Real Options for Geothermal Energy

Lightning Dock Expansion

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https://www.gannett-cdn.com/presto/2019/03/28/PNM2/a16b7b85-101a-4321-8bfa-bf49be1e27d4-dju_20190224_Lordsburg_251.jpg?width=660&height=441&fit=crop&format=pjpg&auto=webp

Cautionary Statement

The work presented here was completed by the author as an academic exercise in partial fulfillment of the requirements for MIT course IDS.330 and are not endorsed by any professional company, organization, or working group.

Information included in the models is based on publicly available data. Model inputs were determined from primary sources or selected as a best educated guess by the author when no suitable information source could be identified.

Although referenced directly in the report, neither Cyrq Energy nor Climeon was directly consulted on the content. Conclusions drawn within this report should not be considered a professional recommendation, but simply a hypothetical analysis for the purposes of educational training.

Lightning Dock History

1948 – Agricultural well struck boiling water at 26.5 m depth

1977 – AMAX Exploration drilled 58 wells as part of an exploration campaign.

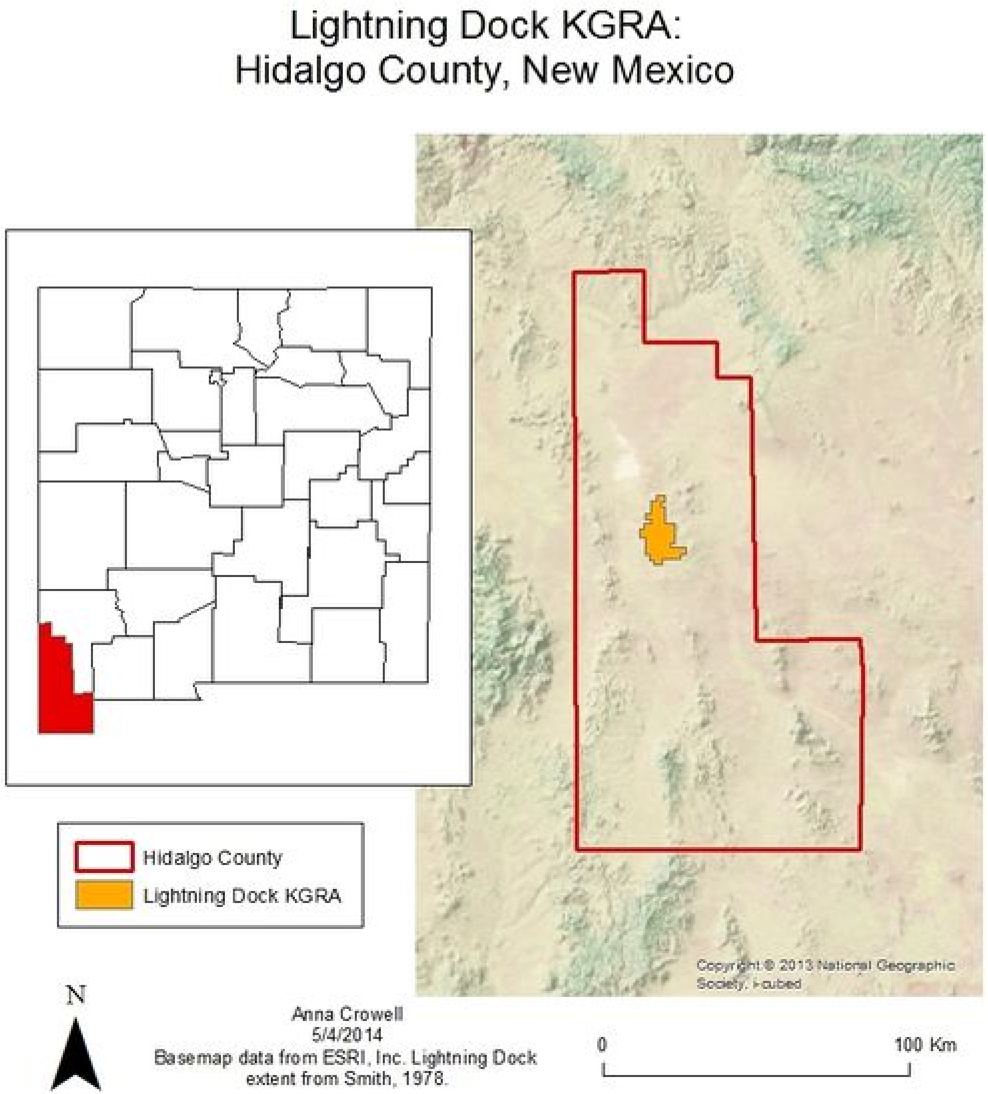
1977 – Burgett Geothermal Greenhouses, Inc. began operating with direct use of geothermal waters.

1982 – Burgett installed 40 kW and 100 kW plants, which failed after installation. Tried again with other designs in 1995 and 2008.

1986 – Lightning Dock Geothermal, Inc. obtained lease to develop a power plant.

2013 – Cyrq Energy (post-acquisition) brought 4 MW plant online and formed a power purchase agreement (PPA) with Public Services of New Mexico (PNM).

2018 – Turboden repowered Lightning Dock, increasing commercial capacity to 10 MW.



From Fig 1 in (Crowell and Crowell, 2014)

Geothermal in NM: Renewable Portfolio Standard (RPS)


NEW MEXICO PUBLIC REGULATION COMMISSION

PRC

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New Mexico Public Regulation Commission and Renewable Energy in New Mexico

The Public Regulation Commission reviews and approves renewable energy procurement plans and reports of Investor Owned Utilities ("IOU's") and Rural Electric Cooperatives ("Coops") pursuant to the Renewable Energy Act ("REA"), §§ 62-16-1 et seq. NMSA 1978 and Title 17.9.572 NMAC ("Rule 572"). IOU's in New Mexico are procuring renewable energy and renewable energy certificates from New Mexico renewable generation facilities to meet the Renewable Portfolio Standard (RPS) requirements of the REA and Rule 572.

Investor Owned Utilities and the RPS

The REA and Rule 572 established an RPS applicable to all investor owned electric utilities in New Mexico. In 2006, the RPS will be 5% of retail sales in kWh's, reaching 10% by the year 2011. Recent legislative changes to the REA (SB418, signed March 5, 2007 by Governor Bill Richardson) have increased the RPS percentages and extended the time lines - IOU's now must have in their portfolio as a percentage of total retail sales to New Mexico customers, renewable energy of no less than 15% (by 2015) and 20% (by 2020).

Resource Diversity and the RPS

In addition to the RPS, Rule 572 requires within the total portfolio percentage requ renewable energy portfolio as follows:

Diversity requirements for IOU's as % of

No less than *30% Wind*

No less than *20% Solar*

No less than *5% Other technologies*

No less than *1.5% Distributed Generation (2011-2014) and 3% Distributed Generation by 2015*

No less than *30% Wind*

No less than *20% Solar*

No less than *5% Other technologies*

http://www.nmprc.state.nm.us/utilities/renewable-energy.html

Source: public domain. Used with permission.

PNM Resources

Geothermal

Geothermal energy uses heat from below the earth's crust to create steam that turns the turbine, ultimately generating electricity. Like wind and solar, geothermal energy emits no pollutants into the air; unlike wind and solar energy, it is available to serve customers around the clock.

PNM is the first customer to take energy from the Lightning Dock Geothermal Plant.

https://www.pnm.com/geothermal

BACKGROUND

Enhanced Geothermal Systems (EGS)

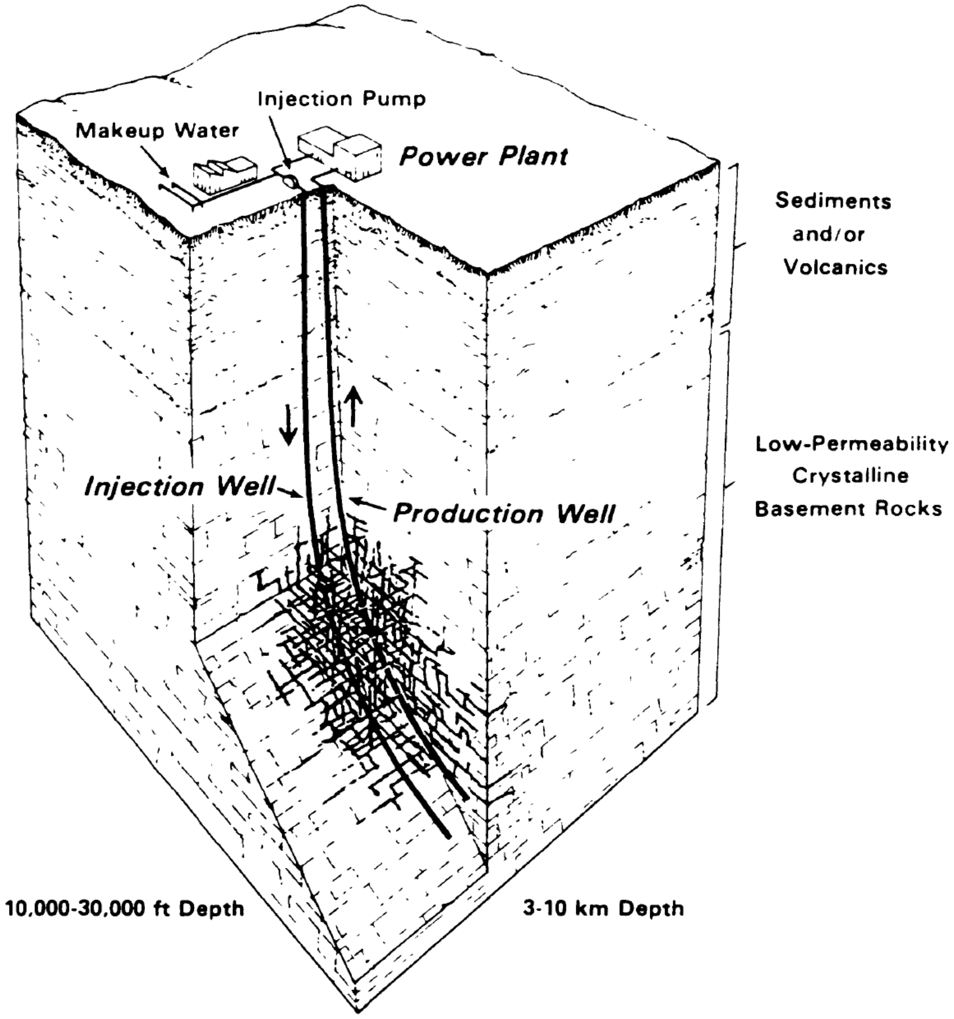
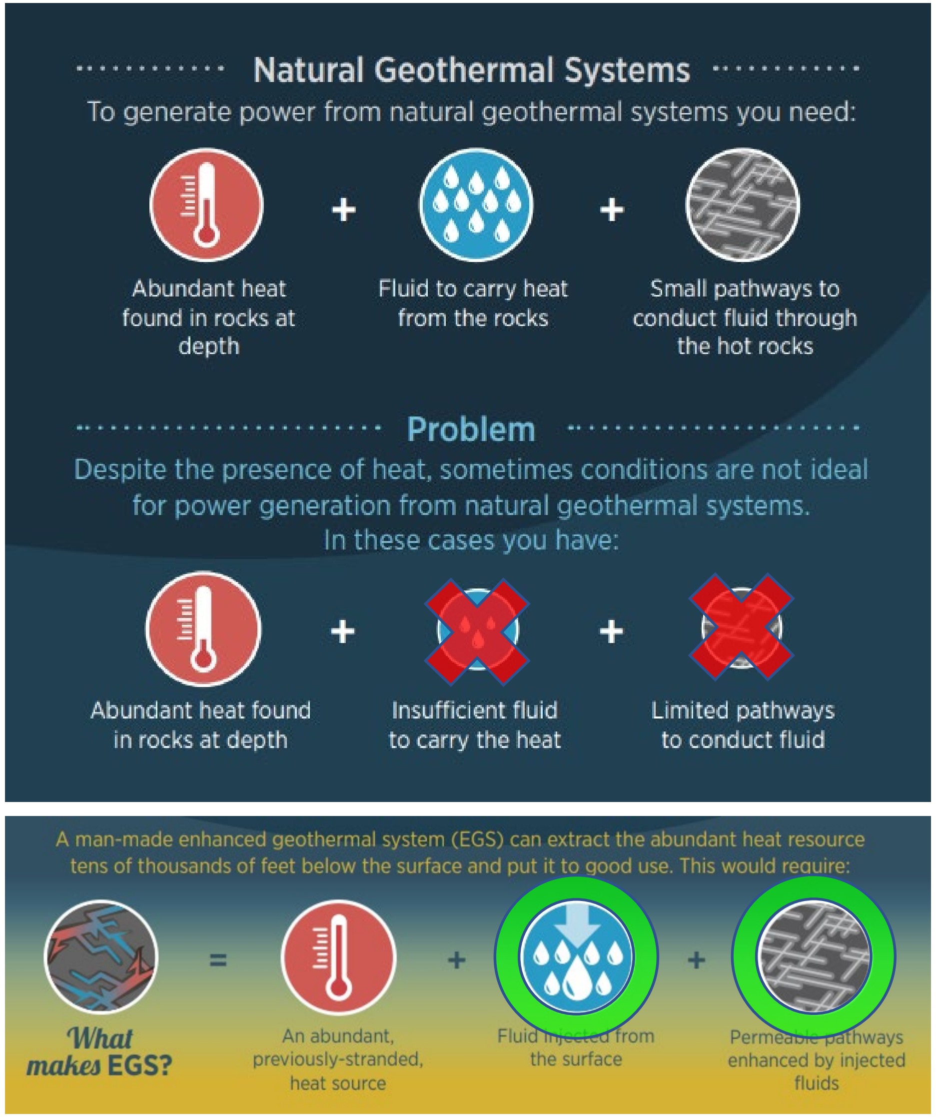


Figure 3.2 in (Tester and Herzog, 1990)

Conventional

Unconventional

EGS



Infographic from U.S. Dept of Energy: energy.gov/sites/default/files/2015/04/f22/EGS%20Infographic_0.pdf

Binary Cycle Power Plants

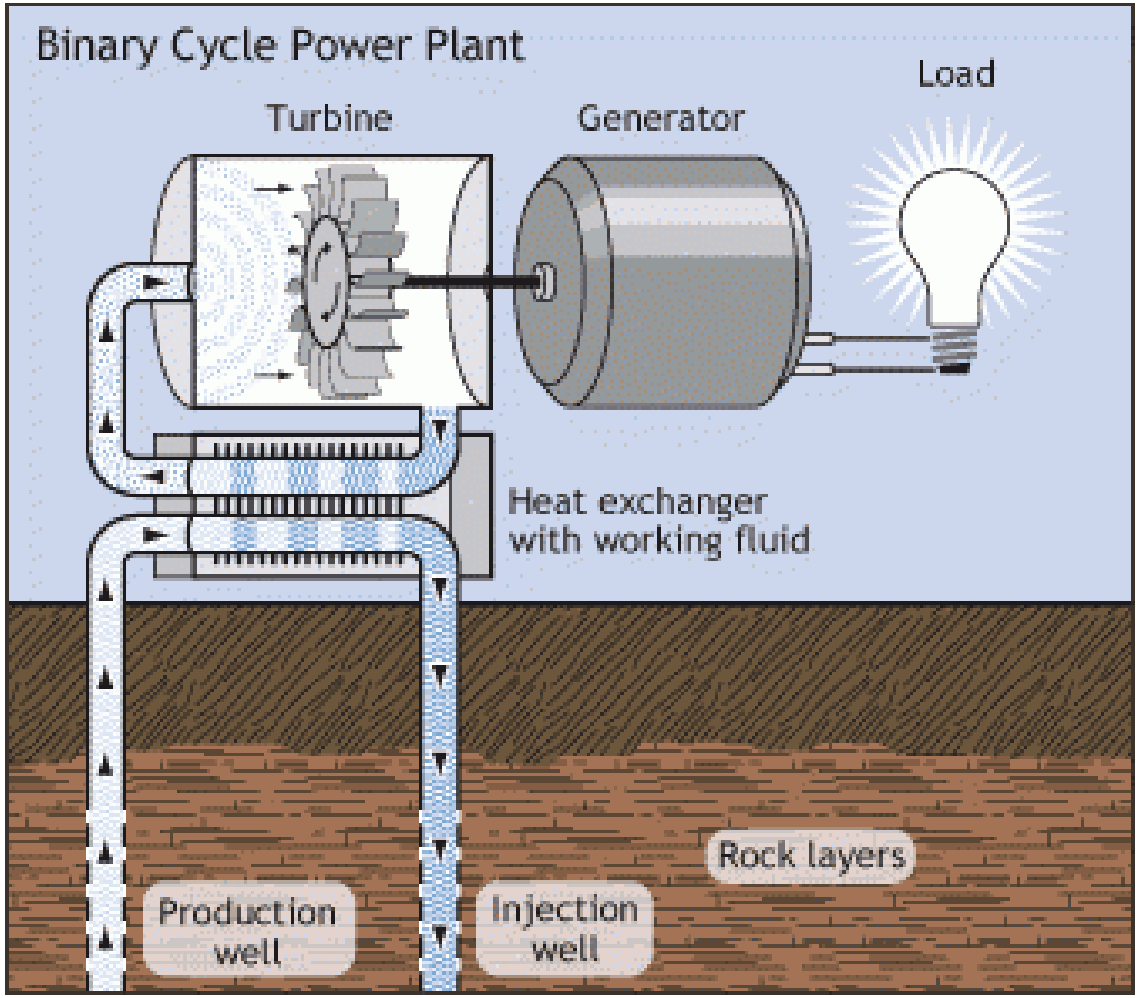


Image from U.S. Dept of Energy
energy.gov/eere/geothermal/electricity-generation

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- Primary fluid produced from the subsurface.
- Heat exchange between primary and secondary fluid with a low boiling point.
- Secondary fluid flashes to vapor and drives the turbines.
- Typically used for moderate to low temperature geothermal (≤180°C).

Modular Concepts

- Climeon offers a compact binary cycle geothermal unit (HP150).
- Units cluster to form a Power Block.
- Power Blocks can be independently installed to build a larger-capacity aggregate facility.

Image from https://climeon.com/geothermal-plants

Image from Slide 15 of Climeon 2018 IGC presentation deck

Static Model

Deterministic Case

- Excel-based model for NPV calculation
- NPV (discount rate = 9%) components:
    - **Income** = electricity generated times PPA pricing (kWh*$/kWh)
    - **CAPEX** = wells + power plant + fluid distribution + stimulation + exploration
    - **OPEX** = power plant O&M + field O&M + water O&M + labor
- Assumes a **30-year life span**
- Assumes a **<u>50%</u> above wholesale electricity price** for power purchase agreement (PPA)
    - Similar to current value of Cyrq/PNM PPA
    - Can be easily adjusted on cover sheet with alternate values

Deterministic Model | Case Study: Lightning Dock, NM

RESOURCE	VALUE	UNITS	REFERENCE	NOTES
Surface Temperature (2020)	15.8	degrees C	Dahal, 2012	
Average Geothermal Gradient	100	degrees C / km	Crowell, 2014; can be hi	based on hole TG 56-14, 4 km SW of anomaly
Average Well Depth (near verical, MD)	**1.1**	km		calculated based on reservoir temperature
Initial Average Reservoir Temperature	125	degrees C		stick to temperature profile of Climeon (max: 120 C)
Production Well Temperature Loss	5	degrees C	Beckers, 2013; GETEM	aggressive value. Beckers uses 10deg w/ 5km well, GETEM calculates <2
Production Temperature (at well head)	**120**	degrees C		re-compute with equation from Beckers, 2016 once other variables defined
Water Loss Rate	2%	% of injected water	SAM	for open loop
Production Flow Rate per Well Pair	35	kg/s	GETEM, NREL	https://atb.nrel.gov/electricity/2020/index.php?t=gt

CAPEX (per module)	VALUE	UNITS	REFERENCE	NOTES
Drilling & Completions Costs	$ 1,305,956.16	USD (1 well)	Beckers 2013	Lukawski, 2016
Wells per module	2	well count per unit		doublet
Surface Plant Costs	**$ 1,000.00**	$/kWe	Beckers 2013	*waiting on reply from Baseload Cap., stick with this for now*
Reservoir Stimulation per injection well	$ 1,250,000.00	USD	Lowry, 2017	$1,250,000 per injector stimulation, recent ballpark figure so no cost adjust
Fluid Distribution Costs	$ 279,300.00	USD	Beckers 2013	also ballpark figure, needs additional study based on New Mexico for more
Redevelopment Factor	0.85		pers. conversation, Prest	could be cheaper to redrill than drill from scratch
Thermal Drawdown Threshold	**13.0**	degrees C	GETEM	0.21*Ti-12.2
Thermal Drawdown Rate	0.5%		GETEM	varies from author-to-author (up to 4%)
Redevelop Every	**24**	years		
Exploration Success Rate	100.0%			assumed 100% since area is already developed, normally ~20% (Glassley
Total Capital Costs (exploration)	$ 2,133,542.54	USD	Beckers 2016	Ccap = Ccap;well + Ccap;pp + Ccap;stim + Ccap;distr + Ccap;expl
Total Capital Costs (drilling)	$ 2,611,912.33	USD	Beckers 2016	
Total Capital Costs (non-drilling)	$ 3,121,310.00	USD	Beckers 2016	

POWER PLANT (modules)	VALUE	UNITS	REFERENCE	NOTES
Plant Type	Binary ORC			governs system physics
Plant Useful Life	30	years	Augustine, 2009	basis for cost analysis
Heat Inlet Temperature	120	degrees C		simplifying assumption, ignoring secondary fluid heat exchange
Cool Inlet Temperature	50	degrees C		backing out from known Climeon Mwe
Heat Capacity	2.28	kJ/kg-K	Dincer, 2010	isobutane, not sure if this is their fluid
Temperature Drop	**70.0**	degrees C (or K)		
Enthalpy Drop	**5.6**	MWth		Q = q x Cp X delta T
Capacity Factor	95%		Glassly 2015, GETEM	
Degradation Factor	0.5%		NREL, 2002	using 0.5% NREL degradation per year
Generation Efficiency (2nd Law Efficiency)	0.3		Beckers 2019, Glassley	relates power production (Mwe) to exergy of geothermal fluid
Avg Net Power Output per Unit	**1.59**	MWe		slightly high compared to Climeon ratings, but will degrade based on C51 f

OPEX	VALUE	UNITS	REFERENCE	NOTES
Labor (per module)	**$ 386,838.52**	USD	GETEM	
Power Plant Ops & Maintenance (per module)	**$ 314,009.04**	USD	Beckers 2013	0.75*Clabor + 0.015*Cpp
Field Ops & Maintenance (per module)	**$ 122,828.75**	USD	Beckers 2013	0.25*Clabor + 0.01*Cwell; assume this includes pump costs
Water Ops & Maintenance	**$ 5,481.02**	USD	GETEM	water loss: $300/acre-ft
Total Annual O&M costs (per module)	**$ 442,318.81**	USD		sum of OMpp+OMfield+OMwater

FACTORS/INDICES	VALUE	UNITS	REFERENCE	NOTES
Price Index from for Q4 2004 to 2020 USD	143%		UCCI (IHS)	
Price Index from for Q4 2009 to 2020 USD	104%		UCCI (IHS)	
Price Index from for Q4 2012 to 2020 USD	107%		UCCI (IHS)	
Employment Cost Index (Utilities) compared to 2004	145%		BLS	https://www.bls.gov/news.release/eci.t02.htm
Discount rate	9%		Sanyal 2007	variable to change for sensitivity study
Learning rate	6%		Lukawski 2014	only using well cost learning rate from this paper (others also listed)
Contract rate above wholesale	50%		PNM, 2014	
Learning rate exponent	**-0.089**			

30 years →

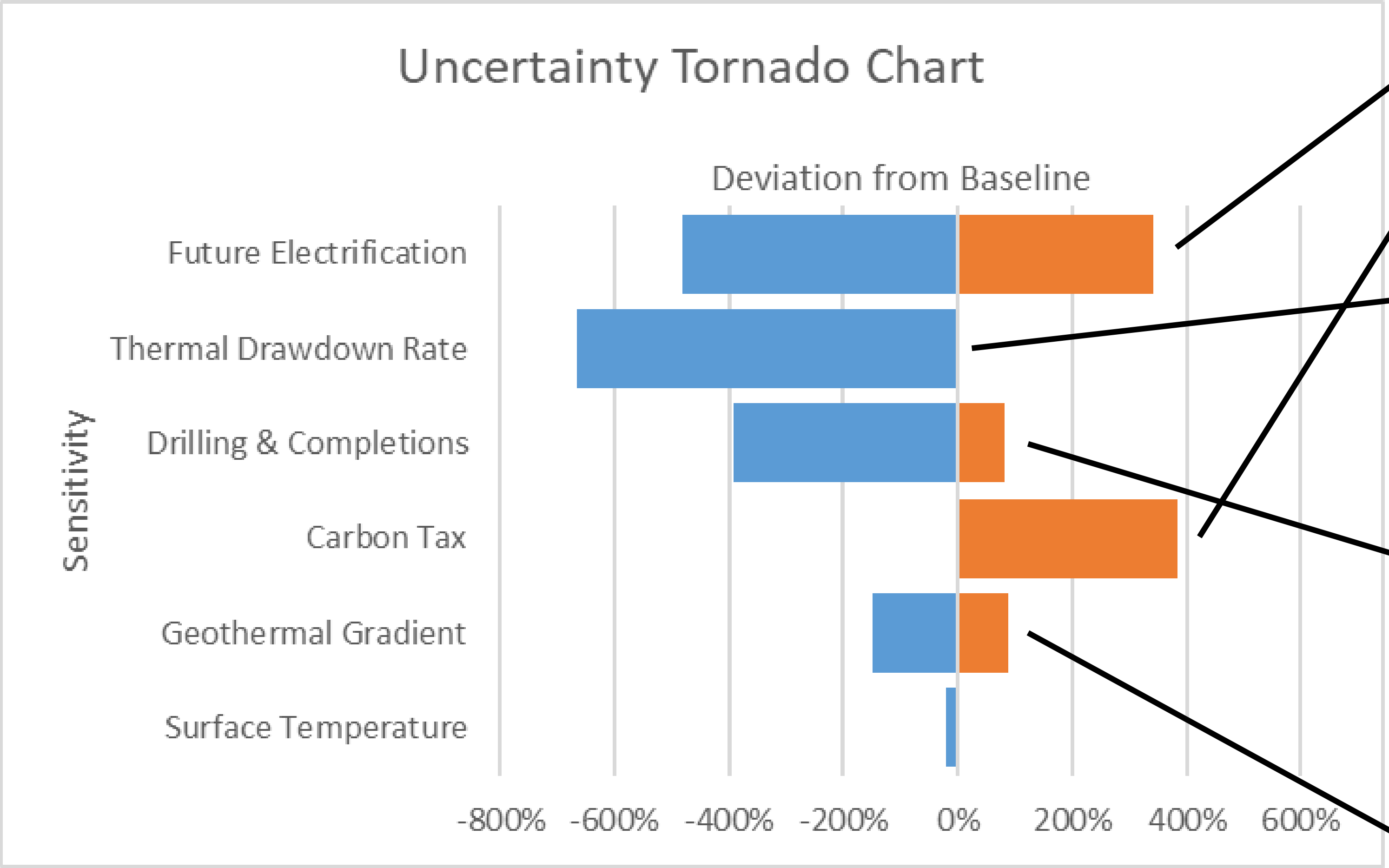
Calendar Year	2020	2021	2022	2023	2024	2025
Nominal Year	0	1	2	3	4	5
Calculated Price	0.086	0.000	0.000	0.000	0.000	0.000
Price ($/kWh)	0.086		0.090	0.090	0.090	0.090
Capacity Level Increase [Input]	1					
Unit Count	1		5	5	5	5
Total Capacity Increase (kWh)	13946008	55784030	0	0	0	0
Total Undegraded Capacity (kWh)	0	13946008	69730038	69730038	69730038	69730038
Thermal Decline (deg C)	120	119	119	118	118	117
Thermal Decline Degradation (kWh)	0	119537	1192384	1784108	2372873	2958695
Power Plant Degradation Factor	1.000	1.000	0.995	0.990	0.985	0.980
Total Overall Capacity (kWh)	0	13826470	68194966	67268170	66351851	65445899
Revenue	$0.00	$1,240,234.39	$6,117,088.46	$6,033,954.81	$5,951,761.00	$5,870,497.10
CAPEX (Drilling)	$2,611,912.33	$9,049,475.21	$0.00	$0.00	$0.00	$0.00
CAPEX (Redevelopment)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
CAPEX (Other)	$5,254,852.54	$12,485,240.00	$0.00	$0.00	$0.00	$0.00
OPEX	$0.00	$442,318.81	$2,211,594.06	$2,211,594.06	$2,211,594.06	$2,211,594.06
Cashflow	$0.00	($20,736,799.63)	$3,905,494.40	$3,822,360.76	$3,740,166.95	$3,658,903.04
DCF	$0.00	($19,024,586.81)	$3,287,176.50	$2,951,563.83	$2,649,628.56	$2,378,035.93
Present value of cashflow	$11,687,244					
Up-front investment	$7,866,765					

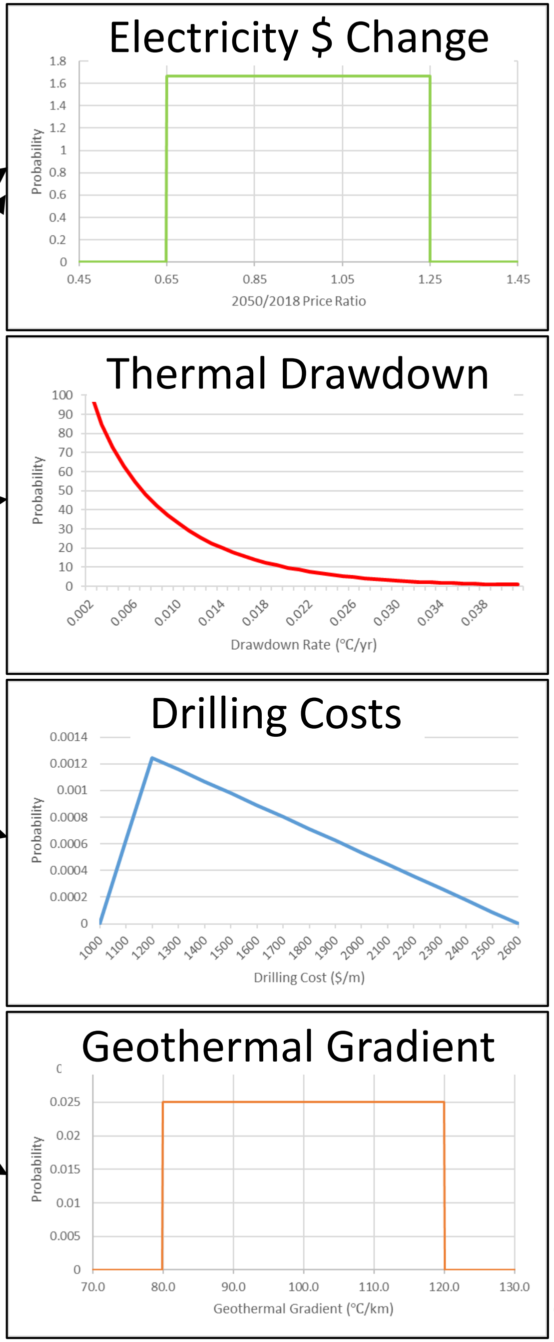
Net present value: $3.8MM

Key Uncertainties

UNCERTAINTIES

Probability density functions (pdfs) for value sampling



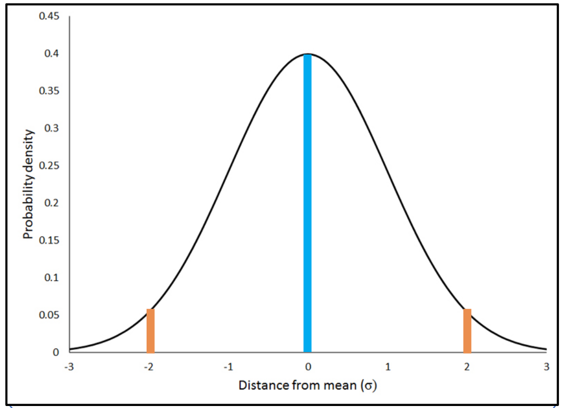


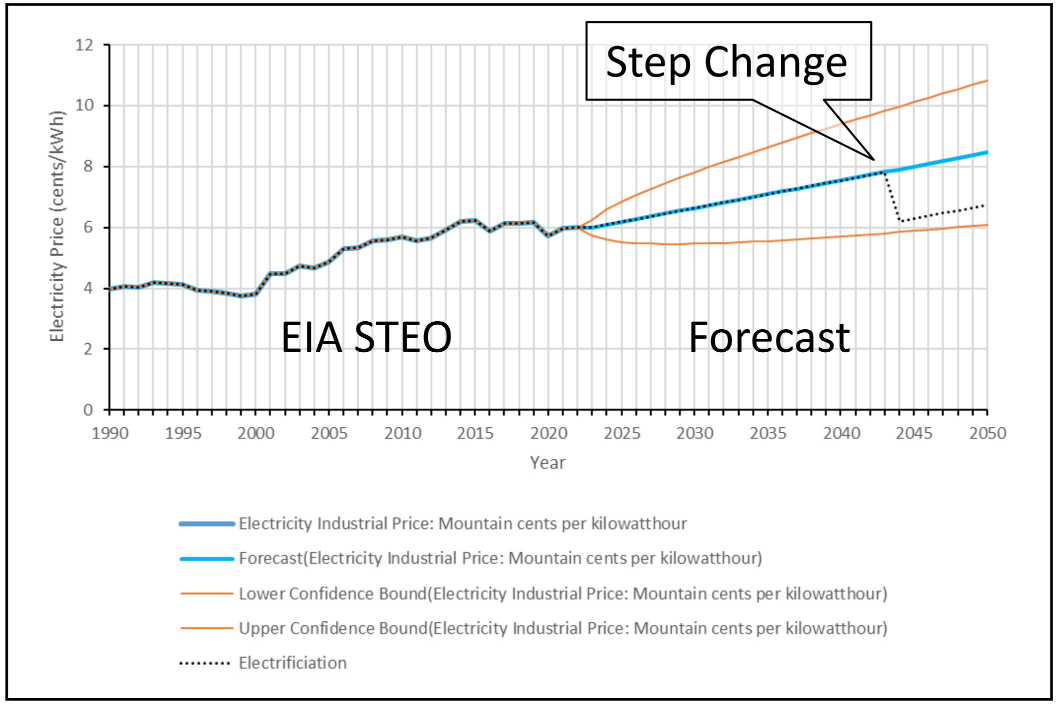
Sensitivity testing to determine variable importances for the model results

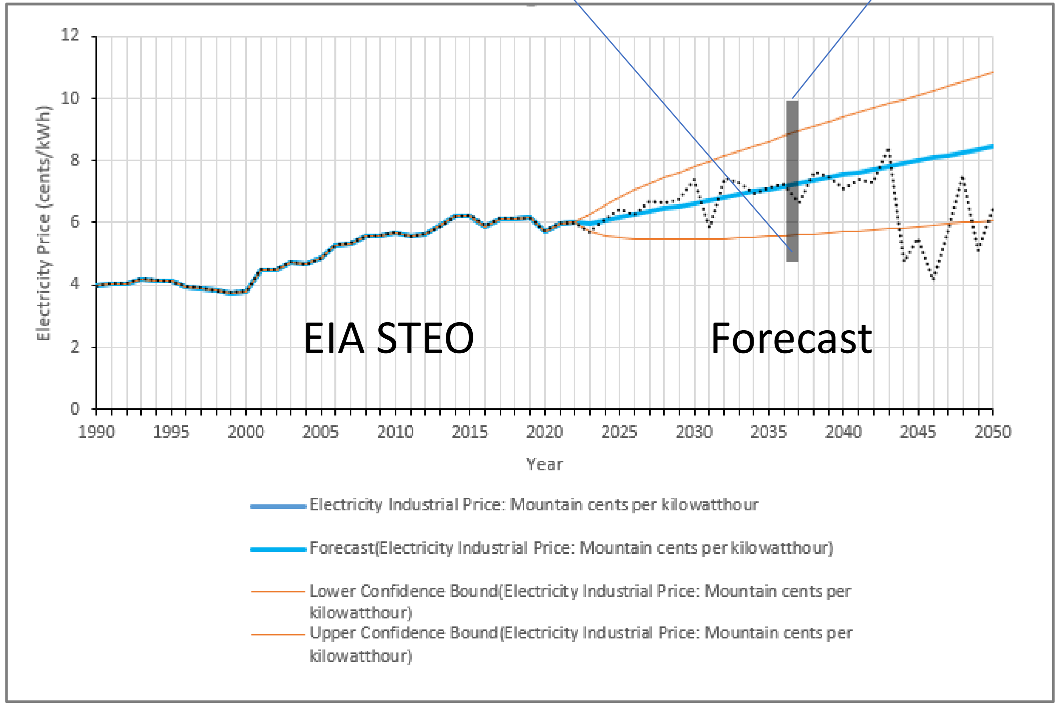
UNCERTAINTIES

Electricity Price

- Price step change inserted on a random date (uniform selection) and magnitude sampled from PDF
- Volatility added by sampling from normal distribution determined from forecast and confidence intervals.







Base Case

NO FLEXIBILITY

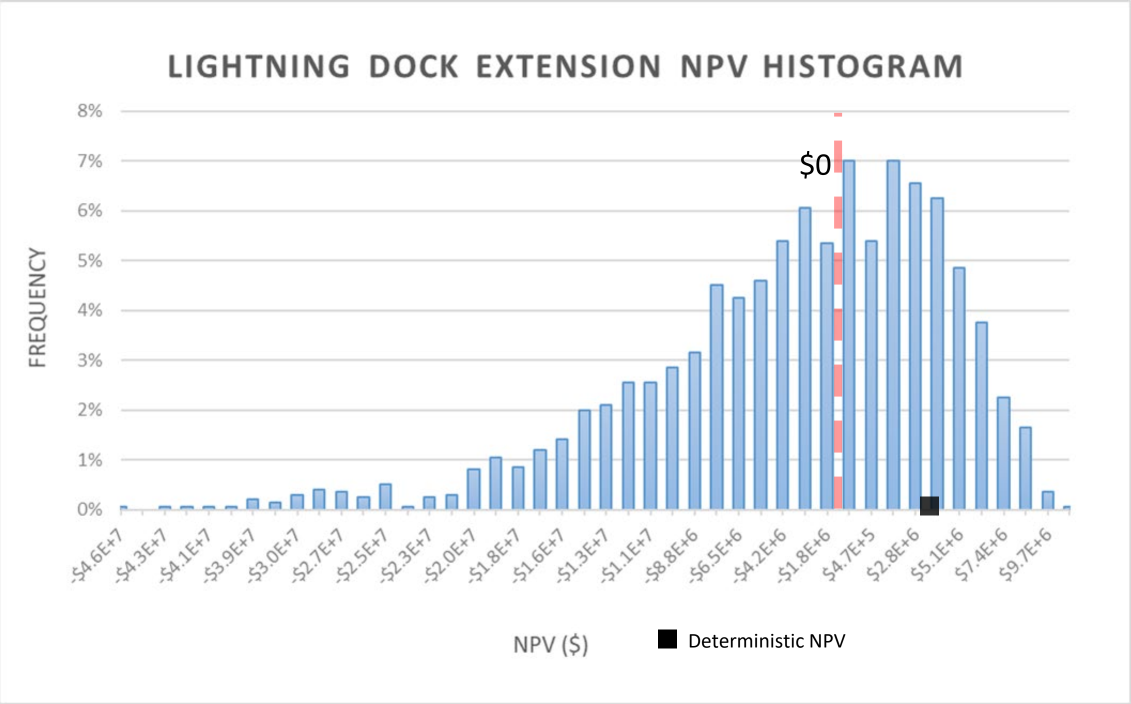
Uncertainties

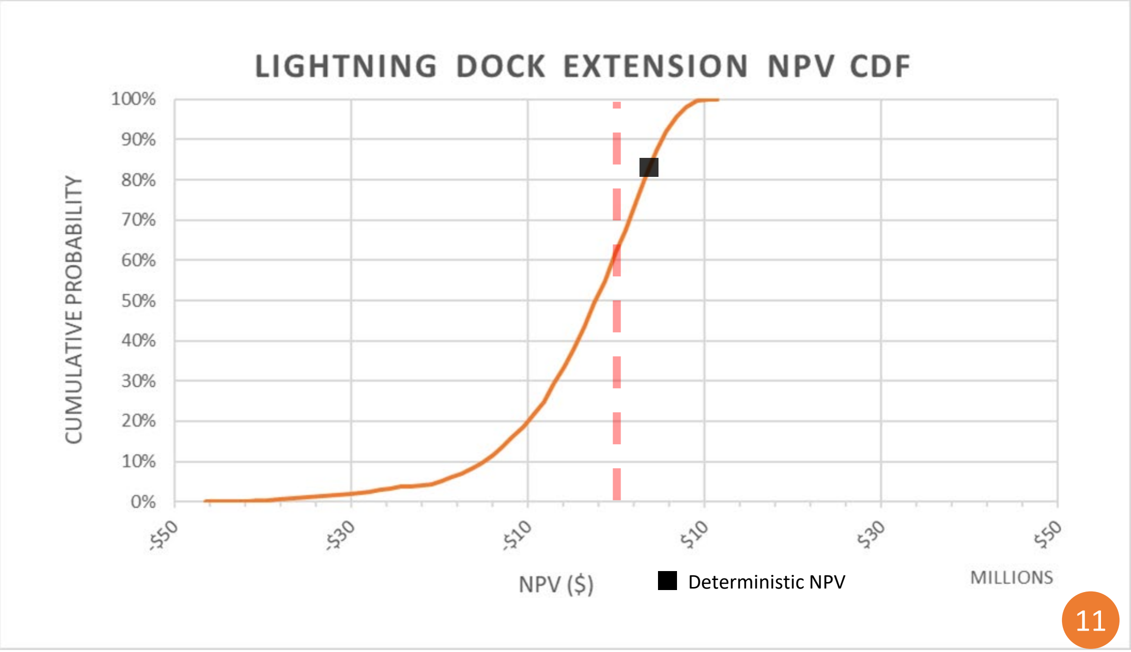
- Drilling & completions costs
- Pricing (future step change)
- Thermal drawdown rate
- Geothermal gradient

Flexibilities

- None

Base Case Statistics	N=2000
ENPV	-$4.0MM
STD(NPV)	$8.7MM
P05 NPV	-$19.8MM
P50 NPV	-$2.3MM
P95 NPV	$6.6MM
% Difference from NPV_{Det}	-207%





Redevelop Only

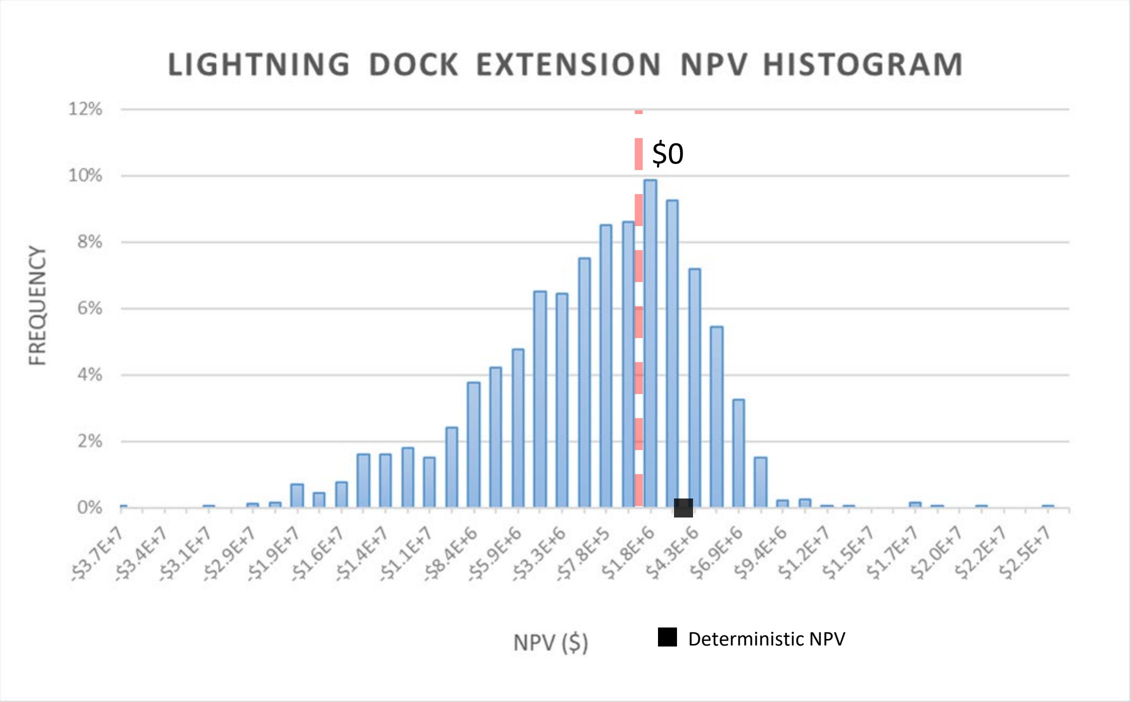
REDRILL

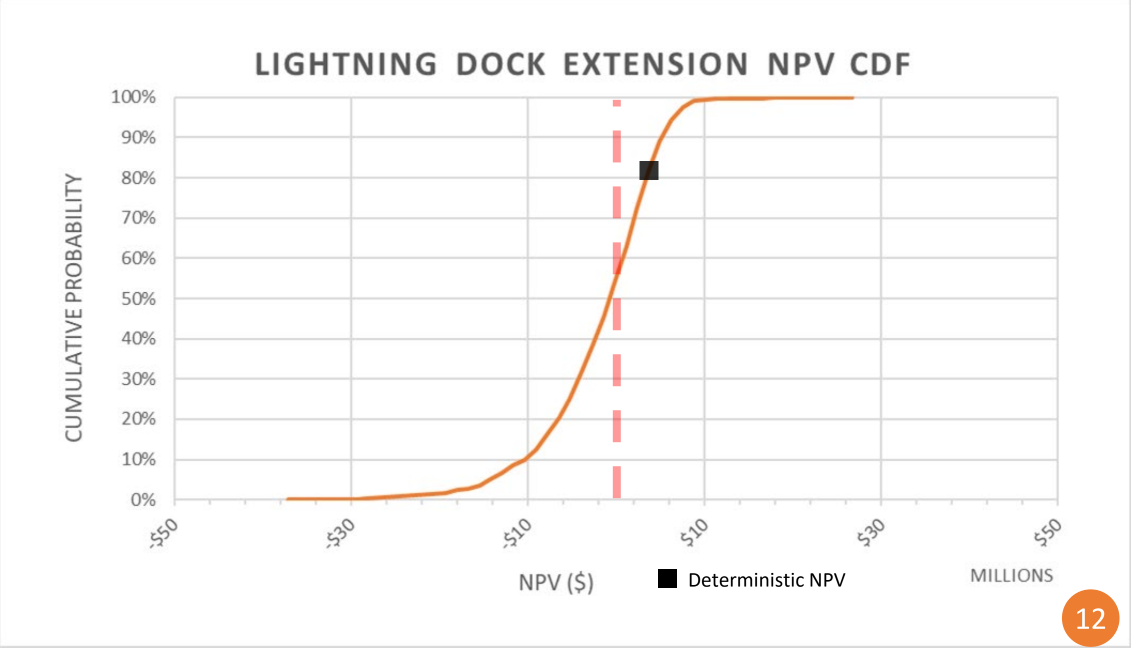
Uncertainties

- Same as Base Case

Flexibilities

- Redrill after 13℃ thermal drawdown. Temperature gets reset for primary fluid entering plant.





Redevelop Only Statistics	N=2000
ENPV	-$1.8MM
STD(NPV)	$6.5MM
P05 NPV	-$14.3MM
P50 NPV	-$0.7MM
P95 NPV	$6.5MM
% Difference from NPV_{Det}	-150%

SCENARIOS

Redevelop and Grow

REDRILL
BUILD

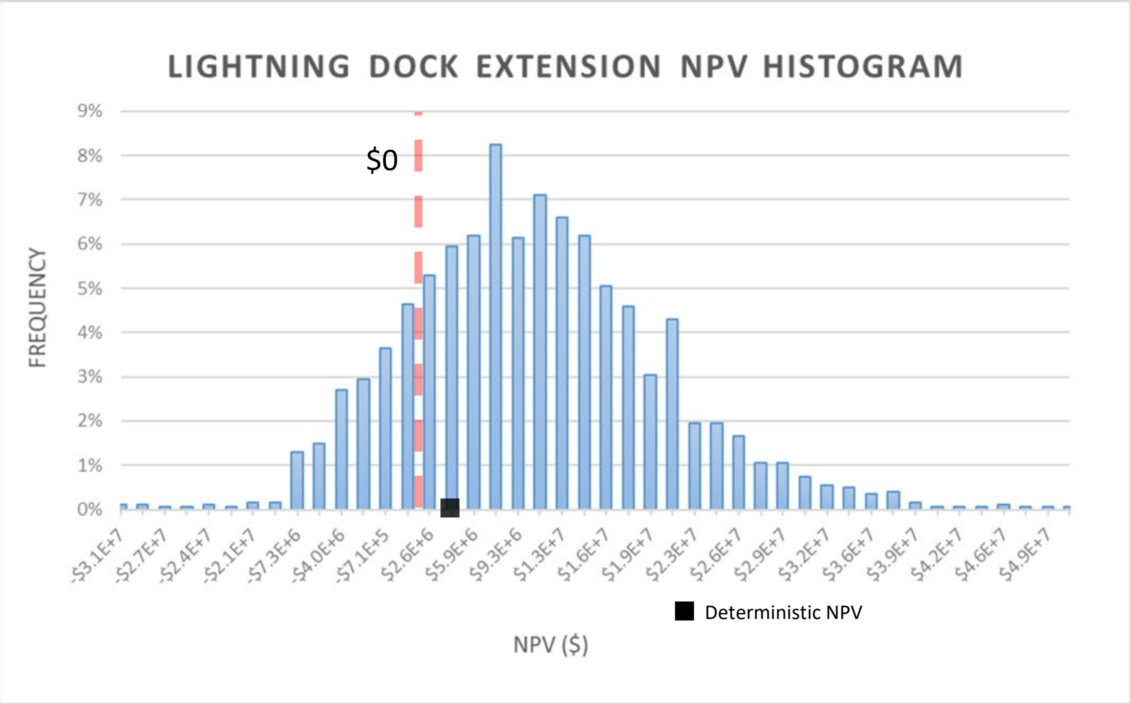
Uncertainties

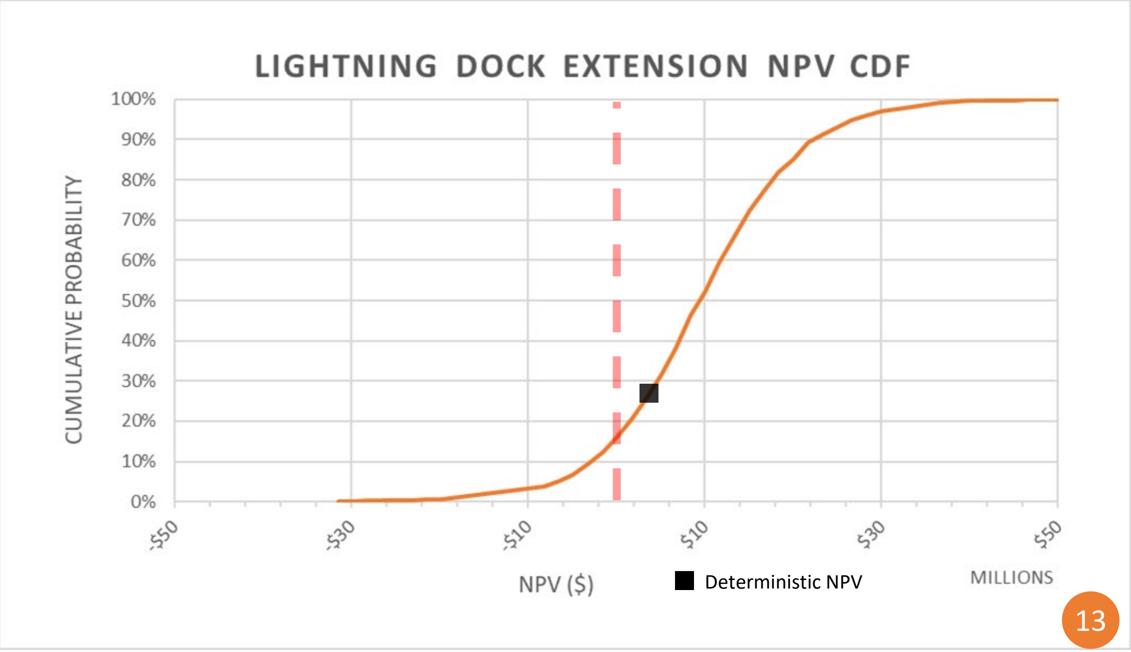
- Same as Base Case

Flexibilities

- Redrill after 13℃ drawdown.
- Increase capacity 25% if prices up ≥20% compared to time of PPA signing.
- PPA rate "renegotiated" with each capacity increase.

Redevelop Grow Statistics	N=2000
ENPV	$9.7MM
STD(NPV)	$10.3MM
P05 NPV	-$6.6MM
P50 NPV	$9.4MM
P95 NPV	$27.0MM
% Difference from NPV_{Det}	162%





SCENARIOS

Full Flexibility

REDRILL
BUILD
SHRINK

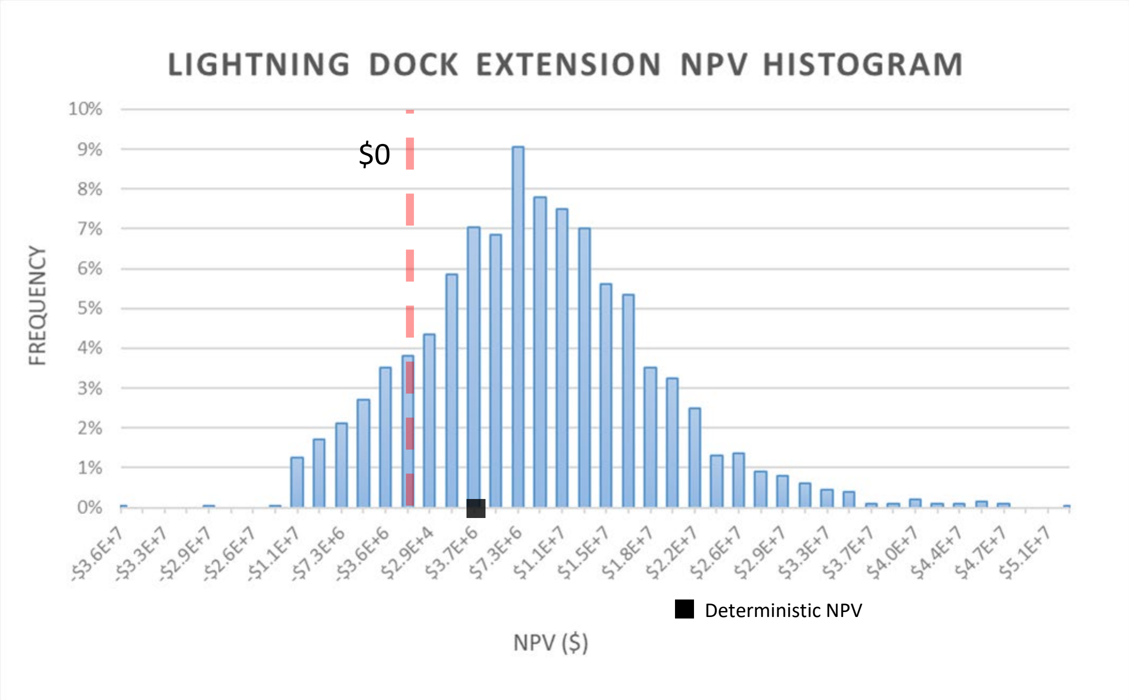
Uncertainties

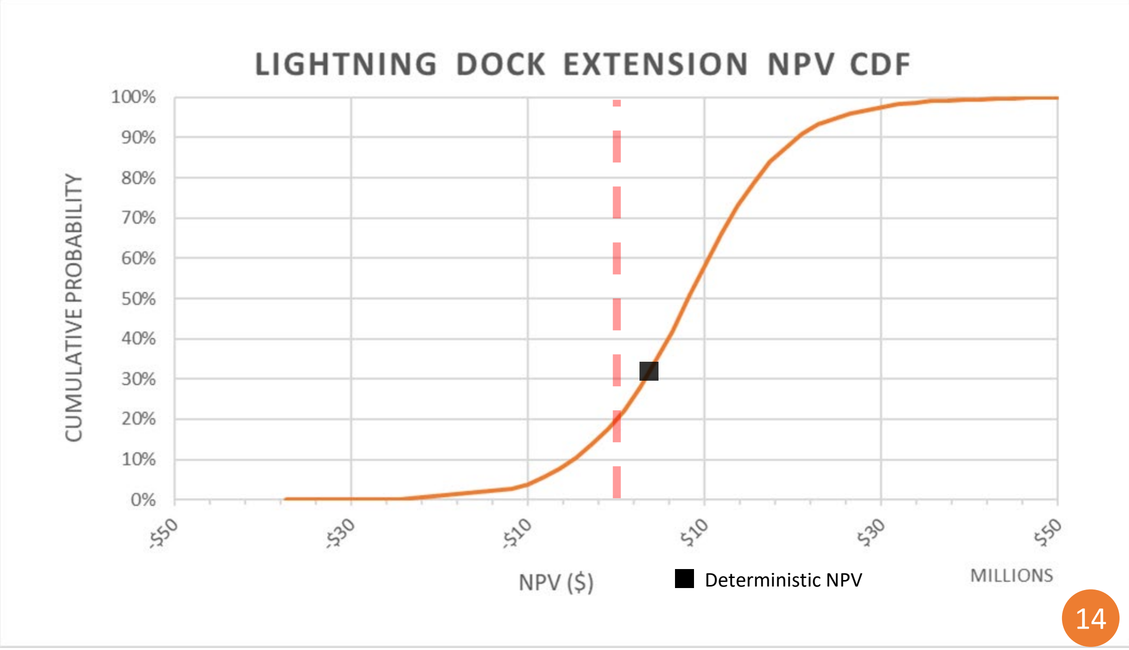
- Same as Base Case

Flexibilities

- Redrill after 13°C drawdown.
- Increase capacity 25% if prices up ≥20% compared to time of PPA signing.
- Shut down 25% of modules if prices suddenly drop by ≥20%.

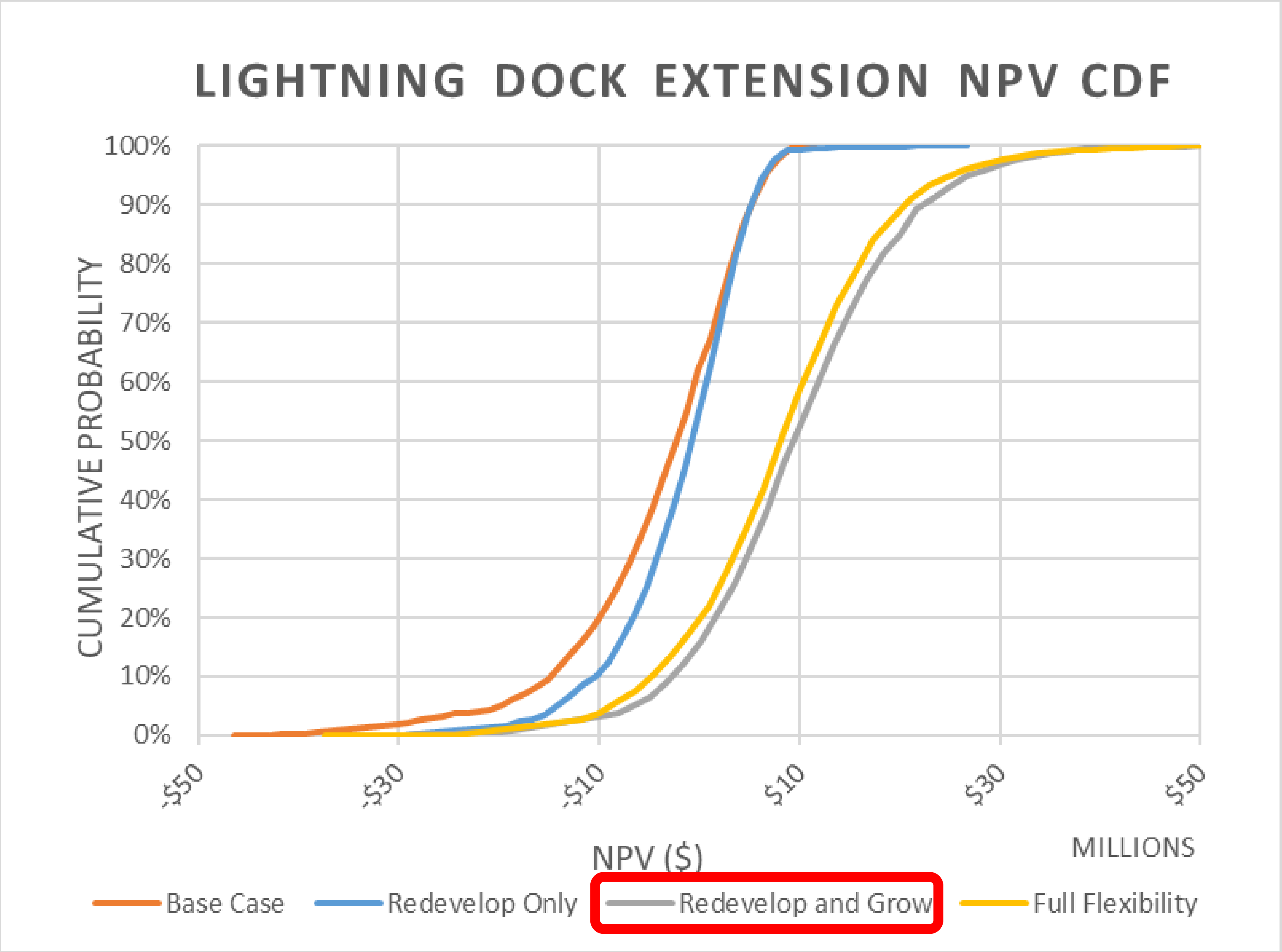
Full Flexibility Statistics	N=2000
ENPV	$8.2MM
STD(NPV)	$10.3MM
P05 NPV	-$8.8MM
P50 NPV	$8.1MM
P95 NPV	$25.2MM
% Difference from NPV_{Det}	121%





Key Insights

- **Redevelop and Grow** case **dominates** all other scenarios. **Best model.**
- **Full Flexibility less attractive** likely due to the loss of income as modules taken offline.

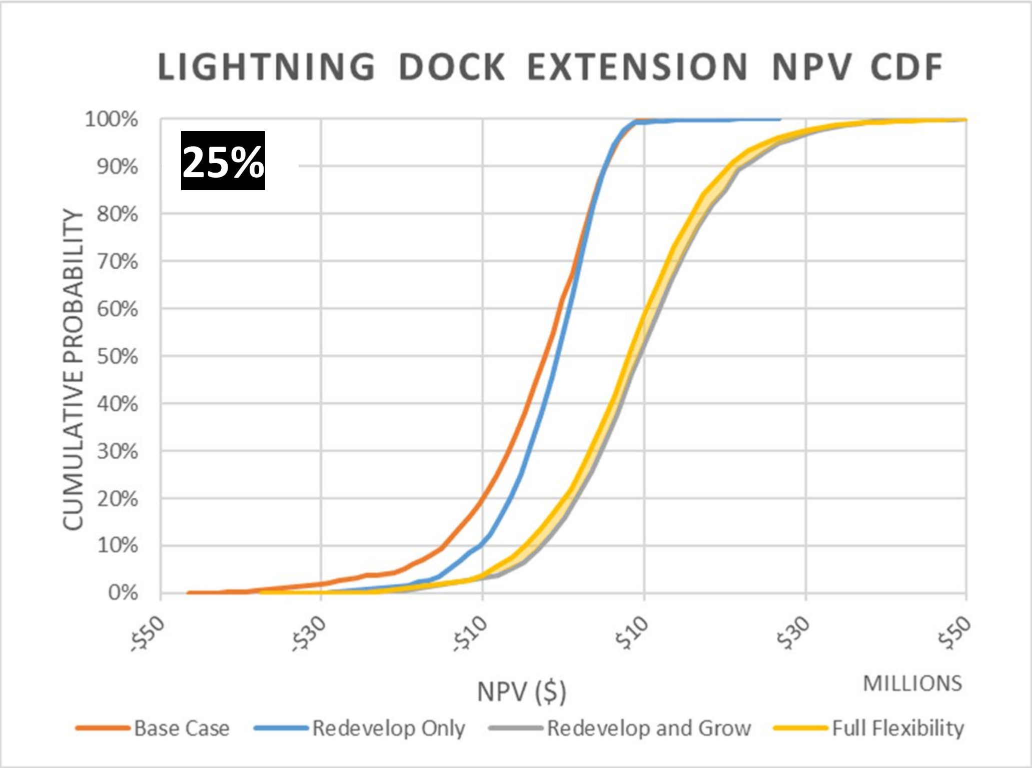


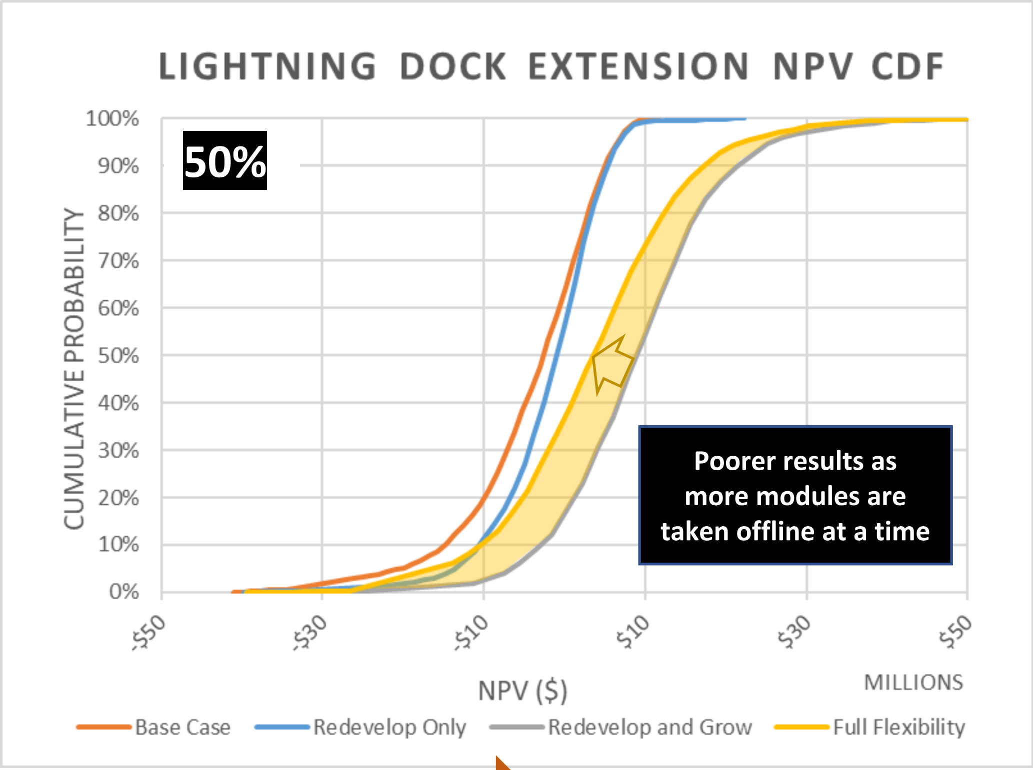
Sensitivity Test for Full Flexibility Case

- Increasing **reduction amount** (RA) leads to greater downside risk and lower ENPV.
- Redevelop and Grow scenario is the natural limit as RF→0.

General Parameters

Contract rate over wholesale	50%
Drilling learning rate	6%
Discount rate	9%
Price trigger for flexibility	20%
Expansion amount	25%
Reduction amount	50%





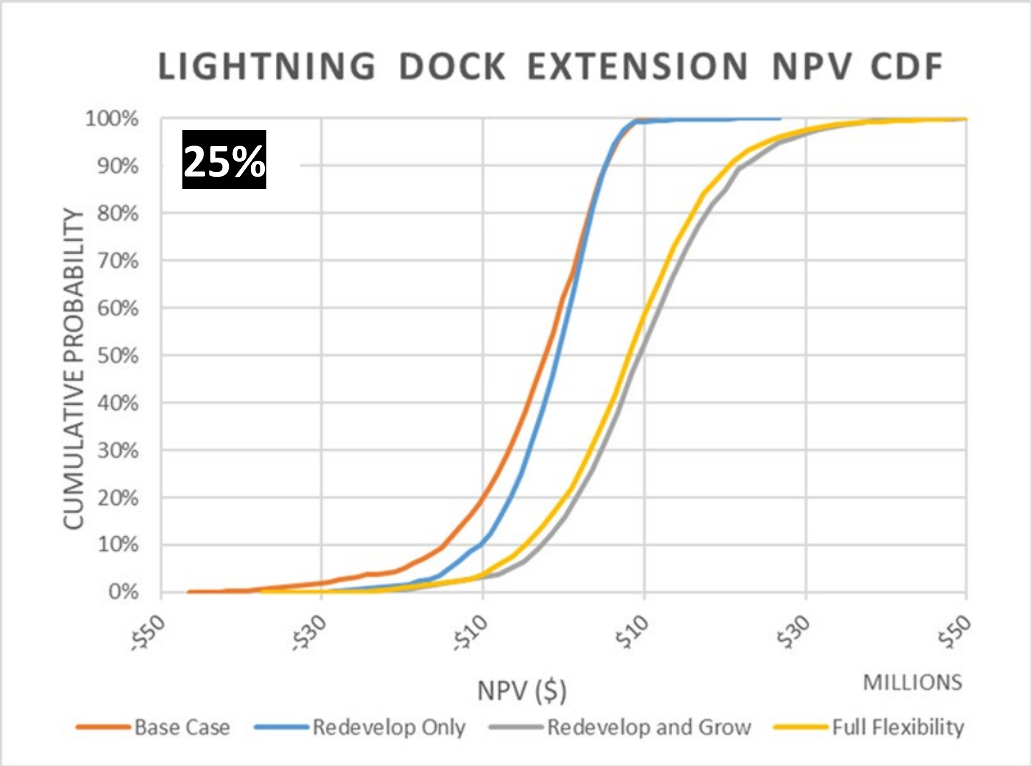
Results get worse

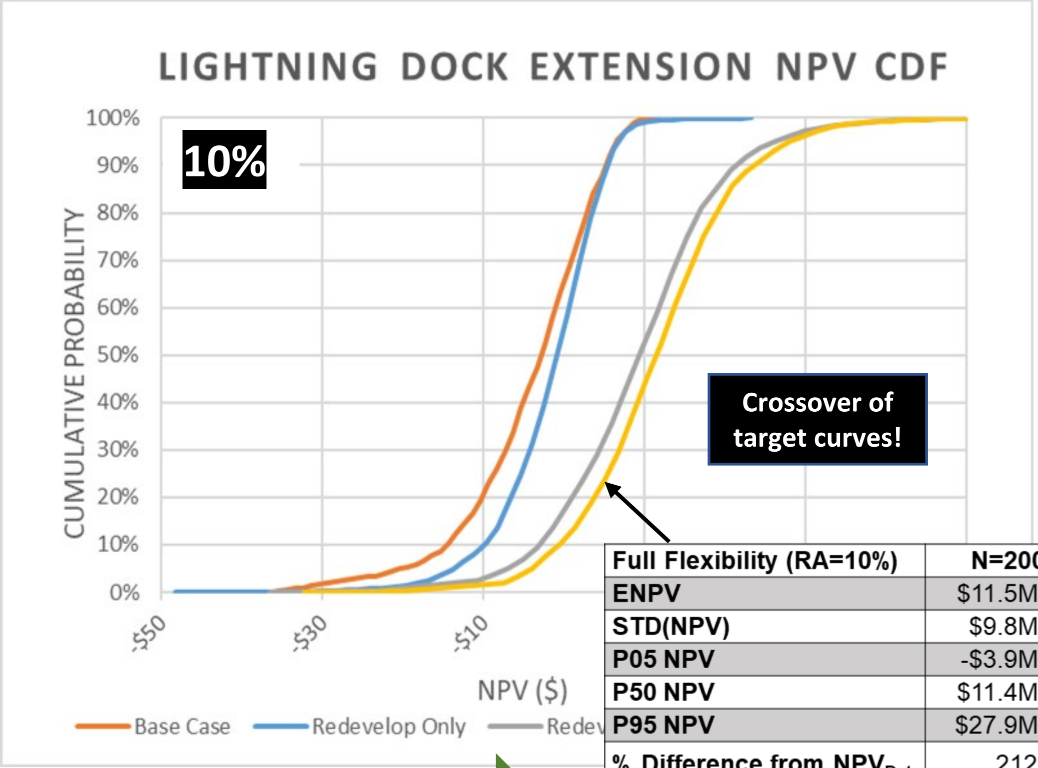
Sensitivity Test for Full Flexibility Case

- Decreasing **reduction amount** (RA) reveals a window where downside risk is lower and ENPV is maximized.
- **Full Flexibility with RA=10% is the preferred model.**

General Parameters

Contract rate over wholesale	50%
Drilling learning rate	6%
Discount rate	9%
Price trigger for flexibility	20%
Expansion amount	25%
Reduction amount	10%





Full Flexibility (RA=10%)	N=2000
ENPV	$11.5MM
STD(NPV)	$9.8MM
P05 NPV	-$3.9MM
P50 NPV	$11.4MM
P95 NPV	$27.9MM
% Difference from NPV_{Det}	212%

RESULTS REVERSAL!

Learnings and Recommendation

- **Deterministic model** overpredicts NPV compared to the Base Case Monte Carlo model (Flaw of Averages). The deterministic predicted profit nearly matches the Base Case predicted loss.
- **Base Case** scenario has significant downside with >60% of modeled realizations ending in losses.
- **Redevelop Only** scenario limits downside risk. ~56% of model realizations still result in a net loss, but the losses are not as extreme as in the Base Case.
- **Redevelop and Grow** scenario significantly improves upside capture by increasing capacity and renegotiating PPAs when electricity prices surge. Also reduces downside risk and has an ENPV of just under $10MM.
- **Full Flexibility** scenario performs worse than Redevelop and Grow when 25%+ of existing power plant modules are shut down in response to a downturn in electricity prices. **10% reduction produces the recommended model** with twice the ENPV of the deterministic case and the least downside risk among all scenarios. This model correctly balances cost savings of lower O&M expenses with income loss from reduced capacity.