Role of high-temperature reactors in sustainable development and synergy with renewable energy sources

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Abstract

There is no credible path forward to energy security enabling sustainable development without clean energy sources including nuclear power. Moreover, in order to achieve significant contribution to the overall primary energy balance, nuclear power should expand beyond electricity generation to other energy sectors such as industrial processes and transportation. This requires deployment of high temperature reactors. Specifically, Fluoride-cooled High-temperature Reactors (FHRs) will be discussed in this presentation, focusing on their attractive features as well as their developmental challenges. Ultimately, the objective is to replace most of the fossil fuel based sources by clean energy sources. To facilitate such deployment, an innovative concept of a synergistic energy park NuRenew (Nuclear &Renewables) has been conceived and will be introduced.

Outline

- Introductory remarks on nuclear power and sustainable development
- Current trends in advanced reactor designs (SMRs, ALWR, VHTR)
- FHRs
- NuRenew concept
- Concluding remarks
- Q&A

Acknowledgments

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Disclaimer: *This presentation is based on publicly available information.*
There is no explicit or implicit guarantee to accuracy or suitability of the presented data.

Introductory Remarks on Energy and Nuclear Power

Energy use

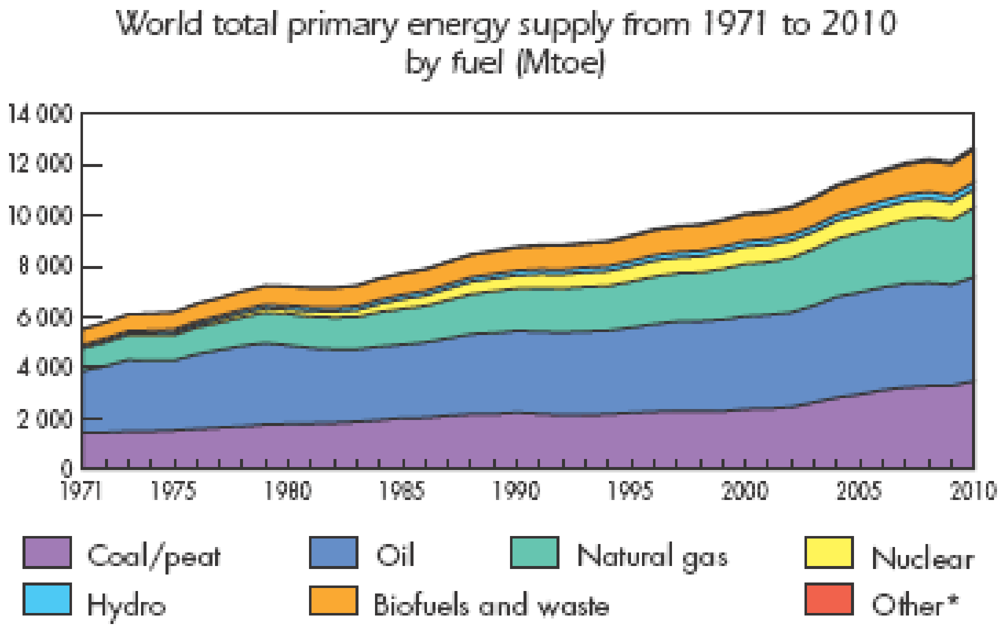
Energy is necessary for development

(well-known strong correlation between GDP/HDI and energy production)

ANNUAL PRIMARY ENERGY CONSUMPTION:

~12 Gtoe (billions ton of oil equivalent) or ~475 QBTU (BTU x 10^{15})

Prediction for 2050: 14-24 Gtoe (depending on the scenario)



(Source: IEA)

Meeting the growing energy needs

- **Energy security** – necessary for national security and development
- Energy **conservation** OR **new sources**? → need **BOTH**
  (Conserve as much as practical, but we still need more; in particular, developing nations.)
- **Hydro/fossil** OR **nuclear** OR **renewable/alternative**? → need **ALL**
  Each as much as justified. A reasonable mix.
  Cannot afford otherwise.
- What is the best option/mix?
  - **No free lunch** – each option has advantages/disadvantages!
  - Need **responsible decision process** – techno-economic comparison of different options (based on well-defined metrics), rather than on pre-conceived opinions

Worldwide commercial use of nuclear power

- 2014: 430 reactors, 369.4 GWe (NN 3/2014)
- About 1/6-th world electricity
- Over 60 new reactors in 13 countries under construction (WNA, 3/2013)
- Major source of electricity in several countries

NUCLEAR POWER UNITS BY NATION

POWER REACTORS BY TYPE, WORLDWIDE

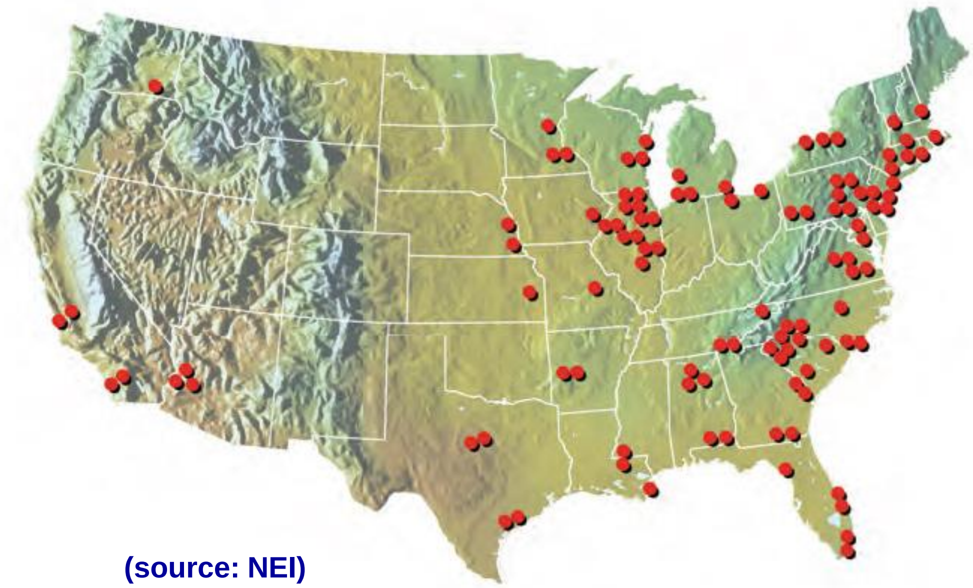
Reactor Type	# Units (in operation)	Net MWe (in operation)	# Units (forthcoming)	Net MWe (forthcoming)	# Units (total)	Net MWe (total)
Pressurized light-water reactors (PWR)	270	250,265.93	89	93,264.00	359	343,529.93
Boiling light-water reactors (BWR)	81	76,353.20	6	8,056.00	87	84,409.20
Gas-cooled reactors, all models	15	8,025.00	1	200.00	16	8,225.00
Heavy-water reactors, all models	48	23,945.00	9	5,772.00	57	29,717.00
Graphite-moderated reactors, all models	15	10,219.00	0	0.00	15	10,219.00
Liquid-metal-cooled reactors, all models	1	560.00	5	1,616.00	6	2,176.00
Totals	**430**	**369,368.13**	**110**	**108,908.00**	**540**	**478,276.13**

March 2014 • Nuclear News • 69

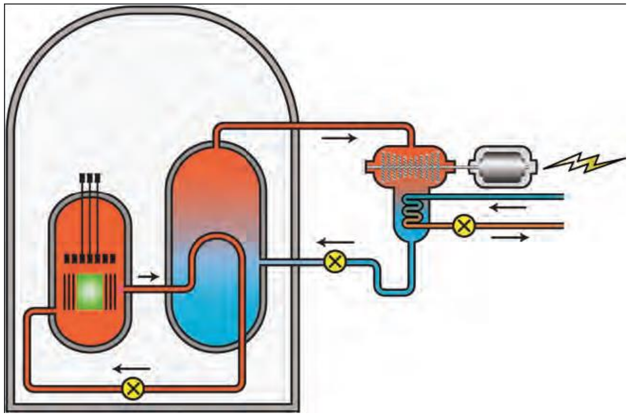
(source: ANS, Nucl. News 3/2014)

Nuclear power plants in the U.S.

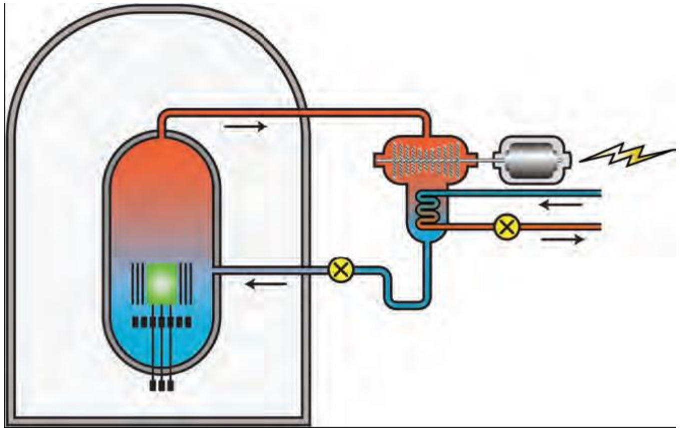
- 100 operating reactors in 31 states
- Close to 20% electricity produced
- 65 PWRs, 35 BWRs
- 103,200 MWe



(source: NEI)

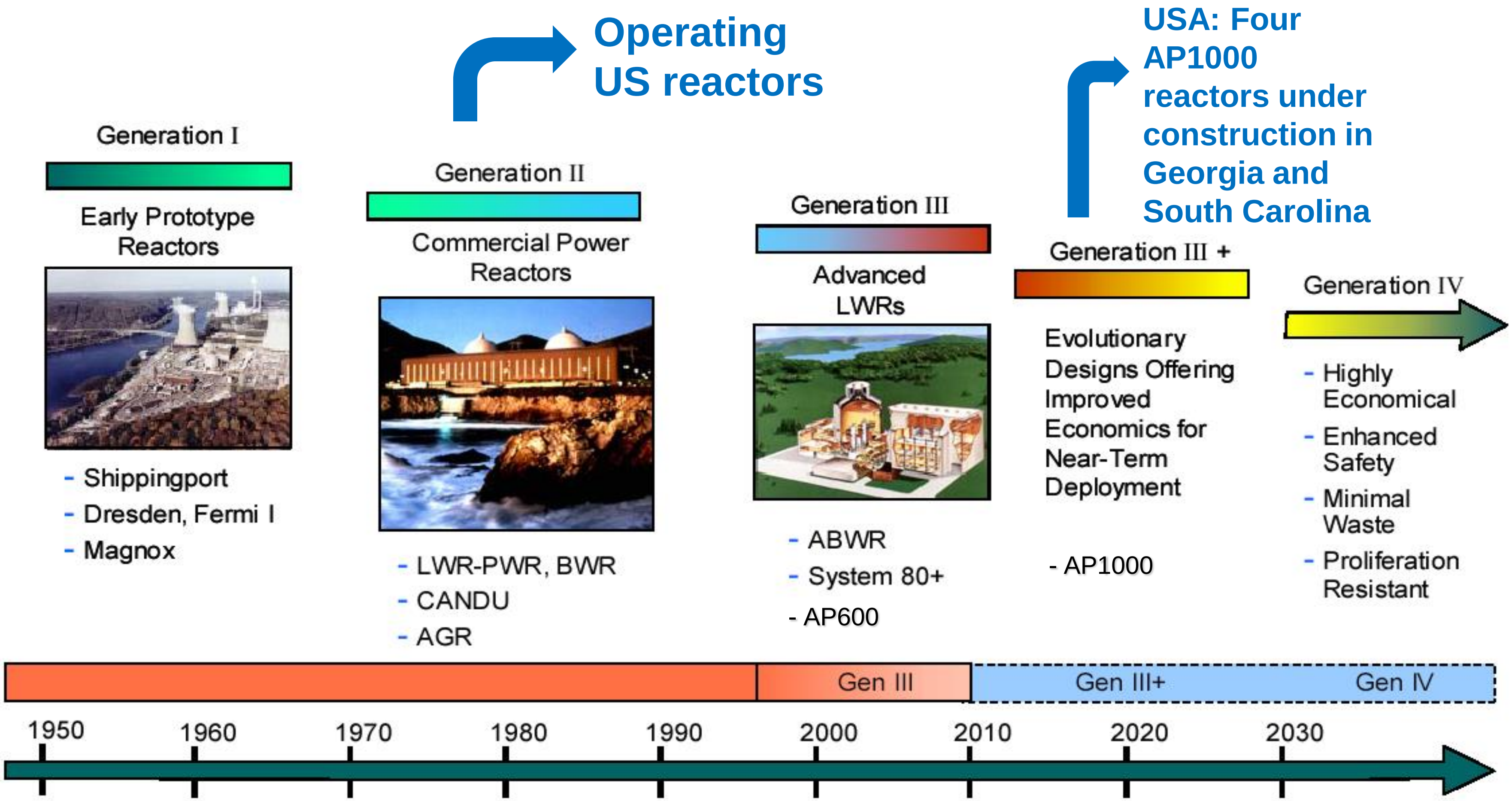


Pressurized Water Reactor (PWR)



Boiling Water Reactor (BWR)

Nuclear power plants by ‘generation’: past/present/(future)



New construction in the U.S.

- 4 new units (AP1000) under construction in USA: 2 in Georgia (Vogtle 3 and 4) and 2 in South Carolina (V.C. Summer 2 and 3); each unit 1,170 MWe


Aerial photograph of Vogtle 3 and 4 construction site. Unit 3 is located at left and top of photo and Unit 4 to the right and bottom. Heavy lift derrick crane foundation in center. August 11, 2011

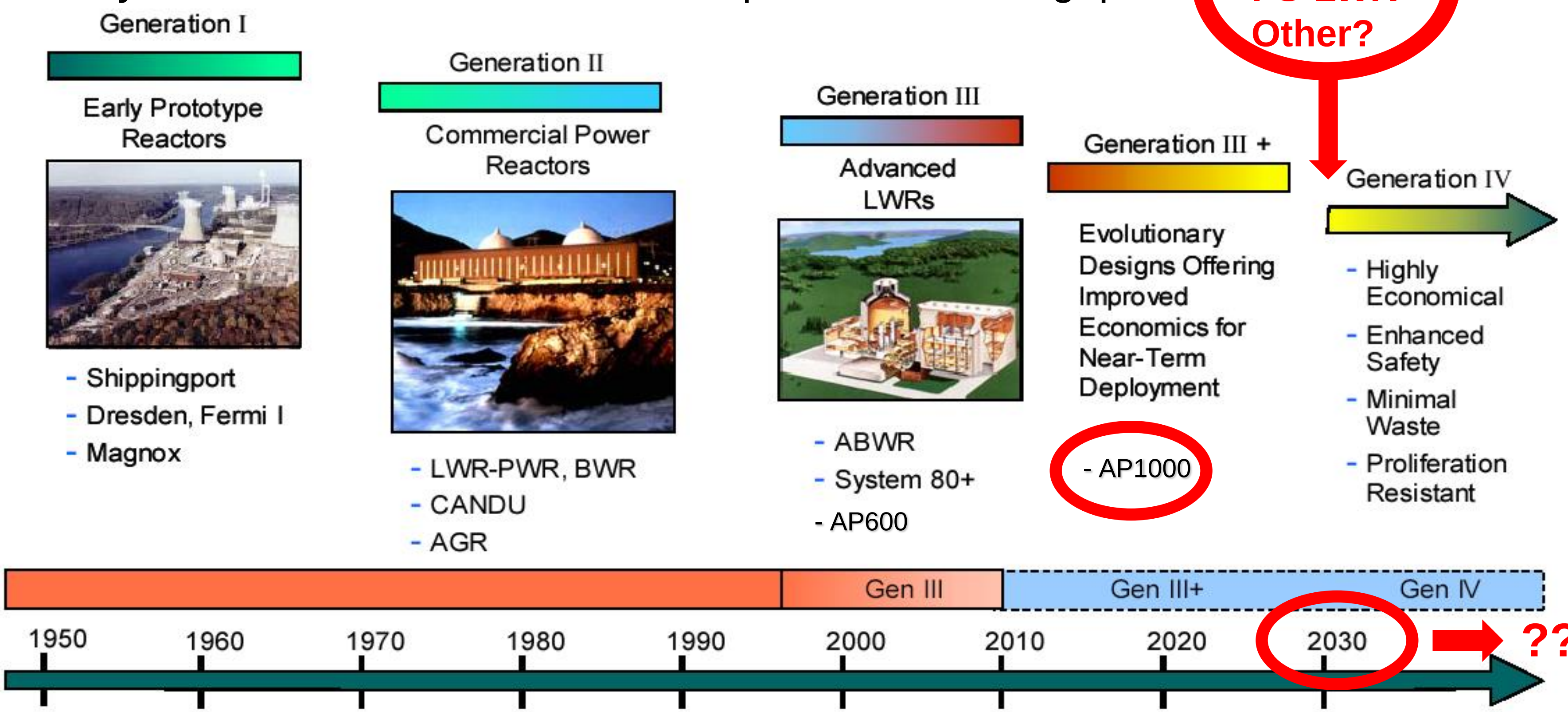
TVA: 1 (or 2) projects to complete
- Watts Bar 2, PWR (1,180 MWe) 2015/2016?
- Bellefonte 1, AL (1,260 MWe), project started in 1974, suspended in 1988, 8/2011 approved, suspended, …?

New construction in the U.S.

- 2 new units (AP1000) under construction in Georgia, Vogtle 3 and 4 (2x1,170 MWe)

Nuclear power plants – what next?

- Commercial nuclear power plants currently being build – mainly Gen-III+ (AP1000, ABWR, EPR) – safe and economical, but not for all markets
- Gen-IV concepts (6 types, non-water cooled except for the supercritical water) probably not ready (licensed etc.) by 2030
- Opportunity for Gen-III++ and SMRs to complement / fill the gap



New/advanced reactor concepts Investigated at Georgia Tech

- SMR (Small Modular Reactors), up to several hundred MWe
  Reduces the required investment from several billion $ to <$1B
  Extremely high interest recently

- I^2S-LWR
  Large power station (~1,000 MWe) Inherent safety features

- **Liquid-salt cooled reactors (LSCR), ORNL**
  High temperature, high efficiency, low reject heat, low pressure, inherent safety features (ORNL AHTR/FHR)

- **Hybrid systems**
  - **High temperature nuclear + energy storage for process heat**
  - **Nuclear + Renewables (NuRenew)**

- Fast reactors, novel fuel concepts (Dr. A. Erickson)

- Fusion-fission hybrid (Dr. W. Stacey)

Energy and Environment

Sustainable development – some considerations

Energy is necessary for development.

At the same time attention is needed with respect to:

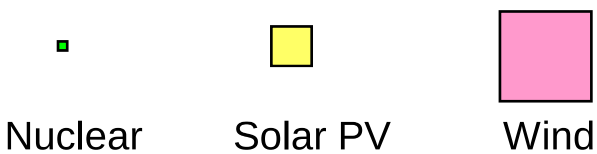
- Environmental impact
- Emission of CO_2 → climate impact
- Particulates emission → health impact
- Resources
- Cost
- Waste
- Land area use
- ….

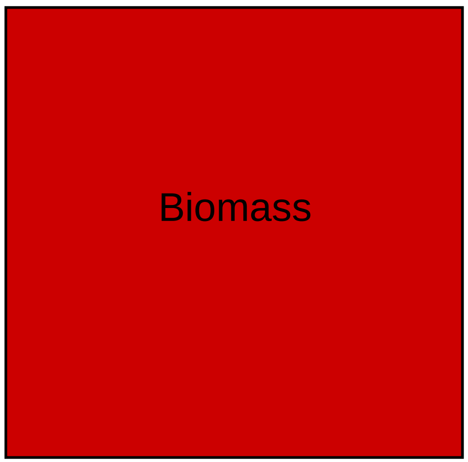
Environmental impact: Footprint (Land use)

- Energy produced by one 1 GWe nuclear power plant is ~8TWh/year
  (Range of land use area estimated using several references and data for representative installations)
  - Nuclear power plant 1-2 (2) km^2
  - Solar PV 20-80 (40) km^2
  - Wind 50-800 (200) km^2
  - Biomass 4,000-6,000 (5,000) km^2

NOTE: Diluted energy density may present some limitations.

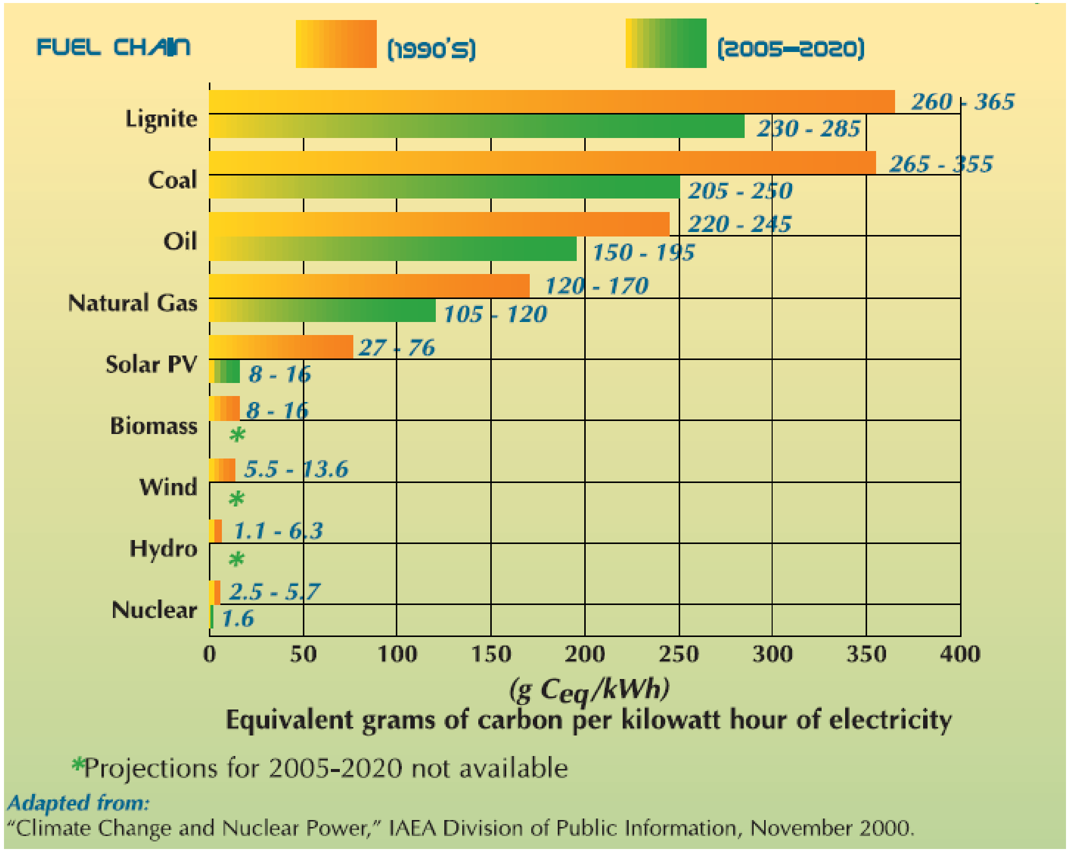
For example, the total world production of corn, if all converted to ethanol, would substitute about 1/3 of the U.S. current gasoline consumption .....





Nuclear power requires limited land area

GHG emissions



Total GHG Emission Factors for the production of Electricity

(source: ANS)

Nuclear reactors generate electricity with very low emissions

Each year, U.S. nuclear power plants prevent 5.1 million tonnes of sulphur dioxide, 2.4 million tonnes of nitrogen oxide, and 164 million tonnes of carbon from entering the earth atmosphere

By using NPPs in the US, already avoided billions (1e9) of tonnes of CO_2 emissions

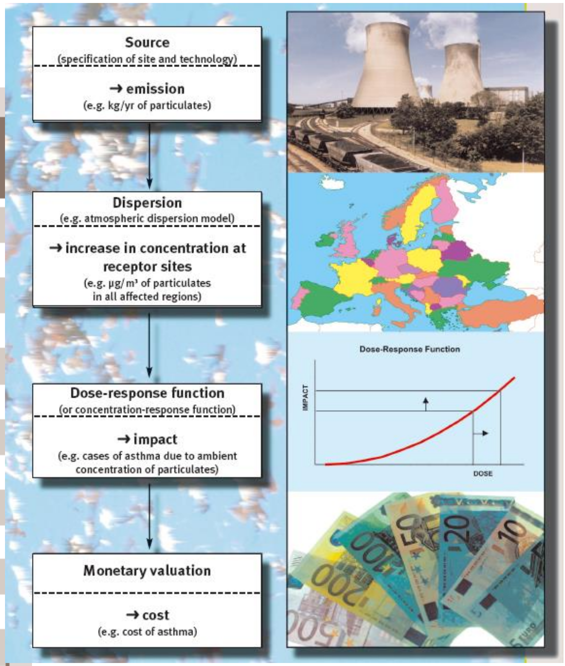
True cost of generating electricity – including externalities

Study ExternE, performed in Europe (European Commission), examined external costs of electricity production

External cost figures for electricity production in the EU for existing technologies[1] (in € cent per kWh*)

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5**			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

* *sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)*
** *biomass co-fired with lignites*



Source: External Costs: Research results on socio-environmental damages due to electricity and transport, EU/EUR 20198 (2003)

Bottom Line: Nuclear power and renewable sources have significantly lower external costs than fossil plants

Nuclear power characteristics

- High energy density; low emission; low land area use; favorable output/input energy factor
- Competitive cost - low external cost, thus **low true total cost to the society**
- U/Th resources sizeable (on the order of hundred(s) years for once through fuel cycle, thousands years with reuse of irradiated fuel)
- Waste must be addressed (technologically manageable, however….)
- Several prominent "founding fathers" of the environmental movement, based on evaluating feasible alternatives, came to the position that nuclear power offers a valid option to address environmental concerns
  - Patrick Moore - Greenpeace founder
  - Stewart Brand - Whole Earth Catalog founder
  - James Lovelock - Gaia theorist
  - Recent UN IPCC report (May 2007) acknowledges the potential role of nuclear power
- **Nuclear power has a role to play in sustainable development. Otherwise, it is difficult to imagine satisfying energy needs without exhausting resources and significantly impacting environment.**

Role of nuclear power in sustainable development How?

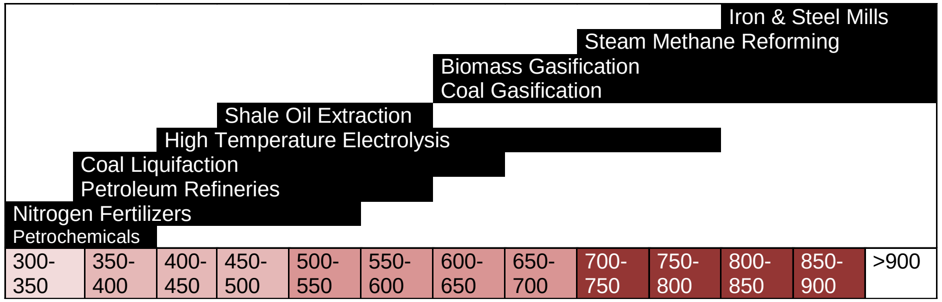
- Electricity – about 1/3 of total energy consumption
- To make a significant impact, nuclear power needs to expand beyond electricity production to other energy sectors → transportation, industrial process heat, … →need high-temperature reactors (at least certain fraction of all reactors)

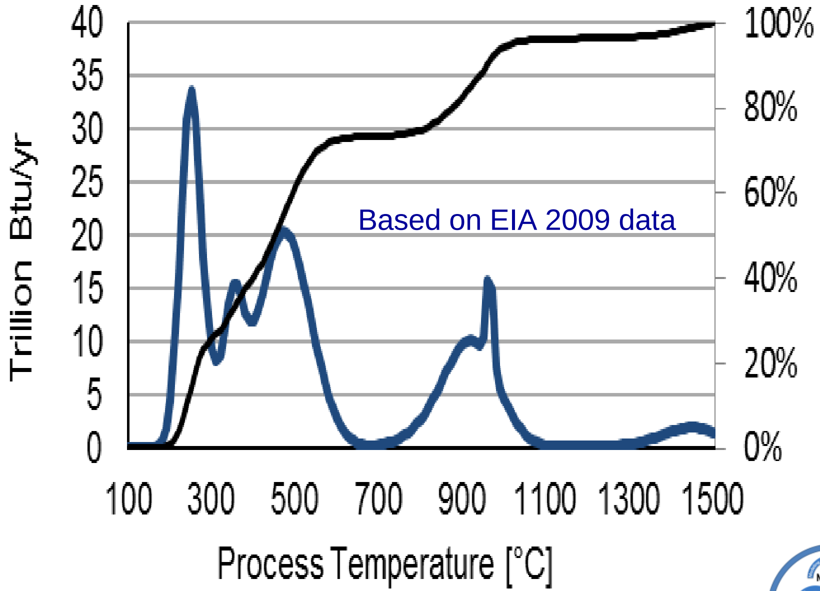
- Nuclear power plants need to be integrated in a cost-effective manner with other non-GHG power sources

High temperature technology(ies)
What temperature is needed?

- Material issues, potentially significant-to-showstopper?
- What fraction of energy needs we can cover with realistic/limited temperatures?

- Based on temperatures needed and current use – differential and cumulative fraction may be determined
- ~600 C covers ~70%. No significant technology gaps to achieve 600 C
- Limited further temperature enhancement economically feasible





Fluoride-salt-cooled High-temperature Reactors (FHR)

(Several FHR slides courtesy of ORNL)

Fluoride-salt-cooled High-temperature Reactors (FHR)

- The FHR concept developed ~10 years ago (ORNL – UCB – MIT)
- Building on the successful Molten Salt Reactor Experiment (MSRE)
- Similar to MSRE: FHR is a molten salt cooled reactor,
  but different from MSRE: uses solid fuel (stationary or moveable)

FHR combines design features and technologies of several different reactor types

- MSRs
  – Fluoride salt coolant
  – Structural materials
  – Pump technologies

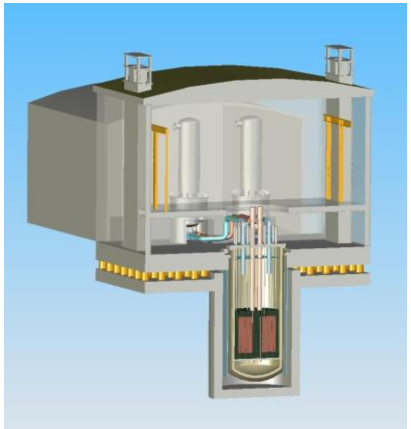
- GCRs
  – TRISO fuel
  – Structural materials
  – Brayton power conversion

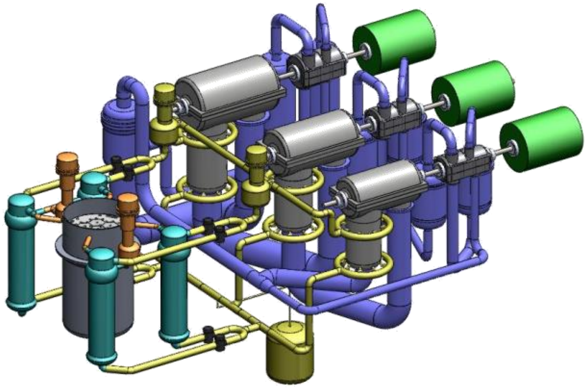
- LWRs
  - Low reactivity of coolant with air
  - Integral primary coolant systems

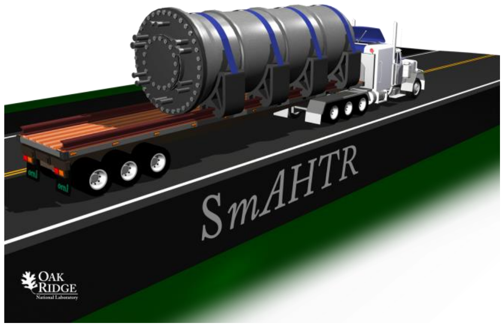
- SFRs
  - Low primary pressures
  - Pool configuration
  - Hot refueling technologies

FHR Concepts Currently Under Active Development

- Advanced High Temperature Reactor (AHTR); large electricity generator at ORNL
- Pebble Bed - AHTR; medium (410 MW_e) electricity generator at University of California Berkeley
- SmAHTR; deliberately small (125 MW_{th}) process heat & electric system at ORNL
- Chinese FHR (SF1)







Source: ORNL

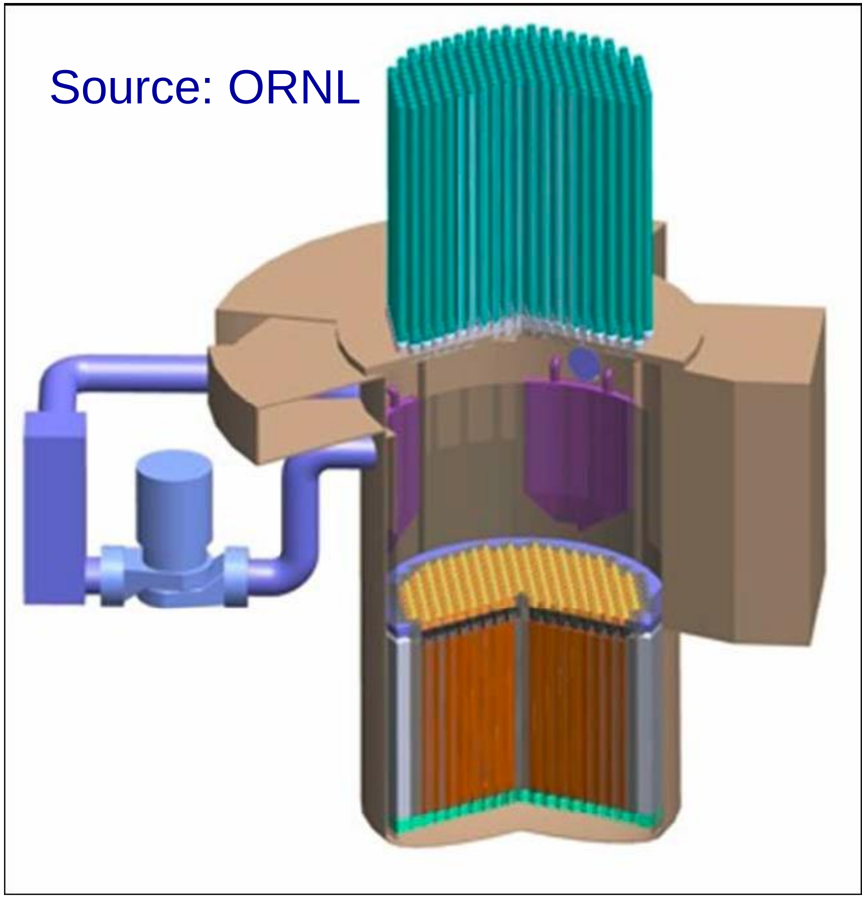
AHTR Liquid Salt Cooled Reactor

Attractive Features

- Very high temperature reactor with F_2LiBe_4 (FLiBe) coolant ~700 °C exit
- Operates at near-atmospheric pressure reducing capital cost
- Fuel is fabricated with TRISO fuel particles providing accident tolerance

Challenges

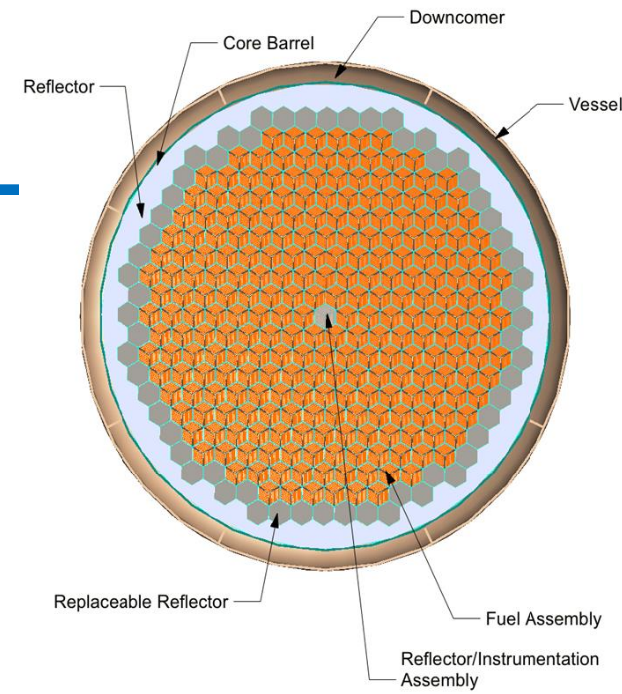
- Small volumetric fraction of fuel kernels in fuel assembly, thus small heavy metal (HM) loading
- Much higher specific power (W/gHM) than LWRs, faster depletion, shorter cycle length



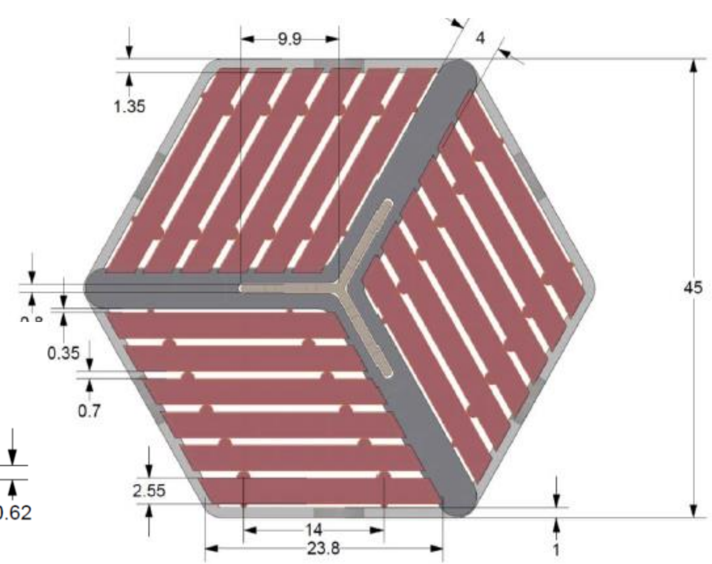
AHTR Reactor Parameters

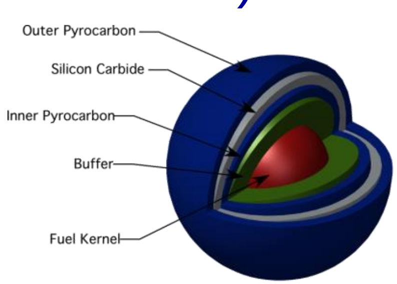
Reactor Power	3400 MWt
Thermal Efficiency	45%
Number of Fuel Assemblies	253
Assembly Half Pitch	23.375 cm
Plate Thickness	2.550 cm
Thickness of Fuel Regions	0.649 cm
Plate Sleeve Thickness	1 mm
TRISO Pitch	926 µm
Fuel Kernel Radius	213.5 µm
Fuel Material	Uranium Oxycarbide
Moderator Material	Graphite/Amorphous Carbon
Coolant	Li_2BeF_4 (Flibe)
Fuel Density	10.9 g/cc
Fuel Enrichment	< 20%
Average Coolant Temperature	948.15 K
Coolant Pressure	atmospheric
Core Volume	263.38 m^3
Core Power Density	12.91 MW/m^3
Mass Flow Rate	28408.1 kg/s
Average Coolant Velocity	1.93 m/s

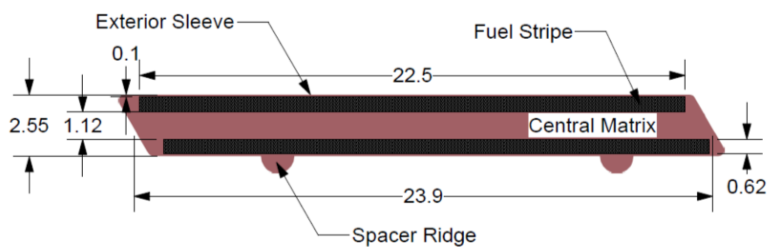
AHTR Core and Fuel Design



- 253 (252) fuel elements
- Hexagonal fuel elements, initially with fuel compacts, similar to gas-cooled VHTR
- Novel fuel plank design improves heavy metal loading compared to fuel compacts
- Cycle lengths 1-2 years achievable with <20% enriched fuel
- Further optimization between enrichment and TRISO particles packing fraction (PF) is needed to reduce fuel cycle cost (trade-off between fuel utilization and outage cost)







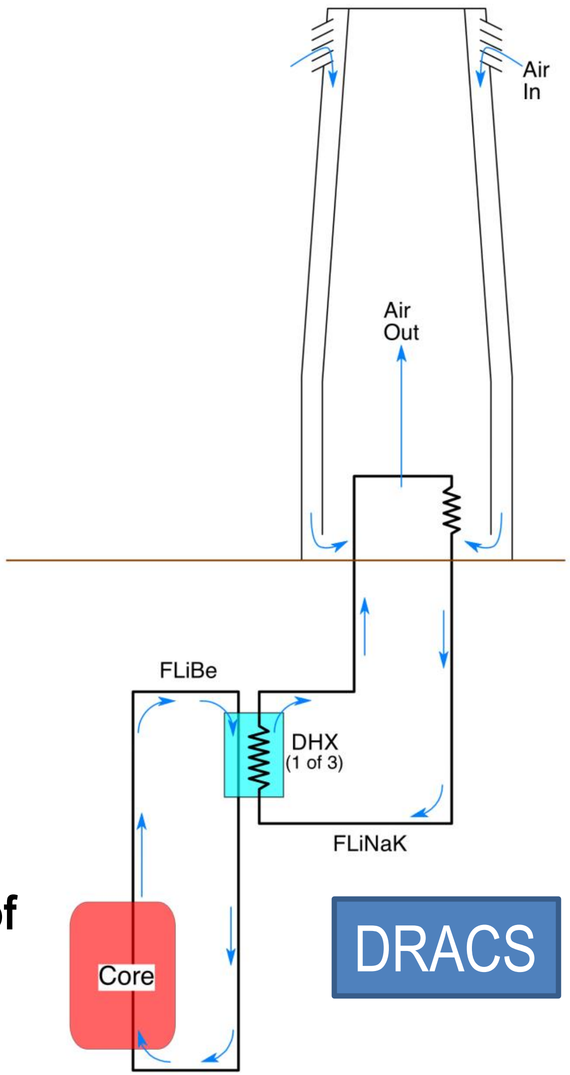
FHR Inherent Attributes Promote Favorable Economics

FHR Attribute	Impact(s)	Cost Implications
High primary coolant volumetric heat capacity	• Low fluid pumping requirements • Near-constant-temperature energy transport	• Compact coolant and heat transport loops (small pipes, pumps, heat exchangers)
Low primary system pressure	• Low pipe break / LOCA energetics • Low source term driving pressure	• Thin-walled reactor vessel and piping • Smaller, simpler containment
Transparent coolant with low chemical activity	• Visible refueling operations • Low pipe break / LOCA energetics	• Efficient refueling • Smaller containment
High primary system temperatures	• High power conversion efficiencies • High temperature fluid – materials corrosion and strength performance	• Lower fuel costs • Higher materials cost • Hot refueling
TRISO fuels	• Large fuel temperature margins • Good fission product containment	• Robust operating margins and safety case
Large primary coolant coefficient of thermal expansion	• Good natural circulation cooling • Passive decay heat removal	• Limited (no?) active safety systems

Source: ORNL

Properly Engineered FHRs Will Passively Endure All Credible Accident Scenarios

- Loss of forced cooling
  - Natural circulation heat rejection
  - Overcooling avoided by maintaining small parasitic heat loss during operation
- Loss of forced cooling without scram
  - Large thermal margins and long response time for failure
  - Large negative temperature reactivity coefficient
  - Thermally-driven primary and secondary shutdown mechanisms
- Inadvertent reactivity insertion
  - Control rod ejection not credible due to lack of stored energy within containment
  - Core voiding averted by large margin to boiling, lack of pressure sources to drive bubble creation, large volume of salt above core, and secondary salt vessel
- Earthquake & impact
  - Below grade siting & seismic mounting



Source: ORNL

NuRenew Concept

NuRenew Concept – Vision / Objective

Issue (for USA):

- >$1T stranded in coal infrastructure
- Large coal resources
- Cannot just stop using (economically NOT acceptable)
- Cannot continue using (environmentally NOT acceptable)

VISION / OBJECTIVE

Transition to sustainable energy production by facilitating economical deployment of a non-fossil energy source, synergistic nuclear-solar power system (“NuRenew”) and phasing out of coal-fired power plants, while enabling continued (but cleaner) use of large coal resources and coal-related infrastructure for transportation

NuRenew – Hybrid Nuclear-Solar Energy Park

Combines several promising technologies

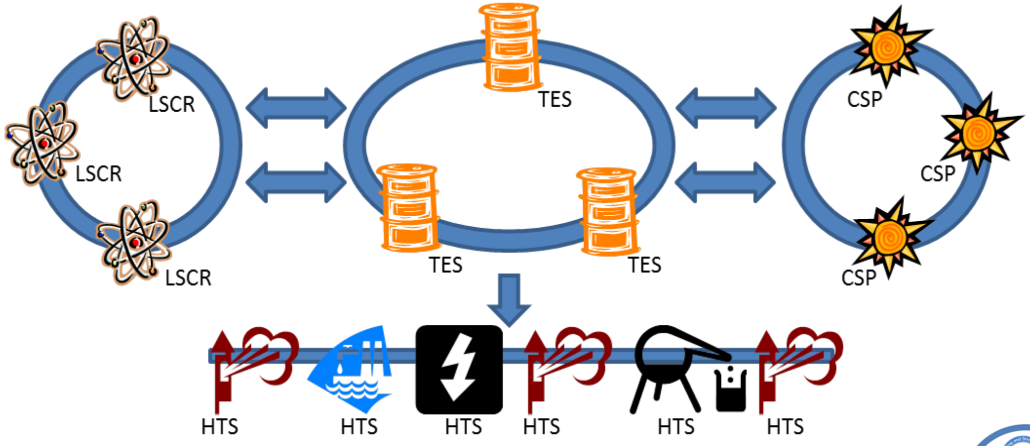
- Molten salt cooled nuclear power plant (LSCR)
- Molten salt based concentrated solar power plant (CSP)
- Molten salt based thermal energy storage (TES)

→ Molten salt technology – synergy – direct integration – hybrid energy system

→ NuRenew energy park

- Electricity, transportation fuel, high-temperature (HT) process heat
- TES - simultaneous multiple use - reduces cost, improves reliability
  Firewalls nuclear safety-wise
  Isolates users from perturbations

Objective:
NuRenew performance: 2+2=5
NuRenew Cost: 2+2=3

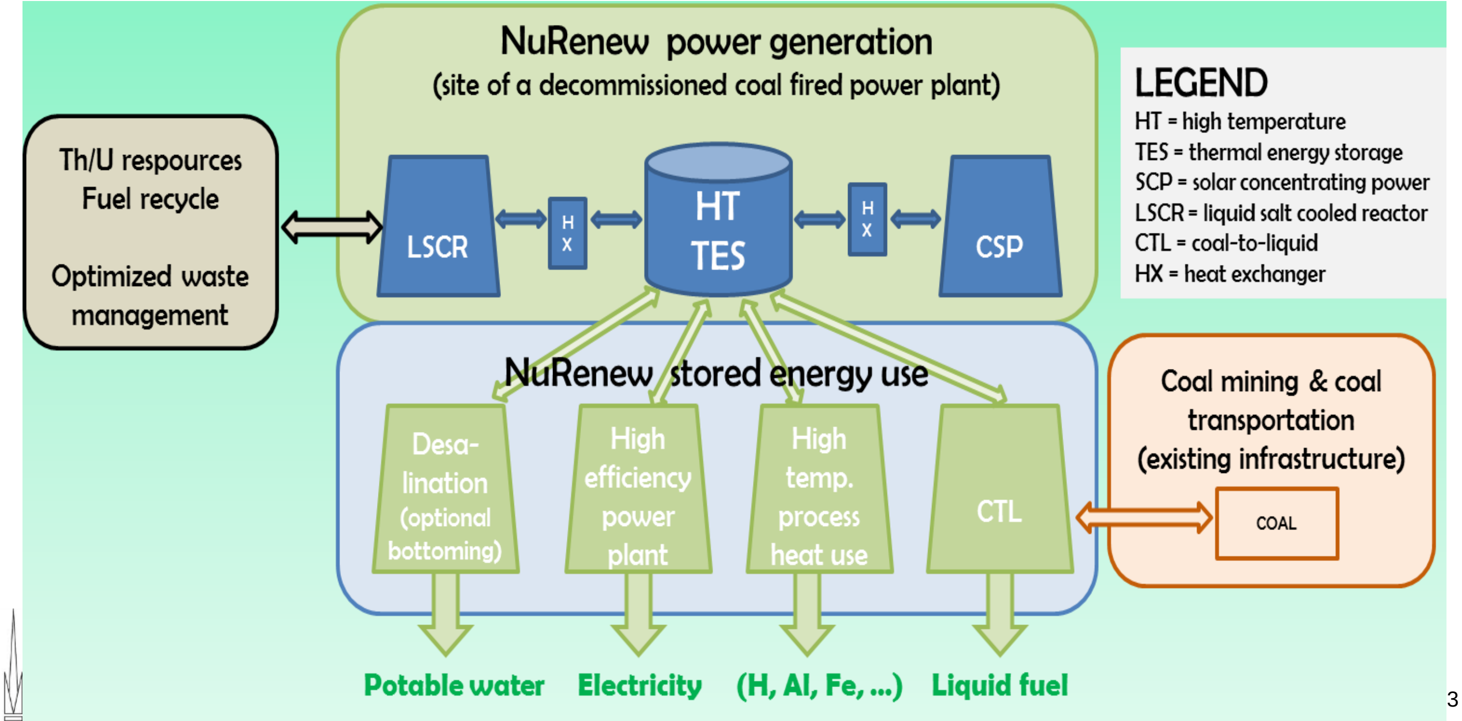


NuRenew

- Expands nuclear generation into transportation (CTL, H) and HT processes
- CTL, fossil plants sites repurposing – continues using coal resources/infrastructure
- Promotes accelerated CSP deployment (reduces effective TES cost)
- Dual layer energy storage: (TES) + (H, HT processes) optimizes supply-demand balancing and stability

  Industrial processes integrated in NuRenew Energy Park:

  (High) capital cost? Technology (Al,..)? need low capital cost & flexible in the mix
- Potential use of thorium fuel to address nuclear resources/waste



Georgia Tech

NuRenew – Summary of Features with Respect to TES

- Concentrated Solar Power (CSP) - promising technology, but requires massive/expensive energy storage to meet energy demand during evening/night hours, and periods of reduced solar radiation.
- Molten salt harbors huge potential for thermal energy storage (TES) for CSP as well as for liquid salt (molten salt) cooled nuclear power plants (LSCR). It is suitable for operation at high temperatures thereby achieving higher efficiency and reduced water use compared to current power plants.
- Such storage has been so far considered for solar and nuclear separately, but the cost is then a significant issue, in particular for solar power.
- Using it in synergy for a directly coupled nuclear-solar system (NuRenew), as proposed here, will significantly reduce the TES cost (enabling earlier deployment of CSP) and increase the energy supply reliability, creating a consistent, low-CO2-emitting, energy supply.

NuRenew – Summary of Features

- High-temperature high efficiency, reduced reject heat (and water use)
- On the nuclear power side, one option is to use thorium, which is about four times more abundant than uranium, and generates wastes of significantly more benign characteristics than the currently used nuclear fuel cycle.
- Technical characteristics of NuRenew facilitate using it for high-temperature processes, and in particular for coal liquefaction (coal-to-liquid or CTL), and synfuel in general, enabling its expansion and positive environmental impact into transportation.
- It will also permit economically-acceptable accelerated phasing out of fossil-fired power plants, while enabling continued (but cleaner) use of large coal resources and infrastructure.
- NuRenew may be considered as a platform to examine possible energy policies in promoting this innovative energy supply technology to cut down carbon emissions and mitigate climate change.

Summary

Summary and Conclusions

- New electricity/energy sources are and will be needed
- Impossible to meet the growing energy demand and support sustainable development without nuclear power (in the mix)

- Nuclear needs to expand beyond the electricity production to other energy sectors

- Nuclear + Renewables can replace most of the fossil energy sources
- Concept of a synergetic energy park NuRenew proposed

Thank you for your attention
Questions?