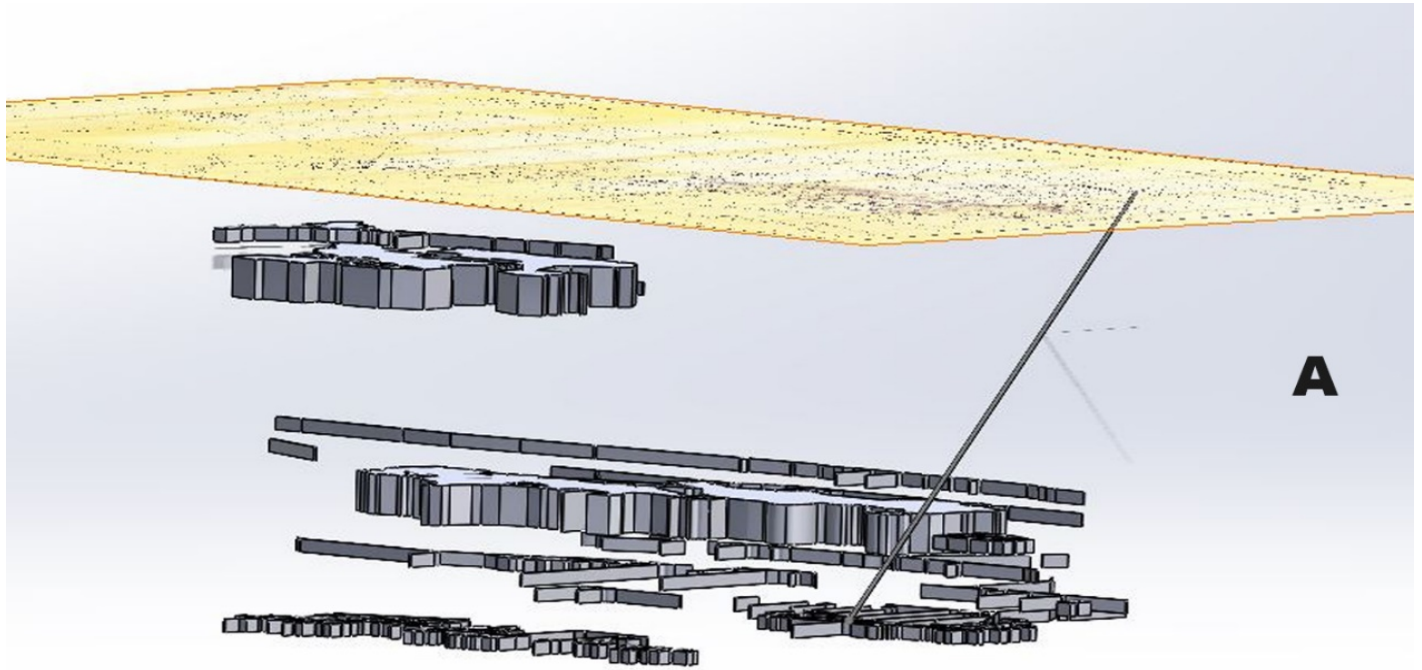

SHOVEL
101-114

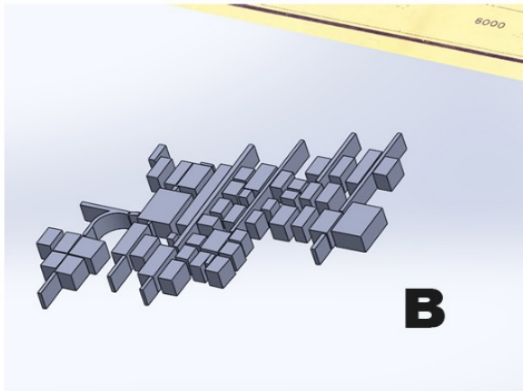

EL. +1560.5
EL. +1479.5
COLLAR EL. +1460.0
SURFACE EL. +1455.5
TUNNEL FL. EL. +1448.0
TUNNEL FL. EL. +1439.5
TUNNEL FL. EL. +1431.2
SURFACE
LEDGE
SHAFT COLLAR CONCRETING
+1460 1 FT. AUG. 1948
+1459 11 FT. SEPT. 1947
+1448 17 FT. AUG. 1947
+1431 28 FT. JULY 1947
+1403
16 JAN. 16 MAY
34' JUNE 17 SEPT.
40' OCT.
88' NOV.
138' MAY 1948
138' JUNE 1948
13'-1"
12'-0"
5'-6"
6'-6"
CAGE
LADDER
2'-5½"
2'-11½"
3'-1½"
18'-7½"
5'-8¾"
4'-8¾"
SKIP
6'-0"
PLAN OF SHAFT
11TH LEVEL
EL. -1791
57' MARCH 1961


SEVENTH LEVEL
2000
THE CLEVELAND-CLIFFS IRON CO.
MATHER MINE
B SHAFT
-825' SUB LEVEL-CENTER
MINING DEPT. SCALE 1"=50FT. DATE
2200
7200
7000
6800
MINING LIMIT

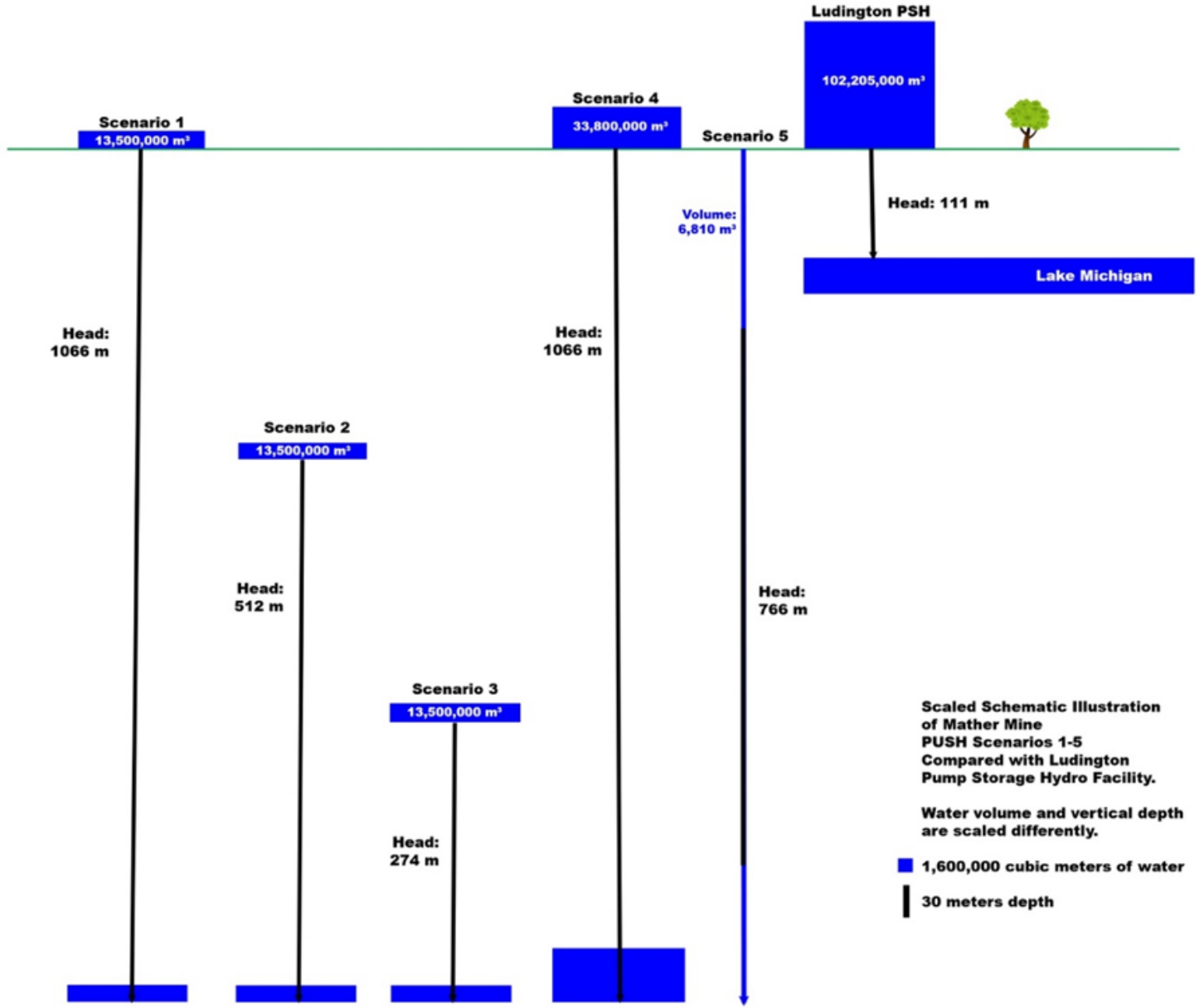

7TH LEVEL
MINING LIMIT

SolidWorks Model





Scenario	High Volume Estimate (m^3)	Low Volume Estimate (m^3)	Maximum Head (m)
Scenario 1: Surface pond to Levels 11-12	13,536,062	4,583,673	1066
Scenario 2: Levels 2-4 to Levels 11-12	13,536,062	4,583,673	512
Scenario 3: Level 6-8 to Levels 11-12	13,536,062	4,583,673	274
Scenario 4: Surface to levels 7-12	33,800,000	18,551,208	792
Scenario 5: Shaft only	6,810	6,810	766


Ludington PSH
102,205,000 m³
Scenario 1
13,500,000 m³
Scenario 4
33,800,000 m³
Scenario 5
Volume:
6,810 m³
Head: 111 m
Lake Michigan
Head:
1066 m
Head:
1066 m
Scenario 2
13,500,000 m³
Head:
512 m
Head:
766 m
Scenario 3
13,500,000 m³
Head:
274 m
Scaled Schematic Illustration
of Mather Mine
PUSH Scenarios 1-5
Compared with Ludington
Pump Storage Hydro Facility.
Water volume and vertical depth
are scaled differently.
1,600,000 cubic meters of water
30 meters depth

Model 2 of daily energy storage scenarios

Volume: 793,800 m^3 (Scenarios 1-4), 6,810 m^3 (Scenario 5), flow rate 10.5 m^3/sec per shaft; pumping time: 7hrs; overall efficiency: 80%						
Scenarios	Gross Head (m)	Head Loss (Hf) m	Net Head (m)	Penstock Diameter (m)	Power (MW)	Energy Generated (MWh)
1	1,066	111	955	1.2*3	295	1,666
2	512	53	459	1.2*3	142	800
3	274	29	245	1.2*3	76	428
4	792	83	709	1.2*3	219	1,238
5	766	80	686	1.2*3	5	31

Model 3 of long-term energy storage scenarios

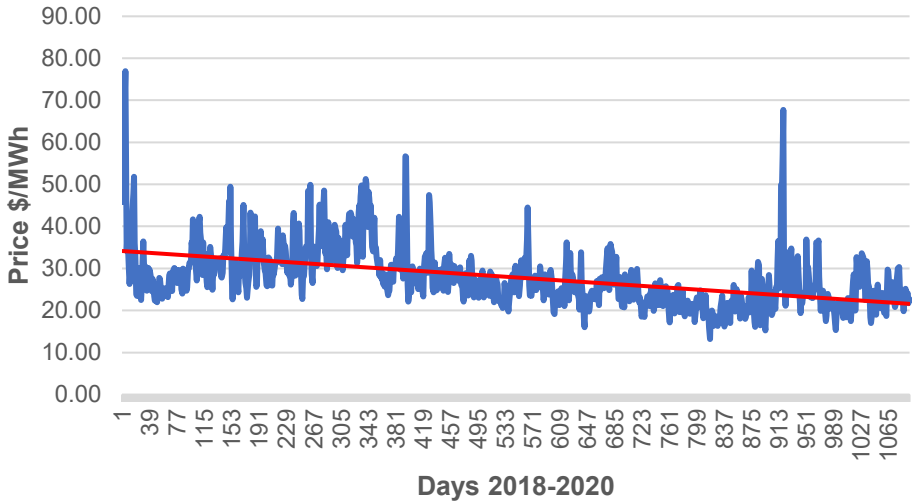
Scenarios	UR and LR Volumes (m3)	Net Head (m)	Flow Rate (single pipe) m3/sec	Generation time (hr)	Power (MW)	Total Power Generation (MWh)
Scenario 1 (High volume estimate)	33,800,000	709	10.5	894	73	52,188
Scenario 1 (Low volume estimate)	18,551,208	709	10.5	491	73	28,643
Scenario 2 (High Volume)	13,536,062	459	10.5	358	47	13,530
Scenario 2 (Low volume)	4,583,673	459	10.5	121	47	4,581

Costs

- CAPEX
  - Analysis of 436 cost data points for PSH facilities, PUSH facilities, or both, from 31 sources
  - PUSH capex range: 1.34 million $/MW to 4.85 million $/MW
- LCOE & LCOS
  - LCOE = fixed costs (FC) ÷ capacity factor (cf) + variable costs (VC)
  - LCOS = LCOE for storage
  - Pumping cost = fuel cost=electricity cost
- Cost recovery
  - PPA
  - Market participation (electricity + ancillary services + capacity)
  - Cost of service recovery

Node	Year	Avg Off Peak Price ($/MWh)	Avg Peak Price ($/MWh)	Price Difference ($/MWh)	Price Difference Delta (Ratio)
Michigan Hub	2018-20	21.69	30.34	8.65	1.40
Integrated Node	2018-20	21.71	31.16	9.45	1.44
Warden Zone	2018-20	21.27	30.54	9.27	1.44

Three-year designated peak and off-peak pricing for the three target nodes



Average Daily pricing at Michigan hub nodes for years 2018-20

Node	Year	Avg Off Peak Price ($/MWh)	Avg Peak Price ($/MWh)	Price Difference ($/MWh)	Price Difference Delta (Ratio)
Michigan Hub	2018-20	21.55	33.56	12.01	1.56
Integrated Node	2018-20	21.12	34.04	12.92	1.61
Warden Zone	2018-20	20.83	34.26	13.43	1.64

Three-year actual peak and off-peak pricing for the three target nodes

- Financial lifeline = little effect
- DR = significant effect
- The existing subsidy = significant effect

Impact of PVPR on the revenue of PUSH facility Scenario 1, 20% Tax incentive, 5% DR

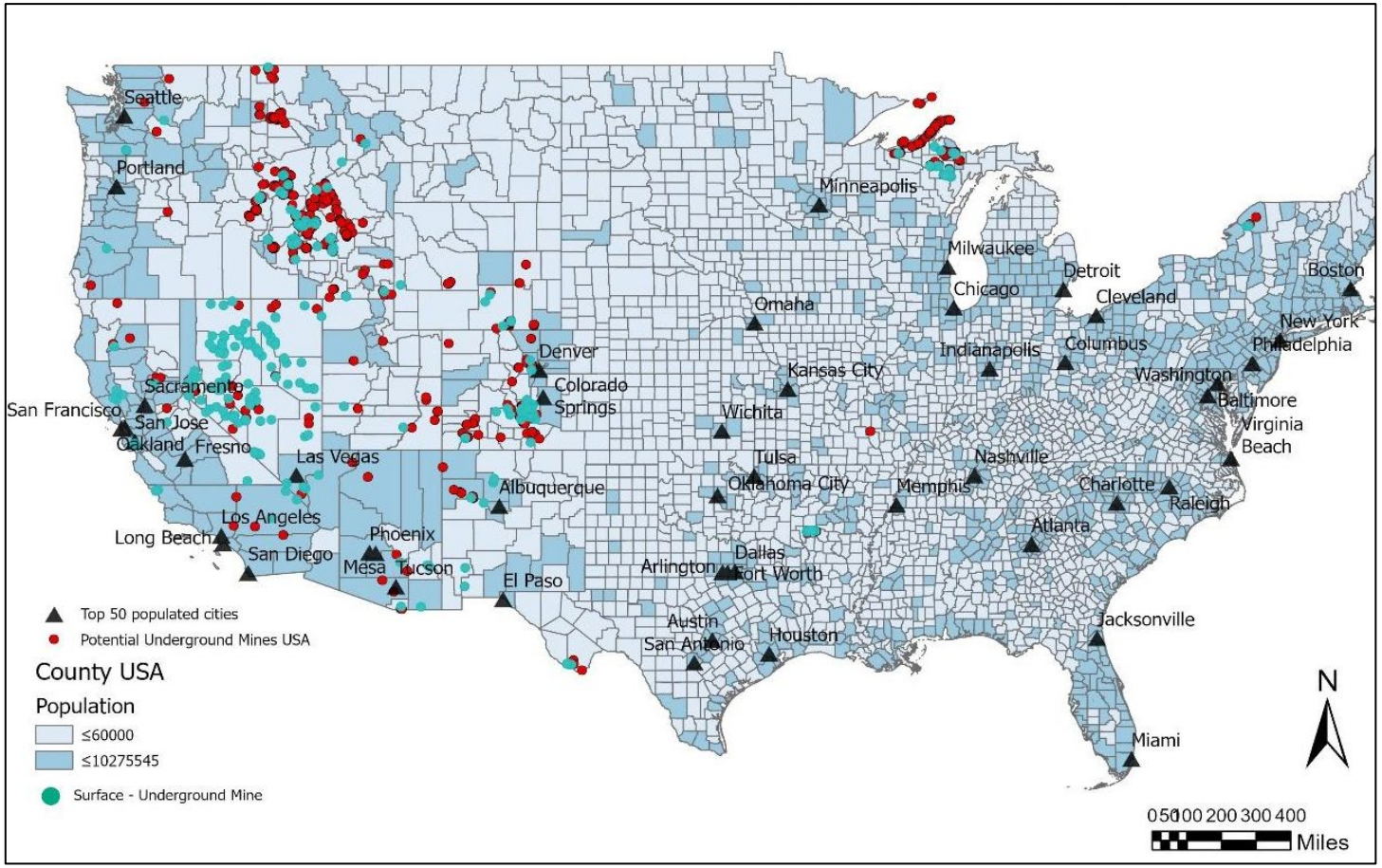
Item	PVPR 1:3	PVPR 1:4	PVPR 1:5	Unit
Electricity Revenue	$36,437,919	$48,583,892	$60,729,865	$/Yr
Annual profit	$6,062,410	$18,208,383	$30,354,356	$/Yr
PUSH facility Scenario 1: Partially subterranean, 295 MW nameplate capacity, 583,100 MWh annual energy stored				

Impact of PVPR ratio on the revenue of PUSH facility Scenario 2, 20% Tax incentive, 5% DR

Item	PVPR 1:3	PVPR 1:4	PVPR 1:5	Unit
Electricity Revenue	$17,497,200	$23,329,600	$29,162,000	$/Yr
Annual profit	$2,719,884	$8,552,284	$14,384,684	$/Yr
PUSH facility Scenario 2: Fully subterranean, 142 MW nameplate capacity, 280,000 MWh annual energy stored				

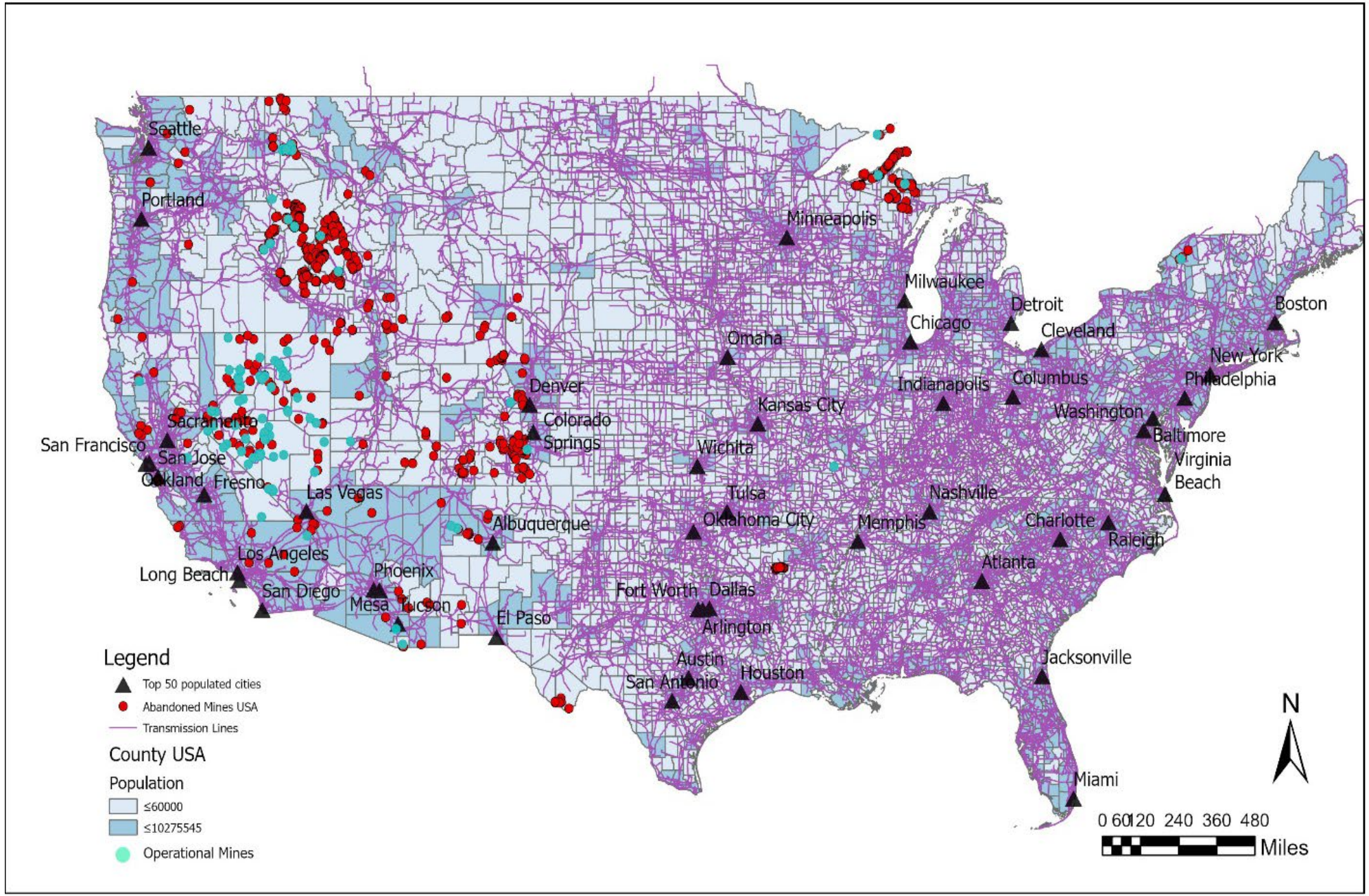
Potential PUSH site location with solar map

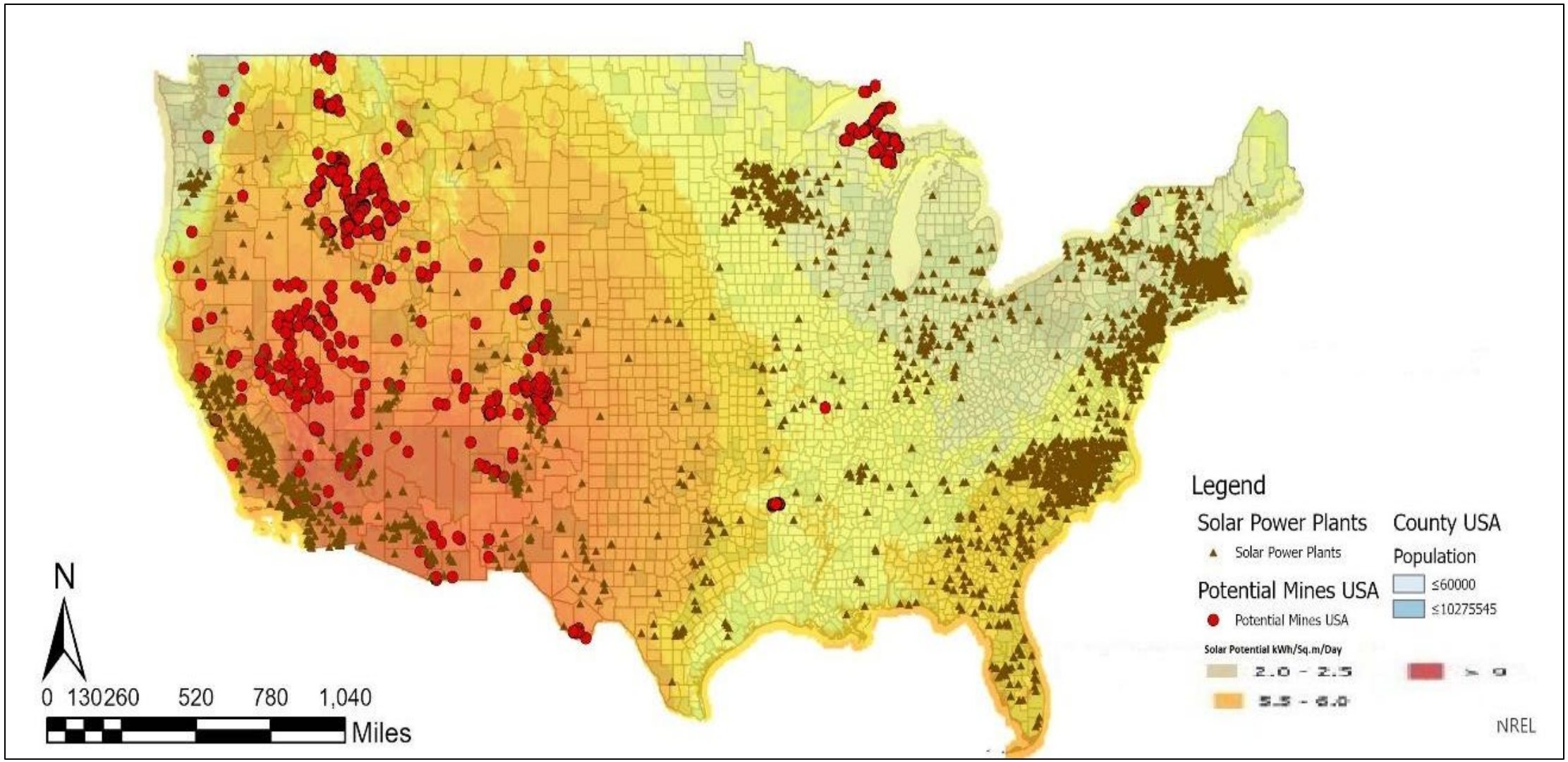
- Total 968 mines identified as feasible mines for PUSH development
- 873 mines are past producing mines and 95 are currently operational
- 706 mines are completely underground and 262 are semi – underground mines
- Marquette county have the most mines feasible for PUSH in a county with over 60,000 people

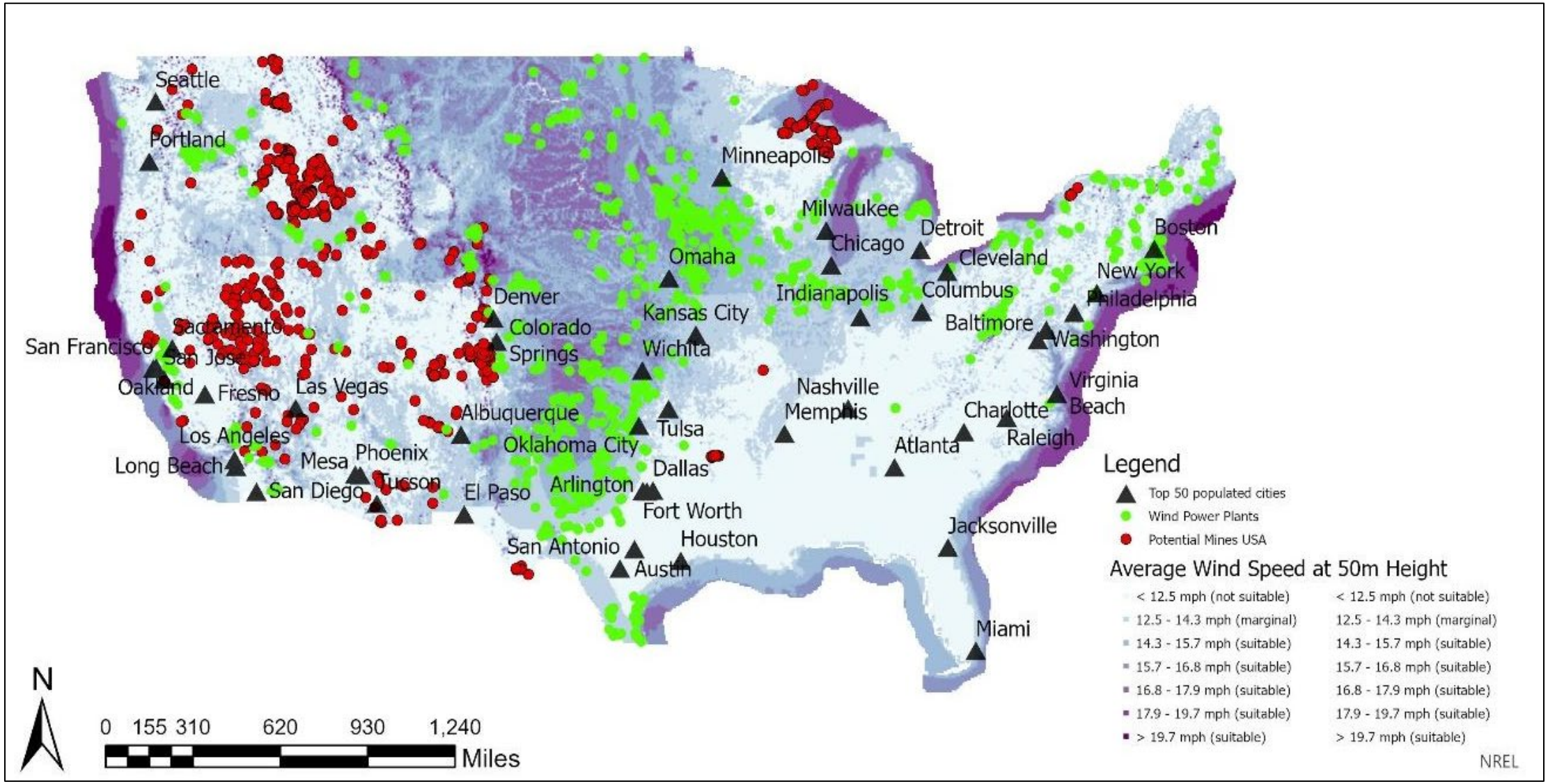


Map showing load centers (cities and counties) with mine location

No.	State	No of mines	Size
1	Arizona	13	Small and large
2	Arkansas	24	Small
3	California	26	Small, medium, large
4	Colorado	145	Small, medium, large
5	Idaho	397	Small, medium, large
6	Michigan	144	Small, medium, large
7	Missouri	1	medium
8	Montana	3	Small and medium
9	Nevada	124	Mix of small medium and large
10	New York	4	Large
11	Oregon	4	Medium and small
12	Texas	19	Small and Medium
13	Utah	11	Mix of small, medium and large
14	Washington	9	Mix of small and medium
15	Wyoming	30	All Small


Seattle
Portland
Minneapolis
Milwaukee
Detroit
Boston
Chicago
Cleveland
Omaha
New York
Columbus
Philadelphia
Indianapolis
Denver
Kansas City
Washington
Sacramento
Colorado
Springs
Baltimore
San Francisco
San Jose
Wichita
Virginia
Beach
Oakland
Fresno
Las Vegas
Tulsa
Nashville
Albuquerque
Oklahoma City
Memphis
Charlotte
Raleigh
Los Angeles
Atlanta
Long Beach
Phoenix
San Diego
Fort Worth
Dallas
Mesa
Tucson
El Paso
Arlington
Austin
Jacksonville
San Antonio
Houston
Miami
Legend
Top 50 populated cities
Abandoned Mines USA
Transmission Lines
County USA
Population
≤60000
≤10275545
Operational Mines
N
0 60 120 240 360 480
Miles


N
0 130260 520 780 1,040
Miles
Legend
Solar Power Plants
Solar Power Plants
Potential Mines USA
Potential Mines USA
Solar Potential kWh/Sq.m/Day
2.0 - 2.5
5.5 - 6.0
County USA
Population
≤60000
≤10275545
NREL


Seattle
Portland
Minneapolis
Milwaukee
Detroit
Boston
Chicago
Omaha
Cleveland
New York
Indianapolis
Columbus
Philadelphia
Denver
Kansas City
Baltimore
Colorado
Springs
Wichita
Washington
Sacramento
San Francisco
San Jose
Oakland
Fresno
Las Vegas
Nashville
Virginia
Beach
Albuquerque
Memphis
Charlotte
Tulsa
Los Angeles
Oklahoma City
Raleigh
Atlanta
Long Beach
Mesa
Phoenix
Dallas
Tucson
San Diego
El Paso
Arlington
Fort Worth
Jacksonville
Houston
San Antonio
Austin
Miami
Legend
Top 50 populated cities
Wind Power Plants
Potential Mines USA
Average Wind Speed at 50m Height
< 12.5 mph (not suitable)
12.5 - 14.3 mph (marginal)
14.3 - 15.7 mph (suitable)
15.7 - 16.8 mph (suitable)
16.8 - 17.9 mph (suitable)
17.9 - 19.7 mph (suitable)
> 19.7 mph (suitable)
< 12.5 mph (not suitable)
12.5 - 14.3 mph (marginal)
14.3 - 15.7 mph (suitable)
15.7 - 16.8 mph (suitable)
16.8 - 17.9 mph (suitable)
17.9 - 19.7 mph (suitable)
> 19.7 mph (suitable)
N
0 155 310 620 930 1,240
Miles
NREL

Yearly U.S. PUSH potential based on 10% Mather B's storage capacity, partially underground

Combinations (Mine Sites)	No of Mines	Cumulative Power Capacity (MW)	Cumulative Yearly Energy Storage (MWh)	Percentage of Total US Electricity Generation in 2020	Percentage of RE electricity generation in 2020
(1) Current and past producers; semi underground and underground	968	285,560	564,440,800	14.11	71.27
(2) Past producers and underground	673	198,535	392,426,300	9.81	49.55
(3) Current producer and underground	33	9,735	19,242,300	0.48	2.43
(4) Past producers; semi and completely underground	873	257,535	509,046,300	12.73	64.27
(5) Surface-underground; past and current producers	262	77,290	152,772,200	3.82	19.29
(6) Surface underground; current producers	62	18,290	36,152,200	0.90	4.56

Yearly U.S. PUSH potential based on 10% Mather B's capacity, completely underground

Combinations (Mine Sites)	No of Mines	Cumulative Power Capacity (MW)	Cumulative Yearly Energy Storage (MWh)	Percentage of Total US Electricity Generation in 2020	Percentage of RE electricity generation in 2020
(1) Current and past producers; semi underground and underground	968	137,456	271,040,000	6.78	34.22
(2) Past producers and underground	673	95,566	188,440,000	4.71	23.79
(3) Current producer and underground	33	4,686	9240,000	0.23	1.17
(4) Past producers; semi and completely underground	873	123,966	244,440,000	6.11	30.86
(5) Surface-underground; past and current producers	262	37,204	73,360,000	1.83	9.26
(6) Surface underground; current producers	62	8,804	17,360,000	0.43	2.19

Yearly U.S. PUSH potential based on 80% Mather B's capacity, four pumping/discharge cycles a year

Combinations (Mine Sites)	No of Mines	Optimal PUSH Facility Scenario	Cumulative Power Capacity (MW)	Cumulative Yearly Energy Storage (MWh, 4 seasonal cycles)	Percentage of Total US Electricity Generation in 2020	Percentage of RE electricity generation in 2020
(1) Current and past producers; semi underground and underground	185	Model 3 scenario 2 (high volume)	8,695	8,009,760	0.20	1.01
(2) Past producers and underground	104	Model 3 scenario 2 (high volume	4,888	4,502,784	0.11	0.57
(3) Current producer and underground	13	Model 3 scenario 2 (high volume	611	562,848	0.01	0.07
(4) Past producers; semi and completely underground	141	Model 3 scenario 2 (high volume	6,627	6,104,736	0.15	0.77
(5) Surface-underground; past and current producers	68	Model 3, Scenario 1 (high volume)	3,196	11,356,000	0.28	1.43
(6) Surface underground; current producers	31	Model 3, Scenario 1 (high volume)	1,457	5,177,000	0.13	0.65

Legal and regulatory issues

1. Hydroelectric power facility
2. Grid-connected storage facility
3. Decommissioned mine as real property
4. Brownfield site
5. Industrial facility within the boundaries of a municipality
6. Heritage site
7. Enabler of the decarbonization effort

Source: Britannica

Thank you!

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