IOWA STATE UNIVERSITY
Hexcrete Tower Project (DE-EE0006737)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
WIND & WATER POWER TECHNOLOGIES OFFICE

Hexcrete Tower for Harvesting Wind Energy at Taller Hub Heights – Phase II

Levelized Cost of Energy (LCOE) Analysis

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NREL's Scope of Work

DOE funded NREL to support the Iowa State University Hexcrete Tower Team:

Techno-economic analysis

- Provided ISU with NREL models to estimate LCOE
  - Cost and Scaling Model
  - Land-Based BOS Model
- Provided generic low wind speed site assumptions for LCOE calculations
- Performed wind plant LCOE for conventional and Hexcrete towers at 80m, 120m, and 140m hub heights

Tower engineering support

- NREL designed and estimated conventional "canned" steel towers for comparison

LCOE Formula

$$LCOE = \frac{(CapEx\ X\ FCR)\ + OpEx}{AEP_{net}/1{,}000}$$

LCOE	=	levelized cost of energy ($/megawatt-hour [MWh])
FCR	=	fixed charge rate (%)
	=	$\frac{d(1+d)^n}{(1+d)^n-1} \times \frac{1-(T \times PVdep)}{(1-T)}$
CapEx	=	capital expenditures ($/kilowatt [kW])
AEP_{net}	=	net average annual energy production (MWh/megawatt [MW]/year [yr])
	=	$MW_{net} \times 8{,}760 \times CF_{net}$
OpEx	=	operational expenditures ($/kW/yr)
	=	$LLC + OPER + MAIN$
d	=	discount rate (weighted average cost of capital [WACC]) (%)
n	=	economic operational life (yr)
T	=	effective tax rate (%)
$PVdep$	=	present value of depreciation (%)
CF_{net}	=	net capacity factor (%)
LLC	=	annual levelized land lease cost ($/kW/yr)
$OPER$	=	pretax levelized operation cost (operation and maintenance [O&M]) ($/kW/yr)
$MAIN$	=	pretax levelized maintenance cost (O&M) ($/kW/yr).

Assumptions:

- FCR = 10.2%
- O&M = $50/kW/year
- Energy Losses = 15%
- Wind plant availability = 98%
- System design life = 20 years

LCOE Framework

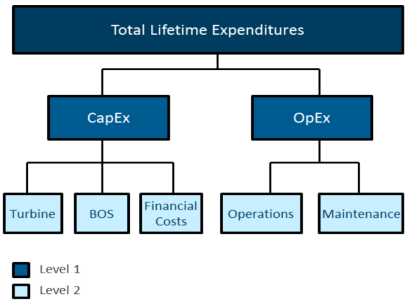
LCOE

Turbine Capital Cost	Balance of System (BOS) Capital Cost	Financial Costs	Fixed Charge Rate	Operations and Maintenance (O&M)	Net Annual Energy Production
NREL cost models, ISU cost models, and industry partner input/data	NREL cost models, NREL published literature, ISU cost models, and industry partner input/data	NREL published literature	NREL published literature	NREL published literature	NREL models and published literature
• Turbine (rotor, nacelle assembly) ○ NREL Cost and Scaling Model • Tower ○ NREL tower design model for 80-m, 120-m, and 140-m steel towers ○ NREL Cost and Scaling Model to estimate cost • Hexcrete Tower ○ ISU design and cost models ○ Review and input from industry partners	• 2013 Cost of Wind Energy Review ○ Development ○ Engineering management ○ Electrical infrastructure ○ Site access and staging • NREL Land-Based BOS Model (for steel tower scenarios) ○ Assembly and installation ○ Foundation cost ○ O&M infrastructure cost • Hexcrete BOS cost estimates ○ ISU cost models ○ Review and input from industry partners	• 2013 Cost of Wind Energy Review Methodology ○ Project Contingency Budget - 6% of combined turbine and BOS capitol cost ○ Construction Financing Costs – 3% of combined turbine and BOS Capital cost	• 2013 Cost of Wind Energy Review ○ Simplified representation of discount rate, effective tax rate, and present value of depreciation	• 2013 Cost of Wind Energy Review ○ $50/kW/yr	• Used a generic low wind speed, high shear site (representative of the US southeast region) • Loss and availability assumptions from 2013 Cost of Wind Energy Review ○ 15% losses ○ 98% availability • AEP estimated using NREL's Cost and Scaling Model

Example of NREL/ISU LCOE Spreadsheet Interface

Capital Costs of Wind Energy Systems ($/kW)

SCBS #	Level	Component/Category	Siemens - 2.3MW - 80m Hub Height - Rolled Steel Tower	Siemens - 2.3MW - 120m Hub Height - Rolled Steel Tower
1	1	CapEX	1,844	2,074
1.1	2	**Wind Turbine**	1,313	1,507
1.1.1	3	Nacelle Module	755	755
1.1.2	3	Tower Module	192	379
1.1.3	3	Rotor Module	335	335
1.2	2	**Balance of Station**	379	397
1.2.1	3	Development	32	32
1.2.2	3	Engineering Management	19	19
1.2.3	3	Electrical Infrastructure	150	150
1.2.4	3	Plant Commissioning		
1.2.5	3	Site Access and Staging	48	48
1.2.6	3	Assembly & Installation	75	84
1.2.7	3	Foundation	52	61
1.2.8	3	Operations and Maintenance Infrastructure	4	4
1.3	2	**Financial Costs**	152	171
1.3.1	3	Project Contingency Budget	102	114
1.3.2	3	Insurance During Construction (IDC)		
1.3.3	3	Carrying Charges During Construction (Construction Financing Costs)	51	57
1.3.4	3	Reserve Accounts (MRA, DSRA)		

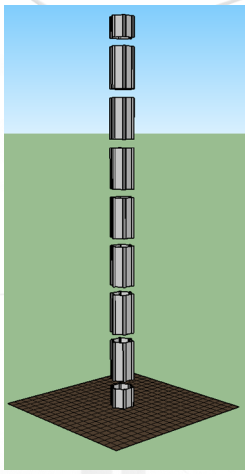


Hexcrete Tower Project
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy WIND & WATER POWER TECHNOLOGIES OFFICE
Commercialization Workshop

Tower Assembly

This project facilitates widespread deployment of the Hexcrete technology which was developed and patented by ISU:

- Hub height of 100-140 m
- High strength concrete (HSC) and ultra-high performance concrete (UHPC) to minimize material volumes
- Utilizes modular construction techniques
- Minimizes transportation and logistic constraints



Components of a Wind Project

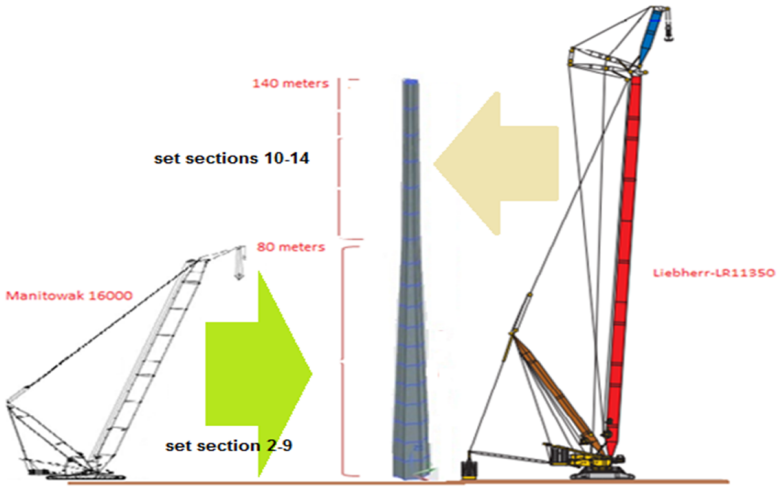
- Access Roads
- WTG Foundations
- WTG Assembly
- Electrical Collection System
- Substation
- Transmission Infrastructure to Point of Interconnect

Industry Assembly Workshop –
a) San Diego in March, 2015 and b) Minneapolis in March 2016.

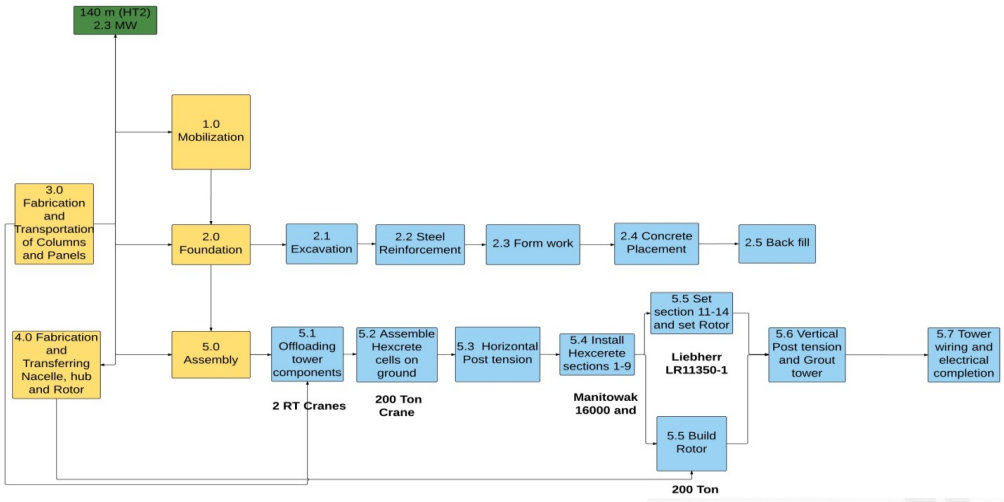
Types of 140m Hexcrete Towers

Type of tower	Number of hexcrete cells	Number of steel sections
HT3a (3.2MW)	17	N/A
HT3a hybrid (3.2MW)	11	3
HT2a (2.3MW)	14	N/A
HT2a hybrid (2.3MW)	10	3

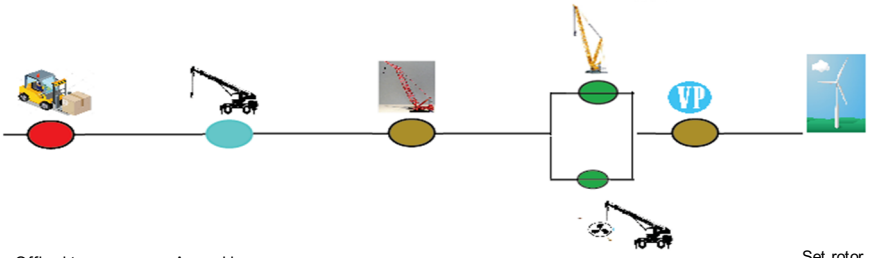
Assembly of 140m Hexcrete Towers (HT2a, 2.3Mw)



Work Break Down Structure (HT2a)



Assembly Work Sequence



Offload tower components

Assembly cells on ground

Setting cells (Manitowoc 16000)

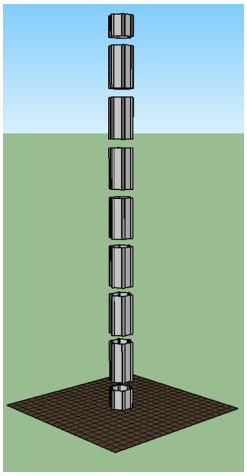
Setting cells (top) on each other (CC6800)

Vertical post tension and building rotor

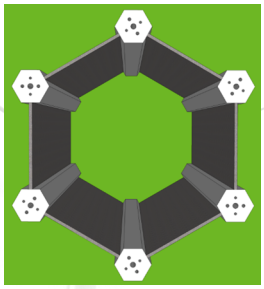
Set rotor, narcelle on top

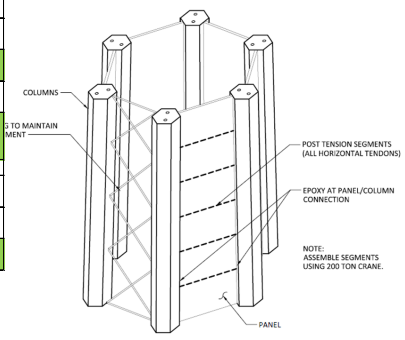
1 2 3 4 5 6 7

Assembly Process

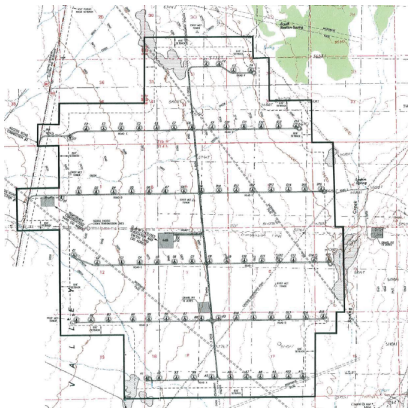


Activity	Task	Crane Type	Productivity of Each Crane/Crew	Number of Cranes/Crews	Total Schedule Days
Offload WTG	Offload Hexcrete Tower	RT Cranes	3 Days/WTG	3 Crews	100 Days
	Offload Nacelle, Hubs, and Blades	RT Cranes			
Assemble Cells on the Ground	Build Cells on Ground	250 ton Crawler	2 Cells per day	7 Cranes/Crews	100 Days
(1-14 Cells)	Horizontal Post Tension				
	Steel Bracing/Ladders				
Set Cells (1-10)	Set Cells on each other	Manitowoc 16000	5 Cells/day	2 Cranes	100 Days
	Temporary Connection				
Set Cells (11-14) and Build Rotor and Set Nacelle/Rotor	Set Cells 11-14	LR11350	4 Cells(1 WTG)/Day	2 carnes	100 Days
	Build Rotor	250 ton Crawler	1 Rotor/Day	1 carne	
	Set Nacelle and Rotor	LR11350	1 Day/WTG	2 carnes	
	Partial Breakdown of Crane and Move		1 Day/WTG	2 carnes	
Vertical Post Tension and Grouting			2 Days/WTG		100 Days



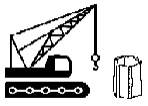
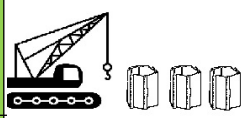
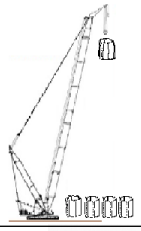


Schedule Development



- Major parameters and assumptions
  - 100 wind towers
  - Location: Iowa (a typical mid-western area)
  - 200 miles: distance from precast manufacturing plant to site
- Work Sequence
  - Access Roads
  - WTG Foundations
  - WTG Assembly
  - Electrical Collection System
  - Substation
  - Transmission Infrastructure to Point of Interconnect

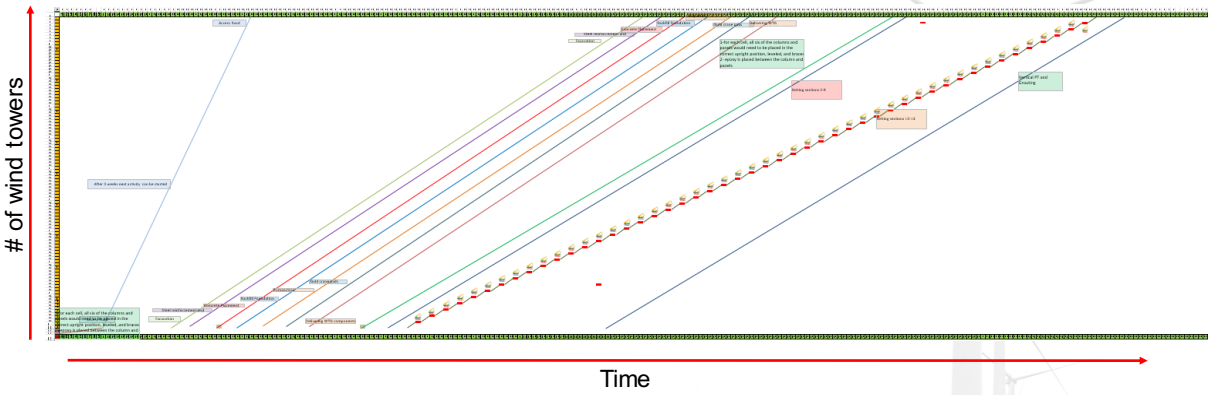
Production Rate Estimation of Key Activities

Activity / Production rates	Worst Case	Most likely	Best Case
Assemble cells on ground	1 cell per day 	2 cells per day 	3 cells per day 
Setting hexcrete cells on each other	3 cells per day 	4 cells per day 	5 cells per day 

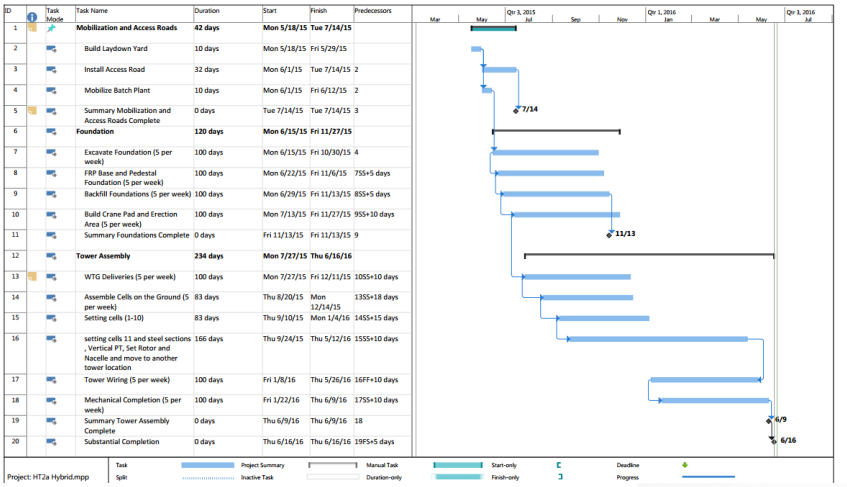
Nine Possible Scenarios

Scenario 1 • Assembling 1 cell on ground per day. • Stacking 3 cells per day	Scenario 2 • Assembling 2 cells on ground per day. • Stacking 3 cells per day	Scenario 3 • Assembling 3 cells on ground per day. • Stacking 3 cells per day
Scenario 4 • Assembling 1 cell on ground per day. • Stacking 4 cells per day	Scenario 5 • Assembling 2 cells on ground per day. • Stacking 4 cells per day	Scenario 6 • Assembling 3 cells on ground per day. • Stacking 4 cells per day
Scenario 7 • Assembling 1 cell on ground per day. • Stacking 5 cells per day	Scenario 8 • Assembling 2 cells on ground per day. • Stacking 5 cells per day	Scenario 9 • Assembling 3 cells on ground per day. • Stacking 5 cells per day

Linear schedule (140m Tower, HT2a – 2.3Mw, Most Likely)



Bar Chart Schedule (140 m Tower – HT2a, 2.3Mw, Scenario 5)



ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Mobilization and Access Roads**	**42 days**	**Mon 5/18/15**	**Tue 7/14/15**	
2		Build Laydown Yard	10 days	Mon 5/18/15	Fri 5/29/15	
3		Install Access Road	32 days	Mon 6/1/15	Tue 7/14/15	2
4		Mobilize Batch Plant	10 days	Mon 6/1/15	Fri 6/12/15	2
5		Summary Mobilization and Access Roads Complete	0 days	Tue 7/14/15	Tue 7/14/15	3
6		**Foundation**	**120 days**	**Mon 6/15/15**	**Fri 11/27/15**	
7		Excavate Foundation (5 per week)	100 days	Mon 6/15/15	Fri 10/30/15	4
8		FRP Base and Pedestal Foundation (5 per week)	100 days	Mon 6/22/15	Fri 11/6/15	7SS+5 days
9		Backfill Foundations (5 per week)	100 days	Mon 6/29/15	Fri 11/13/15	8SS+5 days
10		Build Crane Pad and Erection Area (5 per week)	100 days	Mon 7/13/15	Fri 11/27/15	9SS+10 days
11		Summary Foundations Complete	0 days	Fri 11/13/15	Fri 11/13/15	9
12		**Tower Assembly**	**234 days**	**Mon 7/27/15**	**Thu 6/16/16**	
13		WTG Deliveries (5 per week)	100 days	Mon 7/27/15	Fri 12/11/15	10SS+10 days
14		Assemble Cells on the Ground (5 per week)	83 days	Thu 8/20/15	Mon 12/14/15	13SS+18 days
15		Setting cells (1-10)	83 days	Thu 9/10/15	Mon 1/4/16	14SS+15 days
16		setting cells 11 and steel sections , Vertical PT, Set Rotor and Nacelle and move to another tower location	166 days	Thu 9/24/15	Thu 5/12/16	15SS+10 days
17		Tower Wiring (5 per week)	100 days	Fri 1/8/16	Thu 5/26/16	16FF+10 days
18		Mechanical Completion (5 per week)	100 days	Fri 1/22/16	Thu 6/9/16	17SS+10 days
19		Summary Tower Assembly Complete	0 days	Thu 6/9/16	Thu 6/9/16	18
20		Substantial Completion	0 days	Thu 6/16/16	Thu 6/16/16	19FS+5 days

Project Duration (140m Hexcrete Towers, all scenarios)

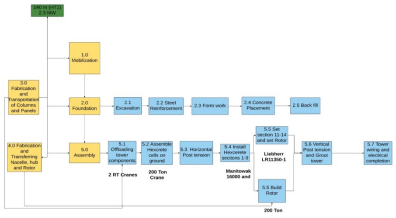
Unit: Calendar Days

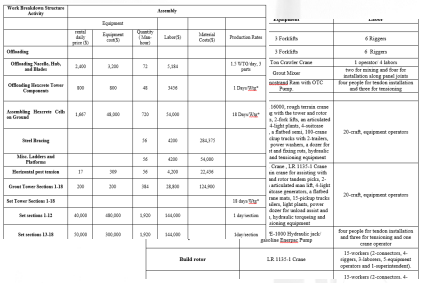
Wind Tower Type	Worst Case	Most Likely	Best Case
HT3a	430	395	350
HT3a – Hybrid	425	355	325
HT2a	365	330	310
HT2a - Hybrid	345	310	290

Note: Five working days a week

Foundation and Assembly Cost Estimation

- Bottom-Up Estimating Approach – Higher Cost Certainty
  - Detailed Estimating with higher granularity (Labor, Equipment, Material)





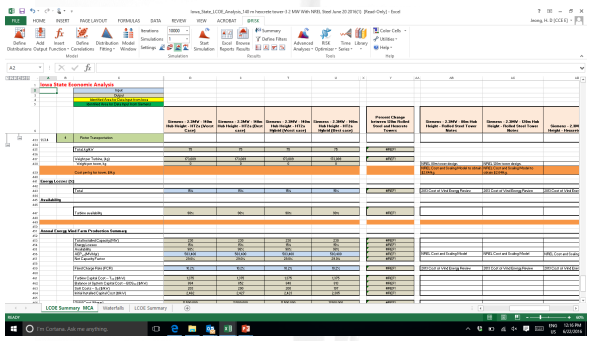
- Top-down Approach (Parametric Estimating) – NREL's LCOE Model

LCOE Analysis (140m, HT2a, 2.3Mw, Scenario 5)

- Foundation and Assembly cost estimation data were plugged into NREL's LCOE spreadsheet program

- Pattern Energy
- Mortensen
- Barr Engineering
- Coreslab
- Old castle, Midstate Precast
- Biggie Crane and Rigging
- Structural Technologies
- Others

NREL's LCOE Spreadsheet



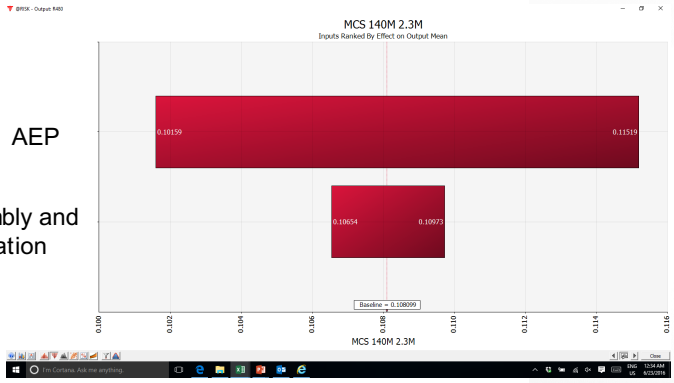
LCOE Analysis Results

- Unit : dollars per kilowatt hour ($/kwh).

Wind Tower Type	Worst Case	Most Likely	Best Case
HT3a	0.1102	0.1090	0.1085
HT3a – Hybrid	0.1065	0.1053	0.1049
HT2a	0.1089	0.1076	0.1072
HT2a - Hybrid	0.1082	0.1072	0.1068

Impact on LCOE – Sensitivity Analysis (Monte-Carlo Sim)

- Assembly costs: the most likely cost estimate± 5%
- Annual Energy Production (AEP): NREL's estimated value ± 5%



± 5.3%

± 1.5%