



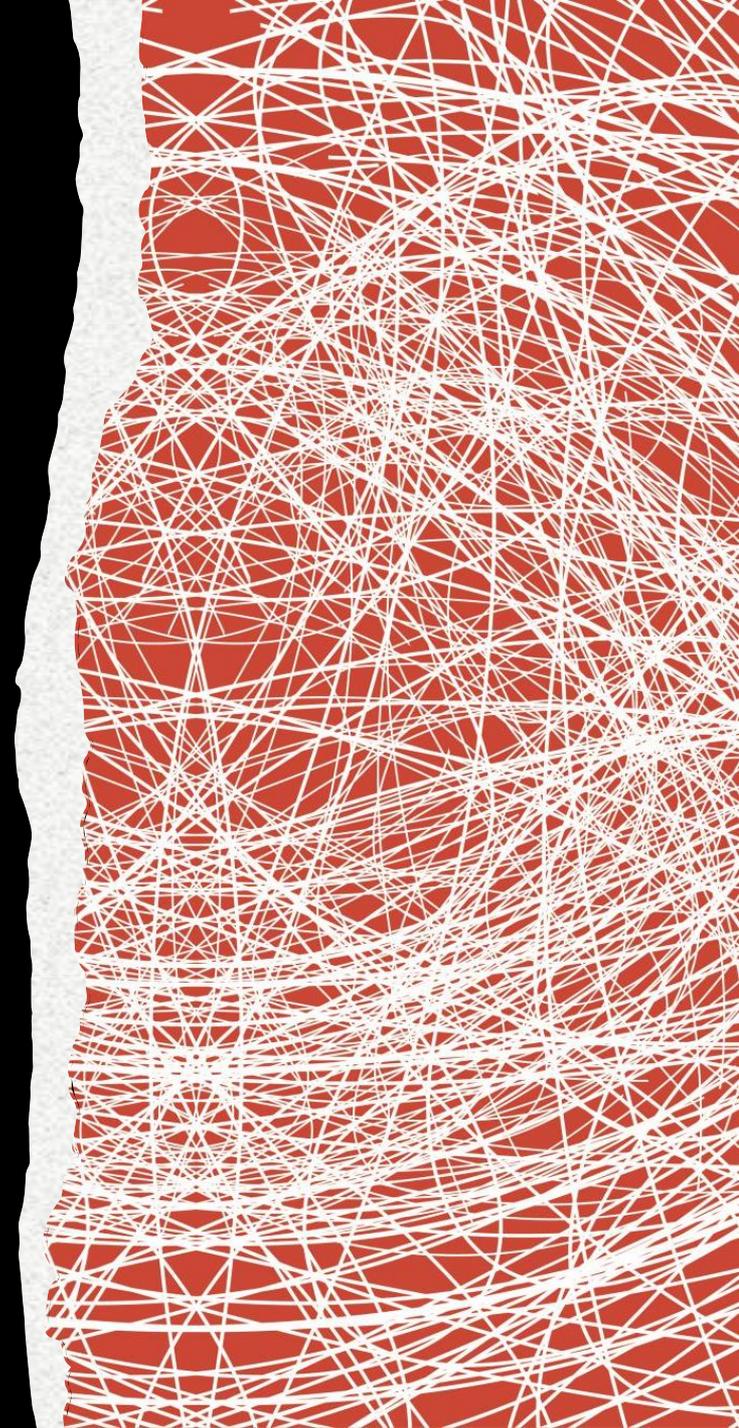
Non-Electric Applications of Advanced Reactors and SMRs

Rami El-Emam



Outlines!

- **Introduction**
- **Nuclear Cogen: Technologies & Status**
- **Assessment Tools on Non-Electric Applications**



NUCLEAR POWER TODAY



Nuclear Power Today

Total Number of Operating Reactors today is **440** reactor with total net electrical capacity of **390,000 MWe**.

This is 10% of Global Electricity Production



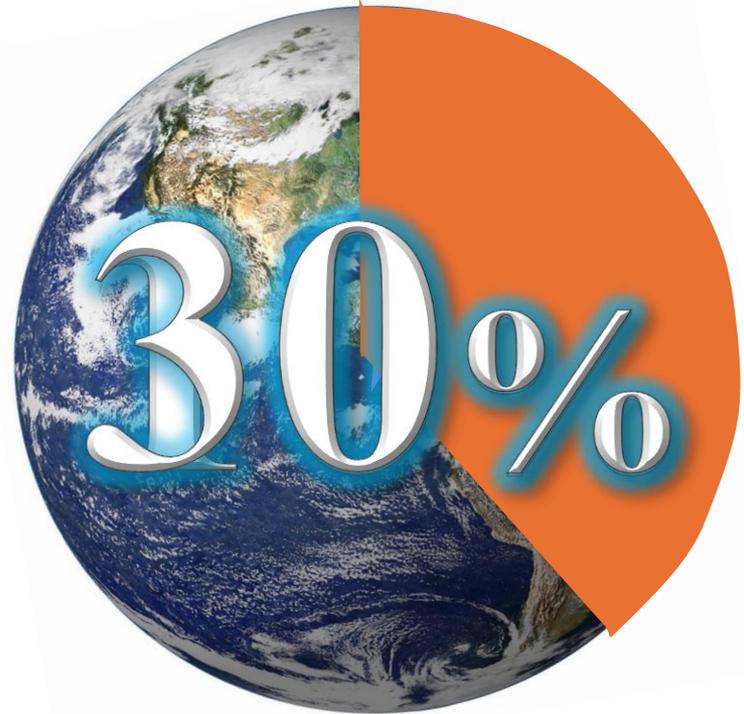
Nuclear Power Today

Total Number of Operating Reactors today is **440** reactor with total net electrical capacity of **390,000 MWe**.

Second Low-Carbon

Power Source

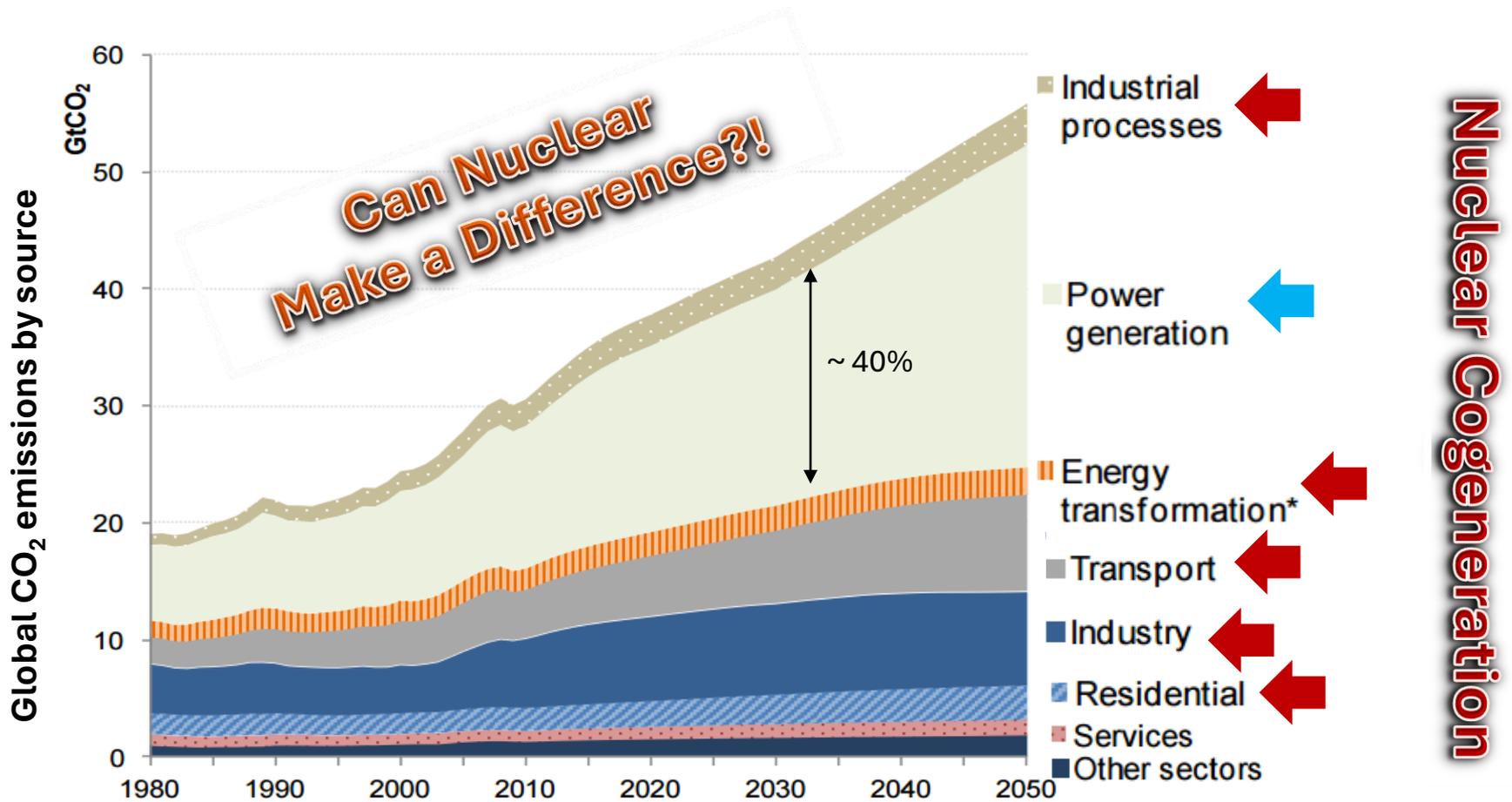
(~30%)



NUCLEAR ENERGY & CLIMATE CHANGE



Role in Climate Change Mitigation

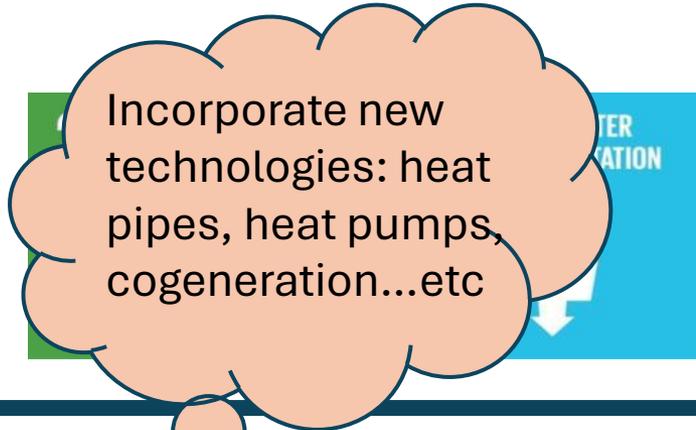




SUSTAINABLE DEVELOPMENT GOALS

 <p>TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT</p>	1 NO POVERTY 	2 ZERO HUNGER 	3 GOOD HEALTH AND WELL-BEING 	4 QUALITY EDUCATION 	5 GENDER EQUALITY 
6 CLEAN WATER AND SANITATION 	7 AFFORDABLE AND CLEAN ENERGY 	8 DECENT WORK AND ECONOMIC GROWTH 	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 	10 REDUCED INEQUALITIES 	11 SUSTAINABLE CITIES AND COMMUNITIES 
12 RESPONSIBLE CONSUMPTION AND PRODUCTION 	13 CLIMATE ACTION 	14 LIFE BELOW WATER 	15 LIFE ON LAND 	16 PEACE, JUSTICE AND STRONG INSTITUTIONS 	17 PARTNERSHIPS FOR THE GOALS 

Nuclear Cogeneration & SDGs



Recover waste heat!!!

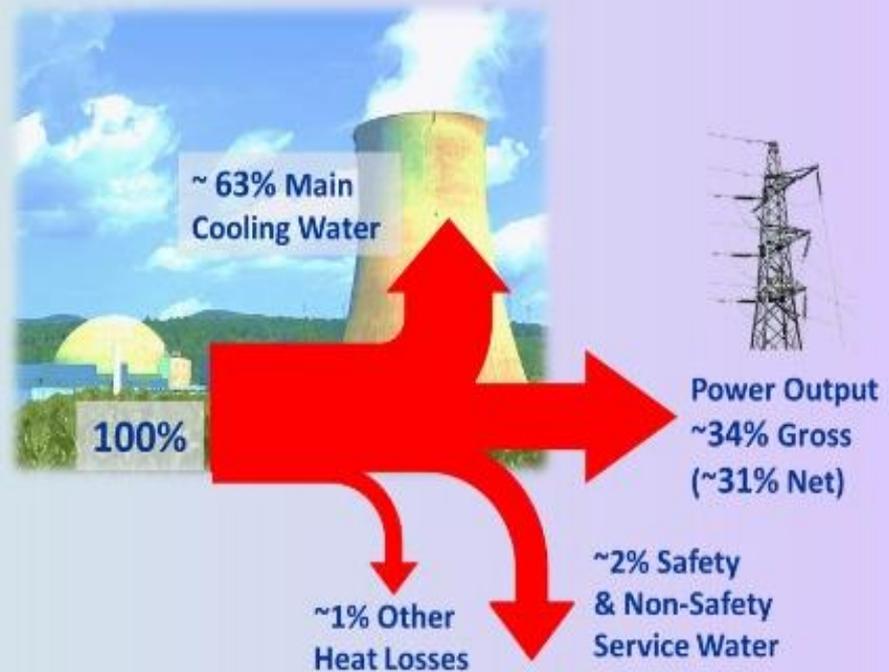


Rely more on non-electric applications



POWER of TODAY's NUCLEAR POWER

more than 700,000 MW (th)
heat wasted from today's operating reactors



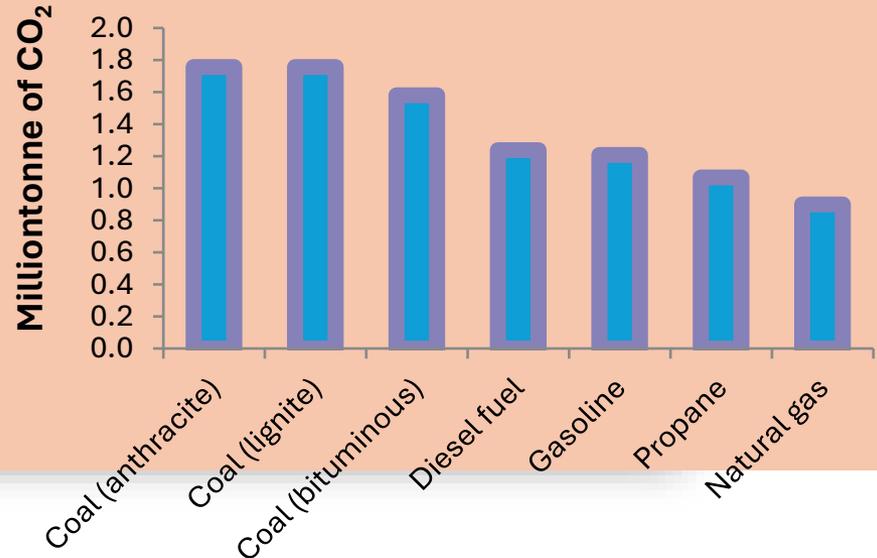
Role in Climate Change Mitigation

Waste heat from these reactors is
700,000 ~ 1,000,000 MW(th)!!

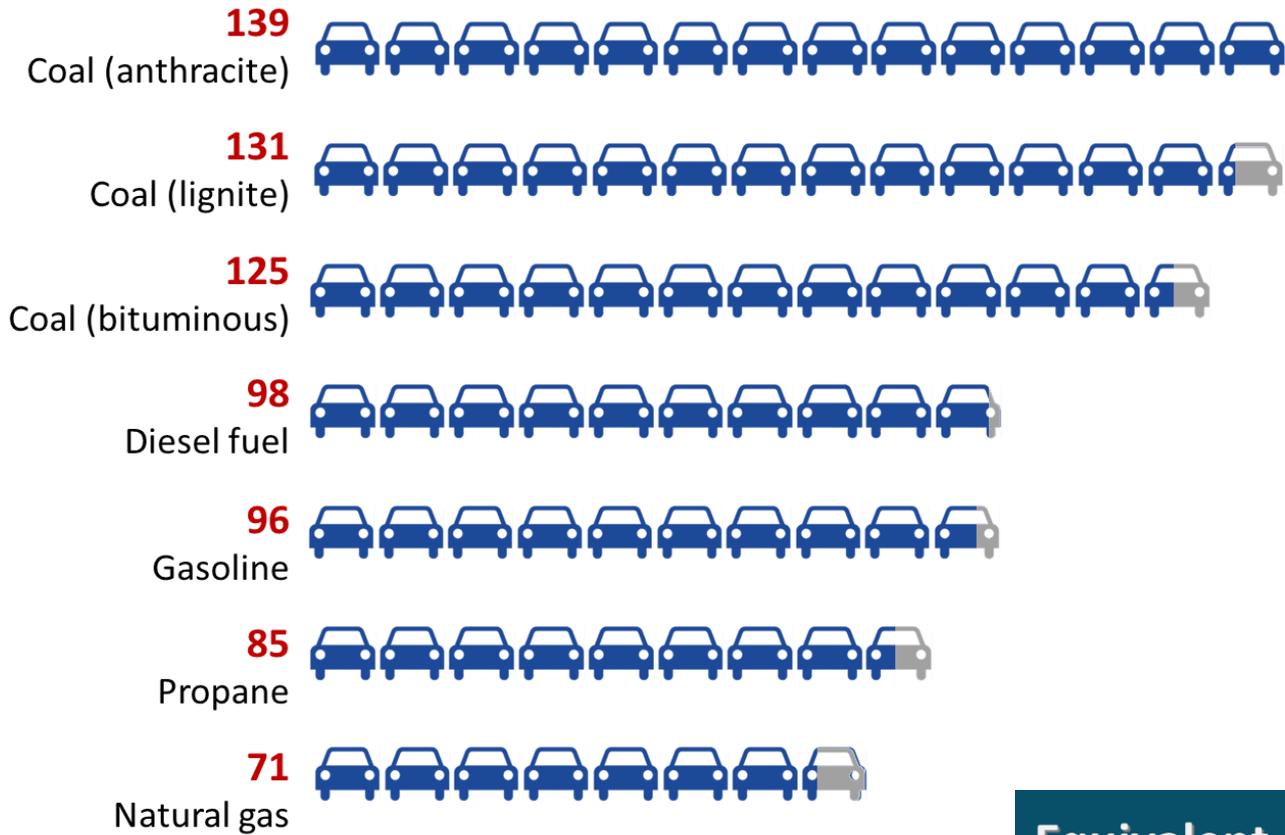
Assume: ~ 25% recovery of waste heat

This is equivalent to daily reduction of
1 - 2 Million tonnes of CO₂ emissions

Based on the type of fossil fuel would be used to cover this thermal demand

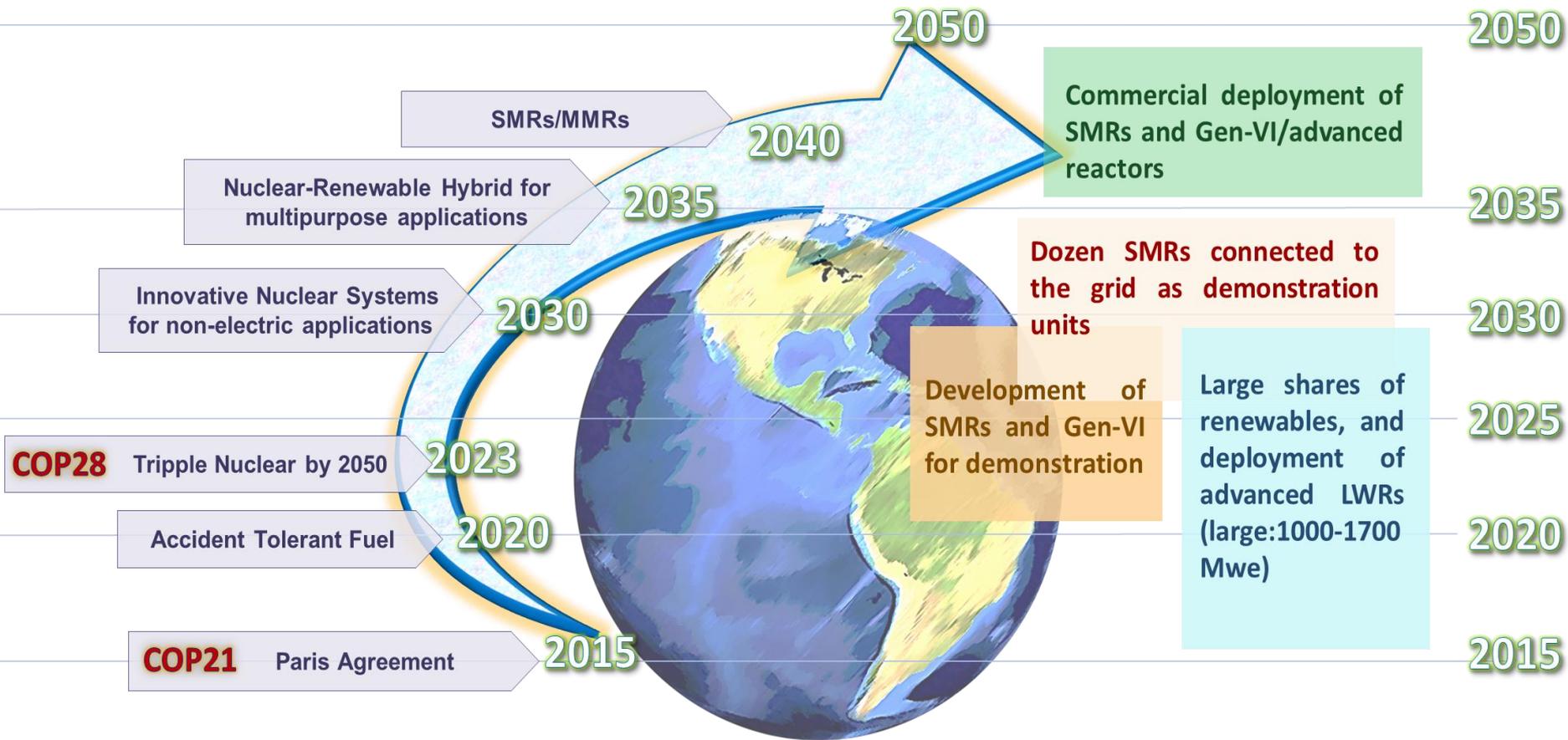


Million Car



Equivalent cars taken off roads in a year when nuclear waste heat is recovered to replace carbon-based heat applications

ROADMAP OF NUCLEAR ENERGY INNOVATIONS



STATUS OF NUCLEAR COGENERATION

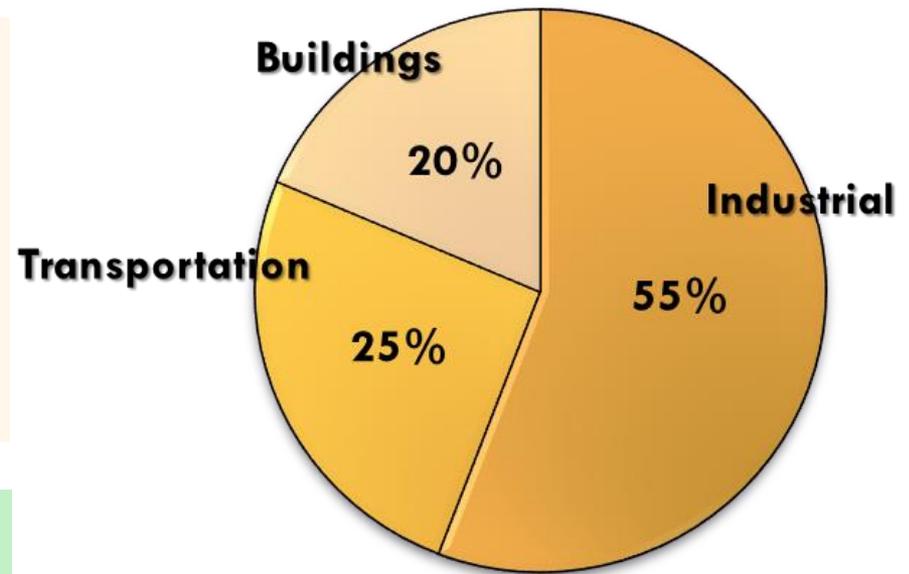
- Nuclear cogeneration is a well proven technology with over 750 reactor years of operation in different applications.
- About 15% of the currently operating nuclear power plants are used to supply heat



POTENTIAL OF NUCLEAR COGENERATION

Nuclear potential is in penetrating **Transportation** and **Heat** (industrial and buildings) sectors using Nuclear Cogeneration of Power and Heat

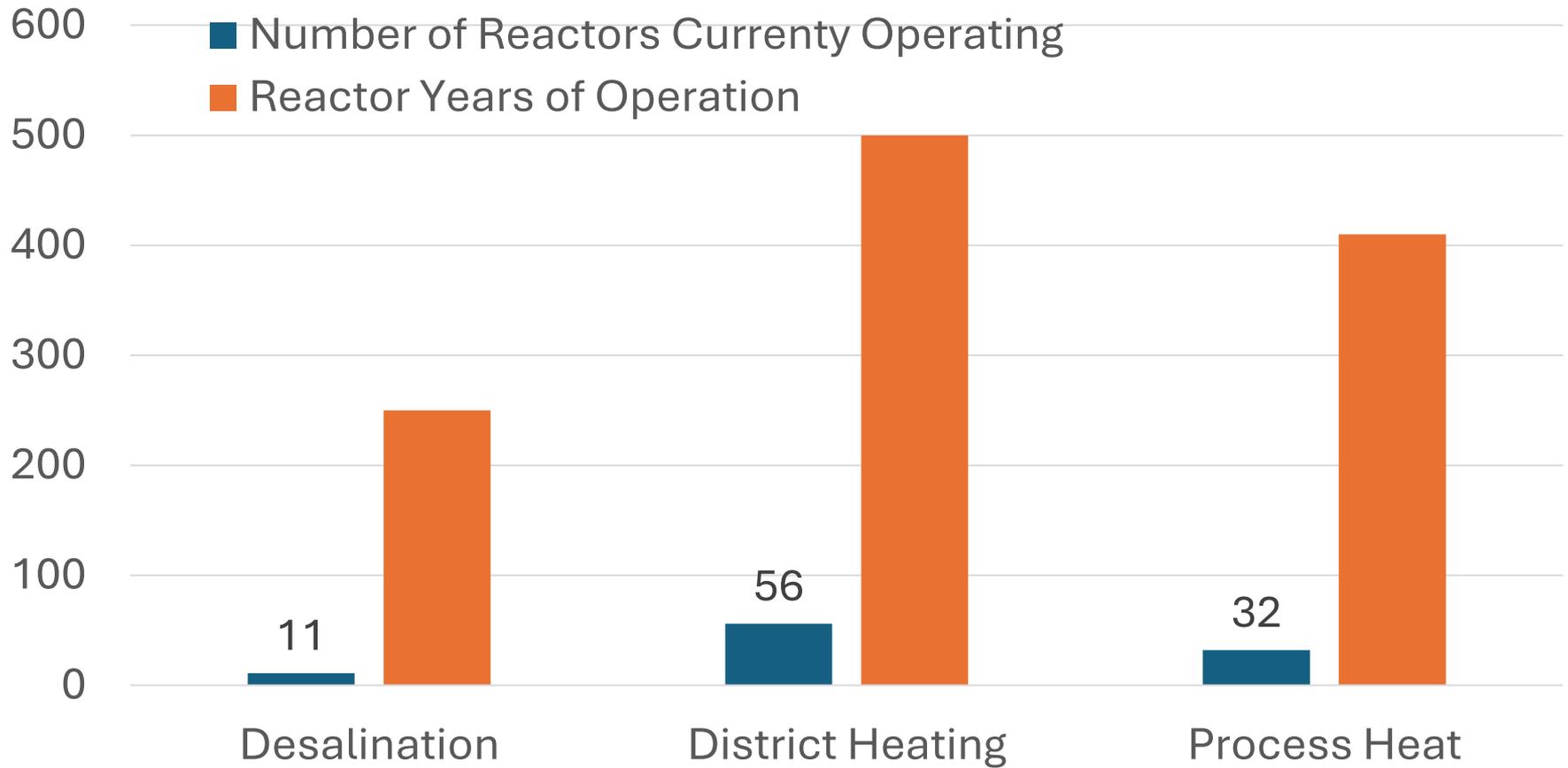
The share of electricity used in **transportation** doubles between 2015 and 2040 as more plug-in electric vehicles enter the fleet and electricity use for rail expands



World energy consumption by end-use sector

The industrial sector includes mining, manufacturing, agriculture, and construction
The buildings sector includes commercial and residential structures (electricity, heating,..)

Status of Nuclear Cogeneration

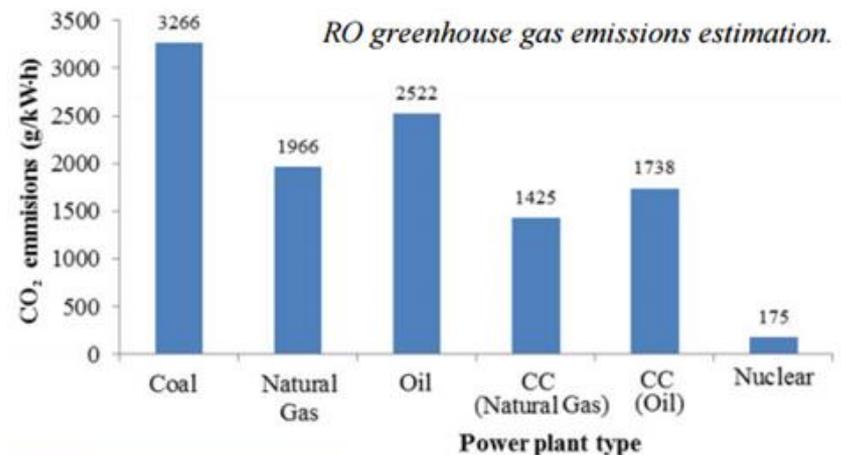
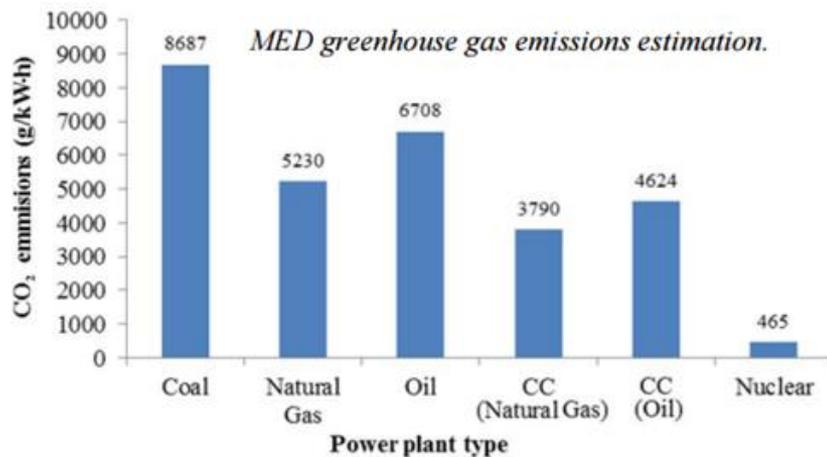
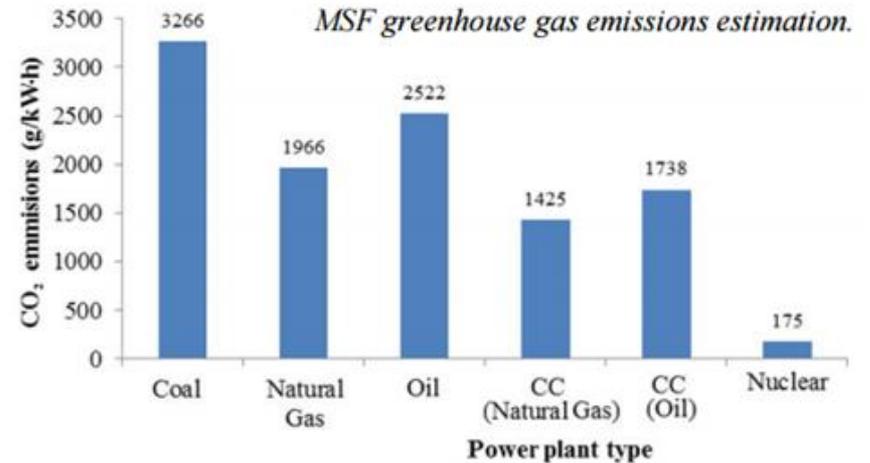


Experience on Nuclear Desalination

Plant name	Location	Gross power MW(e)	Water capacity [m ³ /d]	Reactor type/ Desal. process
Shevchenko	Kazakhstan	150	80000 – 145000	FBR/MSF&MED
Ikata-1,2	Japan	566	2000	LWR/MSF
Ikata-3	Japan	890	2000	LWR/RO
Ohi-1,2	Japan	2 x 1175	3900	LWR/MSF
Ohi-3,4	Japan	1 x 1180	2600	LWR/RO
Genkai-4	Japan	1180	1000	LWR/RO
Genkai-3,4	Japan	2 x 1180	1000	LWR/MED
Takahama-3,4	Japan	2 x 870	1000	LWR/RO
Diablo Canyon	USA	2 x 1100	2180	LWR/RO
NDDP	India	2 x 170	1800	PHWR/RO
Karachi	Pakistan	175	1600	MED



GHG Emissions for Nuclear Desalination



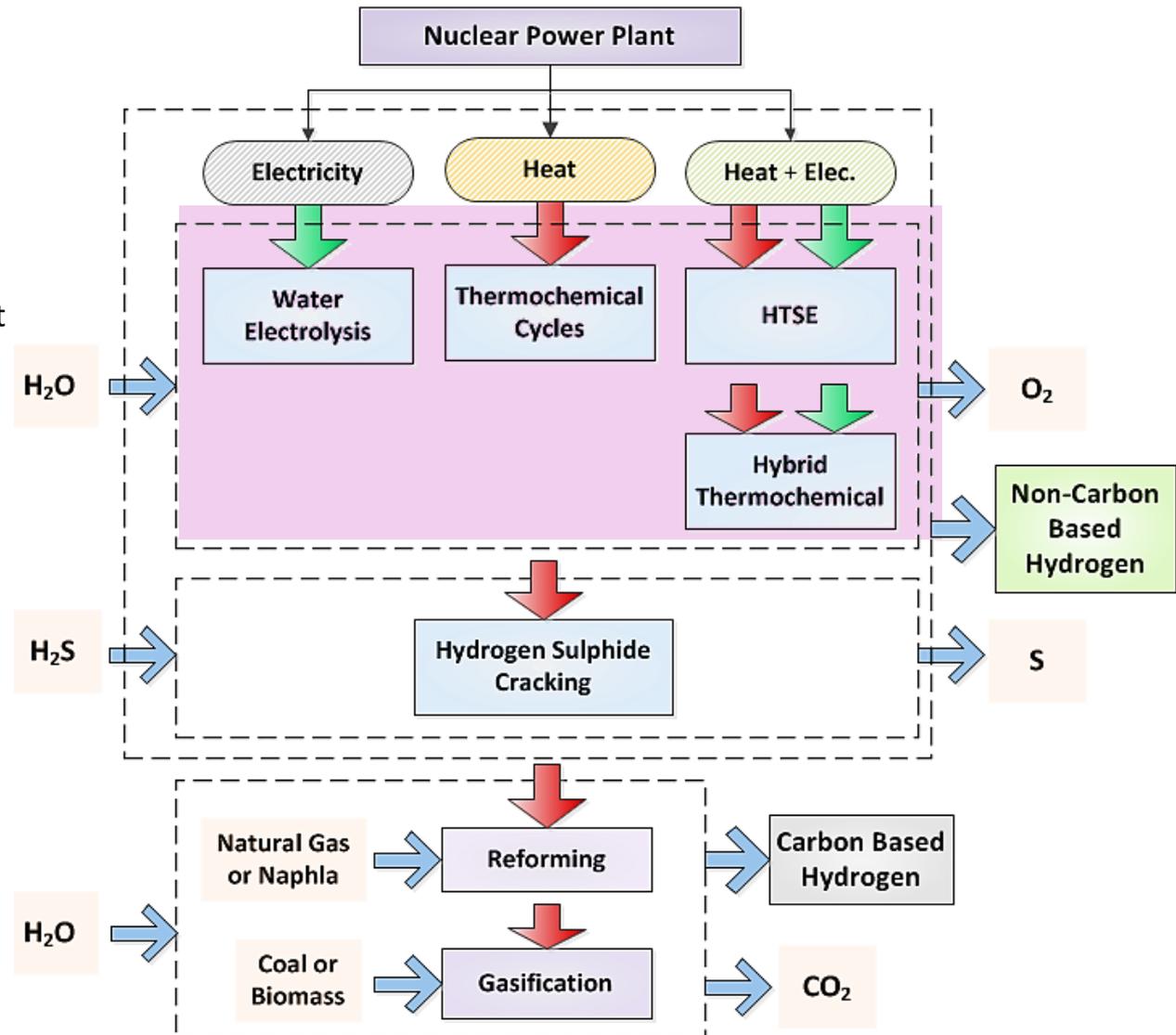
Nuclear Hydrogen Production

Current nuclear reactors:

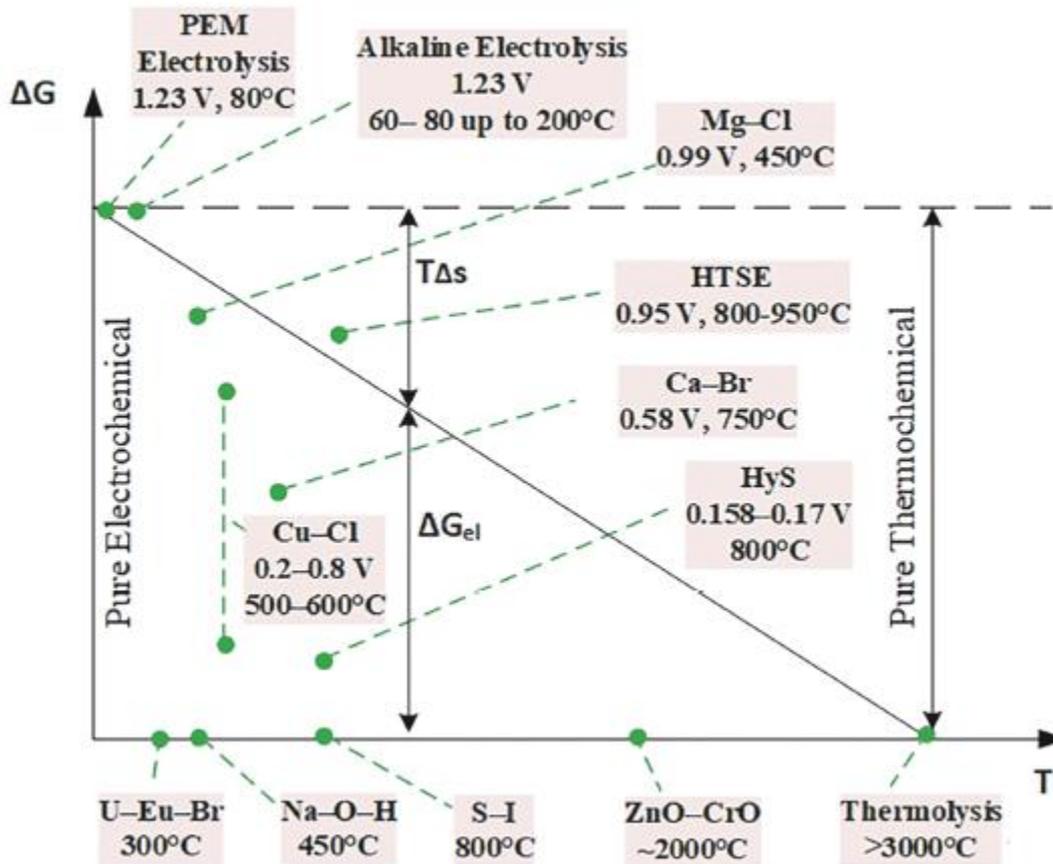
- Low-temperature electrolysis
- Off-peak power or intermittent
- HTSE

Future nuclear reactors:

- Thermochemical/hybrid thermochemical cycles, *efficiency (up to 95%)*
- ✓ Sulfur- Iodine cycle.
- ✓ Sulfur-Bromine hybrid Cycle cycle
- ✓ Copper Chlorine cycle
- ✓ etc



Maximum temperatures and theoretical electrical energy requirements of selected hydrogen production methods



advanced nuclear reactor (Gen-IV) for Hydrogen Production

		GEN IV - Advanced Nuclear Technologies						
		SCWR	VHTR	SFR	GFR	MSR	LFR	
Specifications	Core outlet temperature °C	500 ~ 625	750 ~ 950	450 ~ 550	750 ~ 850	650 ~ 850	450 ~ 800	
	Efficiency (electric based) %	44 ~ 48	40 ~ 50	38 ~ 42	45 ~ 48	45 ~ 55	42 ~ 45	
	Thermodynamic power cycle							
	Brayton Cycle	-	He	S-CO ₂	He	He	S-CO ₂	
	Rankine Cycle	Steam	Steam	Steam	-	-	Steam	
Hydrogen Production Technologies	Electrolysis							
		PEM electrolysis (<100°C)	✓	✓	✓	✓	✓	✓
		Alkaline electrolysis (~200°C)	✓	✓	✓	✓	✓	✓
		High temp electrolysis (> 800°C)	✓	✓	✓	✓	✓	✓
	Thermochemical/Hybrid Cycles							
		Sulfur Iodine (> 800°C)	-	✓	-	✓	-	-
		Hybrid Sulfur (> 800°C)	-	✓	-	✓	-	-
		Copper Chlorine (> 600°C)	✓	✓	-	✓	✓	-
	Carbon Based Thermochemical							
		Steam methane reforming (> 700°C)	-	✓	-	✓	✓	-
	Coal/Biomass gasification (> 650°C)	✓	✓	-	✓	✓	-	

SCWR: Super Critical Water Reactor

VHTR: Very High Temperature Reactor

SFR: Sodium cooled Fast Reactor

GFR: Gas cooled Fast Reactor

MSR: Molten Salt Reactor

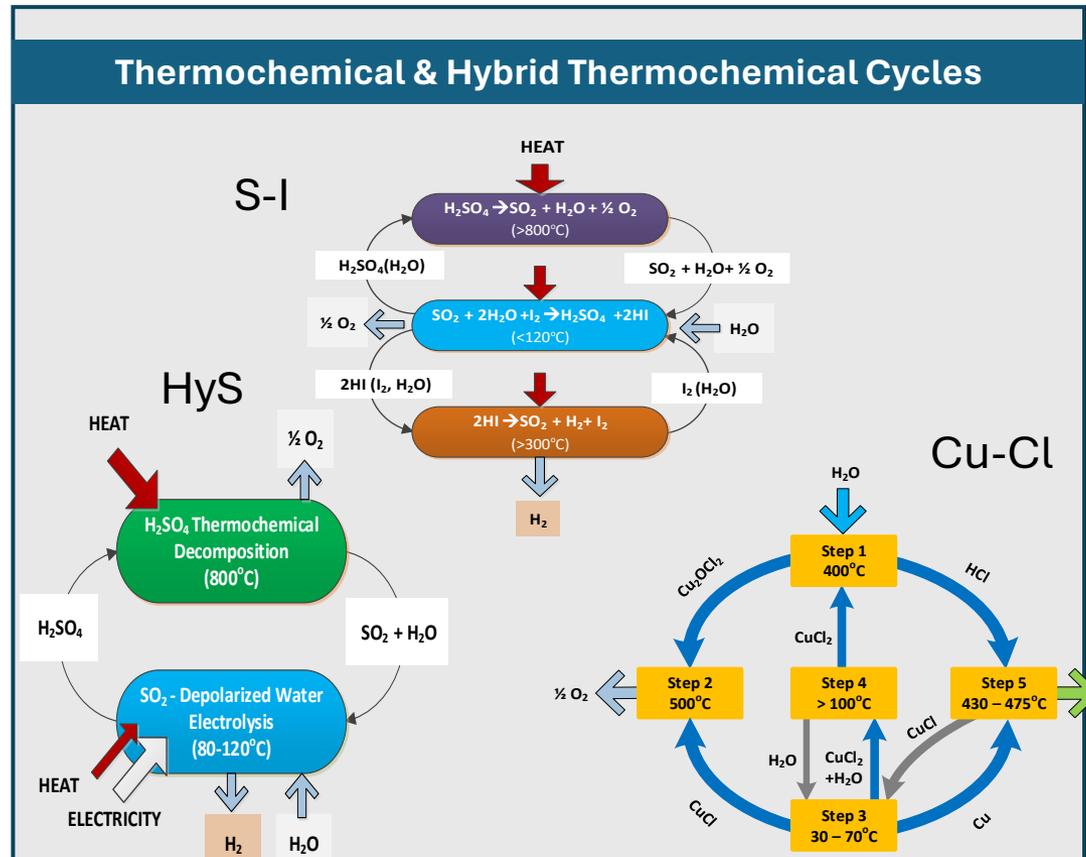
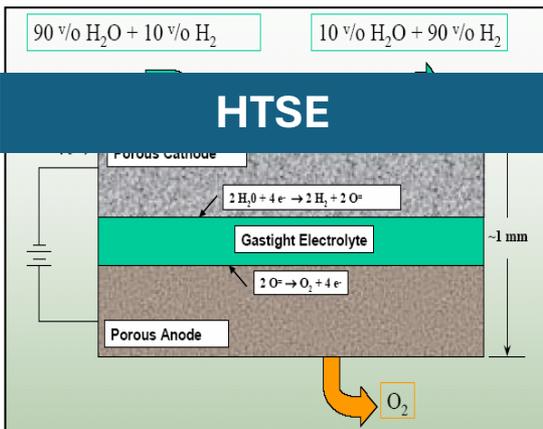
LFR: Lead cooled Fast Reactor

Nuclear Hydrogen Production

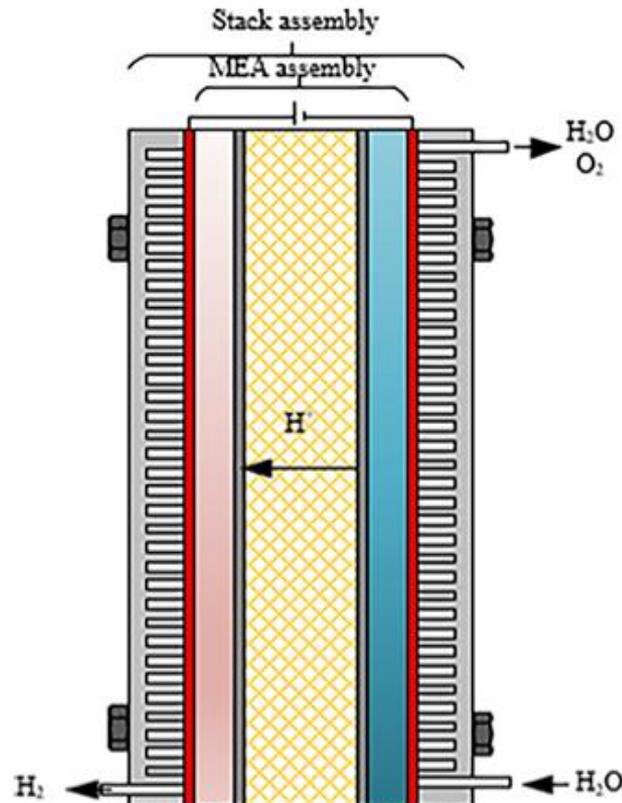
coupling nuclear and hydrogen generation plants would serve in reducing the carbon emissions accompanied with the currently fossil-powered steam methane reforming hydrogen plants.



Conventional Electrolysis



PEM electrolysis



Feasibility aspects:

- Efficiency range: 50-80%
- Current Density: $< 2.0 \text{ mA cm}^{-2}$
- Operation life: ~ 20 years
- Degradation rate: $< 14 \mu\text{V h}^{-1}$
- Energy consumption: $> 4.2 \text{ kWh/Nm}^3$
- Cell temperature: $25\text{-}80 \text{ }^\circ\text{C}$
- Cell pressure: ~ 30 bar

Durability issues:

- Mechanical degradation of cell layers due to clamping pressure
- Chemical degradation due to poisoning and feed water impurities
- Hydrogen embrittlement to Ti based bipolar plates
- Corrosion and passivation of flow plates
- Agglomeration and dissolution of catalyst layers
- Thermal degradation of membrane
- Membrane poisoning due to Ca^{2+} and Na^+
- Membrane thinning due to hydrogen peroxide existence
- Non-uniform stress on bipolar plates

Flow plates (Titanium, Graphite, Coated Stainless Steel)

Current collectors

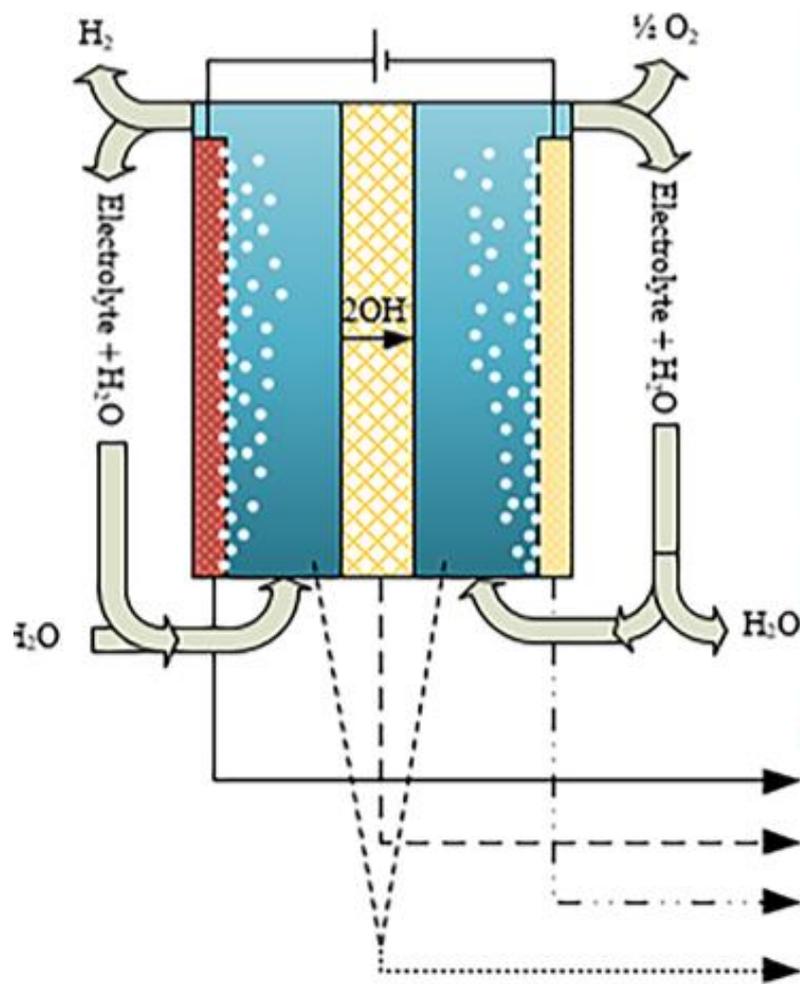
Anode (Ir) and Cathode (Pt) – Gas diffusion layers

Anode catalyst layer (Ir black, Ir Oxides, Ir/C, RuO_2)

Cathode catalyst layer (Pt black, Pt oxides, Pt/C)

Membrane (Nafion®)

Alkaline Electrolyser



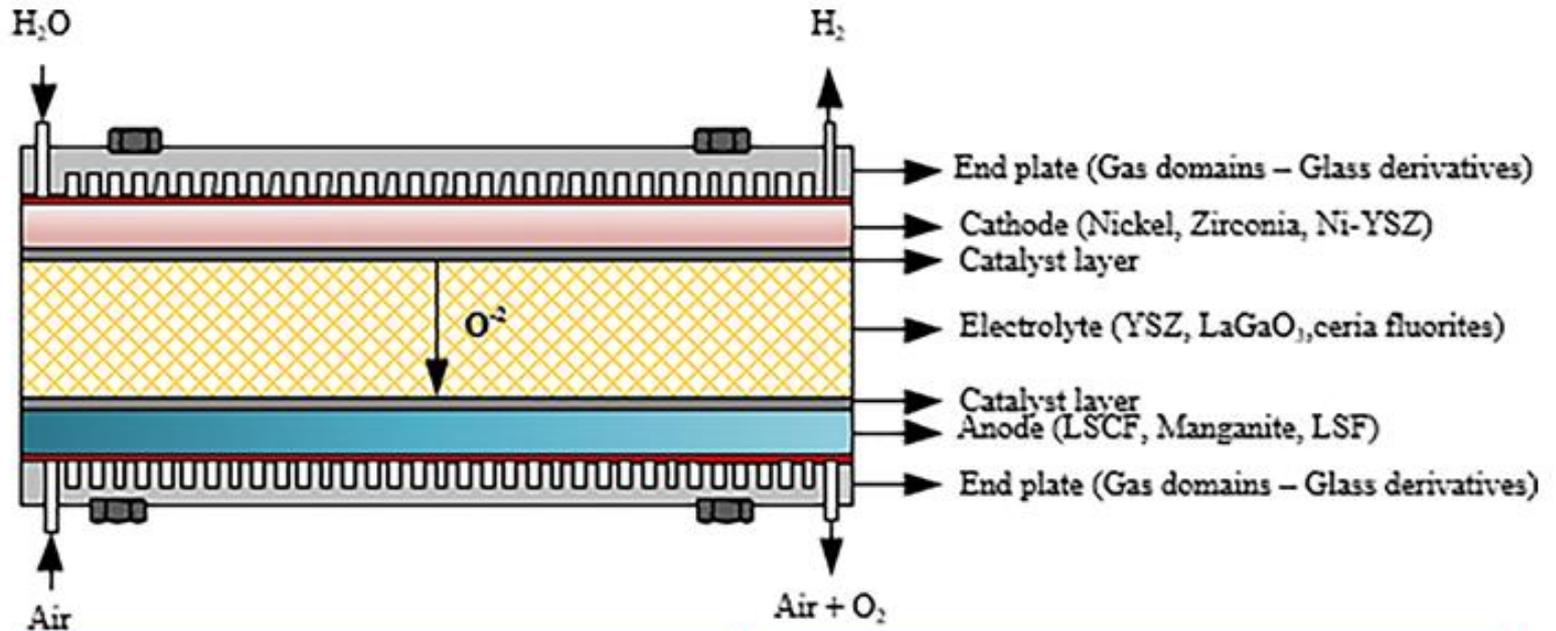
Feasibility aspects:

- Efficiency range: 58-70%
- Current Density: $< 3.0 \text{ mA cm}^{-2}$
- Operation life: ~ 30 years
- Degradation rate: $< 3 \mu\text{V h}^{-1}$
- Energy consumption: $> 4.2 \text{ kWh/Nm}^3$
- Cell temperature: $30\text{-}70^\circ \text{C}$
- Cell pressure: ~ 30 bar

Durability issues:

- operational complexity, hydrogen embrittlement, corrosion at high pressure and temperature
- Bubble layer formation between electrodes and electrolyte
- Gap between electrodes
- Membrane, electrode poisoning due to electrolyte impurities

high-temperature steam electrolysis



Feasibility aspects:

- Efficiency range: 70-100%
- Current Density: $< 3 \text{ mA cm}^{-2}$
- Operation life: 5-11 years
- Degradation rate: $> 32 \mu\text{V h}^{-1}$
- Energy consumption: 2.9-5.0 kWh/Nm³
- Cell temperature: $> 800^\circ \text{C}$
- Cell pressure: $\sim 1-60 \text{ bar}$

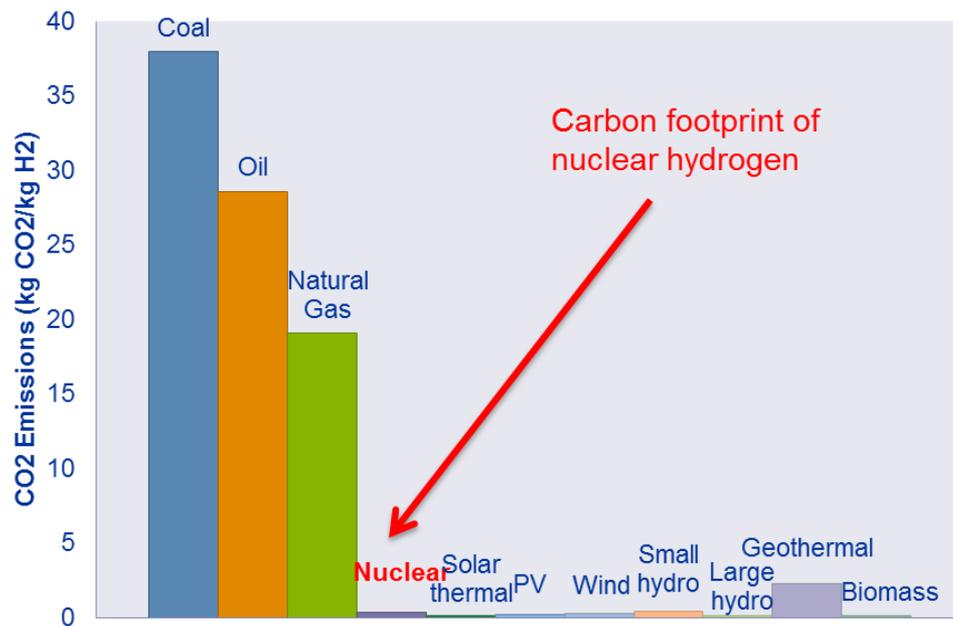
Durability issues:

- Very high degradation rate compared to other electrochemical methods
- Delamination due to high temperature operation
- Pollution on seals and interconnects at stack level
- Sealing leakage due to high temperature operation
- Cell layers positioning due to carbon based sealing materials

Nuclear Hydrogen Production

Driving Forces:

- Replacement of **CO₂** emitting fossil fuels
- Saving of resources by 30-40%
- Securing energy supply by reducing dependency on foreign oil uncertainties



Emissions from
***Nuclear Hydrogen
Production!***

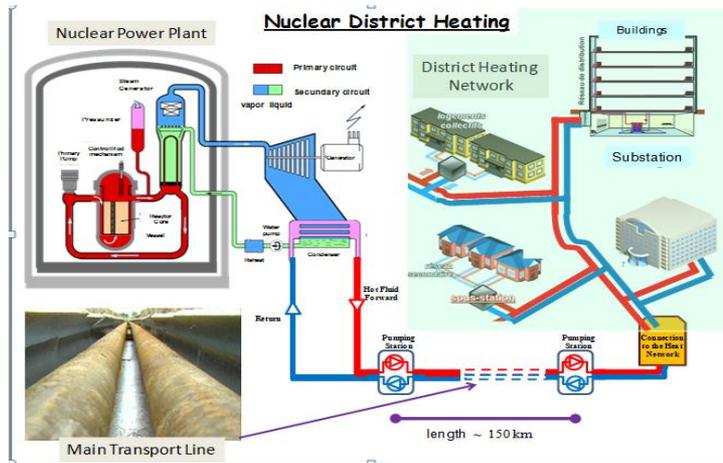
Cogeneration for District Heating

- Heat recovery enhances the plant efficiency and provides a **high energetic gain** (+70%)
- Nuclear heat recovery allows **large reduction** in CO2 emissions
- Heat transport line can reach **long distances** (> 100 km)

Recent developments in piping insulation allows transfer of heat for **100 km** with only **~ 2% heat loss** of the transported power



Cogeneration for District Heating



Loviisa 3 CHP – technical data

Finland

District heat transport system

- Distance over 75 km (Loviisa – eastern Helsinki)
 - 2 x Ø 1200 mm pipes, PN25 bar, Q = 4 - 5 m³/s
 - 4 - 7 pumping stations
 - total pumping power needed tens of MWs
 - compensates for heat losses
- Control scheme
 - district heat water temperature or flow rate
- Heat accumulator needed, heat distribution to the local district heat network via heat exchangers



22 October 2010

Harri Tuomisto

28



Heat from NPPs – a contribution to the solution of the CO₂ problem?

Switzerland



Example REFUNA (70 MW_{th}/140GWh_{th}):

- 10 Mio. liter heating oil per year
- savings of more than 26'500 t CO₂
- equivalent to the CO₂ emissions of about 12'000 cars every year

Russian Federations

NPP	Thermal Power, MW	Electric Power, MW	Heating capacity, MW
Beloyarskaya	1 470	600	260
Balakovskaya	12 000	4 000	920
Volgodonskaya	6 000	2 000	460
Novovoronezhskaya	5 750	1 880	250
Kurskaya	12 800	4 000	700
Smolenskaya	9 600	3 000	520
Kalininskaya	9 000	3 000	420
Leningradskaya	12 800	4 000	700
Kolskaya	5 500	1 760	145
Bilibinskaya	248	48	90

IAEA Tools and Toolkits on Cogeneration and Non-Electric Applications of Nuclear Energy

- Desalination Economic Evaluation Programme
- Desalination Thermodynamic Optimization Programme
- Hydrogen Economic Evaluation Programme
- Nuclear Desalination Toolkit
- Nuclear Hydrogen Production Toolkit

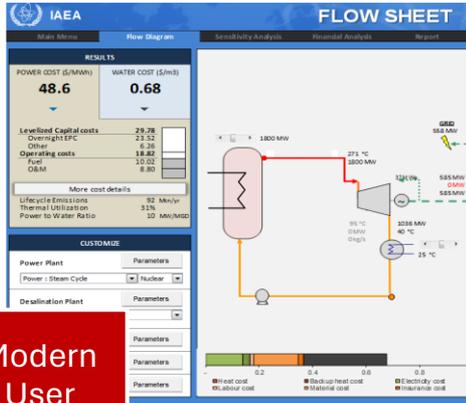
DEEP

performance and cost evaluation of various power and seawater desalination cogeneration configurations.

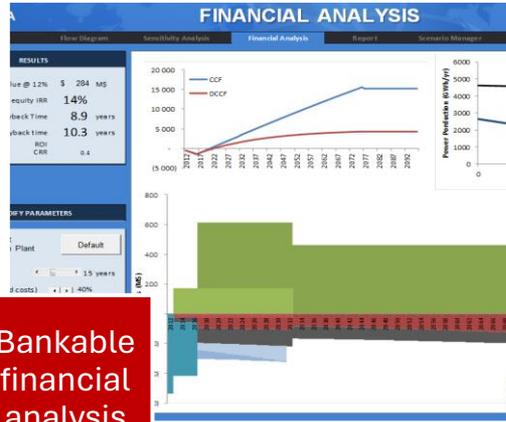


Desalination Economic Evaluation Programme

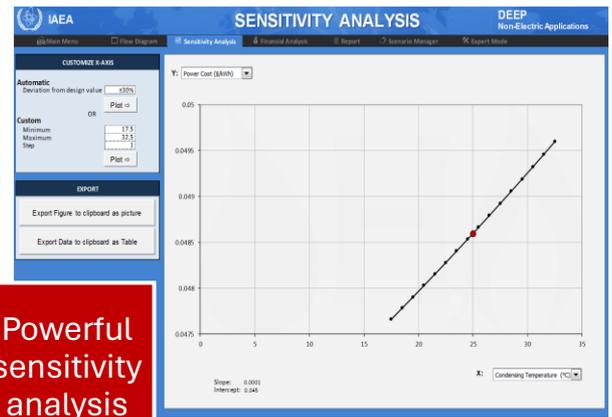
DEEP



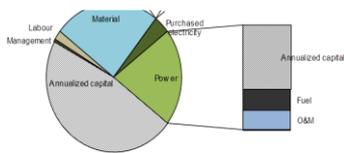
Modern User Interface



Bankable financial analysis



Powerful sensitivity analysis



Detailed Reports

Costs of Desalination Plant					
	MSF	RO	Total (M\$)	Specific (\$/m3 d)	Share
Construction Cost	-	247	247	1.177	80%
site loop cost	-	-	-	-	0%
Heat Source	-	-	-	-	0%
fall costs	-	-	16	77	5%
initial owners cost	-	12	12	59	4%
initial contingency cost	-	26	26	121	8%
initial Construction	-	7	7	34	2%
Capital Costs	-	293	309	1470	
Operating Capital Costs	-	-	22	-	
Total Capital Costs	-	-	-	-	0.31 \$/m3 d



Versatile scenario Manager

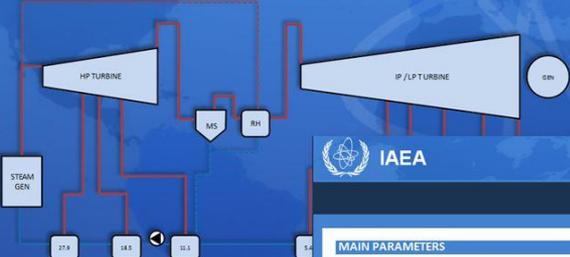
DE-TOP

models the steam power cycle of different WCRs coupled with nonelectrical applications



IAEA

DE-TOP
Desalination Thermodynamic Optimization Program



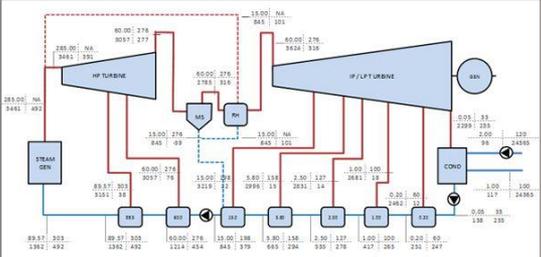
DE-TOP POWER AND DESALINATION Non-Electric Applications

Power plant simulation | Coupling configuration | Home

MAIN PARAMETERS	DUAL PURPOSE	SINGLE PURPOSE
Gross Efficiency	49.9%	49.9%
Net Efficiency	47.4%	47.4%
THERMAL UTILIZATION	47.4%	47.4%
Heat rate	7,201	7,201
HEAT RATE	7,598	7,598

PLANT PERFORMANCE PARAMETERS	DUAL PURPOSE	SINGLE PURPOSE
HEAT INPUT		
Heat input steam generator	1,032,750	1,032,750
Heat input reheater (Nuclear)	265	265
Heat input reheater (fossil)		
GROSS POWER OUTPUT	515.1	515.1
High pressure turbine output	154.2	154.2
Low pressure turbine output	371.4	371.4
Total Mechanical Output	525.6	525.6
AUXILIARY LOADS		
Feedwater pump	12.1	12.1
Condensate water pump	0.4	0.4
Cooling water pump	2.9	2.9
Other auxiliary loads	10.4	10.4
NET OUTPUT	489.3	489.3
HEAT REJECTED CONDENSER	507	507

MASS BALANCE	DUAL PURPOSE	SINGLE PURPOSE
LIVE STEAM FLOW		
Live steam to reheater	101.4	101.4
Steam inlet to High Pressure Turbine	390.6	390.6
High Pressure turbine exhaust	277.2	277.2
Moisture separator condensate	(39.0)	(39.0)
Steam inlet to Low Pressure turbine	316.2	316.2
Low Pressure turbine exhaust	234.7	234.7



DESALINATION TECHNOLOGY	MED TVC	WATER PRODUCTION
Max brine Temperature	115 °C	0 m3/day
TDS	20 ppm	
GOR	51.2 [-]	
Number of Stages	32 [-]	TOTAL POWER REQUIREMENTS
Cooling water temperature	23 °C	
DESALINATION PLANT CONSUMPTION		6.1 MW(e)
Heat to desalination	-	POWER LOST RATIO
Power lost due to extraction	-	
Desal. electric cons.	-	
Total specific cons.	6.12 kWh(e)/m3	
INTERMEDIATE LOOP		#DIV/0!
IL hot temperature	125.5 °C	
IL condenser return temp	117.5 °C	
IL mass flow	-	
IL pumping power	-	

Desalination Thermodynamic Optimization

DE-TOP

COGENERATION PLANT

Net power output [MW(e)]	130
Reference plant net output	132
Var.	-1%
Water production [m ³ /d]	4,642
Cogeneration plant eff.	33.1%
Reference plant efficiency	30.4%
Var.	9%

DESALINATION PLANT

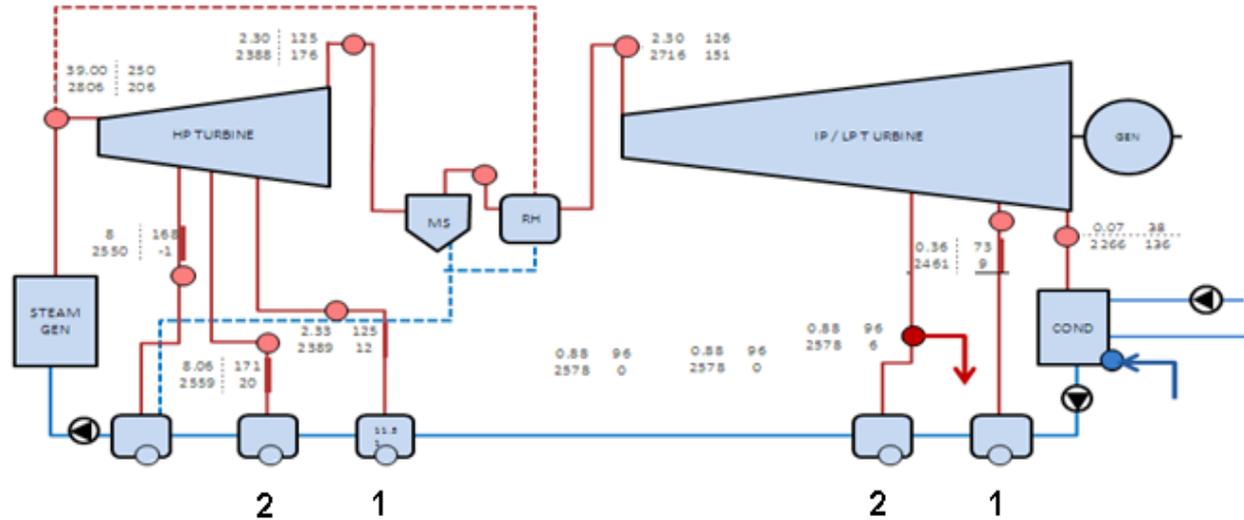
Plant specifications	
Desalination technology	MED
Max brine Temperature [°C]	68
Number of effects [-]	12
GOR [-]	9.6
Energy use	
Heat to desalination [MW(th)]	13.1
Power lost due to extract [MW(e)]	1.7
Desal. electric cons. [MW(e)]	0.3
Int. Loop electric cons. [MW(e)]	0.0
Equiv. specific cons. [KWh(e)/m ³]	10.36

COUPLING OPTIMIZATION

Power lost ratio	12.9%
Optimize steam extraction flows for:	
Current size	Design size

Modify Desalination parameters

Parameters



CHANGE LEGEND

P [bar]	T [°C]
h [kJ/kg]	m [kg/s]

Reset

SELECT STEAM EXTRACTION PARAMETERS



Heat supply
13 MW(th)
Target: 4 MW(th)

Temp steam
96 °C
Min Required: 78.5 °C

Steam at 0.88 bar, 96 °C:
Select extraction clicking a red point
Select extraction clicking a red point

kg/s 6.0

HEEP

Evaluates the economics of the most promising processes for hydrogen production

The screenshot displays the HEEP software interface with several sections:

- Finance Details:** Includes fields for Use "Real" rates, Discount rate (5%), Inflation rate (1%), Equity (%), Debt (%), Borrowing interest (%), Tax Rate (%), and Depreciation period (yrs).
- Chronological details (Years):** Shows Construction (5) and Operating (40) years.
- Facilities to be considered for evaluation:** Checkboxes for Nuclear Power Plant, Hydrogen generation, Hydrogen storage, and Hydrogen transportation.
- Plant Selection:** Lists nuclear plants (APWR1117, APWR360), hydrogen generation plants (SCWR-CuCl, SI-GTHTR300C), H2 storage files (CG), and H2 transportation files (Pipe500, Truck200).
- Parameter Tables:**

Parameter	Value	Add. data
Thermal rating (MWh/unit)	3385	Edit
Heat for H2 plant (MWh/unit)	0	Edit
Electricity rating (MWe/unit)	1117.05	Edit
Number of units	2	Edit
Initial fuel load (kg/unit)	75000	Edit
Annual fuel feed (kg/unit)	25000	Edit
Overnight Capital cost(USD/unit)	5.96E+9	Edit
Capital cost fraction for electricity generating infrastructure (%)	10	Edit
Fuel cost (USD/kg)	1260	Edit
O&M cost (% of capital cost)	1.7	Edit
Decommissioning cost (% of capital cost)*	2.8	Edit

Parameter	Value	Add. data
H2 generation per unit (kg/yr)	2.52E+08	Edit
Heat consumption (MWh/unit)	0	Edit
Electricity required (MWe/unit)	1438	Edit
Number of units	1	Edit
Overnight Capital cost(USD/unit)	8.45E+8	Edit
Energy usage cost# (USD)	0.00E+0	Edit
Other O&M cost(% of capital)	4	Edit
Decommissioning cost (% of capital cost)	10	Edit

Parameter	Value	Add. data
Storage capacity (kg)	4.83E+6	Edit
Compressor cooling water (Lit/hr)	1.50E+6	Edit
Electricity required		Edit
Overnight Capital cost		Edit
Compressor		Edit
Other		Edit
Decommissioning		Edit

Parameter	Value	Add. data
Distance for transport (km)	200	Edit
Overnight Capital cost (USD)	1.92E+8	Edit
- HEEP Results:** A pie chart showing the cost breakdown:
 - Debt: 0.02USD (32.43%)
 - Equity: 0.26USD (42.28%)
 - O&M: 0.01USD (16.85%)
 - Consumables: 0USD (0%)
 - Decommissioning: 0.001USD (2.38%)
 - Fuel: 0.004USD (6%)
- Hydrogen Economic Evaluation Programme:** A title card for the IAEA International Atomic Energy Agency, including contact information for Dr. I. Khamis and the software developer BARC.
- Currency settings:** A section for selecting currency (USD, EURO, INR) and conversion rates.
- Navigation:** Buttons for "Build new case for evaluation", "Quit", "Read existing case", and "Help (?)".

Hydrogen Economic Evaluation Programme

HEEP

HEEP

View Main Page Additional inputs Help Exit

Finance Details Help (?)

Use "Real" rates

Discount rate: 5 % Equity: Debt (%) (%) Borrowing interest (%) Tax Rate (%) Depreciation period (yrs)

Inflation rate: 1 % 70 30 10 10 20

Chronological details (Years) Help (?)

Construction: 5 Operating: 40

View/Edit Additional Inputs

Go Back Estimate hydrogen cost

Update and store Case

Facilities to be considered for evaluation

Nuclear Power Plant Hydrogen generation Hydrogen storage Hydrogen transportation

Nuclear Power Plant Details Help (?)

Use library utility Read from library Create new data Update NPP Database

List of nuclear plant files in the library

APWR
HTPK600

Hydrogen Generation Details Help (?)

Use library utility Read from library Create new data Update H2GP Database

List of Hydrogen plant files in the library

SI216K
SIPBR200

Hydrogen Storage Details Help (?)

Use library utility

H2 Storage Method

Compressed Gas Liquefaction

Hydrogen Transportation Details Help (?)

Use library utility

Type of H2 Transportation

Pipeline Vehicle

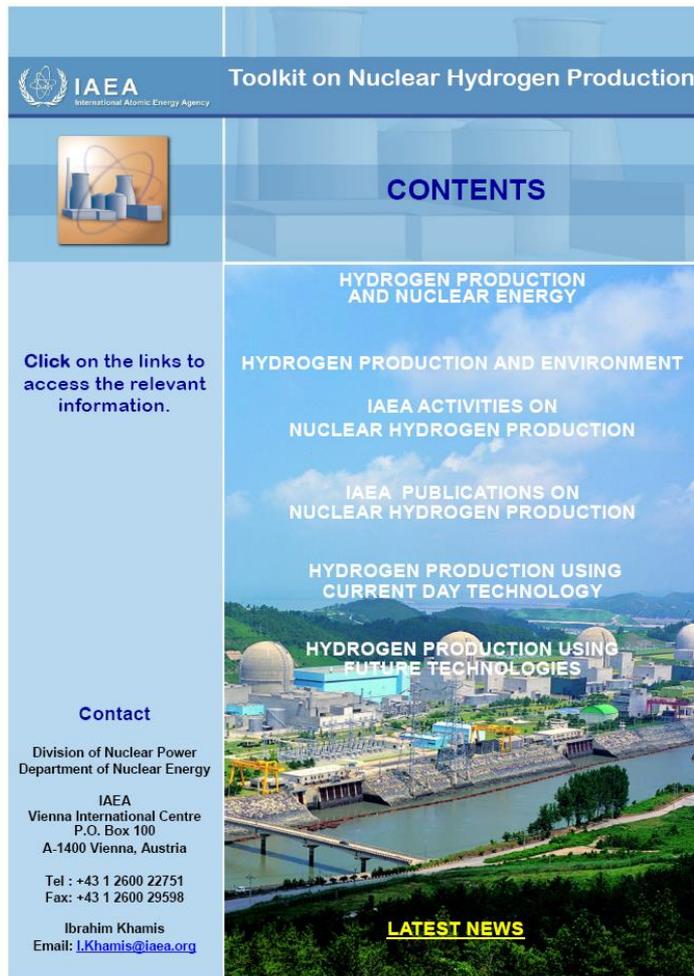
Parameter	Value	Add. data
NPP	HTGR	600 Edit
		540 Edit
	PWR	100000 Edit
	PMR	4.77E+8 Edit
Fuel cost (USD/kg)	250 Edit	
O&M cost (% of capital cost)	2.07 Edit	
Decommissioning cost (% of capital cost)*	10 Edit	

Parameter	Value	Add. input
H₂ Generation	CE	1.94E+8 Edit
	S-I	945 Edit
	HyS	1 Edit
	HTSE	5.46 Edit
	CuCl	10 Edit

Parameter	Value	Add. data
H₂ Storage	CG	1.4E+6 Edit
	LIQ	2.8E+6 Edit
	MH	3.65E+4 Edit
		0.6E+8 Edit
Storage		
Compre		
Electric		
Capital		
Compre		
Other O		
Decommissioning cost (% of capital cost)	0 Edit	

Parameter	Value	Add. data
Transportation	Pipelines	2.95E+8 Edit
	Trucks	

Nuclear Hydrogen Production Toolkit - NPTDS



IAEA
International Atomic Energy Agency

Toolkit on Nuclear Hydrogen Production

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- HYDROGEN PRODUCTION AND NUCLEAR ENERGY
- HYDROGEN PRODUCTION AND ENVIRONMENT
 - IAEA ACTIVITIES ON NUCLEAR HYDROGEN PRODUCTION
 - IAEA PUBLICATIONS ON NUCLEAR HYDROGEN PRODUCTION
- HYDROGEN PRODUCTION USING CURRENT DAY TECHNOLOGY
- HYDROGEN PRODUCTION USING FUTURE TECHNOLOGIES

LATEST NEWS

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- Up-to-date information
- Link to IAEA tools
- Highlights of IAEA Publications
- News on IAEA Activities
- Newsletter on nuclear hydrogen production

Nuclear Desalination Toolkit - NPTDS

- Up-to-date information
- Link to IAEA tools
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- Newsletter on nuclear desalination

IAEA
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Toolkit on Nuclear Desalination

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Click on the links to access the relevant information.

EVALUATING OPTIONS FOR DESALINATION USING NUCLEAR ENERGY

IAEA TOOLS ON NUCLEAR DESALINATION (DEEP & DE-TOP)

IAEA PUBLICATIONS ON NUCLEAR DESALINATION [New Releases!](#)

IAEA ACTIVITIES ON NUCLEAR DESALINATION [Updates!](#)

TECHNICAL WORKING GROUP TWG-ND

LAUNCHING NUCLEAR DESALINATION PROGRAMME

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Thank you!