Real Options for Geothermal Energy

Lightning Dock Expansion



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.

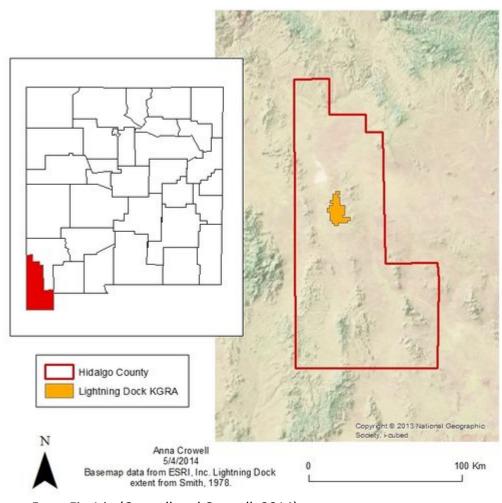
Information included in the models is based on publicly available data. Model inputs were determined from primary sources or selected as a best educated guess by the author when no suitable information source could be identified.

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.

Lightning Dock KGRA: Hidalgo County, New Mexico



From Fig 1 in (Crowell and Crowell, 2014)

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Geothermal in NM: Renewable Portfolio Standard (RPS)



Click below to search the NMPRC website

New Mexico Public Regulation Commission and Renewable Energy in New Mexico

The <u>Public Regulation Commission</u> reviews and approves renewable energy procurement plans and reports of <u>Investor Owned Utilities</u> ("IOU's") and <u>Rural Electric Cooperatives</u> ("Coops") pursuant to the <u>Renewable Energy Act ("REA"), §§ 62-16-1 et seq. NMSA 1978</u> and <u>Title 17.9.572</u> <u>NMAC</u> ("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 Aule 572 requires within the total portfolio percentage requirenewable 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 technologic

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

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

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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

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Enhanced Geothermal Systems (EGS)

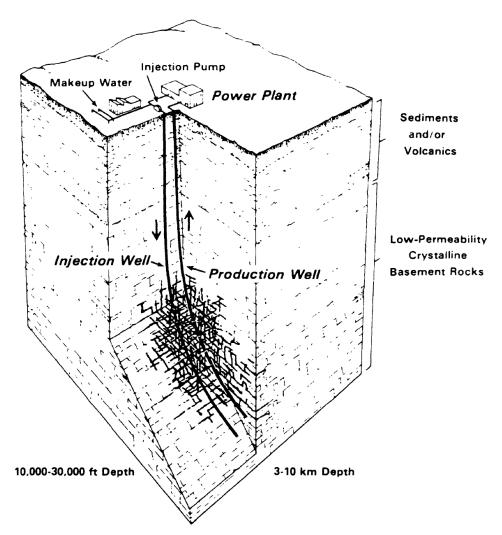
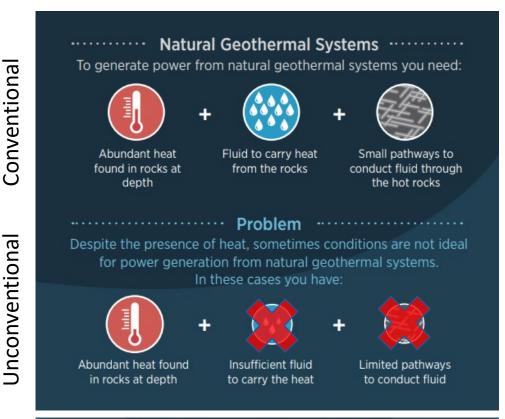
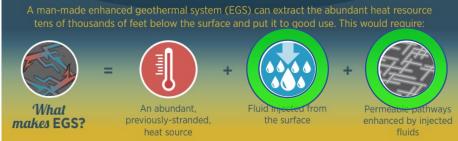


Figure 3.2 in (Tester and Herzog, 1990)

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IDS.330 Final Project





Infographic from U.S. Dept of Energy:

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energy.gov/sites/default/files/2015/04/f22/EGS%20Infographic_0.pdf

EGS

Binary Cycle Power Plants

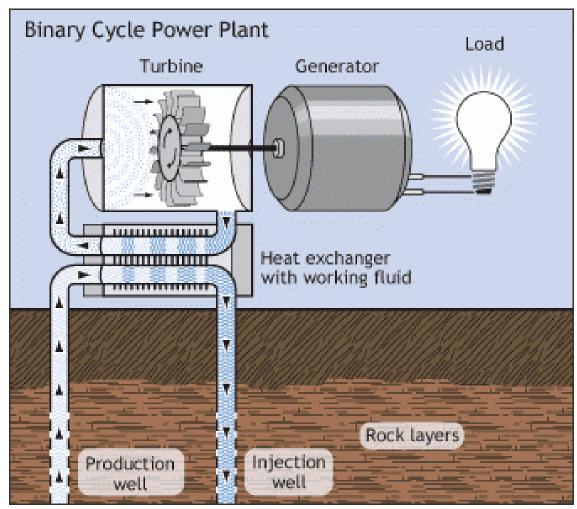


Image from U.S. Dept of Energy energy.gov/eere/geothermal/electricity-generation

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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.



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Deterministic Case

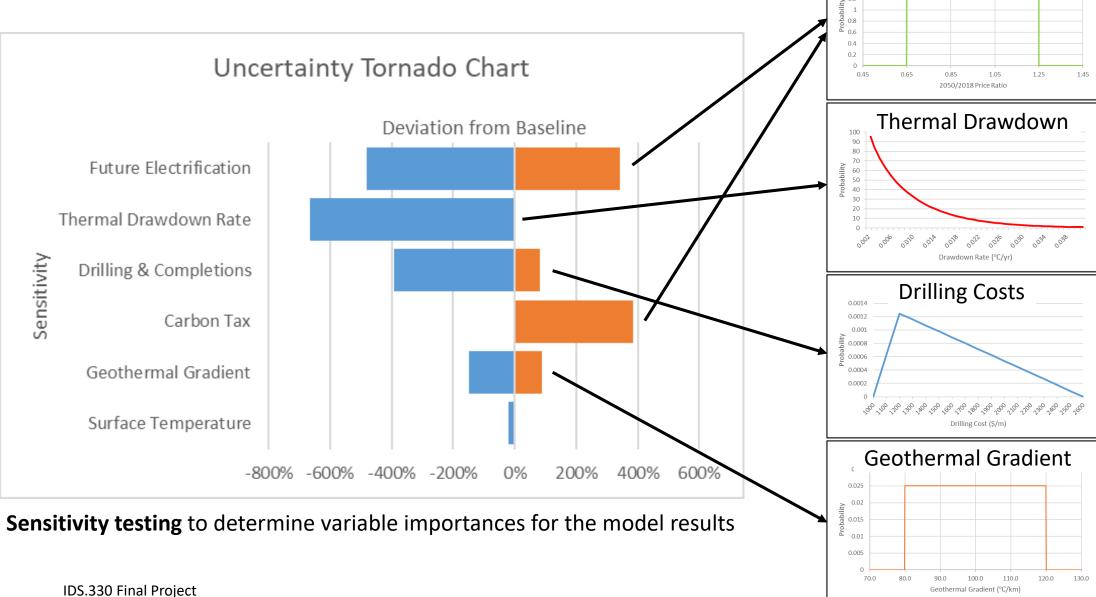
- Excel-based model for NPV calculation
- NPV (discount rate = 9%) components:
 - Income = electricity generated times PPA pricing (kWh*\$/kWh)
 - CAPEX = wells + power plant + fluid distribution + stimulation + exploration
 - OPEX = power plant O&M + field O&M + water O&M + labor
- Assumes a 30-year 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, I					
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 high	based on hole TG 56-14,	4 km SW of anomaly	
Average Well Depth (near verical, MD)		1.1	km		calculated based on rese		
nitial Average Reservoir Temperature		125	degrees C			file of Climeon (max: 120	C)
Production Well Temperature Loss		5	degrees C	Beckers, 2013; GETEM	aggressive value. Becker	rs uses 10deg w/ 5km we	II, GETEM calculates <
Production Temperature (at well head)		120	degrees C		re-compute with equation	n from Beckers, 2016 onc	e other variables defined
Vater 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/electr	ricity/2020/index.php?t=gt	t
APEX (per module)	VALUE		UNITS	REFERENCE		NOTES	
rilling & Completions Costs	S	1,305,956.16		Beckers 2013	Lukawski, 2016	HOTES	
Vells per module	Ť		well count per unit	Doctoro Lo to	doublet		
urface Plant Costs	Ś	1,000.00		Beckers 2013	waiting on reply from Bas	seload Cap., stick with th	is for now
eservoir Stimulation per injection well	S	1,250,000.00		Lowry, 2017		stimulation, recent ballpar	
luid Distribution Costs	S	279.300.00		Beckers 2013		ds additional study based	
edevelopment Factor		0.85			could be cheaper to redri		
hermal Drawdown Threshold			degrees C	GETEM	0.21*Ti-12.2		
hermal Drawdown Rate		0.5%	augicoco o	GETEM	varies from author-to-auth	hor (up to 4%)	
		0.5%		OLILIVI	varies ironi dutiloi-to-auti	1101 (up to 470)	
edevelop Every		100 0%	years				
xploration Success Rate	-		uon	D 1 0046		ea is already developed, r	
otal Capital Costs (exploration)	\$	2,133,542.54		Beckers 2016	Ccap = Ccap;well + Cca	p;pp + Ccap;stim + Ccap	gastr + Ccap;expl
otal Capital Costs (drilling)	\$	2,611,912.33		Beckers 2016			
otal Capital Costs (non-drilling)	\$	3,121,310.00	USD	Beckers 2016			
OWER PLANT (modules)	VALUE		UNITS	REFERENCE		NOTES	
lant Type		ary ORC			governs system physics		
Plant Useful Life		30	years	Augustine, 2009	basis for cost analysis		
leat Inlet Temperature		120	degrees C		simplifying assumption, i	ignoring secondary fluid h	eat exchange
Cool Inlet Temperature		50	degrees C		backing out from known	Climeon Mwe	
eat Capacity		2.28	kJ/kg-K	Dincer, 2010	isobutane, not sure if this	s is their fluid	
emperature Drop		70.0	degrees C (or K)				
nthalpy Drop		5.6	MWth		Q = q x Cp X delta T		
apacity Factor		95%		Glassly 2015, GETEM	4 4 1 4 1 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1		
Jegradation Factor		0.5%		NREL, 2002	using 0.5% NREL degrad	dation per vear	
Generation Efficiency (2nd Law Efficiency)		0.3		Beckers 2019, Glassley		(Mwe) to exergy of geoth	ermal fluid
Avg Net Power Output per Unit		1.59	MWe			Climeon ratings, but will	
PEX	VALUE		UNITS	REFERENCE		NOTES	
abor (per module)	\$	386,838.52	USD	GETEM			
ower Plant Ops & Maintenance (per module)	Ś	314,009.04	USD	Beckers 2013	0.75*Clabor + 0.015*Cpp		
	ě	122,828.75		Beckers 2013			
ield Ops & Maintenance (per module)	3					l; assume this includes p	ump costs
Vater Ops & Maintenance	Ş		USD	GETEM	water loss: \$300/acre-ft		
otal Annual O&M costs (per module)	\$	442,318.81	USD				
					sum of OMpp+OMfield+C	JMwater	
	VALUE		UNITS	REFERENCE	sum of OMpp+OMfield+C		
ACTORS/INDICES	VALUE	143%	UNITS	REFERENCE UCCI (IHS)	sum of OMpp+OMheld+C	NOTES	
ACTORS/INDICES rice Index from for Q4 2004 to 2020 USD	VALUE	143% 104%	UNITS	REFERENCE UCCI (IHS) UCCI (IHS)	sum of OMpp+OMfield+C		
ACTORS/INDICES Trice Index from for Q4 2004 to 2020 USD Trice Index from for Q4 2009 to 2020 USD	VALUE		UNITS	UCCI (IHS)	sum of OMpp+OMheid+C		
ACTORS/INDICES Trice Index from for Q4 2004 to 2020 USD Trice Index from for Q4 2009 to 2020 USD Trice Index from for Q4 2012 to 2020 USD	VALUE	104% 107% 145%	UNITS	UCCI (IHS) UCCI (IHS) UCCI (IHS) BLS	https://www.bls.gov/news	NOTES s.release/eci.t02.htm	
ACTORS/INDICES rice Index from for 04 2004 to 2020 USD rice Index from for 04 2009 to 2020 USD rice Index from for 04 2009 to 2020 USD rice Index from for 04 2012 to 2020 USD mployment Cost Index (Utilities) compared to 2004 iscount rate	VALUE	104% 107% 145% 9%	UNITS	UCCI (IHS) UCCI (IHS) UCCI (IHS) BLS Sanyal 2007	https://www.bls.gov/news	NOTES s. release/eci t02.htm	
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Key Uncertainties

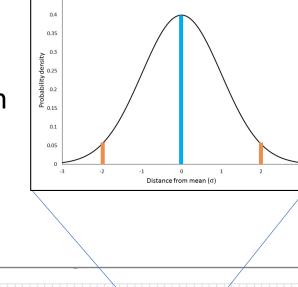
Probability density functions (pdfs) for value sampling

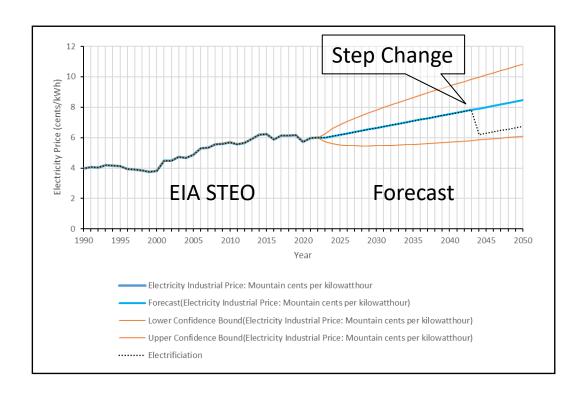
Electricity \$ Change

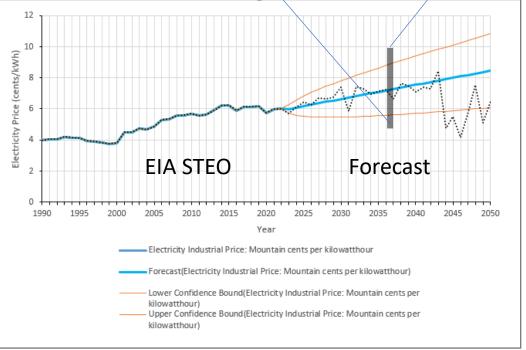


Electricity Price

- 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

Uncertainties

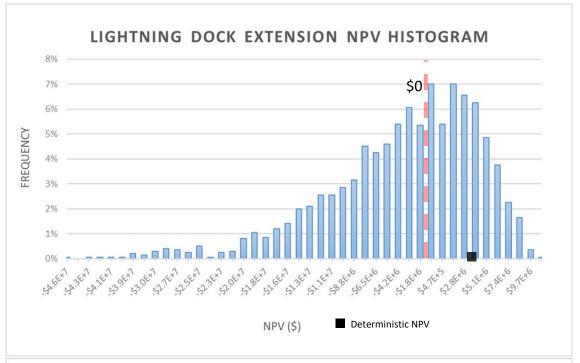
NO FLEXIBILITY

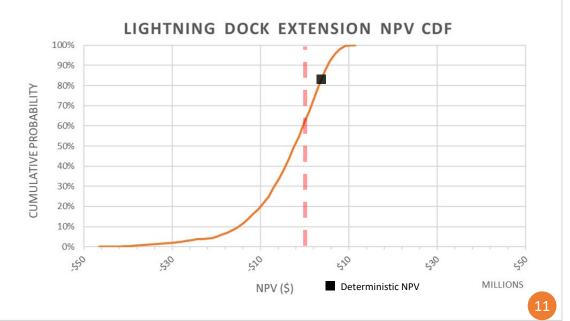
- Drilling & completions costs
- Pricing (future step change)
- Thermal drawdown rate
- Geothermal gradient

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

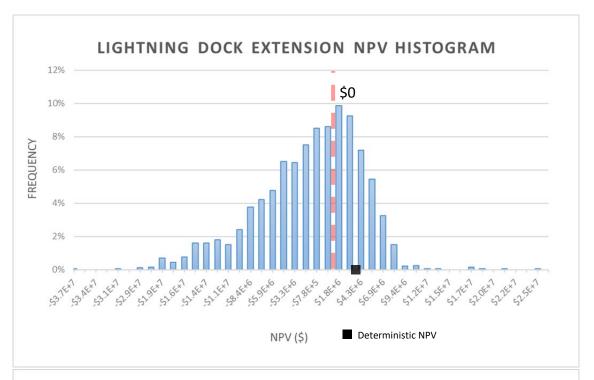
Uncertainties

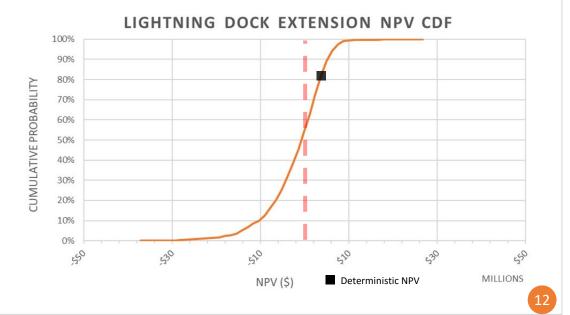
Same as Base Case

Flexibilities

Redrill after 13°C 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%





Redevelop and Grow

Uncertainties

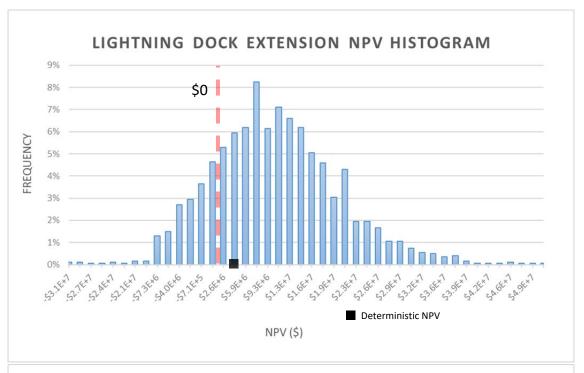
Same as Base Case

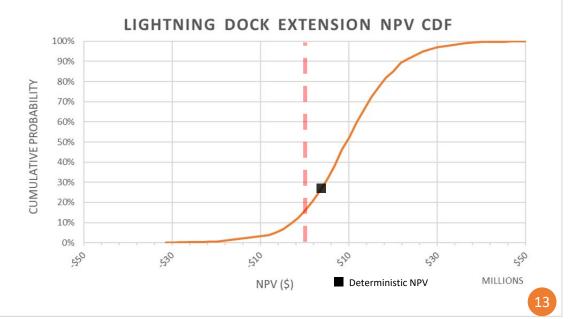
REDRILL BUILD

Flexibilities

- Redrill after 13°C 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%





Full Flexibility

Uncertainties

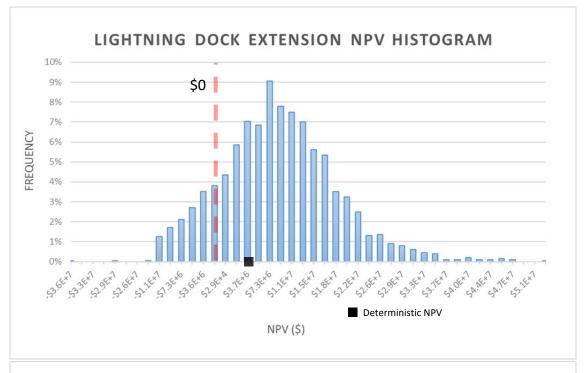
Same as Base Case

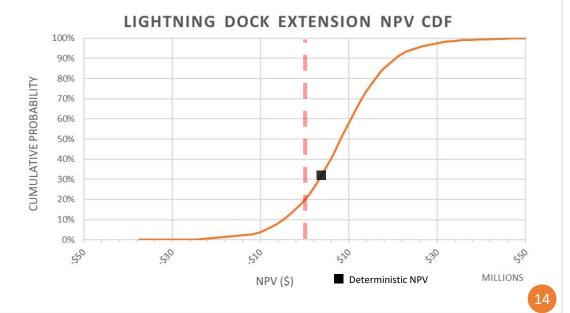
Flexibilities

- 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%



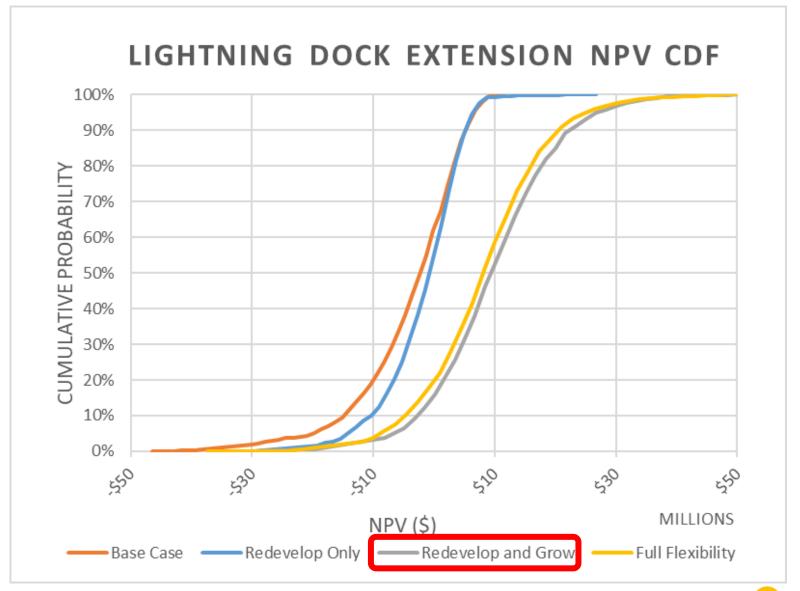




Key Insights

 Redevelop and Grow case dominates all other scenarios.
 Best model.

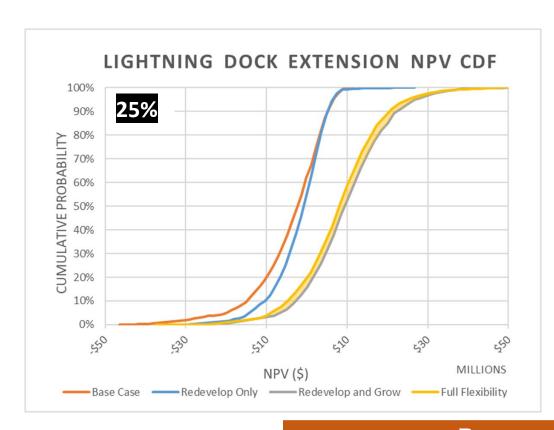
• Full Flexibility less attractive likely due to the loss of income as modules taken offline.

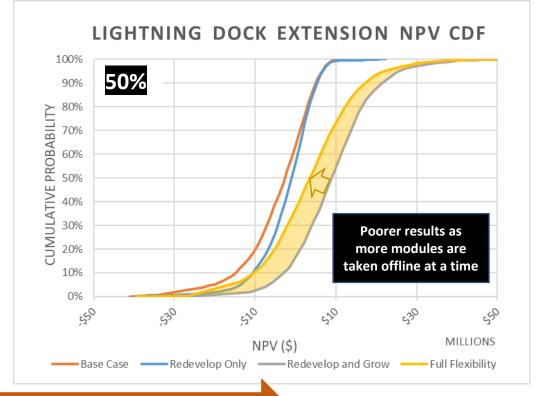


Sensitivity Test for Full Flexibility Case

- 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%



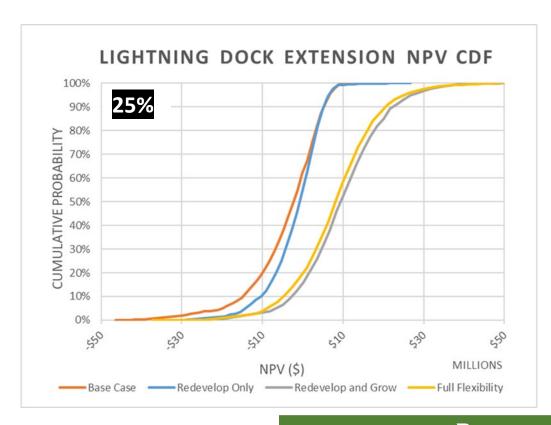


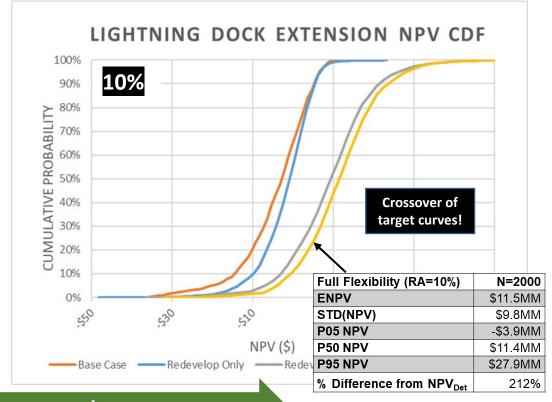
RESULTS GET WORSE

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%	





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.

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IDS.333 Risk and Decision Analysis Fall 2021

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