IES
Integrated Energy Systems

Cost Estimation for Advanced Nuclear

FORCE Overview and Training

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Overview

- **Background**: IES program is focused on advanced reactor costs and technoeconomic evaluations, but limited consensus on what the cost of these systems will be. This effort is working towards providing initial estimates in short-term and more robust ones in longer term.
- Initial scope consists of literature survey of existing cost estimates for advanced reactors and providing preliminary recommendations that can be leveraged within FORCE evaluations.
- Findings will be published in upcoming INL public report (reach out if you want to be on the distribution when it comes out)
- Overview of presentation scope:
  1. High-Level Estimates (CAPEX in $/kW, OPEX)
  2. Lower-Level Estimates (reactor components, more granularity)
  3. How to Use in FORCE simulation (example walkthrough)

Cost Estimation Literature Review - I

PWR

Ref	Reactor Concept	Learning	Units	Power	CAPEX	LCOE	OPEX
[1]	NuScale iPWR	FOAK	12	1920MWth/570MWe	5600$_{2015}$/kW	114$_{2015}$/MW-hr	
[2]	NuScale iPWR	NOAK	12	685MWe	3856$_{2018}$/kW		
[3]	NuScale iPWR	NOAK	12	924MWe	2850$_{2018}$/kW		
[4]	SMART iPWR				5600$_{2015}$/kWe	105$_{2015}$/MW-hr	25$_{2015}$/MW-hr
[5]	NuScale SMR			1920-2400MWth/600-720MWe		51-54$_{2019}$/MW-hr 112$_{2016}$/MW-hr [6] 101$_{2016}$/MW-hr [7]	
[8]	NuScale			600MWe		65$_{2015}$/MW-hr	
[9]	SMR			570MWe		80$/MW-hr	
[5]	BWRX-300			870MWth/300MWe		44–51$_{2019}$/MW-hr	
[10]	PWR-12	FOAK	1	3417MWth/1144MWe	6345$_{2017}$/kWe		
[10]	PWR-12	NOAK	1	3417MWth/1144MWe	3650$_{2017}$/kWe		
[10]	AP1000	FOAK	1	3417MWth/1144MWe	6671$_{2017}$/kWe		
[10]	AP1000	NOAK	1	3415MWth/1100MWe	3838$_{2017}$/kWe		
[11]	AP1000	FOAK	1	3415MWth/1100MWe	7349$_{2022}$/kWe	81$_{2022}$/MW-hr	
[12]	PWR	FOAK	1	3415MWth/1100MWe	6154$_{2018}$/kWe		
[12]	PWR	NOAK	1	3415MWth/1100MWe	6986$_{2014}$/kWe		
[13]	PWR		2	2156 MWe	6041$_{2019}$/KWe		
[5]	PWR		2	2256MWe	6317$_{2019}$/KWe	82$_{2019}$/ MW-hr	25$_{2019}$/MW-hr
[14]	PWR					141-221$/MW-hr	19-21$/MW-hr
[15]	PWR12BE	NOAK	1	3417MWth/1144MWe	4012$_{2011}$/kWe		
[15]	PWR12ME	FOAK	1	3417MWth/1144Mwe	5305$_{2011}$/kWe		
[15]	PWR		1	3417MWth/1144Mwe	2534$_{2011}$/kWe		

HTGR

Ref	Reactor Concept	Learning	Units	Power	CAPEX	LCOE	OPEX
[10]	NGNP		1	275 MW	9900$_{2017}$/kWe		
[4]	HTGR				6600$_{2015}$/kWe	128$_{2015}$/MW-hr	30$_{2015}$/MW-hr
[10]	MIGHTR		1	350MWth/154MWe	7346$_{2017}$/kWe		
[16]	NGNP	FOAK	1	350MWth/154MWe	20994$_{2009}$/kWe		
[16]	NGNP	FOAK	1	600MWth/267MWe	14479$_{2009}$/kWe		
[16]	NGNP	NOAK	1	350MWth/154MWe	7324$_{2009}$/kWe		
[16]	NGNP	NOAK	1	600MWth/267MWe	5841$_{2009}$/kWe		
[12]	NGNP		4	2400MWth/1000MWe	5246$_{2009}$/kWe	114$_{2009}$/MW-hr	
[10]	NGNP		4	1100 MW	4814$_{2017}$/kWe		
[16]	NGNP	NOAK	4	1400MWth/624MWe	5720$_{2009}$/kWe		
[10]	MIGHTR	NOAK	4	1400MWth/616MWe	3585$_{2017}$/kWe		
[16]	NGNP	NOAK	4	2400MWth/1068MWe	4663$_{2009}$/kWe		
[17]	NGNP		4	2400MWth/1068MWe	5600$_{2018}$/kWe		
[17]	HC-HTGR	FOAK	4	920MWe	4550$_{2018}$/kWe		
[17]	HC-HTGR	10-OAK	4	920MWe	3000$_{2018}$/kWe		
[18]	X-Energy HTGR		4	320MWe	7500$_{2020}$/kWe		
[19]	MHTGR-SC	FOAK	4	1800MWth/693MWe	3153$_{1992}$/kWe		
[19]	MHTGR-SC	NOAK	4	1800MWth/693MWe	2347$_{1992}$/kWe	50$_{1992}$/MW-hr	8$_{1992}$/MW-hr
[19]	MHTGR-GT/IC	FOAK	4	1800MWth/806MWe	3290$_{1992}$/kWe		
[19]	MHTGR-GT/IC	NOAK	4	1800MWth/806MWe	2458$_{1992}$/kWe	48$_{1992}$/MW-hr	6$_{1992}$/MW-hr
[19]	MHTGR-GT/DC	FOAK	4	1800MWth/869MWe	2656$_{1992}$/kWe		
[19]	MHTGR-GT/DC	NOAK	4	1800MWth/869MWe	1908$_{1992}$/kWe	39$_{1992}$/MW-hr	5$_{1992}$/MW-hr
[20]	HTGR	NOAK		1124MWe	5469$_{2017}$/kWe	55$_{2017}$/MW-hr	

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Cost Estimation Literature Review - II

SFR

Ref	Reactor Concept	Learning	Units	Power	CAPEX	LCOE
[12]	SFR		4	3360MWth/1100MWe	5632$_{2013}$/kWe	113$_{2013}$/MW-hr
[21]	4S Sodium		1	30MWth		130-290$_{2009}$/MW-hr
[22]	LSPB		1	1100MWe	4734$_{2013}$/kWe	
[23]	ABR1000		1	380MWe	5613$_{2017}$/kWe	
[24]	S-PRISM		4	1520MWe	2664$_{2005}$/kWe	39$_{2005}$/MW-hr
[24]	S-PRISM		4	1520MWe	3046$_{2005}$/kWe	60$_{2005}$/MW-hr
[25]	S-PRISM		2	1651MWe	1335$_{1996}$/kW	32$_{1996}$/MW-hr
[24]	S-PRISM Mod B		6	1866MWe	2073$_{2005}$/kWe	39$_{2005}$/MW-hr
[24]	S-PRISM Mod B		6	1866MWe	2371$_{2005}$/kWe	55$_{2005}$/MW-hr
[20]	LSPB	NOAK		1311Mwe	4241$_{2017}$/kWe	80$_{2017}$/MW-hr

Microreactor

Ref	Reactor Concept	Learning	Units	Power	CAPEX	LCOE	OPEX
[27]	Reference micro-reactor	FOAK	1	10MWth/5MWe	10000$_{2019}$/kWe	150$_{2019}$/MW-hr	69$_{2019}$/MW-hr
[27]	Reference micro-reactor	FOAK	1	10MWth/5MWe	15000$_{2019}$/kWe	310$_{2019}$/MW-hr	103$_{2019}$/MW-hr
[27]	Reference micro-reactor	FOAK	1	10MWth/5MWe	20000$_{2019}$/kWe	410$_{2019}$/MW-hr	137$_{2019}$/MW-hr
[27]	Reference micro-reactor	NOAK	1	10MWth/5MWe	3996$_{2019}$/kWe	80$_{2019}$/MW-hr	
[27]	Reference micro-reactor	NOAK	1	10MWth/5MWe	8276$_{2019}$/kWe	200$_{2019}$/MW-hr	
[27]	Reference micro-reactor	NOAK	1	10MWth/5MWe	14973$_{2019}$/kWe	340$_{2019}$/MW-hr	
[28]	Design A	FOAK	1	5MWth/1.8MWe	65445$_{2017}$/kWe	2174$_{2017}$/MW-hr	
[28]	Design A’	FOAK	1	8MWth/2.9MWe	19241$_{2017}$/kWe	363$_{2017}$/MW-hr	122$_{2017}$/MW-hr
[28]	Design A’	NOAK	1	8MWth/2.9MWe	6575$_{2017}$/kWe	135$_{2017}$/MW-hr	53$_{2017}$/MW-hr

MSR

Ref	Reactor Concept	Learning	Units	Power	CAPEX	LCOE	OPEX
[12]	AHTR		1	3000MWth/1350MWe	5217$_{2011}$/kWe	111$_{2011}$/MW-hr	
[12]	MSR		1	2275MWth/1000MWe	6113$_{2011}$/kWe	119$_{2011}$/MW-hr	
[12]	FHR		12	2904MWth/1330MWe	5423$_{2015}$/kWe	135$_{2015}$/MW-hr	
[26]	DMSR		1	1000MW	653$_{1978}$/kWe		
[15]	AHTR	NOAK	1	3400MWth/1530MWe	3384$_{2011}$/kWe		34-60$_{2011}$/MW-hr
[20]	MSR	NOAK		190-1000MWe	3664$_{2017}$/kWe	51$_{2017}$/MW-hr	

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High-Level Estimates

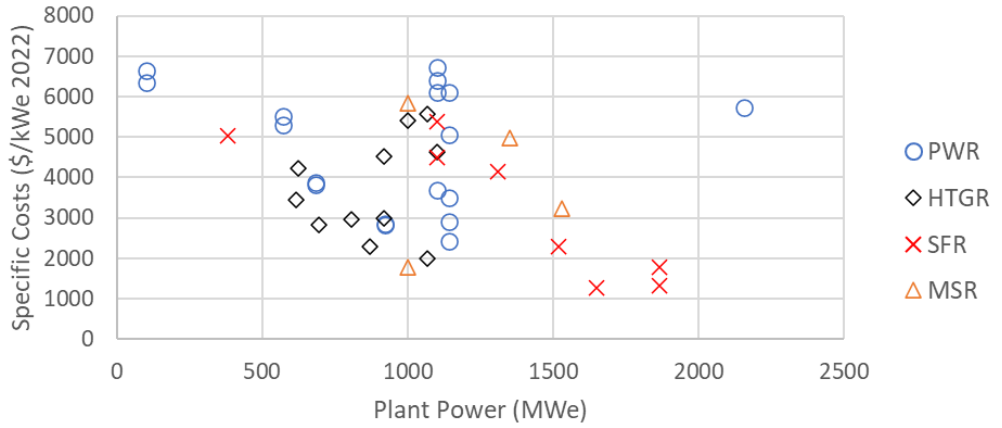
- Recommendations for overnight and annualized costs provided in tables below: metadata evaluation of literature
- Note that these estimates for reactor Between first and n^{th} of a kind (BOAK)
- Significant overlap in literature among different reactor types and large vs. SMR
- Recommend using the same reference values for either at this stage
- Separate recommendations for microreactors provided as well. But note that cost estimates studies limited to 2.

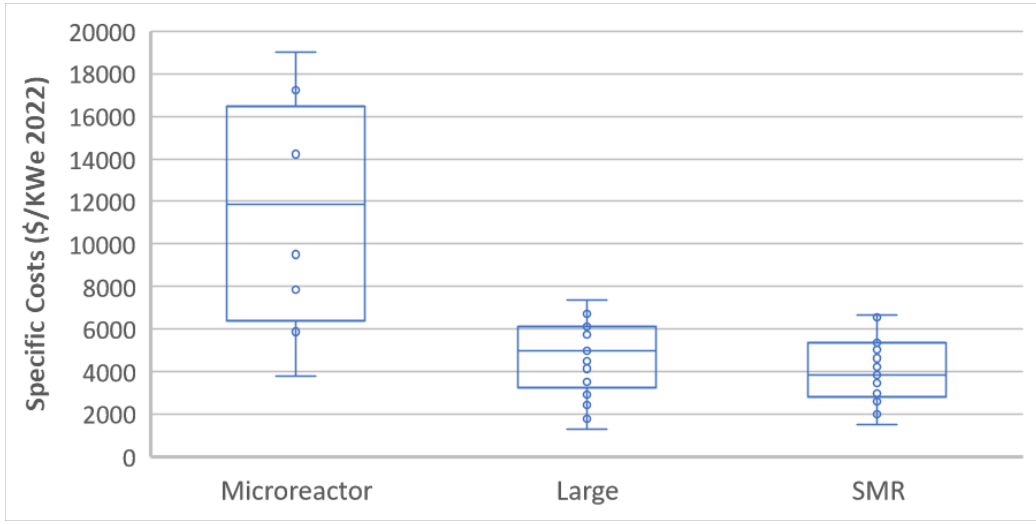
Large and SMR

	Low	Med	High	Sd
Overnight Costs	$3,000 /kWe	$4,500 /kWe	$6,000 /kWe	$1,500 /kWe
O&M Costs	$15 /MWh	$25 /MWh	$35 /MWh	$17 /MWh
LCOE (estimated)	$45 /MWh	$70 /MWh	$95 /MWh	$57 /MWh

Microreactors

	Low	Med	High	Sd
Overnight Costs	$8,000 /kWe	$12,000 /kWe	$16,000 /kWe	$5,500 /kWe
O&M Costs	$70 /MWh	$100 /MWh	$122 /MWh	$30 /MWh
LCOE (estimated)	$150 /MWh	$300 /MWh	$370 /MWh	$110 /MWh





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Lower-Level Detailed Estimates

- Reference reactors selected for each type:
  - Pressurized Water Reactor: PWR-12BE (reference)
  - Sodium Fast Reactor: ABR1000 and LPBR
  - High-temperature Gas Reactor: NGNP
  - Molten Salt Reactor: DMSR
- Lower-level more estimates structured via the Generalized Nuclear Code of Account (GN-COA)
- Similar to Bill of Material (BOM)
- Provides structured and consistent way of comparing advanced reactor costs across different categories

10s				**Project development**
	11			Land and land rights
	12			Site permits
	13			Plant licensing
	14, 15, 16			Plant permits & studies
	18			Community outreach & education
20s				**Direct costs**
	21			Plant Structures
		211		Yardwork
		212		Reactor containment
		213		Building and utilities
			218T	Reactor startup facility
	22			Reactor system
		221		Reactor components
			221.12	Outer vessel structure
			221.13	Inner vessel structure
			221.21	Reactivity control system
			221.22	Reflector
			221.23	Shield
			221.24	Moderator
		222		Main heat transport
			222.12	Reactor coolant system (heat pipes)
			222.13	Heat exchangers
		227		Instrumentation & control
	23, 24, 25			Turbine and electric systems
30s				**Indirect services**
	31, 35, 36, 37, 38			Field & factory Indirect support
	32			Factory & construction supervision
	33			Commissioning and startup
	34			Demonstration test run

40s				**Capitalized owner's costs**
	41,42,43			Operating staff recruitment, training etc.
50s				**Capitalized supplementary costs**
	51			Shipping and transportation
		511		Reactor module shipping & transportation
		512		Fuel shipping
	53, 54			Taxes & insurance
	55			Initial fuel load
	58			Decommissioning costs
		581		Reactor module decommissioning
		582		Site decommissioning
		583		Spent fuel decommissioning
60s				**Capitalized financial costs**
	61			Escalation (price inflation)
	62			Fees
	63			Interest
70s				**Annualized O&M costs**
	71			O&M staff
		711		On-site technicians and operators
		712		Remote monitoring technicians
		713		Security staff
		714		Maintenance
80s				**Annualized fuel costs**
	81			Refueling operations
	84			Additional nuclear fuel

Example of GN-COA breakdown

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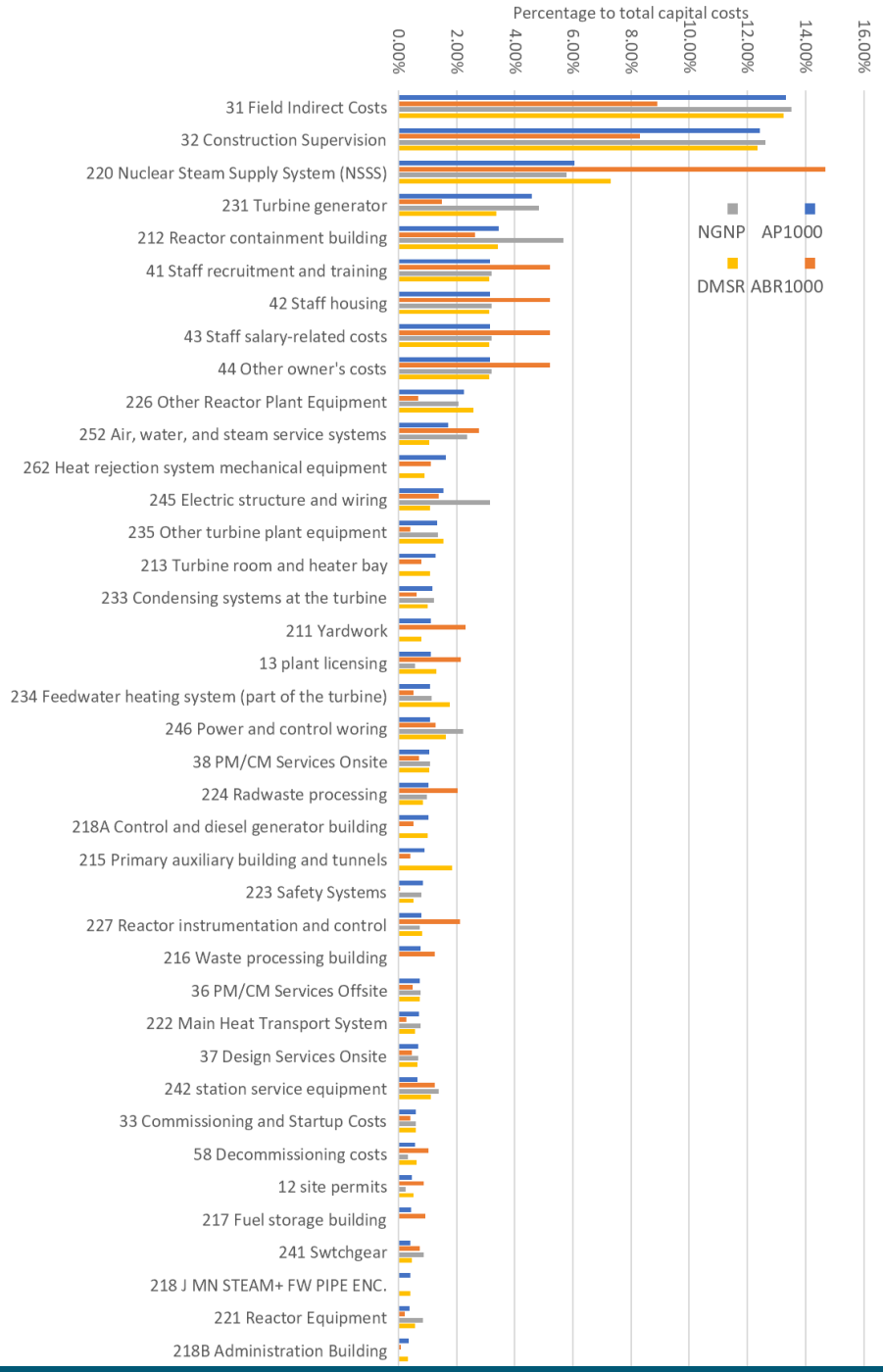
Example Detailed Cost Estimates

- Showing breakdown of different cost contributors to each reactor types
- Generally in-line between reactors but there are some differences
- Report will contain large tables with detailed breakdown for FORCE users to leverage (e.g., excluding reference turbine costs)

			PWR	SFR	HTGR	MSR
		…				
22		22 Reactor Equipment	12.50%	20.61%	14.79%	14.51%
	220	220 Nuclear Steam Supply System (NSSS)	6.05%	14.69%	5.79%	7.30%
	221	221 Reactor Equipment	0.38%	0.22%	0.83%	0.56%
	222	222 Main Heat Transport System	0.69%	0.28%	0.77%	0.56%
	223	223 Safety Systems	0.84%	0.05%	0.77%	0.52%
	224	224 Radwaste processing	1.04%	2.04%	0.97%	0.83%
	225	225 Fuel Handling Systems	0.14%	0.14%	2.57%	0.84%
	226	226 Other Reactor Plant Equipment	2.26%	0.68%	2.07%	2.57%
	227	227 Reactor instrumentation and control	0.78%	2.10%	0.74%	0.82%
	228	228 Reactor plant miscellaneous items	0.31%	0.40%	0.28%	0.51%
23		23 Energy conversion system (Rankine)	8.76%	3.34%	9.13%	8.16%
	231	231 Turbine generator	4.58%	1.48%	4.84%	3.37%
	233	233 Condensing systems at the turbine	1.17%	0.63%	1.21%	0.99%
	234	234 Feedwater heating system (part of the turbine)	1.10%	0.51%	1.13%	1.75%
	235	235 Other turbine plant equipment	1.33%	0.40%	1.35%	1.53%
	236	236 Instrumentation and control	0.27%	0.14%	0.27%	0.17%
	237	Turbine plant miscellaneous items	0.32%	0.18%	0.33%	0.34%
		…				



Additional Considerations

- Costs of reactors strongly depend on several factors beyond technology type
- Captured in study:
  - **Learning rates**: as more reactors are deployed
  - **First of a Kind (FOAK) premium**: e.g., if considering ongoing ARDP projects
  - **Multi-unit plants**: can pool facilities and staff between several reactors.
- Can apply these ***cost adjustments*** based on use case considered
- Not captured (future work?):
  - Modularization
  - Advanced construction
  - Seismic isolation
  - Etc.

$$\mathrm{NOAK} = (\mathrm{FOAK}) \times (1 - \mathrm{LR})^{\log_2 N}$$

Learning Rates (LR)	5%	10%	15%

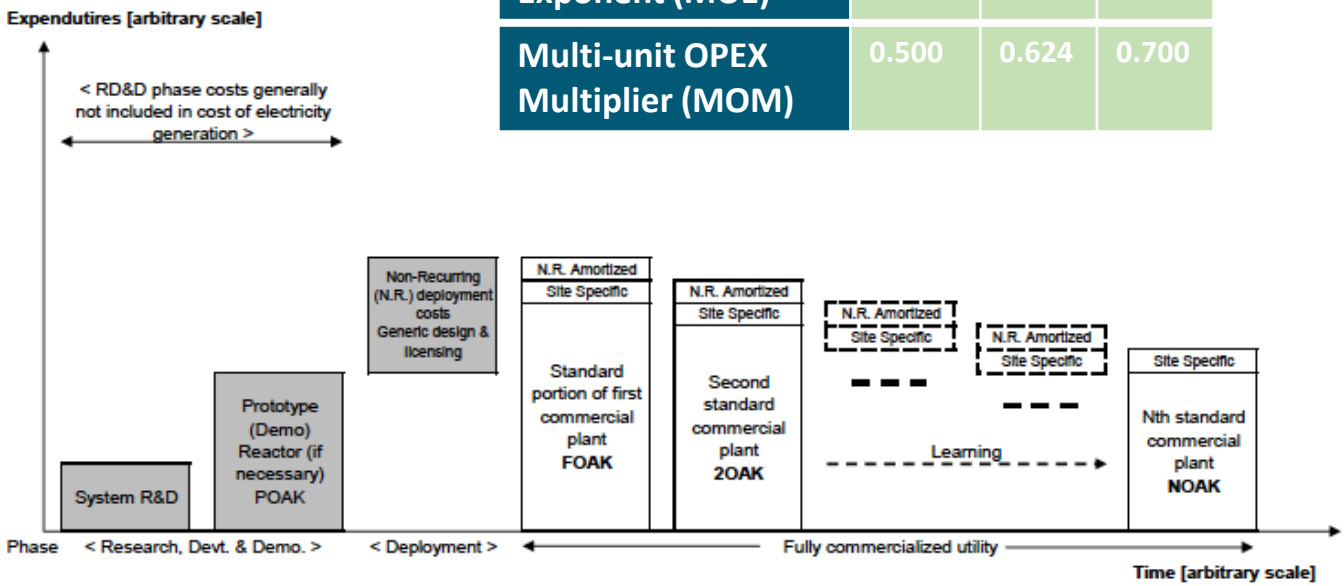
$$\mathrm{FOAK} = (\mathrm{BOAK}) \times \mathrm{Premium}$$

FOAK premium	1.4	1.8	2.9

$$CAPEX_{multi\ unit} = CAPEX_{1\ unit} \times (\#\ of\ units)^{MUE}$$

$$OPEX_{multi\ unit} = OPEX_{1\ unit} \times MOM$$

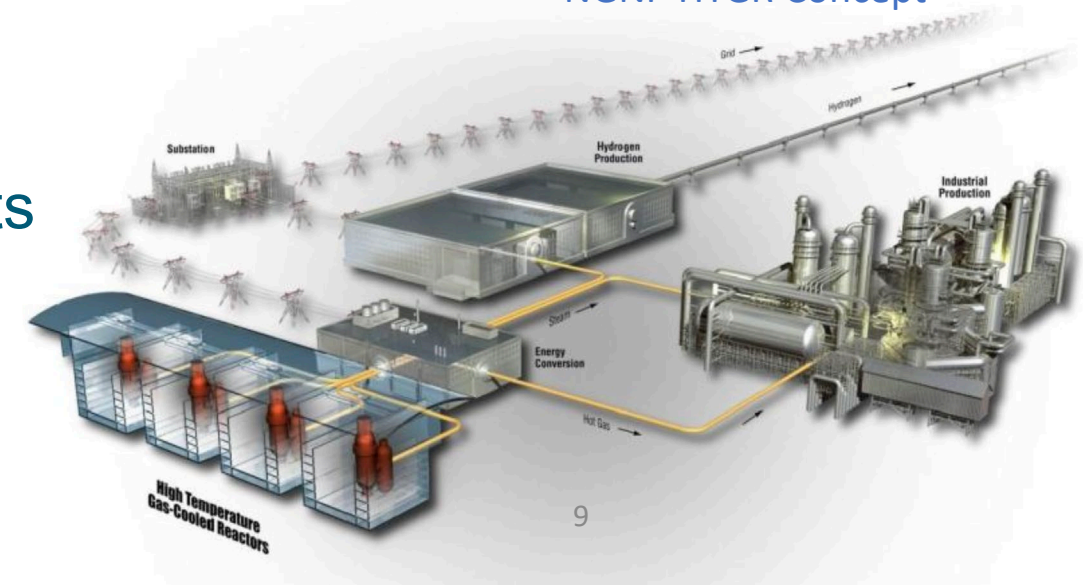
Multi-unit CAPEX Exponent (MUE)	0.800	0.825	0.850
Multi-unit OPEX Multiplier (MOM)	0.500	0.624	0.700



Example Use Case: HTGR with only heat

- **FORCE Model Scenario**: A gas-cooled reactor plant producing heat (no electricity) for various industrial applications
- Assumptions:
  - Neither FOAK nor NOAK: BOAK estimates
  - No detailed specifications on HTGR design
  - No need for turbine and corresponding systems
  - Sensitivity on cost range
  - Assuming 4 reactors per plant
  - Assess cost impact of follow-up projects

NGNP HTGR Concept



Example Walkthrough

1. High Level Estimate
   - Pick CAPEX and OPEX range to consider
2. Lower-Level Corrections
   - Remove accounts 23: 'Energy Conversion System'
3. Learning Adjustments
   - Pick multi-unit correction factors
   - Pick learning rate range
4. Plug Additional Cost Models
   - HTSE plant? Water desal plant? Thermal storage? Etc.

Large and SMR

	Low	Med	High	Sd
Overnight Costs	$3,000 /kWe	$4,500 /kWe	$6,000 /kWe	$1,500 /kWe
O&M Costs	$15 /MWh	$25 /MWh	$35 /MWh	$17 /MWh
LCOE (estimated)	$45 /MWh	$70 /MWh	$95 /MWh	$57 /MWh

			PWR	SFR	HTGR	MSR
		...				
23		23 Energy conversion system (Rankine)	8.76%	3.34%	9.13%	8.16%
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		...				

Learning Rates	5%	10%	15%
Multi-unit CAPEX Exponent (MUE)	0.800	0.825	0.850
Multi-unit OPEX Multiplier (MOM)	0.500	0.624	0.700

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Summary & Future Work

- Literature review conducted to provide:
  - High-level $/kW & $/MWh cost estimates for FORCE evaluations
  - Lower-level detailed cost breakdown for main reactor types
  - Adjustment factor based on learning, etc.
- Potential Future Improvements of the cost databas:
  - Gaussian distribution for data? → RAVEN?
  - Uncertainty quantification and evaluation of contributors? → RAVEN?
  - More bottom-up cost estimates? → Subcontract
  - Recommended values instead of aggregate data ? → DOE-NE discussions
  - Advisory board to review reference costs? → DOE-NE discussions

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