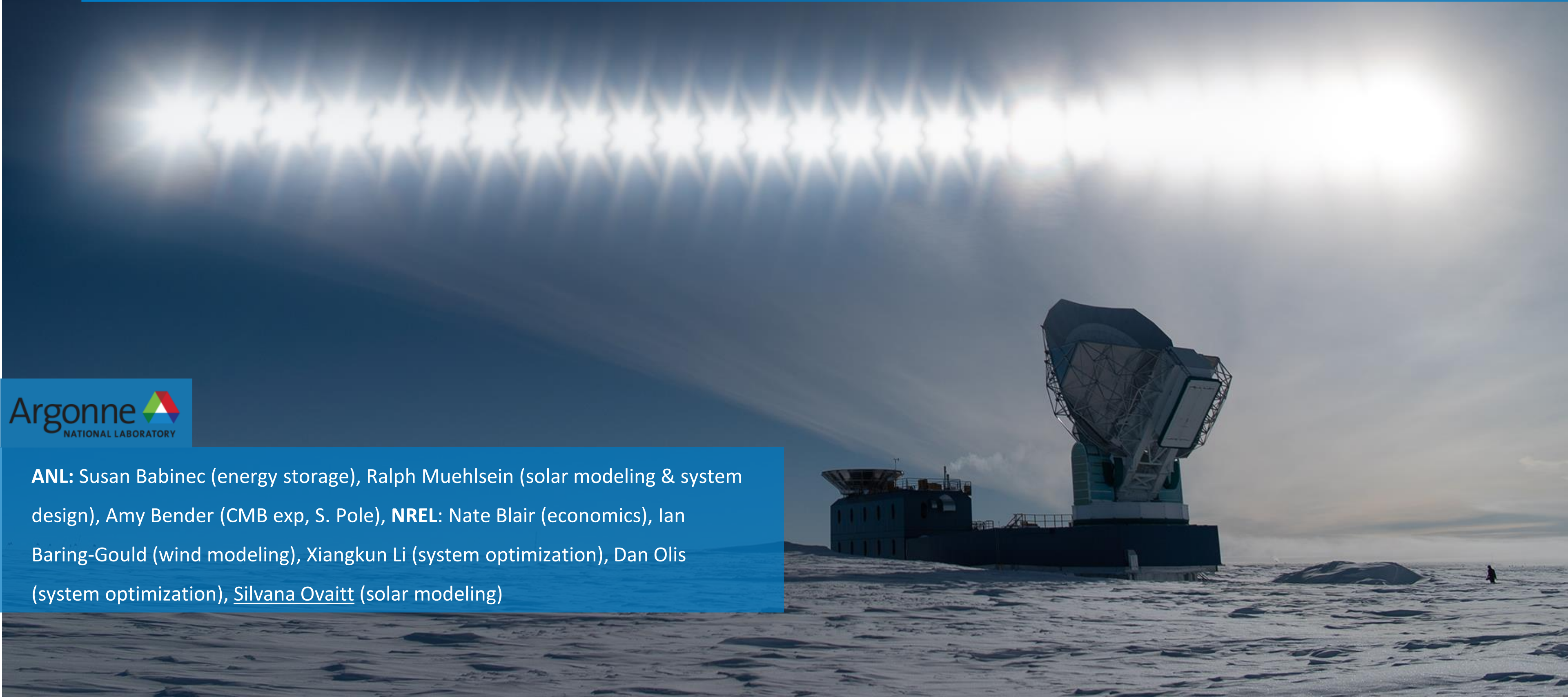
NREL
Transforming ENERGY

Towards a greener Antarctica: A techno-economic analysis of renewable energy generation and storage at the South Pole

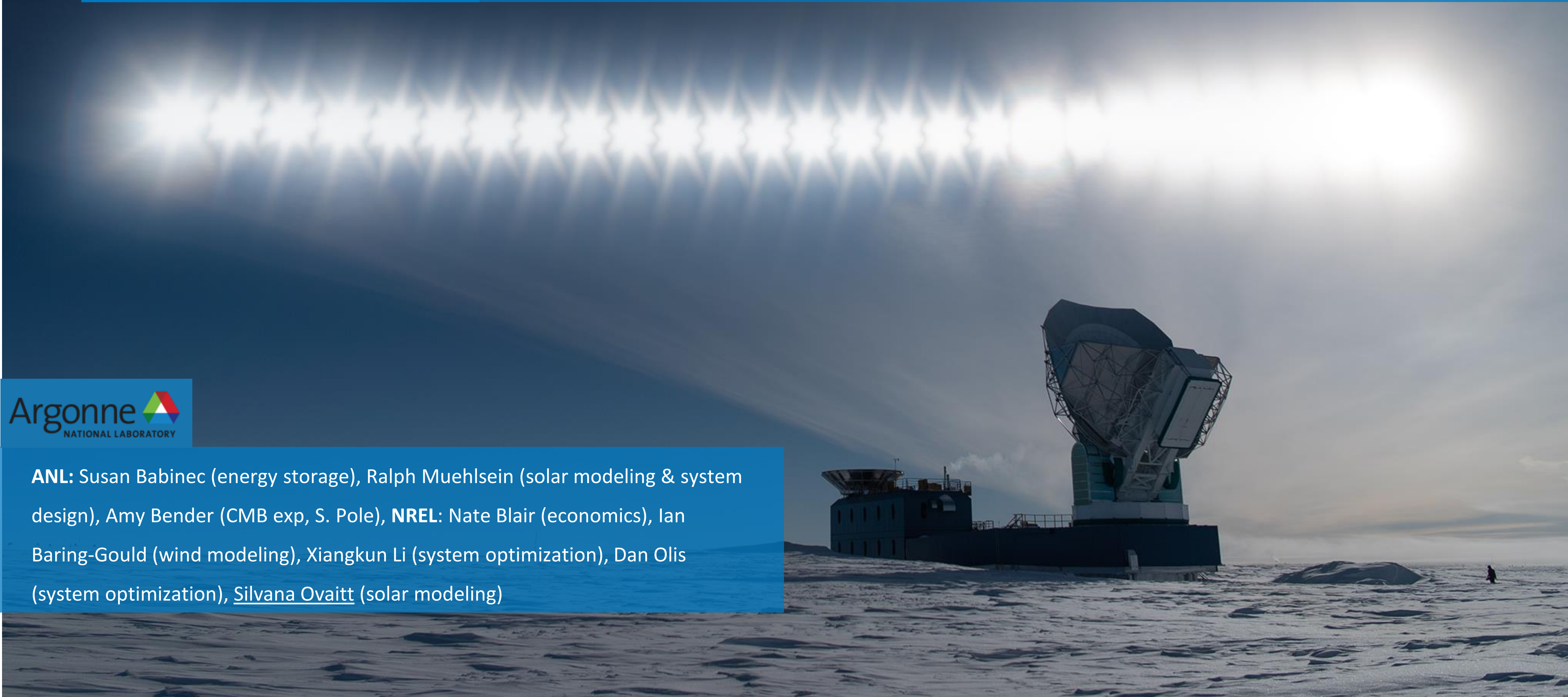


Argonne NATIONAL LABORATORY

ANL: Susan Babinec (energy storage), Ralph Muehlsein (solar modeling & system design), Amy Bender (CMB exp, S. Pole), **NREL**: Nate Blair (economics), Ian Baring-Gould (wind modeling), Xiangkun Li (system optimization), Dan Olis (system optimization), Silvana Ovaitt (solar modeling)

PENGUINS AND PV

Even better than PV and kittens



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Artic and Extreme Climate Research

NREL’s Alaska Campus in Fairbanks

Working toward an **equitable energy transition** through the development of resilient building and energy technologies in the world’s extreme climates and frontline communities.

Applied Research for Communities in Extreme Environments (ARCEE), previously CCHRC, joined NREL in 2020, bringing 20 years of unrivaled experience in extreme-climate sustainable housing.

Photo by Seth Adams, NREL 69640

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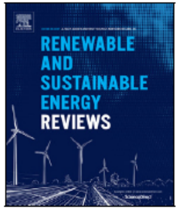

Original research article

Techno-economic analysis of renewable energy generation at the South Pole

Susan Babinec [a], Ian Baring-Gould [b], Amy N. Bender [a,*], Nate Blair [b], Xiangkun Li [b], Ralph T. Muehleisen [a], Dan Olis [b], Silvana Ovaitt [b]

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ABSTRACT

Transitioning from fossil-fuel power generation to renewable energy generation and energy storage in remote locations has the potential to reduce both carbon emissions and cost. This study presents a techno-economic analysis for implementation of a hybrid renewable energy system at the South Pole in Antarctica, which currently hosts several high-energy physics experiments with nontrivial power needs. A tailored model of resource availability and economics for solar photovoltaics, wind turbine generators, lithium-ion energy storage, and long-duration energy storage at this site is explored in different combinations with and without existing diesel energy generation. The Renewable Energy Integration and Optimization (REopt) platform is used to determine the optimal system component sizing and the associated system economics and environmental benefit. We find that the least-cost system includes all three energy generation sources and lithium-ion energy

https://doi.org/10.1016/j.rser.2023.114274

The Plan

McMurdo Station -77.8500, 166.6667

Provide 15 years of clean energy for the 170 kW for the upcoming Cosmic Microwave telescope (CMB-S4) with generation and storage that offer cost savings and decarbonization

CMB-S4 mock-up
Image from https://cmb-s4.org/experiment/sites/

The requirements

NSF Photo

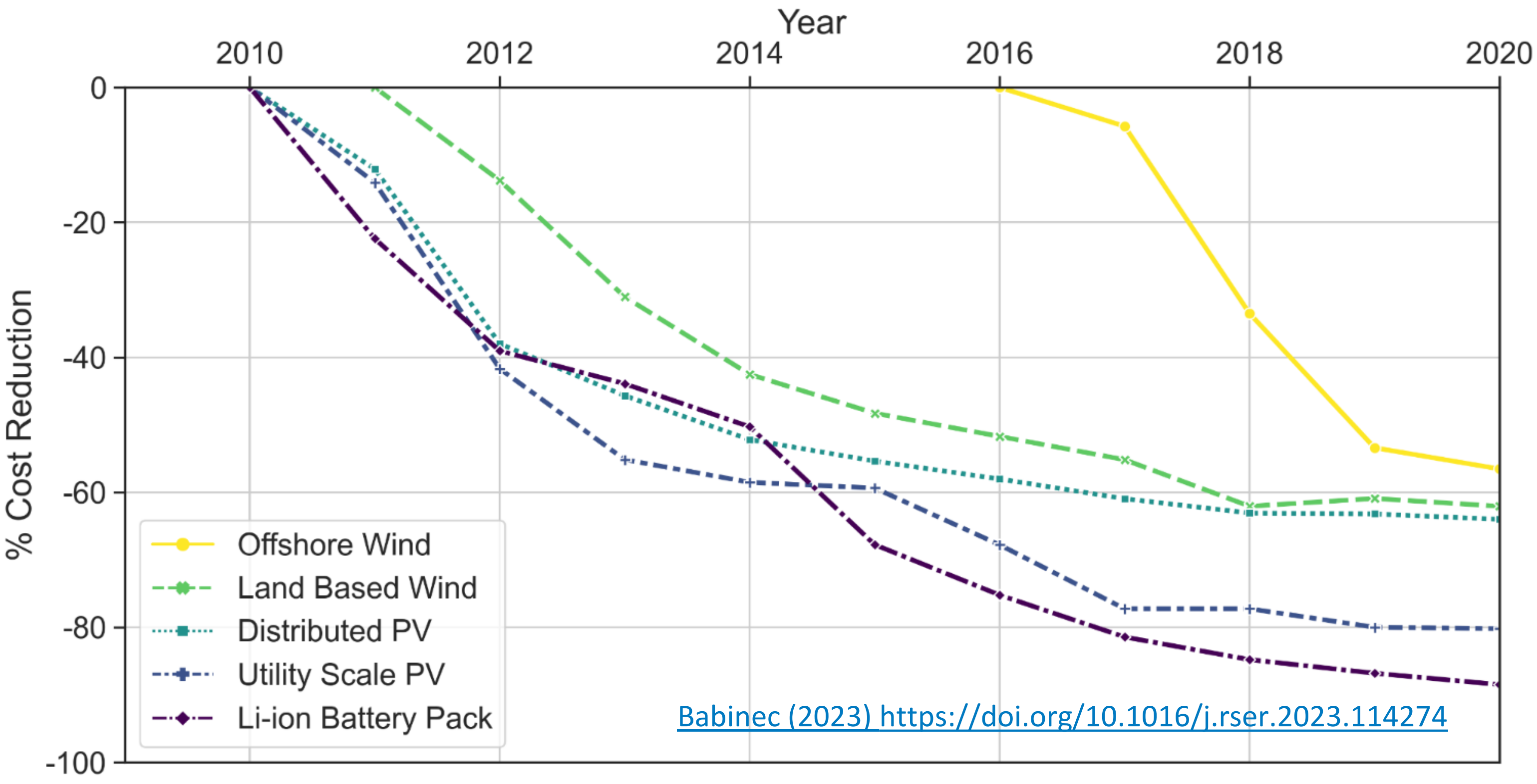
Diesel annual consumption: 124k gallons, ~$40 per gallon

Sky above horizon Sept 21- March 21 only

Low level wind available year-round

Equipment must survive T of -80 C

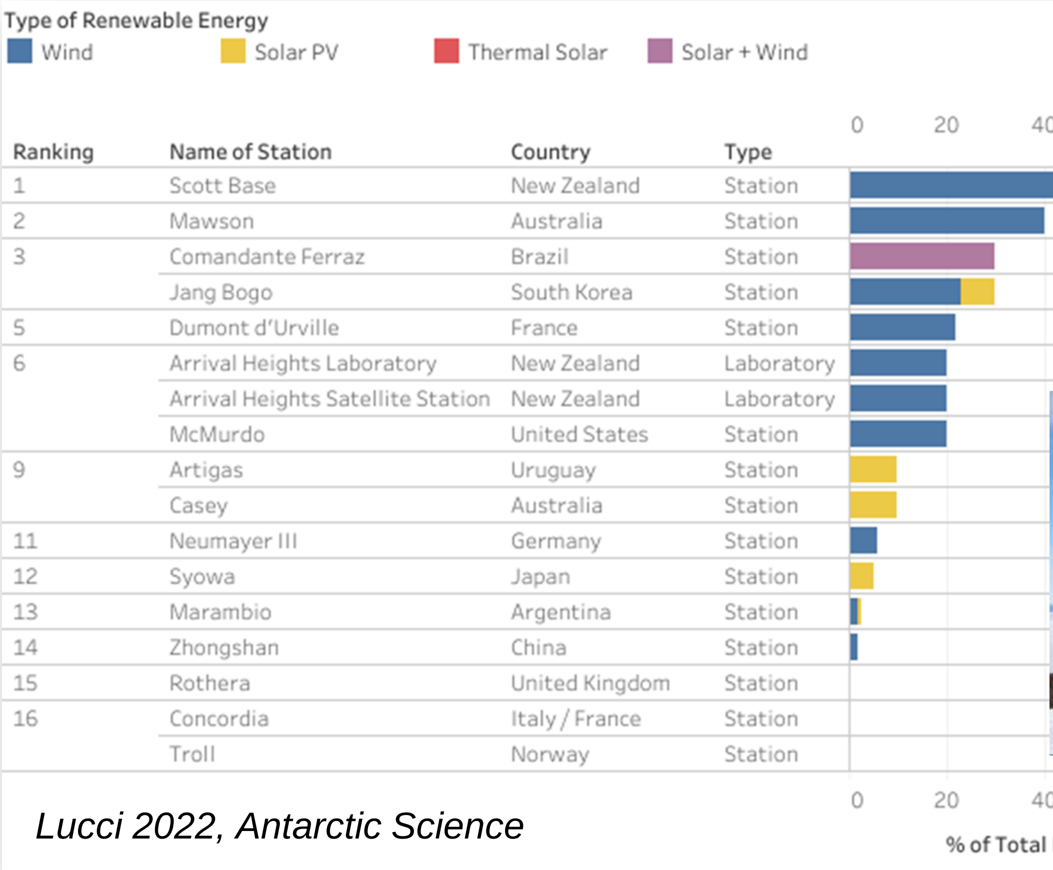
Cost of renewable energy generation and energy storage has decreased dramatically over the past decade



Babinec (2023) https://doi.org/10.1016/j.rser.2023.114274

Technology has increased maturity and reliability at the same time.

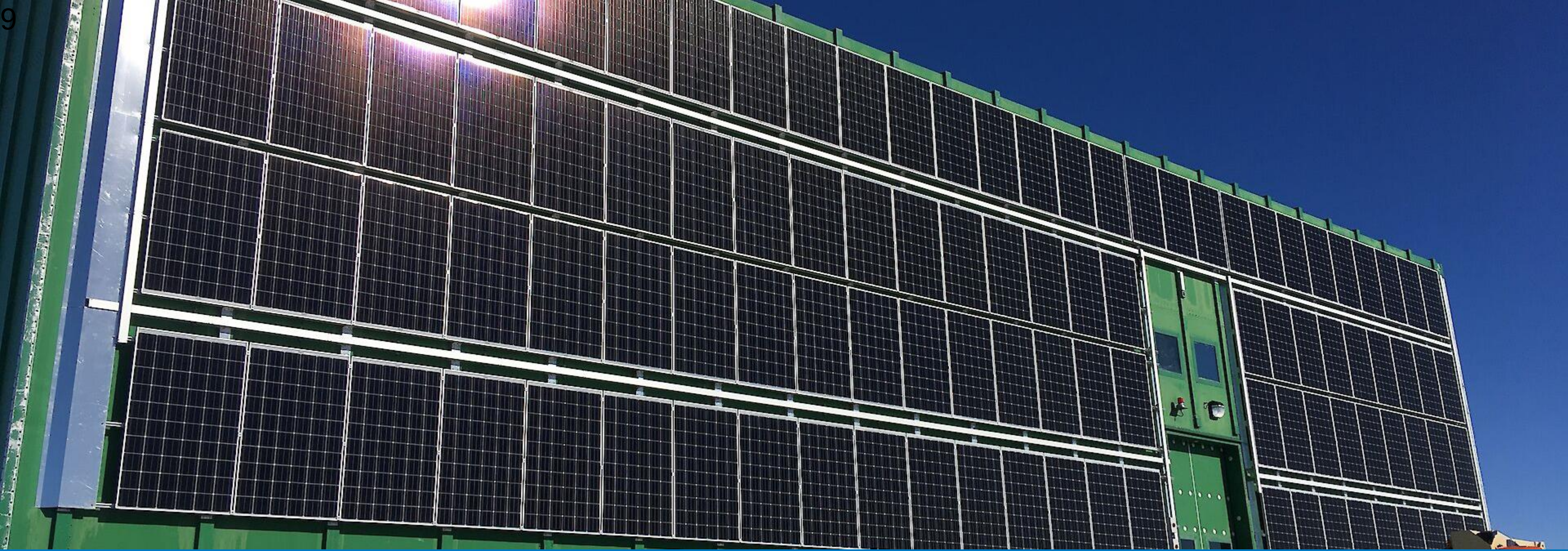
Renewable Energy is in use at Some Antarctic Stations



Ranking	Name of Station	Country	Type
1	Scott Base	New Zealand	Station
2	Mawson	Australia	Station
3	Comandante Ferraz	Brazil	Station
	Jang Bogo	South Korea	Station
5	Dumont d'Urville	France	Station
6	Arrival Heights Laboratory	New Zealand	Laboratory
	Arrival Heights Satellite Station	New Zealand	Laboratory
	McMurdo	United States	Station
9	Artigas	Uruguay	Station
	Casey	Australia	Station
11	Neumayer III	Germany	Station
12	Syowa	Japan	Station
13	Marambio	Argentina	Station
14	Zhongshan	China	Station
15	Rothera	United Kingdom	Station
16	Concordia	Italy / France	Station
	Troll	Norway	Station

Lucci 2022, Antarctic Science


McMurdo Station (USA), Scott Base (New Zealand)



Casey Station, AUS 2019

66.2821° S, 110.5285° E

- 105 Aleo Solar panels, 30kW, 2019, Fronius inverters
- 10% of facility demand
- Installation of ~15 panels per day (17 mph, -7 C slowed work)

https://www.antarctica.gov.au/news/2019/first-australian-solar-farm-in-antarctica-opens-at-casey-research-station/

Princess Elisabeth Station, Belgium 2009

71.9499° S, 23.3470° E

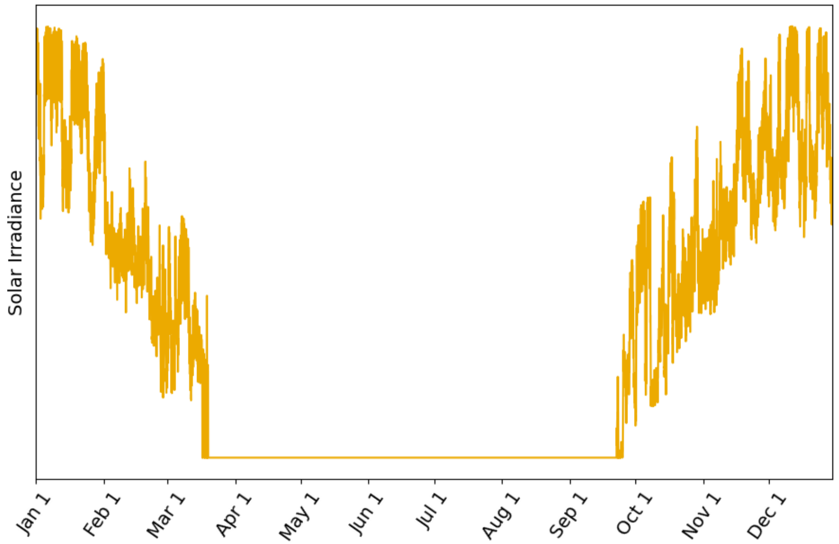
- First and only net zero station (seasonal),
- 50 people accommodations
- 9 wind turbines (54kWp)
- Design service life: 25 years
- 284 to 332 panels PV panels - Kyocera modules; 88 bifacial LG [1]
- 30 solar thermal panels
- 192 lead-acid batteries (Hoppecke Sun Power VRL 2V 125)

[1] https://www.sma-sunny.com/en/upgrades-for-emissions-free-research-station-in-antarctica/

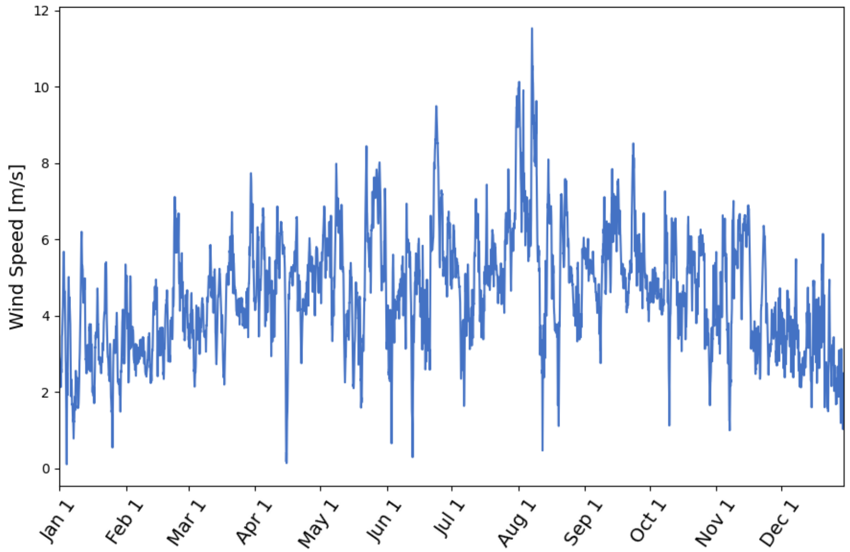
Image from: http://www.antarcticstation.org/station/renewable_energies

Renewable Resource Availability

Solar available only during part of year

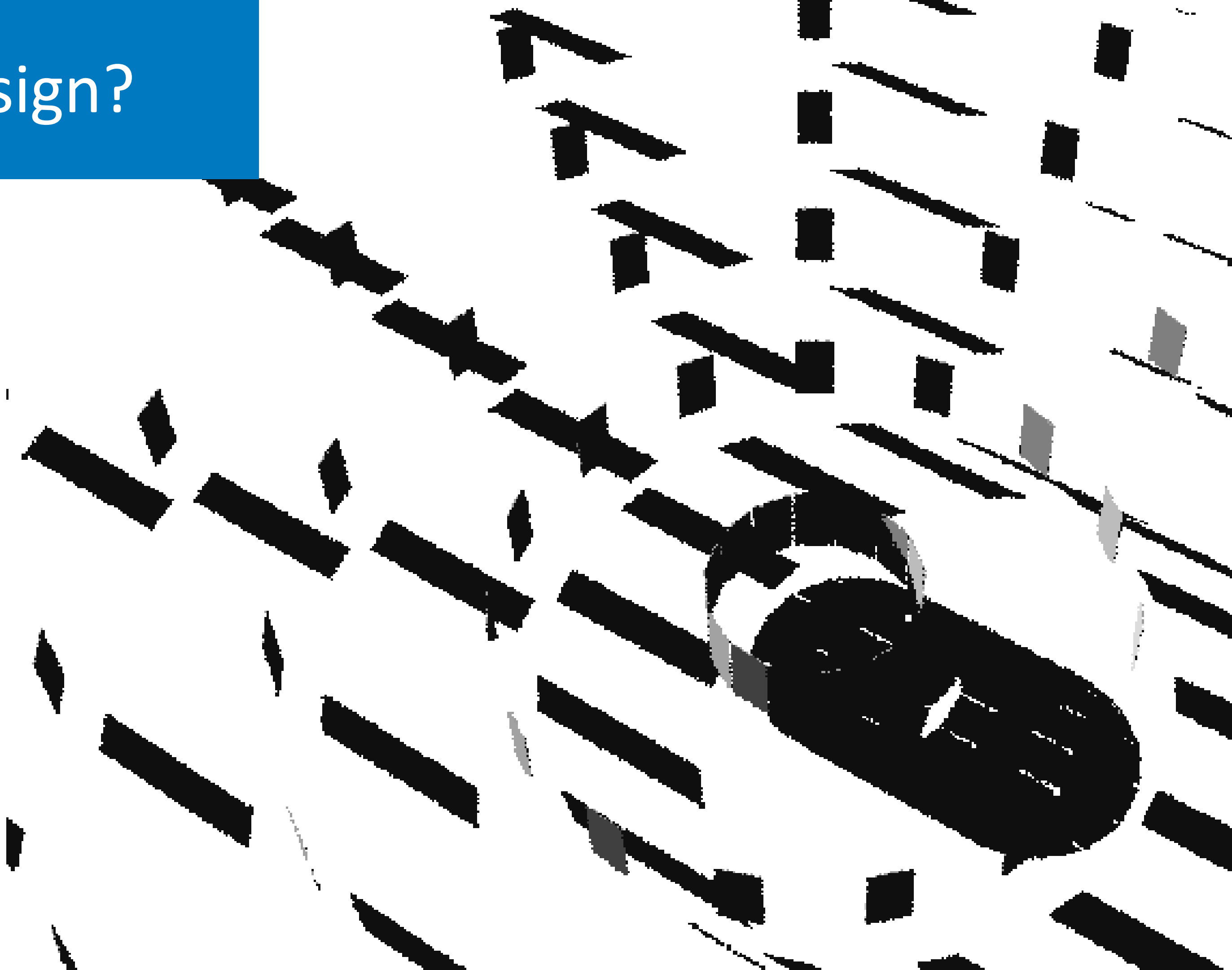


Wind available year-round, stronger in winter.

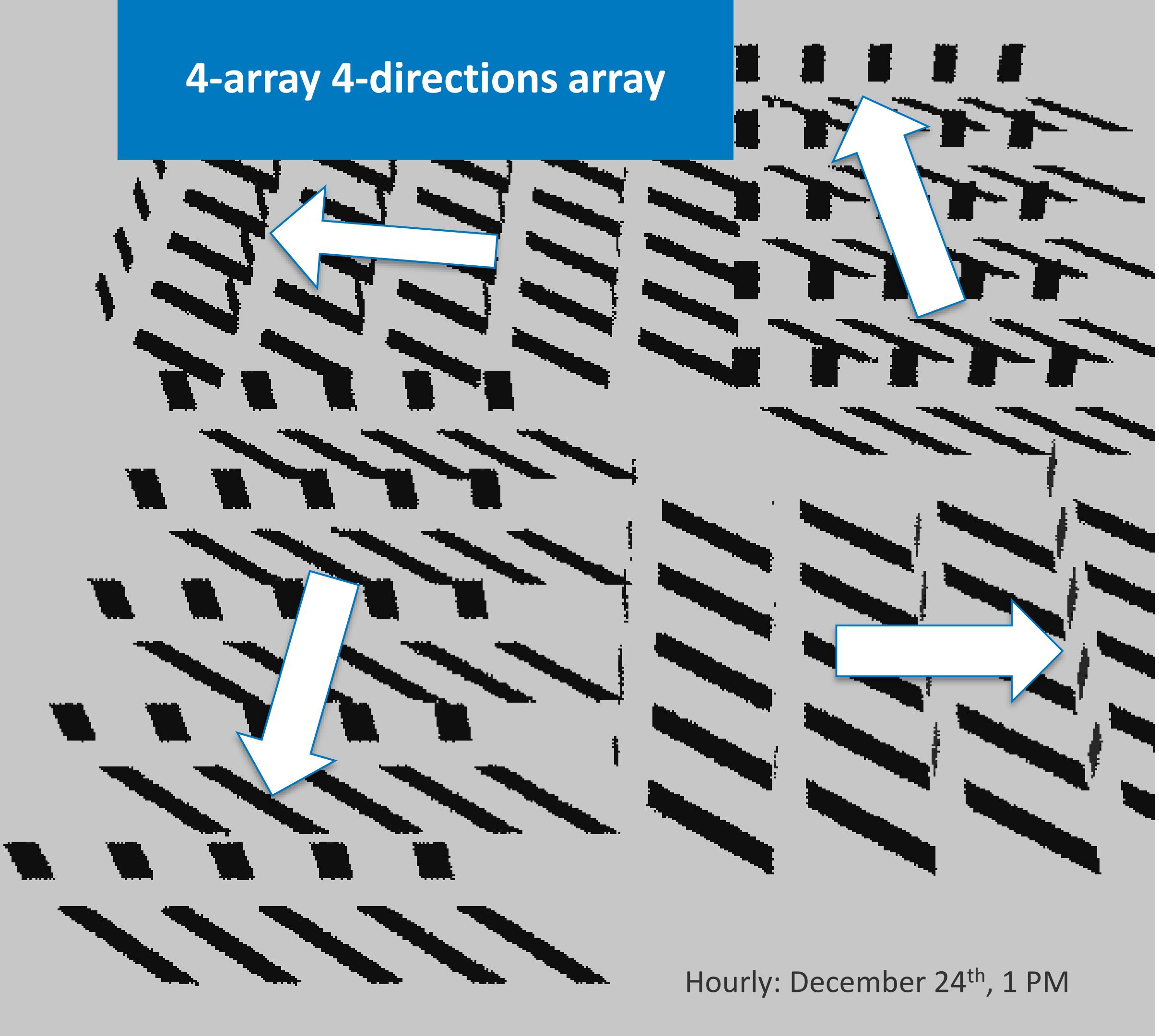


- NASA satellite data
- NOAA ground-data from the past decade is used to inform solar availability over the year

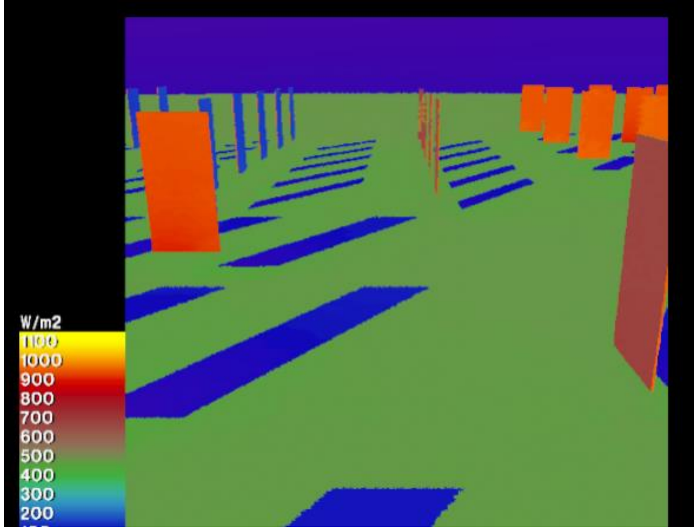
Radial design?

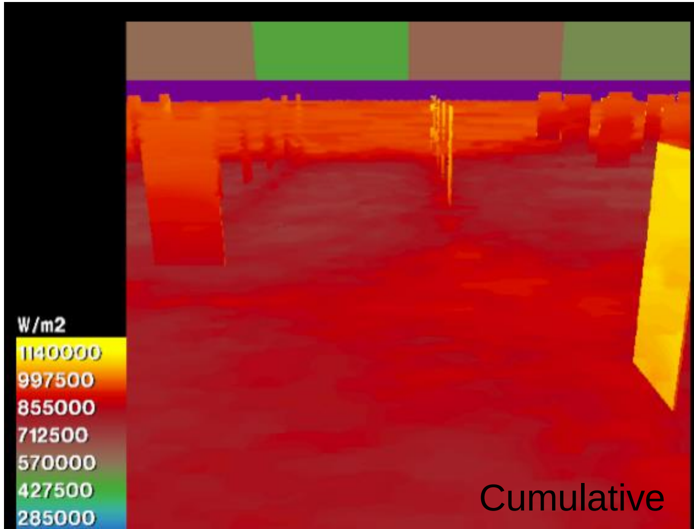


4-array 4-directions array



Hourly: December 24th, 1 PM

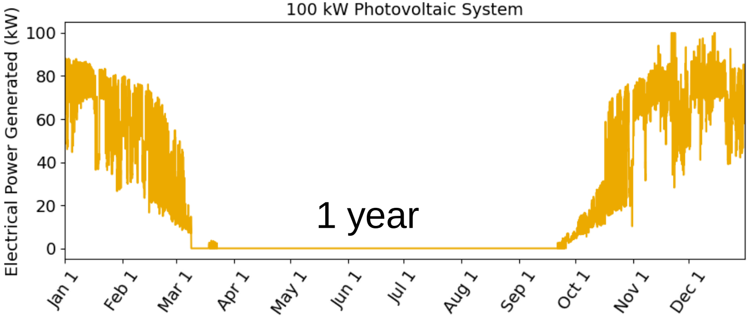


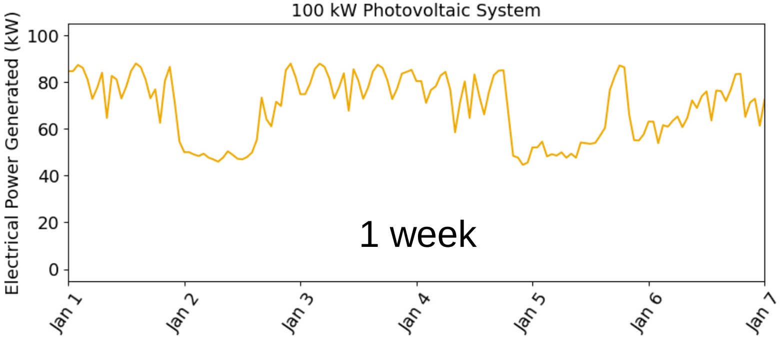


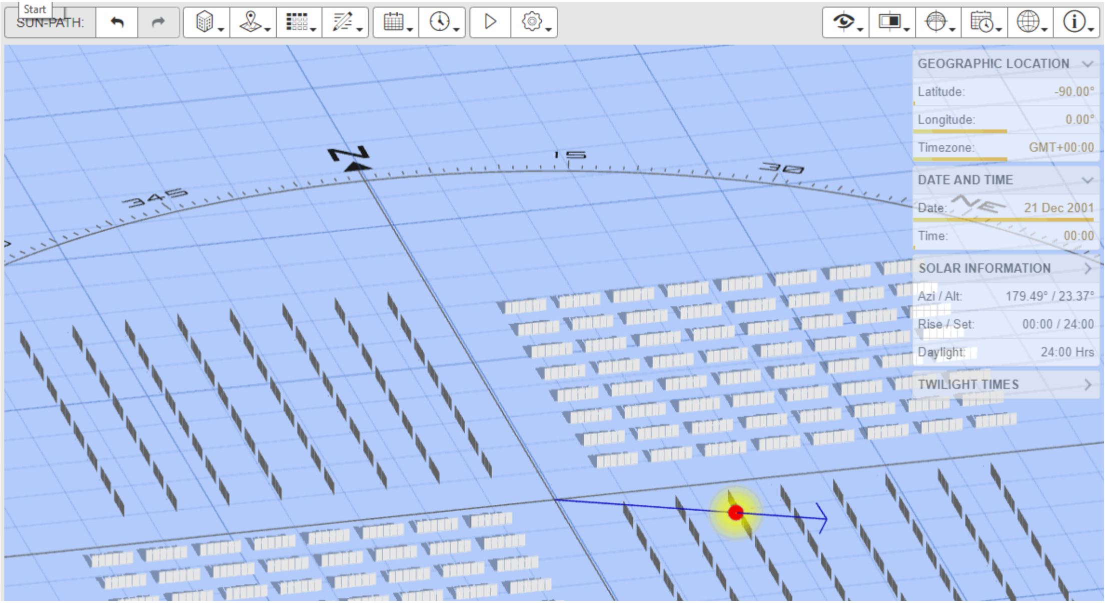
Cumulative

Energy Generation Resources: SOLAR

bifacial_radiance + PVLib







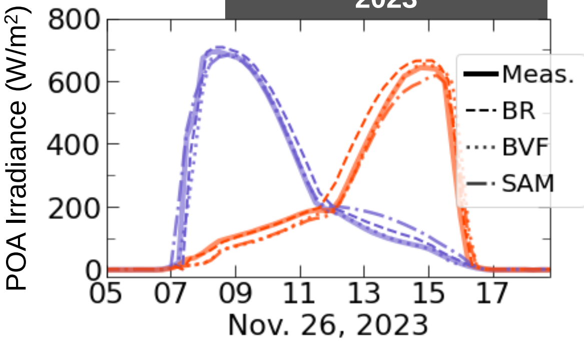
Animation created with sketchup +
https://andrewmarsh.com/apps/staging/sunpath3d.html

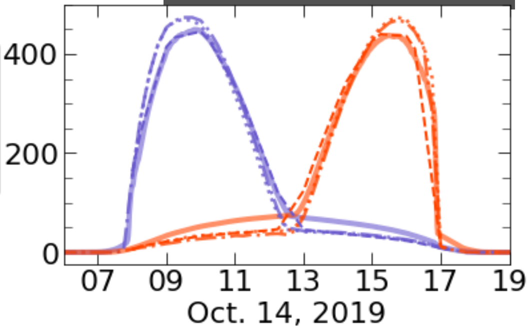
Model Validation

bifacial_radiance vs bifacialVF vs System Advisor Model (SAM)

Golden Site, Nov. 2023

Fairbanks Site, June 2019





RMSE Example Clear Sky Day (%)

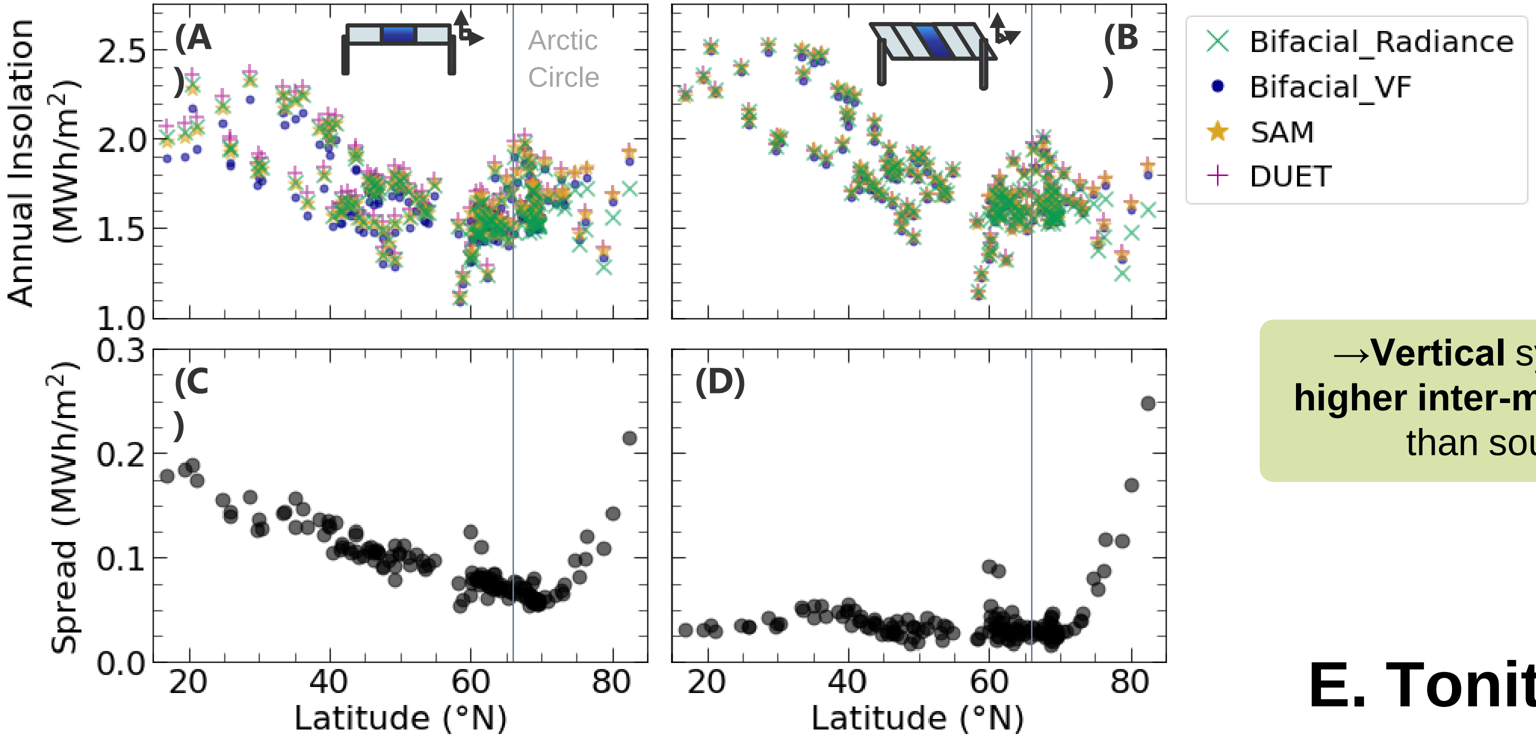
	Golden		Fairbanks	
	East	West	East	West
BR	10.4	21.7	9.6	12.4
B_VF	16.9	15.7	16	15.4
SAM	16.3	21.7	15	16.3

→**BR** tends to have **lower RMSE**

E. Tonita
PVSC 2024

Model Comparison

bifacial_radiance vs bifacialVF vs System Advisor Model vs DUET SUNLAB



→**Vertical** systems have **higher inter-model variance** than south tilted

E. Tonita
PVSC 2024

 etoni044@uottawa.ca

Snow Drift

- **1 ft accumulation per year. DOES NOT MELT AWAY!**
- PV panels will create snow drifts, must design accordingly
  - Mobile rows: PV backing structure mounted on skis. Rearranging rows could even out drift accumulation and/or allow snow grooming
  - Locate PV array down-wind of known buildings
  - Existing drift modeling software package can inform design choices[1]

Image from [2], Svalbard, Norway

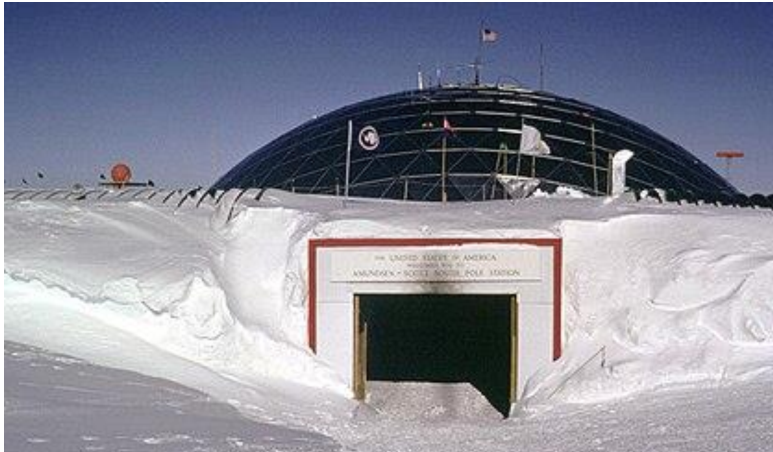
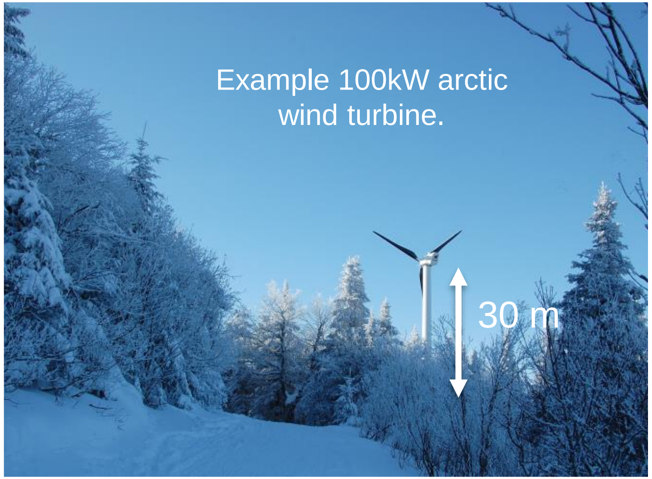


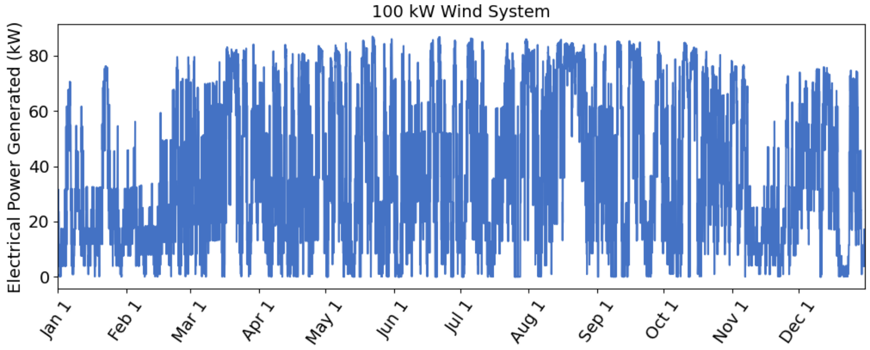
Image from Wikipedia, Amudsen-Scott Station 1975-2010

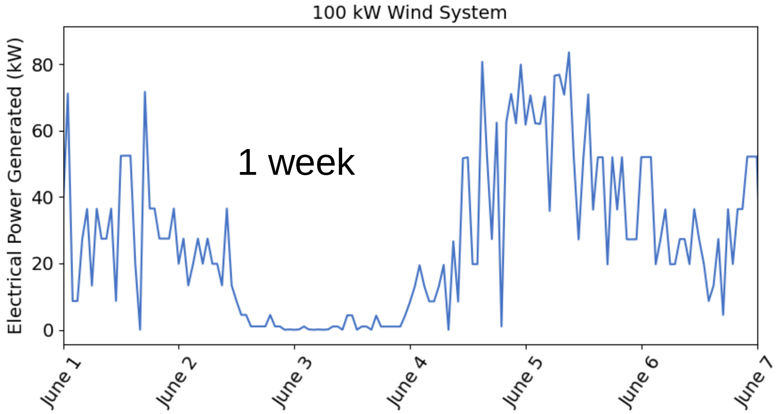
[1]https://apps.dtic.mil/sti/pdfs/AD1176163.pdf

[2]https://www.sciencedirect.com/science/article/pii/S0038092X21004394

Energy Generation Resources: WIND







Wind Engineering Challenges

Low temperature operation of wind turbine

- Some models verified & rated to -40 C to meet commercial market demand, but originally designed to -70 C
- Reaching lower temperature requires customization of lubrication and other materials, removal of LCD screens, installation of heating elements etc.

Ice based foundation for wind turbines needs development

- South Pole Telescope ice foundation provides stable support of the telescope, represents a good starting place
- Smaller turbines/towers have been guyed

Battery System

LI-ION

- High capex
- Low shipping cost (high energy density)
- Flammable (most of them)
- Designed for < 6-8 hours discharge
- Mature

LDES

- Low capex when mature
- Low energy density - High shipping cost
- Aqueous = nonflammable
- Designed for 10s-100's hour discharge
- Emerging

- Storage system will require heated enclosure for operation
  - Use of a simple insulated container using battery heat is one option
  - Excess renewable energy can also be used for heating
- Nonflammable options vetted for South Pole use
  - These also require less heating – good to -50°C

Babinec (2023) https://doi.org/10.1016/j.rser.2023.114274

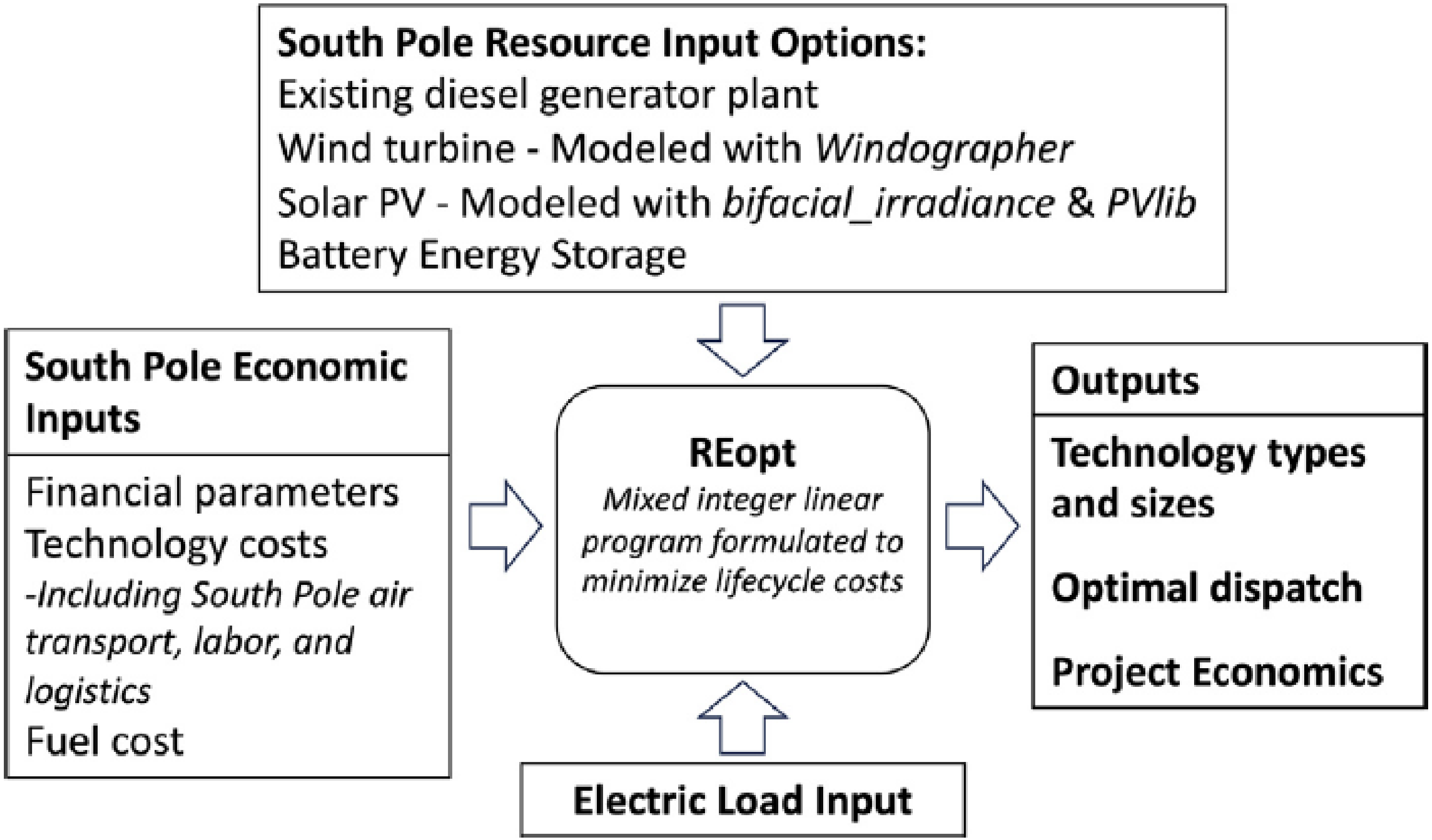
Configuration Overview

	DIESEL	SOLAR	WIND	Lithium-Ion	LDES
BAU	●				
A	●	●		●	
B	●		●	●	
C	●	●	●	●	
D		●	●	●	
E	●	●	●		●

System size optimized for Nov 1 –Jan 31 period, then analysis expanded to full year solar collection at that size

Optimization tool

Flow



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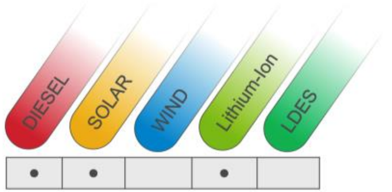
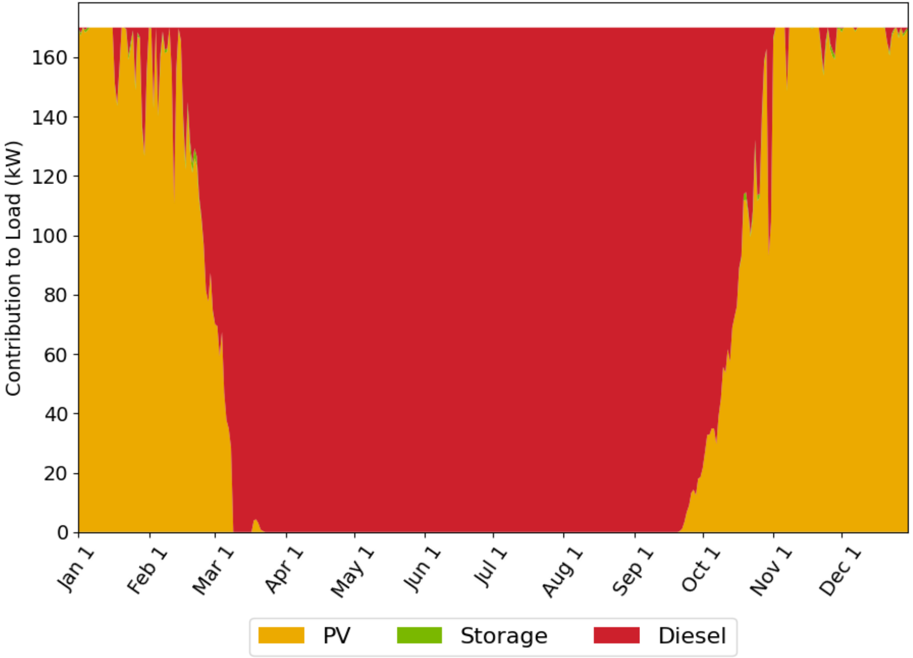
Configuration A



- 98% less fuel consumed during austral summer optimization period; **36% reduction in diesel fuel consumed when full year considered**

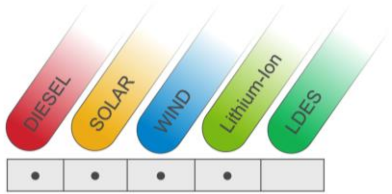


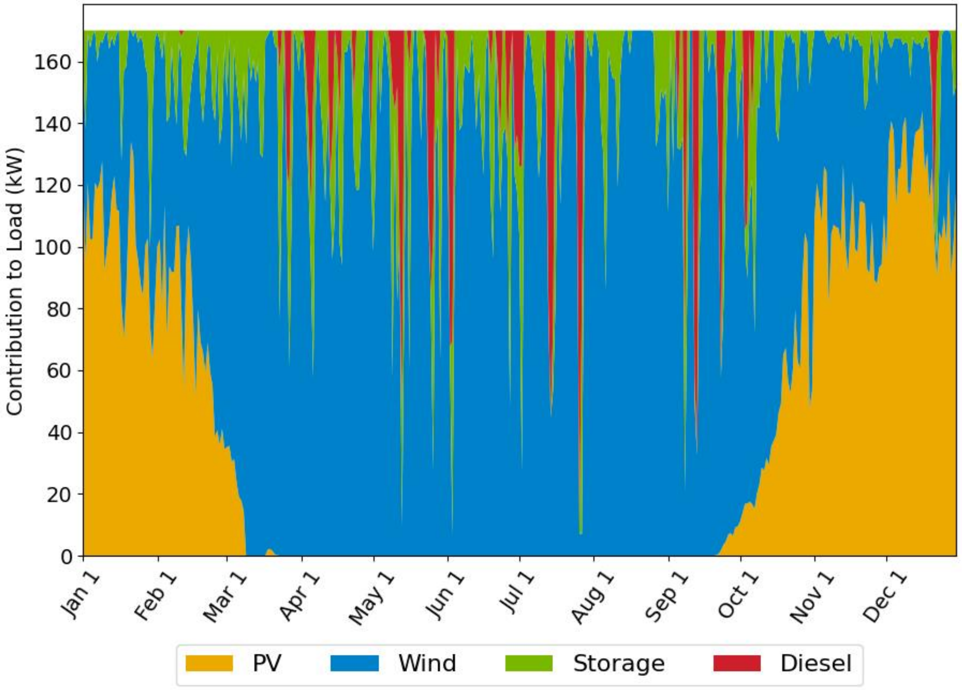
Upfront Capital	**$3.8 M**
% Diesel Reduction	41%
Years to Payback	**1.1**
Lifetime cost	$47.5 M
Net Present Value	$25.3 / 35%
PV Size	680 kW
Wind Size	0 kW
Battery Size	50 kW for <2.3> hours
Yearly Diesel Used	73, 700 gal
Fuel reduction	41%
Avoided CO_2/year	510 metric tons

savings compared to 100% diesel

Configuration produces energy in addition the required load (170kW) shown here.

Configuration C



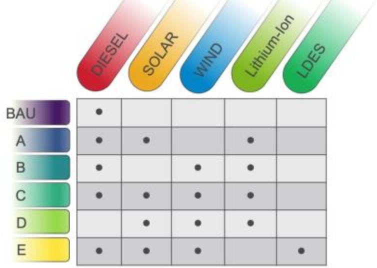


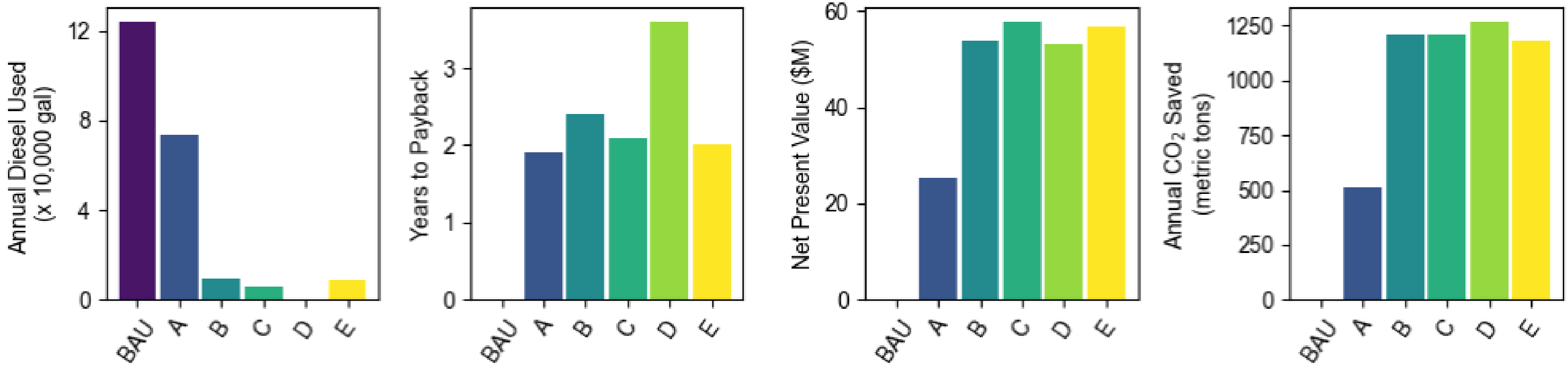
Upfront Capital	**$14.9 M**
% Diesel Reduction	96%
Years to Payback	**2.1**
Lifetime cost	$14.9 M
Net Present Value	$57.8 M / 80%
PV Size	180 kW
Wind Size	570 kW
Battery Size	180 kW for <18.9> hours
Yearly Diesel Used	5,553 gal
Fuel reduction	96%
Avoided CO_2/year	1210 metric tons

Configuration produces energy in addition the required load (170kW) shown here.

Comparative Results

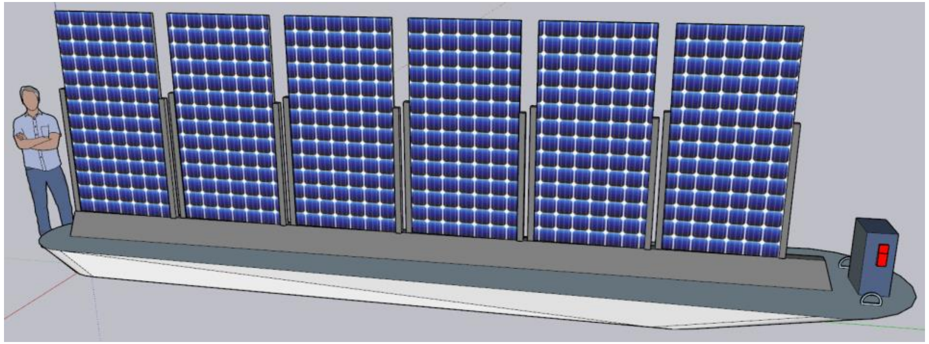
- Diesel fuel reduction ranges from 40-100%
- All options have significant net present value (cost savings over life cycle)
- Additional configurations and constraints have been modeled to
  - characterize sensitivity to assumptions
  - determine payback at different system sizes





Future Research & Developments

- Solar
  - Model validation
  - Durability
  - Snow drift modeling
  - **Racking design**
  - Electrical one line with components selection
- Wind
  - Improved wind measurements
  - EMI
  - Durability
- Energy Storage
  - Understand power: energy ratio & time constants (noise in power in and out of the storage)
  - Predict durability of Lithium-Ion over time
  - As long-duration technology (LDES) increases maturity characterize impact
- Development of safety technology, standards, o&m plan and mitigations



Short Summary

- **IT WORKS!** Pay back time ~ 2 years
- A significant reduction in diesel consumption is possible using mature renewable energy technology and energy storage. Directly translates into Engineering developments specific to South Pole implementation are identified
- A path forward is identified
- ***Significant reductions in both carbon footprint and cost of operations***

Collaboration?

- How to design a rack that is stable, but that can be moved? Or other ideas on dealing with the stackable snow drift?
- Modeling accurate to what others are seeing?
- Do you have irradiance sensors data and/or performance data for modelling? **Erin**
- Input on other high latitude deployments practices, experiences, lesson learned, things to avoid?
- Applying this systems-level optimization all the way to diesel and CO_2 reduction to other sites?

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NREL Transforming ENERGY

SIDE BY SIDE Comparison

	Baseline Existing	RE Config 1 (PV + Li-Ion)	RE Config 2 (PV + wind + Li-Ion)	RE Config 3 (PV + wind + LDES)
Upfront Capital	0	$1,926,806	$9,681,999	$8,903,020
% Diesel Reduction	0	36%	95.5%	93.1%
Years to Payback	-	1.1	2.1	2.0
Lifetime cost	$72,745,453	$48,941,401	$14,938,109	$15,944,373
Net Present Value	0	$23,804,052	$57,807,344	$56,801,080
PV Size	0	354 kW	182 kW	199
Wind Size	0	0 kW	569 kW	576
Battery Size	0	8 kW for <3.6> hours	180 kW for <18.9> hours	203 kW for <10.9> hours
Yearly Diesel Used	124,095 gal	79,831 gal	5,553 gal	8,540 gal

Assumptions

Table 3

Cost estimates and system-wide assumptions used in REopt analysis.

Parameter	Value	Annual maintenance cost	Additional factors
Power demand	170 kW		Constant
Diesel fuel cost[a]	$40/gallon delivered		2.7% annual escalation rate
Diesel plant fuel[b] economy	12 kWh/gallon		Marginal fuel economy
PV cost	$5330/kW-DC installed	$42.50/kW-DC	0.5% annual degradation[c]
Wind turbine cost	$9670/kW installed	$230/kW	
BESS, Li-ion cost[d]	$1910/kW + $840/kWh installed		97.5% round trip efficiency, direct current to direct current[e] 96% inverter & rectifier efficiencies 20% minimum state-of-charge
BESS, LDES cost[f]	$1810/kW + $860/kWh installed		55% round trip efficiency, direct current to direct current 96% inverter & rectifier efficiencies 10% minimum state-of-charge
Analysis period	15 years		
Discount rate	3%		
Inflation rate	2.5%		Non-fuel maintenance

ReOpt optimization

Table 6
Summary of results from REopt optimization.

	Diesel BAU	Diesel, PV, Li-ion A	Diesel, Wind, Li-ion B	Diesel, PV, Wind, Li-ion C	PV, Wind, Li-ion D	Diesel, PV, Wind, LDES E
Life-cycle cost ($M, discounted)	$72.8	$47.5	$18.9	$14.9	$19.4	$15.9
Net present value ($M)	–	$25.3	$53.9	$57.8	$53.3	$56.8
Capital expenditure ($M)	–	$3.8	$10.7	$9.7	$17.4	$8.9
Simple payback (years)	–	1.9	2.4	2.1	3.6	2.0
PV system size (kW-DC)	–	680	–	180	120	200
Wind system size (kW)	–	–	780	570	600	580
BESS power (kW)	–	50	200	180	180	200
BESS energy (kWh)	–	110	3310	3410	12,570	2210
Hours of storage	–	2.3	16.9	18.9	70.1	10.9
Annual fuel consumption (gallons)	124,000	73,700	9500	5600	0	8500
Fuel reduction	0	41%	92%	96%	100%	93%
Annual avoided CO_2 (metric tons)	0	510	1170	1210	1270	1180

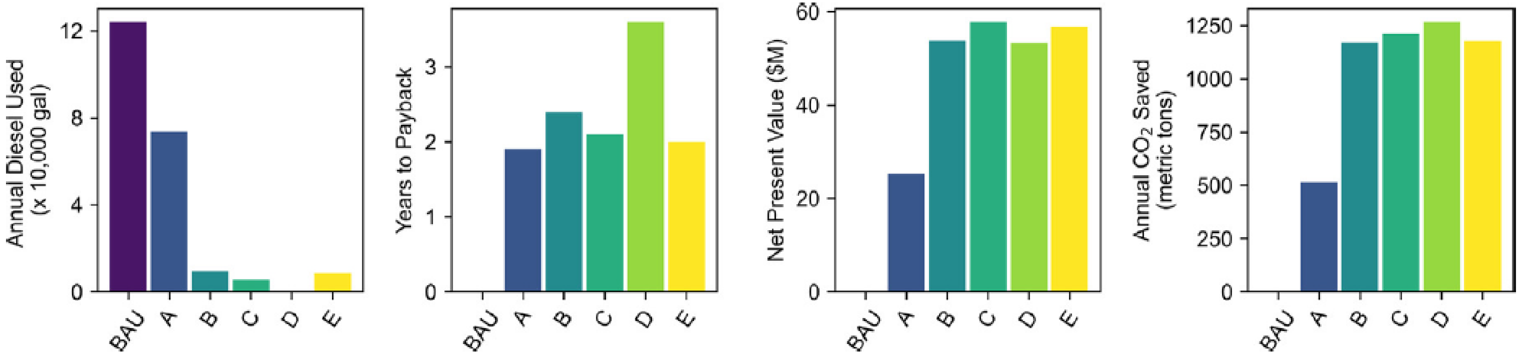


Fig. 8. Comparison of optimization results between the scenarios.

Table 6
Summary of results from REopt optimization.

	Diesel BAU	Diesel, PV, Li-ion A	Diesel, Wind, Li-ion B	Diesel, PV, Wind, Li-ion C	PV, Wind, Li-ion D	Diesel, PV, Wind, LDES E
Life-cycle cost ($M, discounted)	$72.8	$47.5	$18.9	$14.9	$19.4	$15.9
Net present value ($M)	–	$25.3	$53.9	$57.8	$53.3	$56.8
Capital expenditure ($M)	–	$3.8	$10.7	$9.7	$17.4	$8.9
Simple payback (years)	–	1.9	2.4	2.1	3.6	2.0
PV system size (kW-DC)	–	680	–	180	120	200
Wind system size (kW)	–	–	780	570	600	580
BESS power (kW)	–	50	200	180	180	200
BESS energy (kWh)	–	110	3310	3410	12,570	2210
Hours of storage	–	2.3	16.9	18.9	70.1	10.9
Annual fuel consumption (gallons)	124,000	73,700	9500	5600	0	8500
Fuel reduction	0	41%	92%	96%	100%	93%
Annual avoided CO_2 (metric tons)	0	510	1170	1210	1270	1180

Studies at/for S. Pole:


Image from [1]

Solar:

- PV panel installation onto Atmospheric Research Observatory building for over a year[1]. Electrical power output dependent on solar angle and visibility, no noticeable panel degradation at conclusion

Wind:

- NREL study on wind feasibility (2005)
- One example at right shows turbine used by Antarctic Arianna experiment[3]


Image from [3]

[1] https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/5467/1/ERDC-CRREL-TR-00-4.pdf
[2] https://www.nrel.gov/docs/fy05osti/37504.pdf [3] https://pos.sissa.it/358/968/pdf

Cargo for RE Installation

- Initial estimate of cargo weight has been made for least-cost configuration
  - 180 kW PV array
  - 6x wind turbines [100kW]
  - 3.4 MWh Lithium-ion batteries
- Total renewable energy system weight comparable to one major season of CMB-S4 scientific cargo
  - PV panels, racking, turbine towers & blades are all traverse compatible
  - Batteries & electronics are DNF
    - Could be traverse compatible inside container that would house them at S. Pole
- Cargo scales roughly linearly with desired electrical load
  - 18% system (~30 kW) requires ~ 20% cargo
- Cadence of cargo delivery is extremely flexible
- Plan to maximize pre-assembly in N. America to minimize work on-site

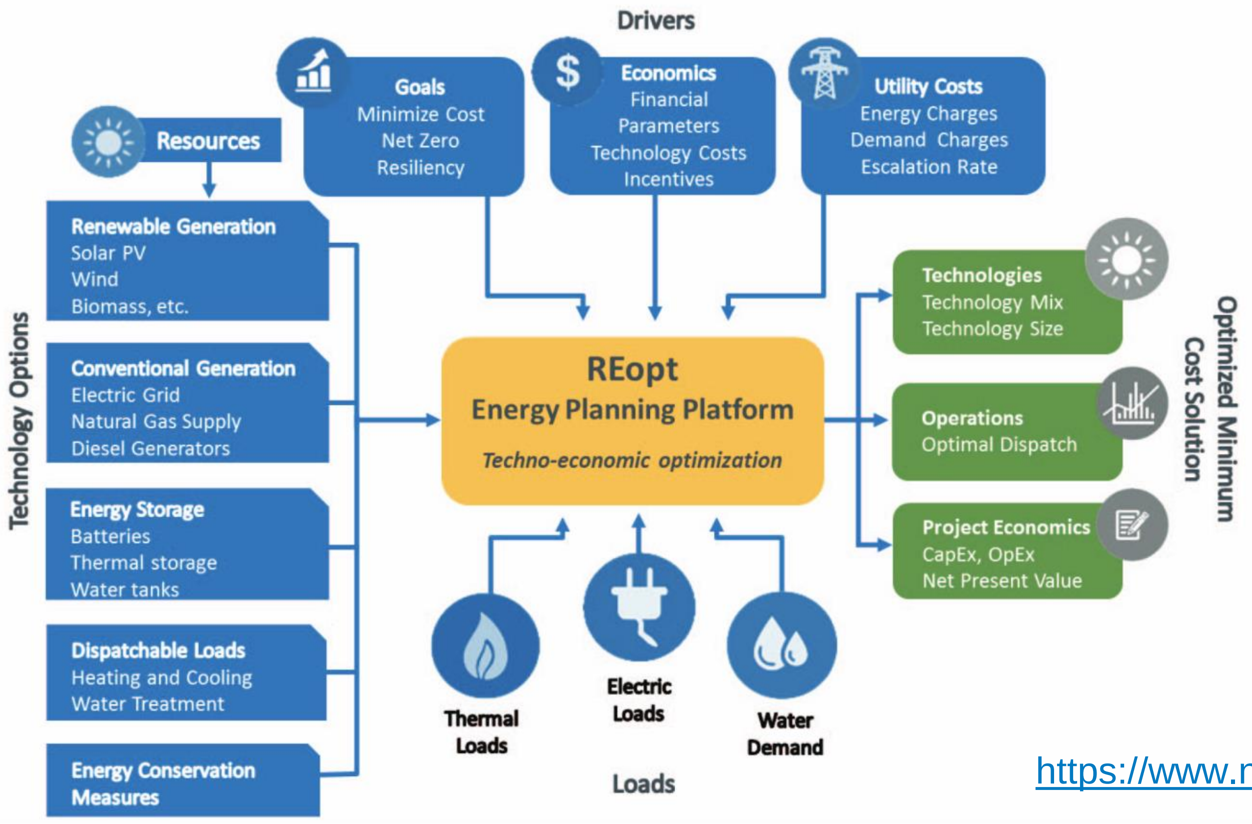
Component	Weight [x1000 lbs]
PV panels & racking	70.8
6x wind turbines	384.1
Lithium-Ion batteries	61.6
Estimated total	517

Concept Development

- We are optimizing detailed economics
  - Team examined inputs and base assumptions together in detail and adjusted them for specifics of ***this scenario***
- Required the unique combined expertise of this team

Many Assumptions & Inputs Evaluated	
Load	Battery energy density
Lifetime	Position & number of inverters for batteries
Installation labor	Battery round trip efficiency
Solar panel geometry	Battery cycling approach & system sizing
Temperature rating of components vs cost	Housing of batteries
South logistical constraints & costs	Operation and maintenance

REopt



https://www.nrel.gov/docs/fy17osti/70022.pdf

Technical Challenges

Solar & Wind

Mature

Focus: extreme environment durability

Solar

- Snow accumulation on face
- Snow drifting
- Temperature

Wind

- Turbines at low temperatures
- Ice foundations

More on this later

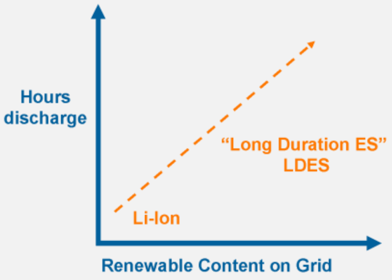
Energy Storage

Both mature & emerging options

Focus: maintaining best available option

<u>Important ES variables</u>

- Capex
- Shipping cost ∝ energy density
- Flammability
- Hours of discharge
- Maturity



Present best is Li-Ion: designed for EV markets

Future best may be mature version design for stationary markets

Mobile power station

https://www.antarctica.gov.au/site/assets/file
s/48933/rs64243_doug-checking-solar-panels
on-the-outside-of-the-repeater-
hut.1200x0.jpg