INL/MIS-15-34247

Small Modular Reactor Design and Deployment

Curtis Wright Symposium

xx/xx/xxxx

www.inl.gov

Idaho National Laboratory

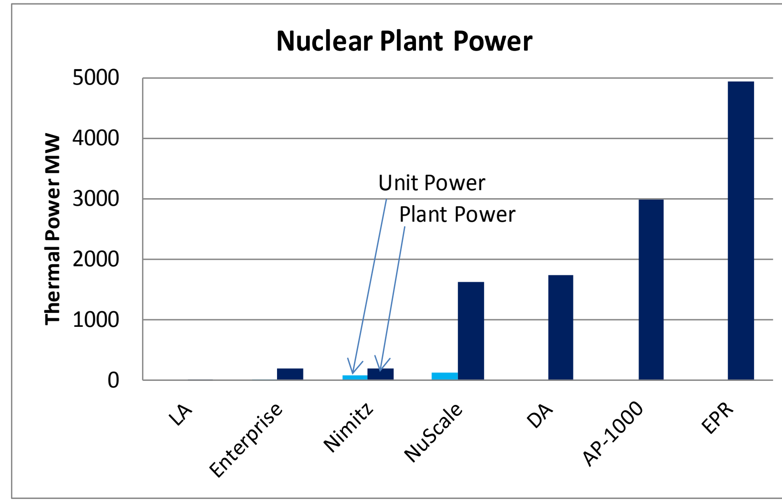
INL SMR Activities

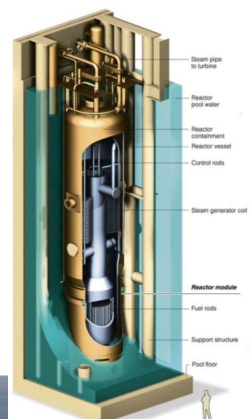
- INL works with all vendors to provide fair access to the laboratory benefits
- INL works with industry on SMR technology and deployment

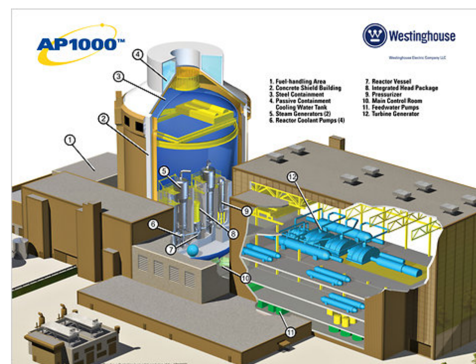
- INL is supporting multiple LWR SMR vendors
  - Small, <300MWe reactors and less expensive reactors compared to current LWR reactors (Small)
  - Often, but not always, multiple reactors at the same site that can be deployed as power is needed (Modular)
  - Primary cooling system and reactor core in a single containment structure, but not always (Reactors)
  - Factory built, usually, which improves quality and costs
- Integrated PWR SMR's are closest to deployment
  - designed to be inherently safer and simple
  - primary reactor system inside a single factory built containment vessel
  - Higher dependence on passive systems to simplify operation and design

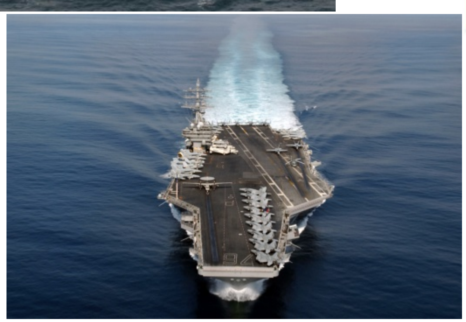
Reactor Power

Los Angeles Class Submarine -26 MW
Enterprise Class Aircraft Carrier 8x
Nimitz Class Aircraft Carrier 2x97MW, 194MW
NuScale Reactor 12 x 150MW, 1800MW
Cooper BWR, 1743MW
Westinghouse AP-1000, 3000MW
European Pressurized Reactor, 4953MW









SMRs are Smaller

- Power less than 300MWe.
  - Current Plants 1000MWe
  - Physically smaller
  - Fewer inputs
  - Fits on power grid with less infrastructure
  - Built in a factory
  - Simplified designs
    - Passive systems
    - Fewer components

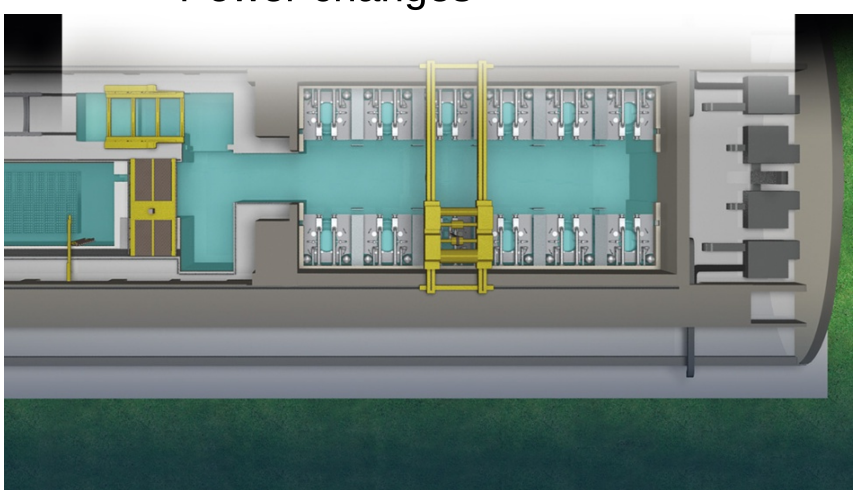
VC Summer Dearater

VC Summer Core

NuScale Reactor

Multiple Units

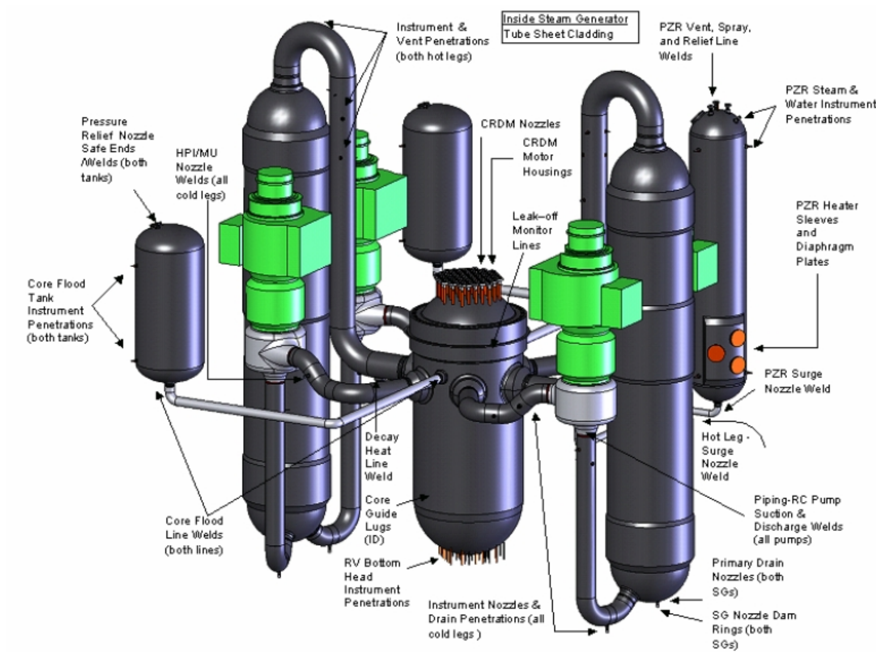
- SMR Nuclear Power Plants are built with multiple reactors
  - mPower Nuclear Power Plant 2 units 125 MWe
  - NuScale Nuclear Power Plant 12 units 45 MWe
- Benefit of smaller size
- Fit on grid with fewer changes to high power electrical grid
- Allows operational flexibility and alternate uses
- Unique operational challenges
  - Units in different operating modes at the same time
    - Maintenance
    - Outage
    - Power changes

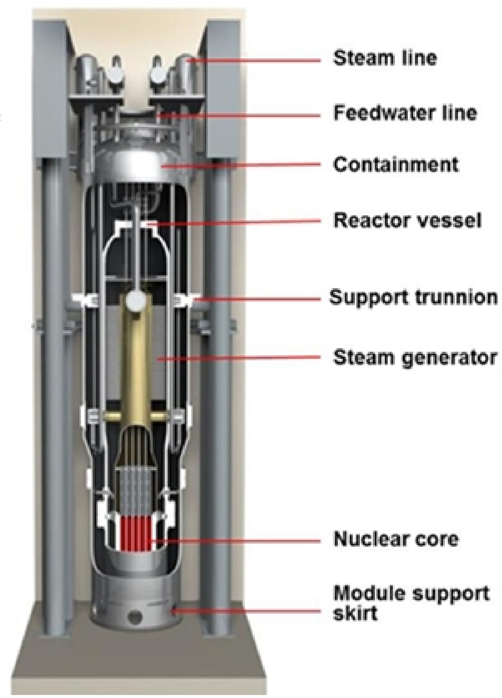


Integrated Reactor

SMR reactor and full primary system in one vessel

- Simplified systems
- Fewer Failure Modes





PWR Reactor

IPWR Reactors

Factory Built

Not a reactor but similar quality and complexity

Challenges to Nuclear Power

- Two AP1000 Power Plants are being built currently
  - Licensing started in 2002
  - Westinghouse experienced vendor
  - Construction started in VC Summer 3/2013 online in 2017
    - $9.8B+$1.2B project cost
    - 1 year schedule slip to 2017
  - Construction Started on Vogtle 3/2013 online in 2016
    - $14B project cost
    - $2M/day cost incurred
    - Georgia Power $18.5B Capitalization
    - Oglethorpe Power $3.9B Capitalization
    - EXELON $30B
  - Unpredictable Final Costs
  - Requires utility cost collection before completion

AP1000 Licensing Milestones

Early AP600 Design Activities

1985 DOE / EPRI contracts, conceptual design, simplified, mid-size PWR

1990 U.S. DOE / EPRI contract for Design Certification $120M

AP600 Design Certification

1992 SSAR and PRA reports submitted to NRC

1993 ARC FOAKE Program $158M

1994 Draft Safety Evaluation Report issued by NRC

1999 Design Certification received (effective for 15 years)
110 man-year NRC review effort over 7 years, $30 million
7400+ questions answered, 380+ NRC mtgs, 43 ACRS mtgs

AP1000 Design Certification $900M cost

2002 Licensing information (DCD, PRA) submitted to NRC
2005 Design Certification received (effective for 15 years)
6/2011 Rev 19 design submitted
12/2011 Final amendment approved

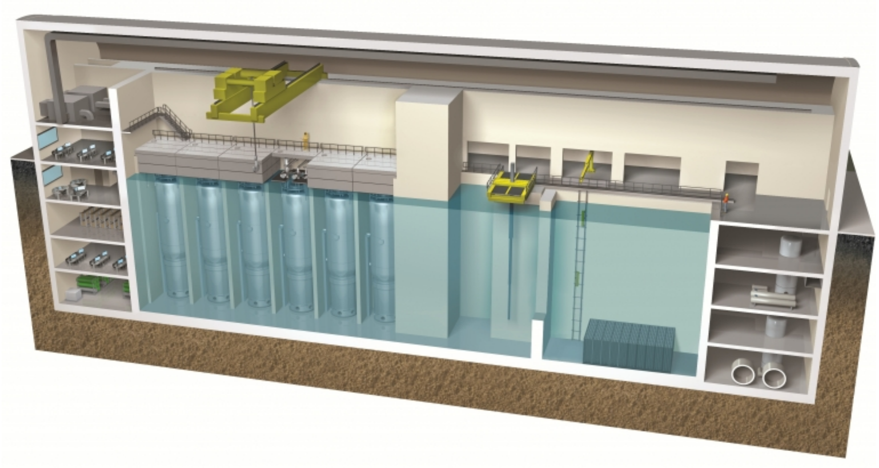
From AP1000 Overview, Chuck Brockhoff ,
ASME O&M Committee Meeting, 2007

Challenges to Nuclear Power

- Safety Requirements
  - Fukushima 3/2011
  - Station Black Out/Loss of ultimate heat sink
  - Extensive damage beyond design basis
  - Restarted nuclear power discussion
  - Additional regulations
  - Continued regulatory discussion

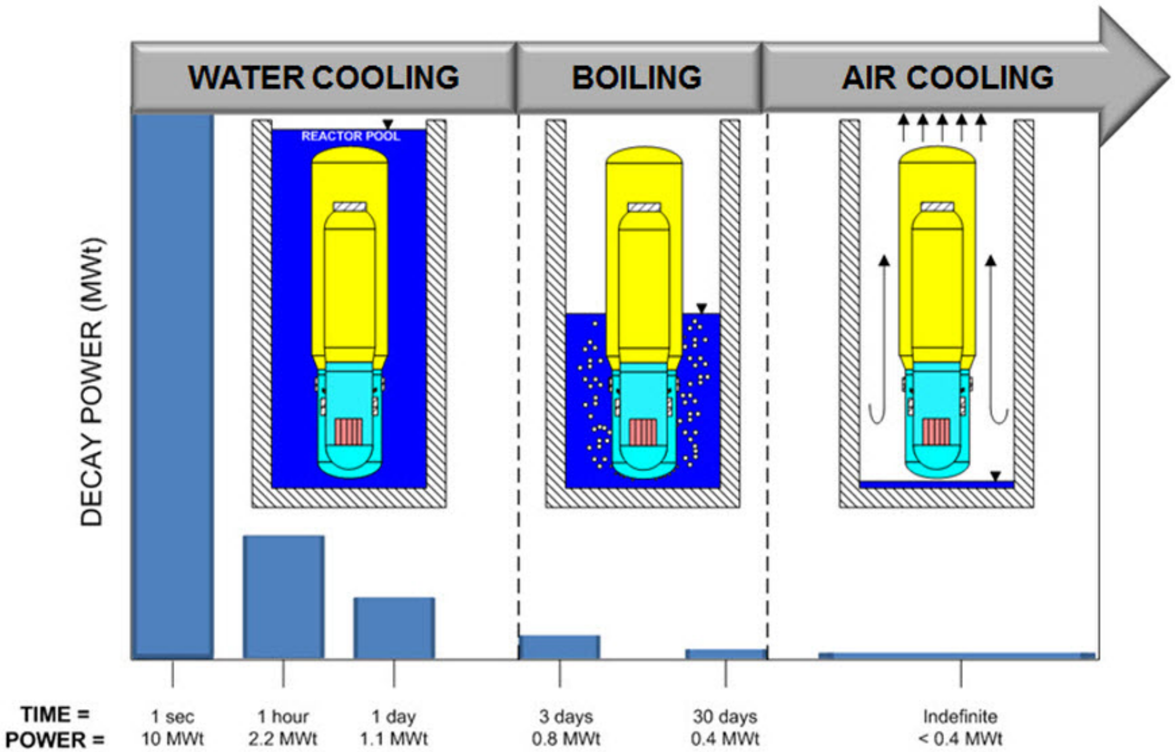
iPWR Solutions

- Cost
  - Smaller size, smaller inputs, smaller projects
    - $225M/Reactor, $3.0B Nuclear Power Plant
    - Can be installed in stages
    - Smaller changes in required grid
    - Factory built
      - Reduces construction uncertainties
      - Changes quality control
      - Less uncertainty in schedule
- Economic Flexibility
  - Smaller units operating economically
  - Complex power grid with renewables
- Improved safety
  - Simplified
  - Integrated
  - Passive
  - Below grade construction



Nuscale plant showing multiple reactors with largely below grade construction

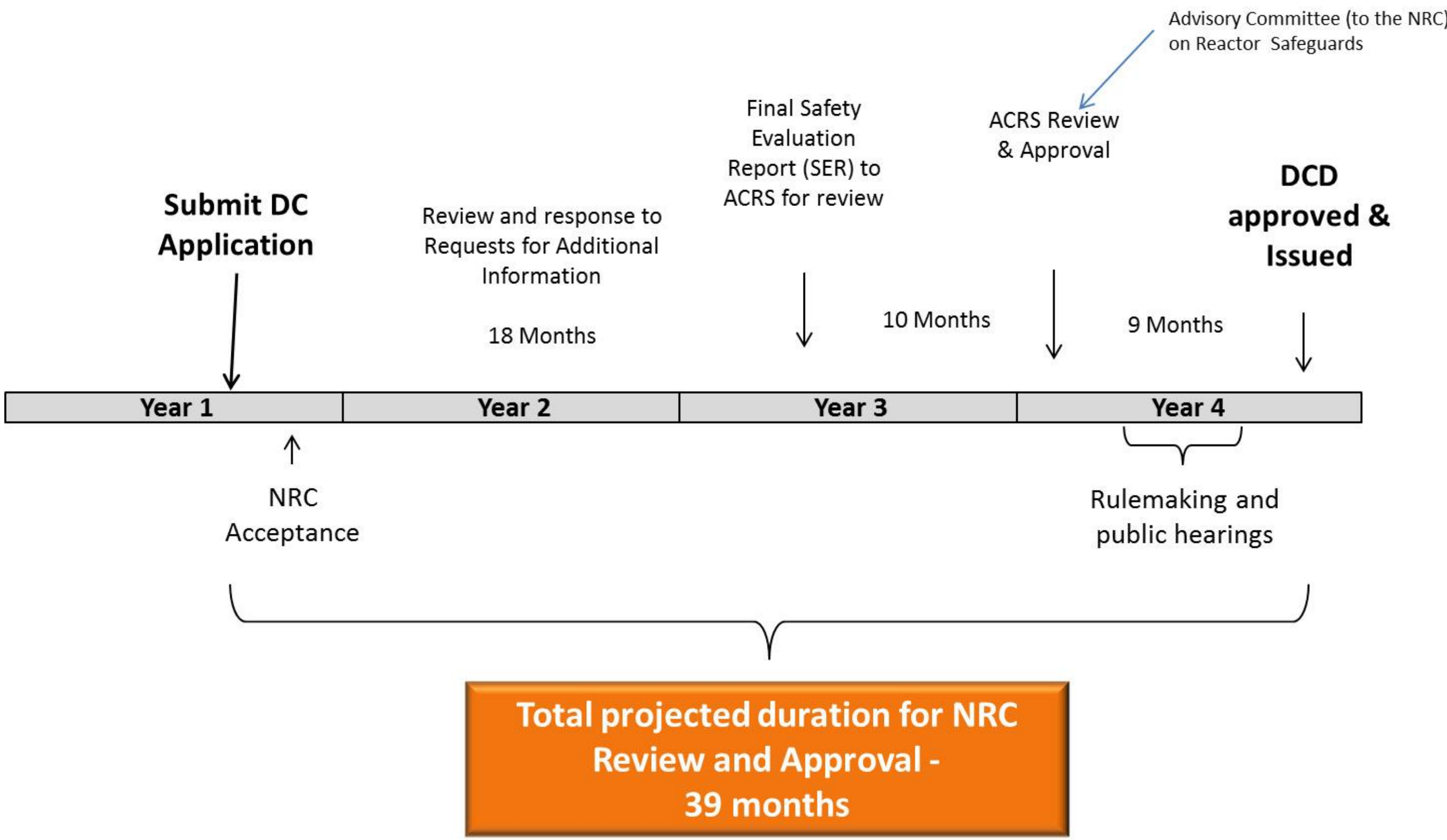
Nuscale



- No operator action
- No electricity
- No additional water

- Gravity driven circulation
- No external power needed for emergency systems
- Passive decay heat removal system
- ECCS floods containment
- Air cooling long term cooling

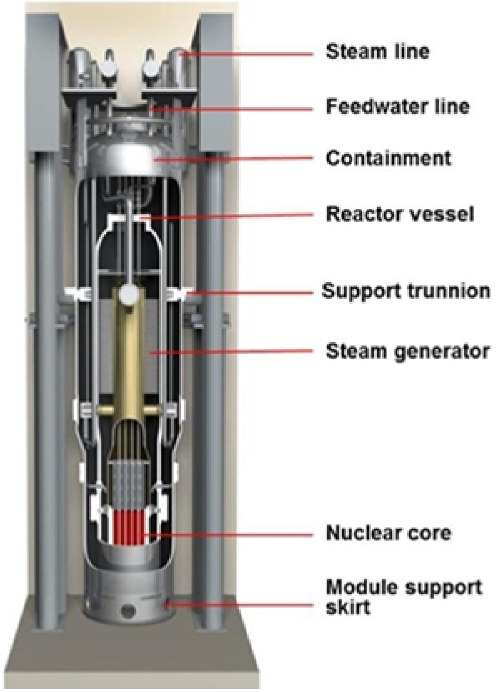
IPWR Improvements

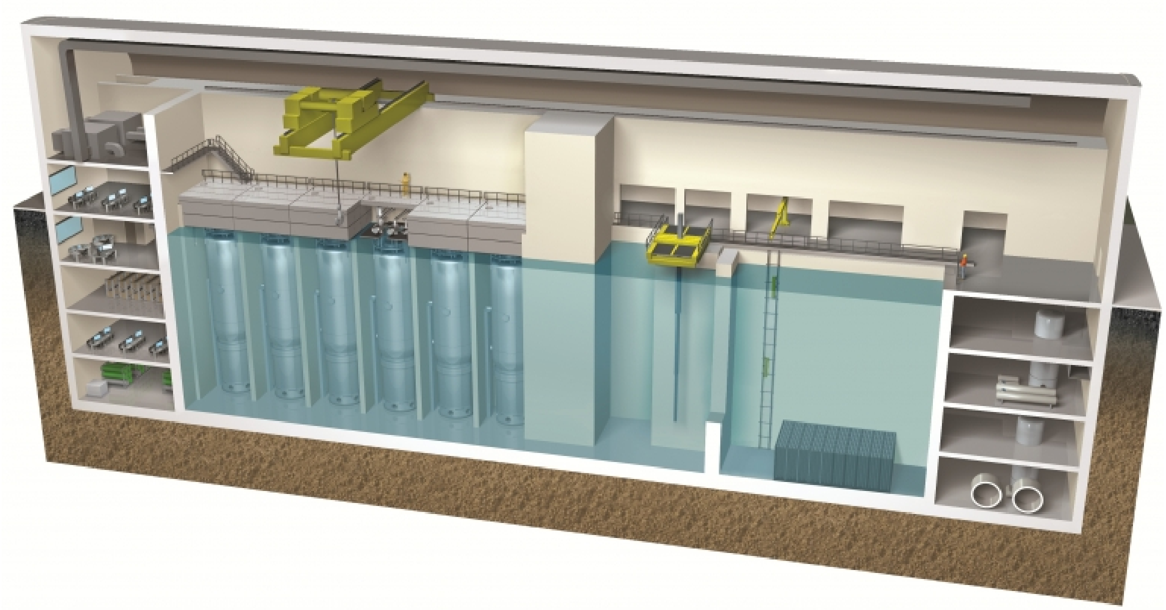


NuScale

Single unit

•160 MWt, 45 MWe, 28% efficient
12 units per plant planned 540 MWe total
•Vessel 2.7m diameter, 20m high, 264t
•Rail, truck or barge shipping
•**Natural circulation operation**
•ECCS is passive and depends on natural circulation





NuScale plant showing multiple reactors with
largely below grade construction

Nuscale

- Winners of second DOE licensing funding opportunity ~$250M
- Developing NRC licensing application
- Design started at Oregon State University
- INL is supporting the developing safety evaluation code, RELAP-5 3D, to perform licensing calculations
- Supporting the analysis to site a 12 unit, 540 MWe plant at INL Laboratory with Nuscale and their partners (owner and operator)

IAEA Identified SMR Benefits and Issues

	Advantages	Challenges
Technological Issues	• Shorter construction period (modularization) • Potential for enhanced safety and reliability • Design simplicity • Suitability for non-electric application (desalination, etc.). • Replacement for aging fossil plants, reducing GHG emissions	• Licensability (due to innovative or first-of-a-kind engineering structure, systems and components) • Non-LWR technologies • Operability performance/record • Human factor engineering; operator staffing for multiple-modules plant • Post Fukushima action items on design and safety
Non-technical Issues	• Fitness for smaller electricity grids • Options to match demand growth by incremental capacity increase • Site flexibility • Reduced emergency planning zone • Lower upfront capital cost (better affordability) • Easier financing scheme	• Economic competitiveness • First of a kind cost estimate • Regulatory infrastructure (in both expanding and newcomer countries) • Availability of design for newcomers • Infrastructure requirements • Post Fukushima action items on institutional issues and public acceptance

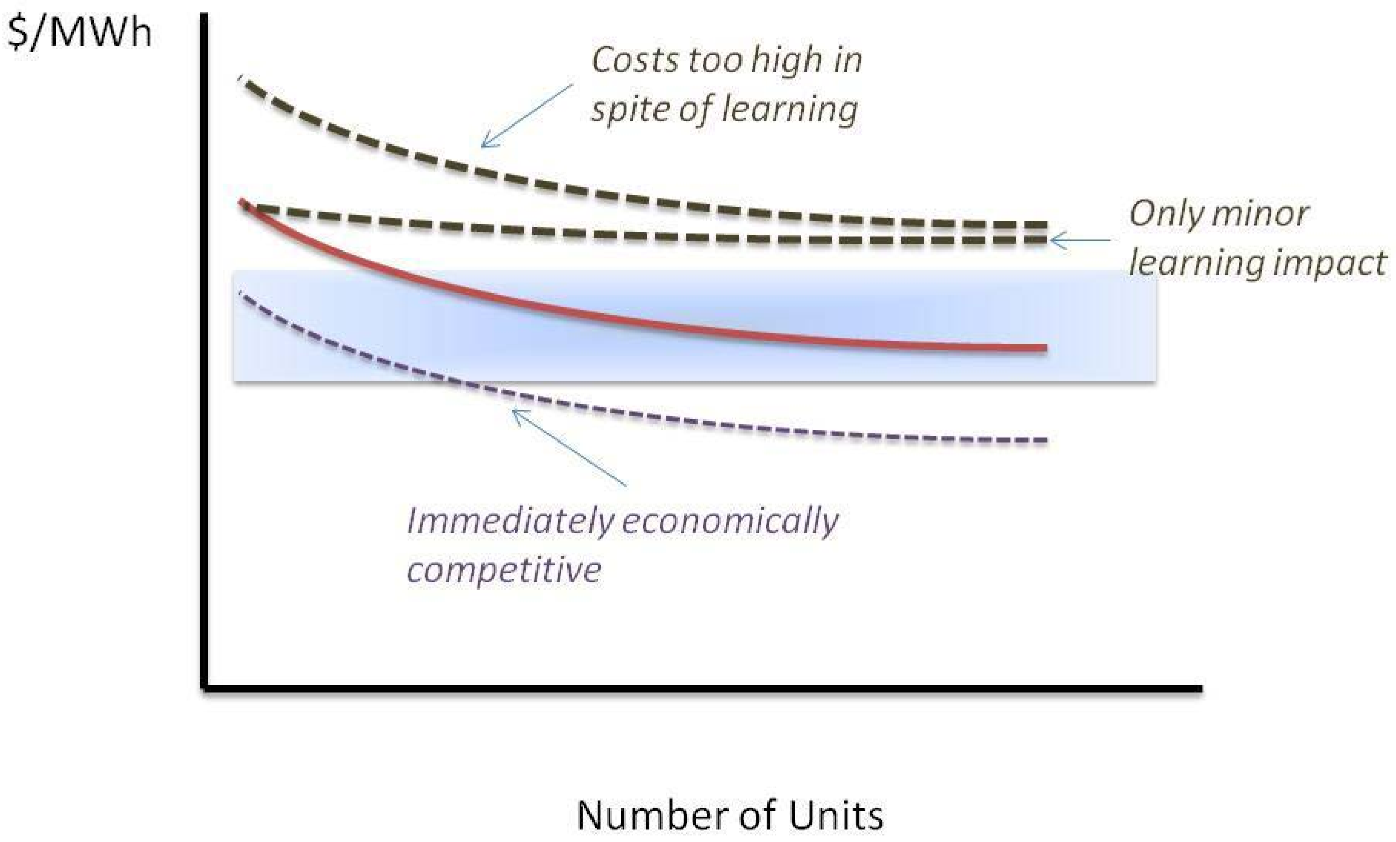
23rd Technical Working Group Meeting, *Global Development Trends and Prospects and Issues for SMR Deployment*, Dr. M. Hadid Subki, March 5-7 2013

Potential SMR design benefits

- **Industrial Applications**
  - Non-electric applications
  - Petroleum refineries
  - Chemical plants
  - Bio- and synthetic-fuels productions
  - Coal/shale oil/oil sands to liquid petroleum
- **Options to Enhance Energy Supply Security using Hybrid Energy System based on SMRs**
  - Synergizing renewable-electric plants, industrial applications and small reactors based on dynamic energy switching
  - **Economics**
  - Producing electricity with higher efficiency*
  - Higher burn-up*
  - Burns uranium, plutonium, thorium and MOX*
  - Fuel form easy to dispose *

*Advanced reactors include fast reactor and high temperature reactor designs. Deployment of these reactors will require additional development and advanced licensing.

SMR economics depend on the unproven, for nuclear reactor, benefits of learning multi-unit factory manufacturing



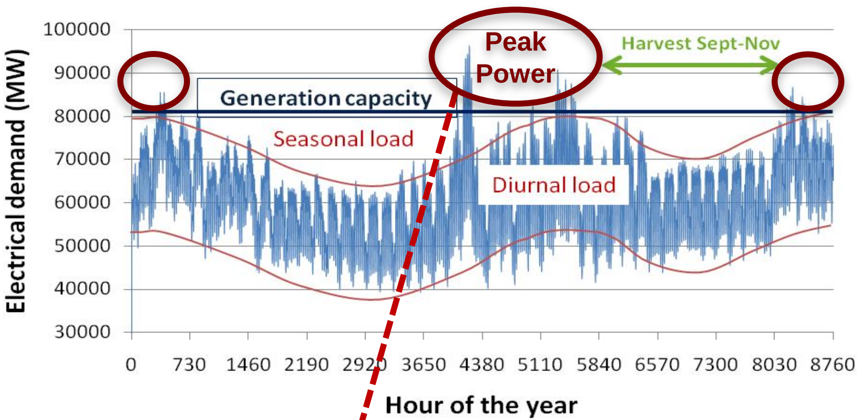
Future Electrical Grid Issues

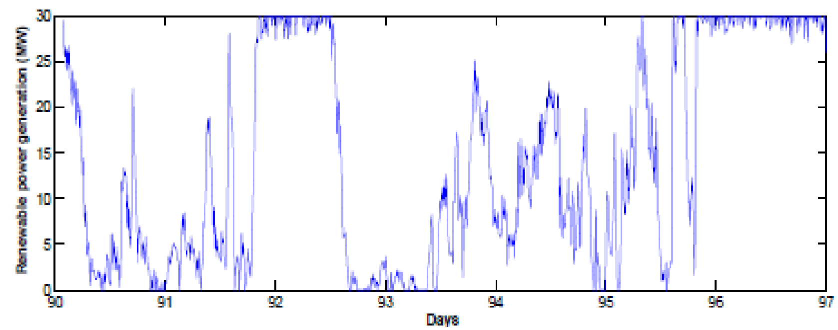
- The increase of fraction of renewable energy production increases the volatility of the market
- The stiffness of supply/demand curve suggest that if the volatility can lead to disruptive electricity price spikes up and down
- Compensation of volatility by spare capacity will introduce higher overall electricity prices to compensate for the additional capital costs
- May need alternate energy uses beyond electricity for base load plants

SMRs benefits:

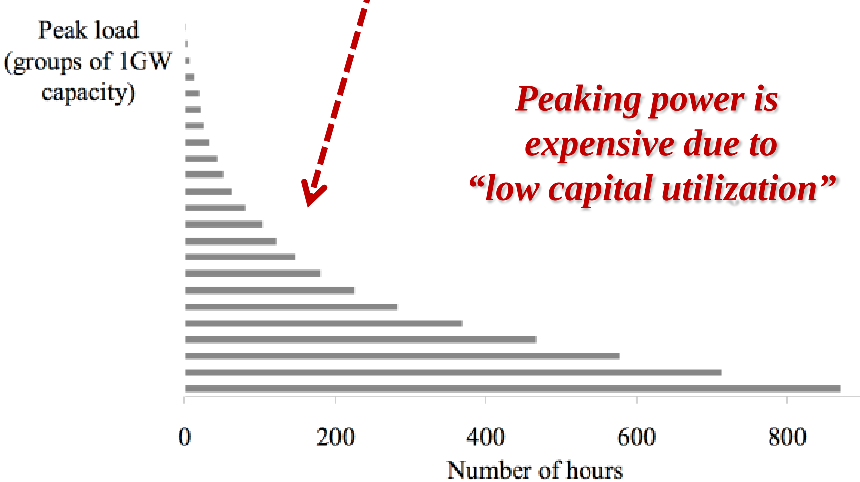
- Smaller power units will offer:
  - Smooth on/off multi-unit offer threshold
  - Better combine with chemical plants to dump energy in low price environments
  - Reduce the distortion in the local grid spot pricing

Volatility of Renewables





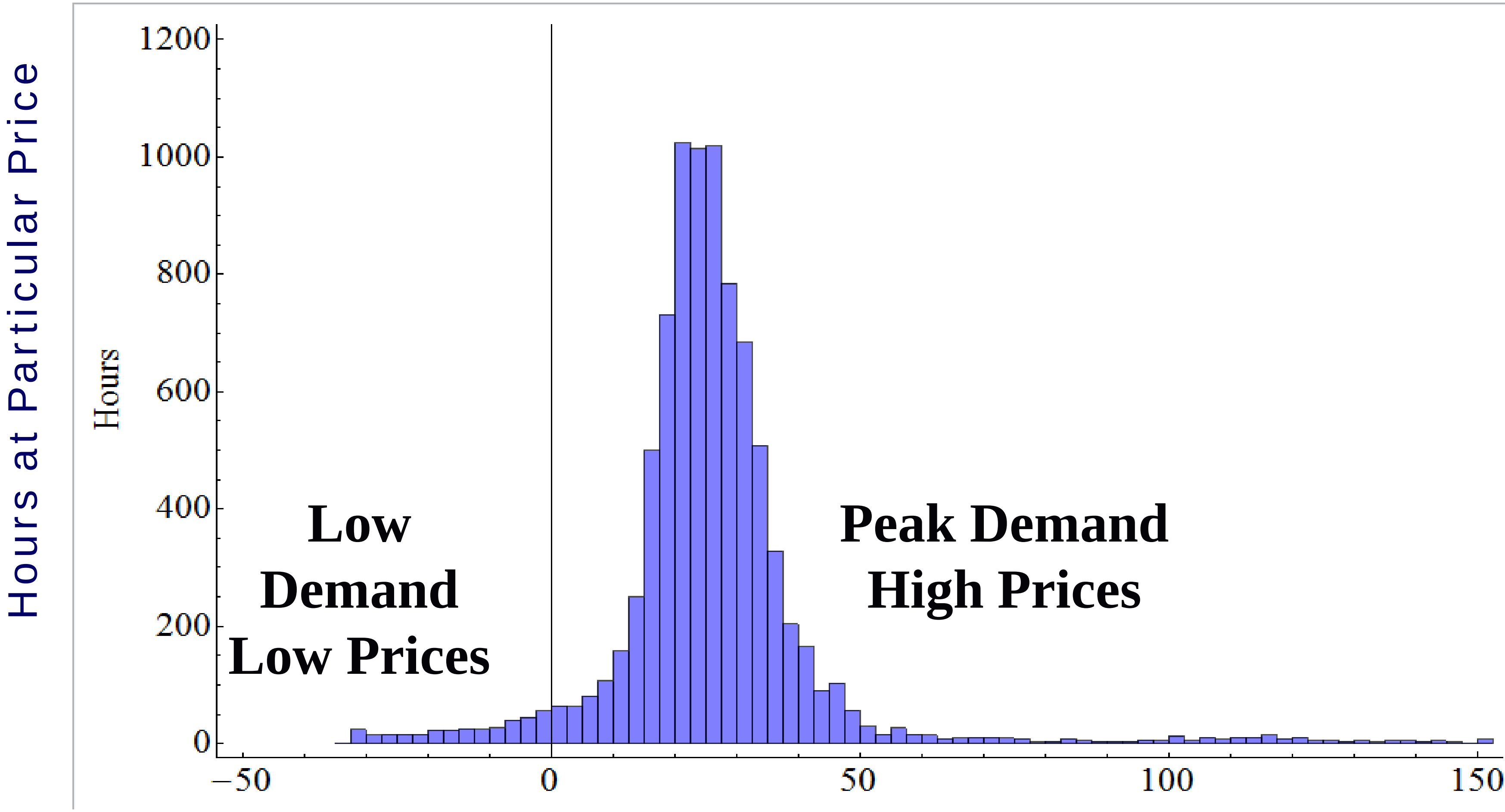
Representative Wind Generation Profile in Wyoming



Peaking power is expensive due to "low capital utilization"

Paducah 124 MWe Peaking Power Plant

Price Dispersion in California Market



Price of Electricity, $ MW(e)h

Forsberg, MIT 2014

Questions For SMR design – S. Herring Presentation

- Expectation of greater seismic robustness/tsunami protection – small, robust
- Adaptation to climate change - flexible operation, air cooled
  - Droughts – lack of river flow, lack of cooling water, competing needs
  - Hurricanes – coastal flooding and wind
  - Sea level rise – long-term displacement of facilities and population
- Need for flexibility to adapt to multi-decade changes - flexible operation, economic
  - Economic growth and competing fuels
  - Evolving understanding of seismic hazards
  - Evolving technology, instrumentation, power cycles, etc.
  - Political – e.g. loss of investment in Germany, perhaps in Japan
  - Natural disasters, fuel supply disruptions,
- Accident response - passive safety, smaller, robust
  - Minimize population displacement and economic impact
  - Established plan for clean-up and decommissioning

Conclusions

- SMRs designs address many of the barriers to increased use of nuclear energy
  - Cost
  - Schedule
  - Uncertainty
- SMR designs may allow improved economics and safety
- Open issues remain on SMR licensing, deployment, economics and market
- Complex changes in the electrical grid add uncertainty

SMR Reactors

SMR Name	Company	MWe net	Type	Status	
4S	Toshiba	10	LMR	Under Development	
ABV	OKBM	3-10	PWR	Under Development	
ACP100	CNNC	100-150	PWR	Under Development	
AHWR	Babha Atomic Research Center	284	PHWR	Under Development	
ALLEGRO	European Partners	25	GCFR	Conceptual Design	
ANGSTREM	OKB Gidropress		6	LMR	Conceptual Design
ANTARES	AREVA	285	HTR	Conceptual Design	
ARC-100	Advanced Reactor Concepts	100	LMR	Under Development	
BREST-OD	NIKIET	300	LMR	Under Development	
CAREM	Comision Nacional de Energia Atomica	25	PWR	Licensing Stage	
CNP-300	SNERDI	300	PWR	Operating	
EGP-6	Teploelectroproekt	11	LGR	Operating	
ELENA	Kurchatov Institute	0.1	PWR	Conceptual Design	
EM2	General Atomics		240	HTR	Conceptual Design
ENHS	University of California, Berkeley		50	LMR	Conceptual Design
FBNR	Federal University of Rio Grande do Sul	40	Fixed Bed	Conceptual Design	
Flexblue	Direction des Constructions Navales Services	50-250	PWR	Conceptual Design	
Fuji MSR	IThEMS	200	LMR	Conceptual Design	
G4M (HPM)	Gen4 Energy, Inc.	25	LMR	Under Development	
GEMSTAR	ADNA)Corporation	220	LMR	Conceptual Design	
GT-MHR	General Atomics		286	HTR	Under Development
GTHTR	Japan Atomic Energy Agency (JAEA)	275	HTR	Under Development	
HTR-PM	Institute of Nuclear Energy and New Technology		200	HTR	Under Construction
Indian PHWR	Babha Atomic Research Center (BARC)	202	PHWR	Operating	
IRIS	Westinghouse	335	PWR	Shelved	
KLT-40S	OKBM Afrikantov	35	PWR	Under Construction	
LSPR	Tokyo Institute of Technology	53	LMR	Conceptual Design	
MARS	Kurchatov Institute	6	LMR	Conceptual Design	
mPower	B&W Company		80	PWR	Under Development

SMR Reactors

SMR	Name Company	MWe net	Type	Status
MRX	Mitsubishi Heavy Industries	30	PWR	Conceptual Design
MTSPNR	NIKIET	2	HTR	Conceptual Design
NHR-200	Institute of Nuclear Energy (INET)	65	PWR	Under Development
NIKA-70	NIKIET	15	PWR	Conceptual Design
NP-300	Technicatome (AREVA)	100-300	PWR	Conceptual Design
NuScale	NuScale Power Inc.	45	PWR	Under Development
PBMR	PBMR (Pty) Ltd.	165	HTR	Shelved
PEACER	NUTRECK	300/550	LMR	Conceptual Design
PRISM	General Electric-Hitachi	311	LMR	Under Development
RADIX	Radix Power and Energy Corporation	10-50	PWR	Under Development
RAPID	CRIEPI	1	LMR	Conceptual Design
RITM-200	OKBM Afrikantov	55	PWR	Under Development
RUTA-70	NIKIET	n/a	PWR	Conceptual Design
SAKHA-92	OKBM Afrikantov	1	PWR	Conceptual Design
SmAHTR	Oak Ridge National Laboratory (ORNL)	50+	FHR	Conceptual Design
SMART	KAERI	100	PWR	Licensed
SMR-160	Holtec	160	PWR	Under Development
STAR	Argonne National Laboratory	10-100/178	LMR	Conceptual Design
SVBR-100	VNIPIET	101.5	LMR	Licensing Stage
TPS	General Atomics	16.4	PWR	Conceptual Design
TWR	TerraPower	500/1,150	TWR	Conceptual Design
UNITERM	NIKIET	1.5	PWR	Conceptual Design
VBER-300	OKBM Afrikantov	295	PWR	Licensing Stage
VK-300	NIKIET	150-250	BWR	Shelved
VKT-12	OKB Gidropress	12	BWR	Shelved
VVER-300	OKB Gidopress	300	PWR	Conceptual Design
WEC SMR	Westinghouse	225+	PWR	Under Development