Role of nuclear cogeneration in a low carbon energy future

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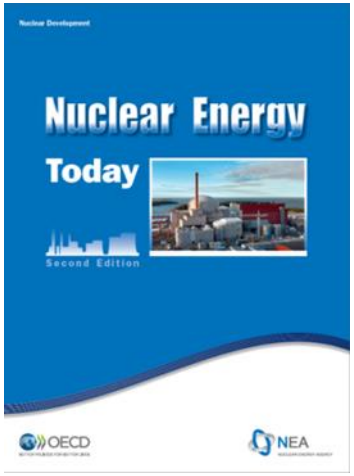
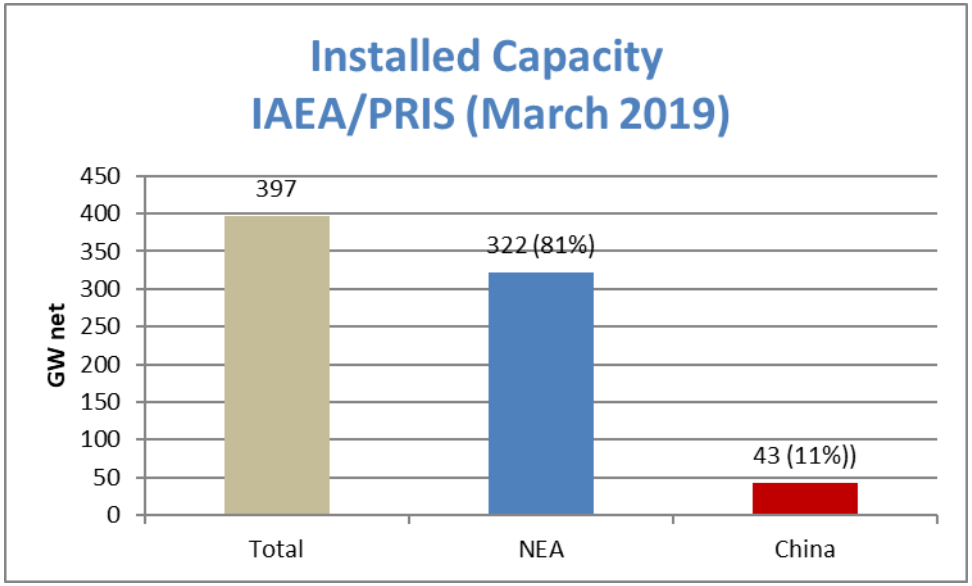
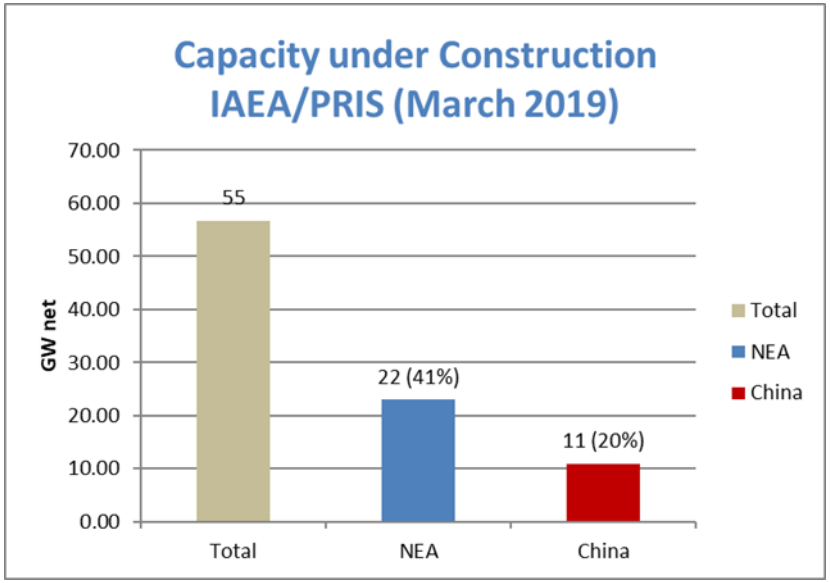
24 September 2019, Warsaw, Poland



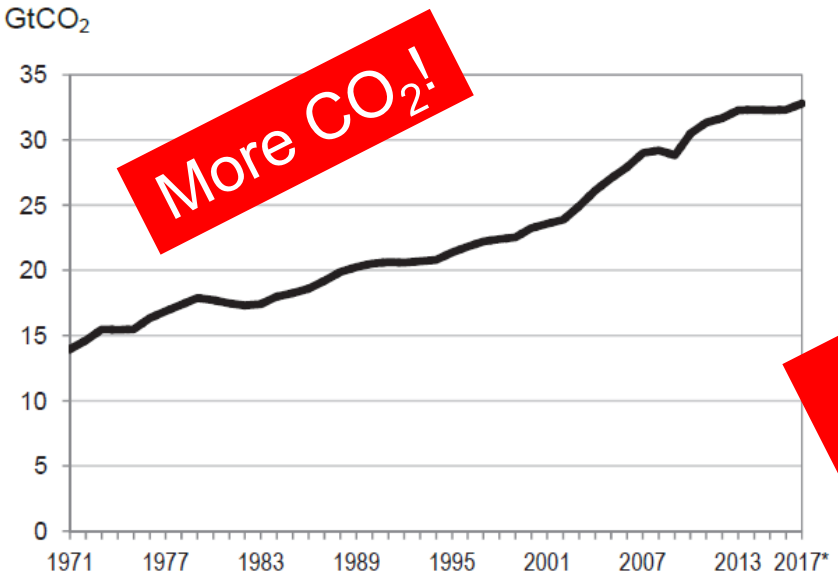
33 members including two "new comers": Poland (planning) and Turkey (building)





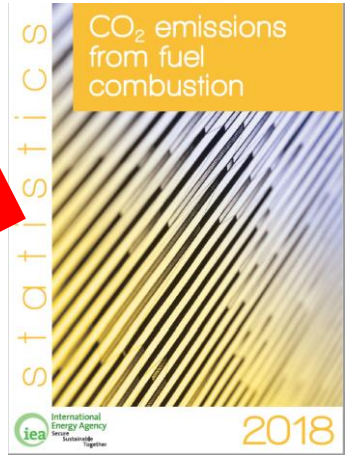
81% of world installed capacity… but **41%** of capacity under construction

CO2 emissions global, per fuel & per sector

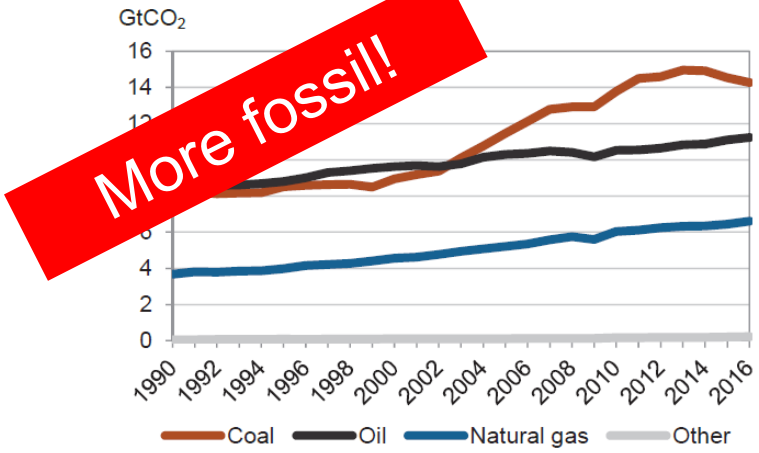


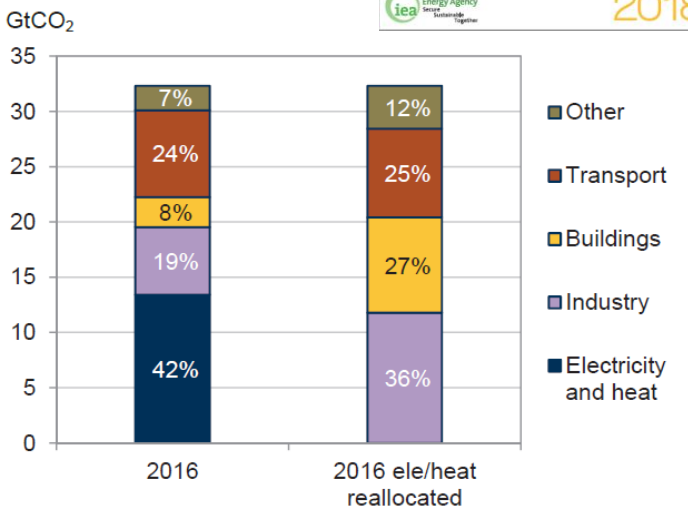
More CO_2!

Industry largest emitter!



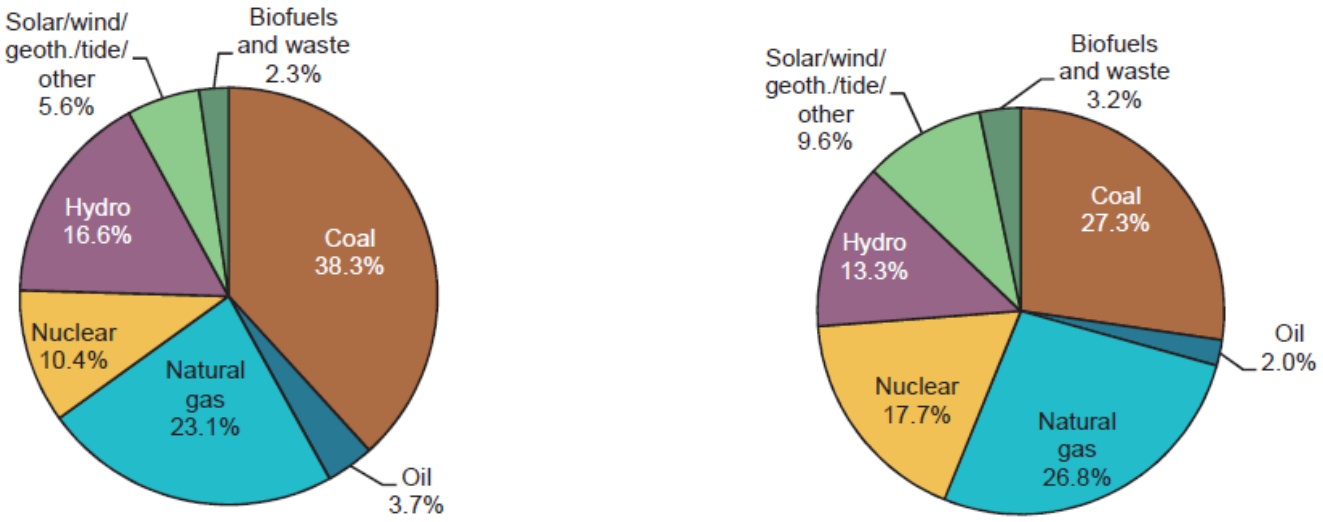
More fossil!





World CO2 emissions from fuel combustion by sector in 2016

Electricity Generation by Source (%), World (left) and OECD (right)



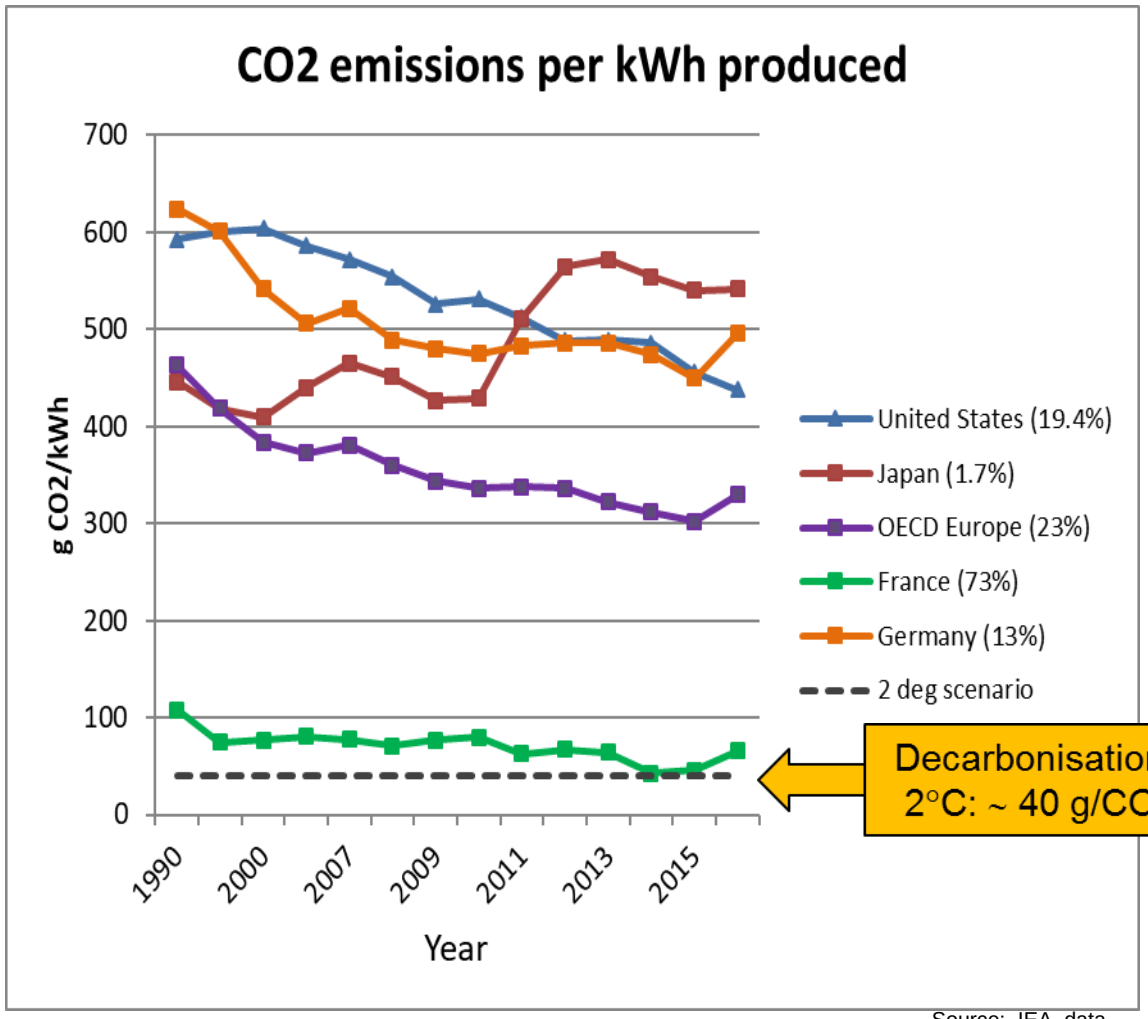
Source: 2016 data from IEA Electricity Information (2018)

Nuclear energy is:

- The largest source of low C electricity in OECD countries (**17.7%** > 13.3% hydro)
- The 2nd largest at world level behind hydro (**10.4%** < 16.6% hydro)
- In 2018/2019 – nuclear share ~10%

2/3 world electricity still produced from fossil fuel!

Electricity mix and carbon footprint (g CO_2 per kWh produced)



Source: IEA, data

Main trends:

- US: coal to gas switch, ↗ RES
- Japan: nuclear ↘↘↘, fossil ↗↗↗
- France: fossil ↘, RES ↗ and > 75% nuclear
- Germany: nuclear ↘↘, RES ↗↗ (but still a lot of coal and gas)

Decarbonisation policies based on promoting variable renewables (only) not effective?

CO2 is not the only problem! Air pollution is a greater health problem – and a shorter term driver for clean air technologies

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Nuclear scare stories are a gift to the truly lethal coal industry

Coal is a much nastier power source than the one we have chosen to fear in a deadly form of displacement activity

George Monbiot
The Guardian, Monday 16 December 2013 20.45 GMT
Jump to comments (883)

A man walks past a coal plant in Lingwu, northern China. 'Research suggested by Greenpeace suggests that a quarter of a million deaths a year could be avoided if coal power [in China] were shut down.' Photograph: Stringer/China/Reuters

Most of the afflictions wrongly attributed to nuclear power can rightly be attributed to coal. I was struck by this thought when I saw the graphics published by Greenpeace on Friday, showing the premature deaths caused by coal plants in China. The research it commissioned suggests that a quarter of a million deaths a year could be avoided if coal power there were shut down. Yes, a quarter of a million.

World Health Organization

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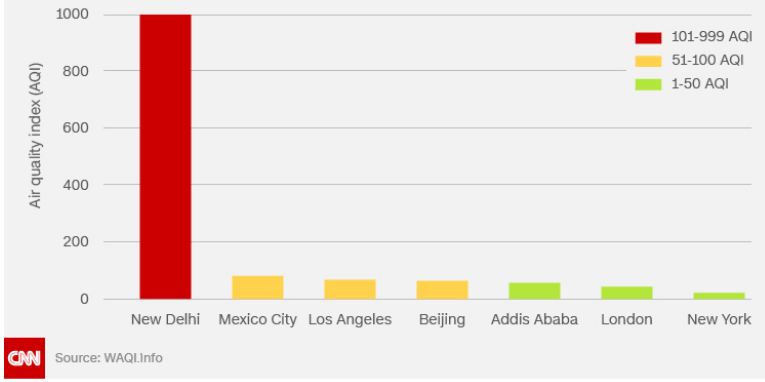
7 million premature deaths annually linked to air pollution

WHO:
7 million deaths/year due to air pollution (from cooking stoves, transport, and fossil-fuelled power and industrial plants

CNN Regions » New Delhi is the most polluted city on Earth right now

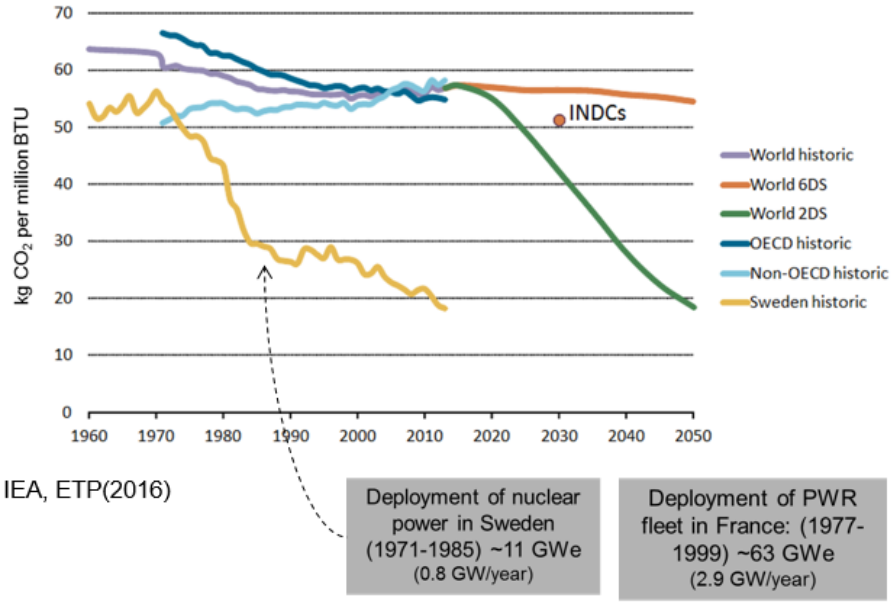
Air quality in world cities, November 7



CNN Source: WAQI.Info

Policies supporting decarbonisation?

- In many countries, policies are more often directed at achieving deployment targets of selected technologies than at GHG reduction targets.
  - "technological neutrality" of policies in question → effectiveness of current policies?
- Very few support mechanisms for nuclear (LTO or new build).
  - EU Parliament voted to exclude nuclear from "green credits"; EU Sustainable Finance taxonomy excluding nuclear, …
  - US 'Green New Deal' & nuclear
- But historically, nuclear has proven to be a **very effective technology** at reducing carbon intensity



IEA, ETP(2016)

Nuclear Reactors: Generations I to IV

Generation I

Early prototype reactors

- Shippingport
- Dresden
- Magnox

Generation II

Commercial power reactors

- PWRs
- BWRs
- CANDU

Bulk of today's nuclear fleet

Generation III

Advanced LWRs

- CANDU6

Generation III+

Evolutionary designs

- ABWR

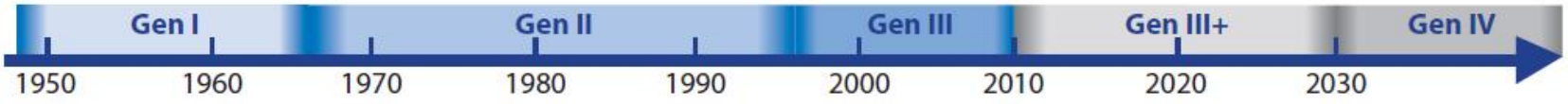
New build (essentially after Fukushima Daiichi accident)

Generation IV

Revolutionary designs

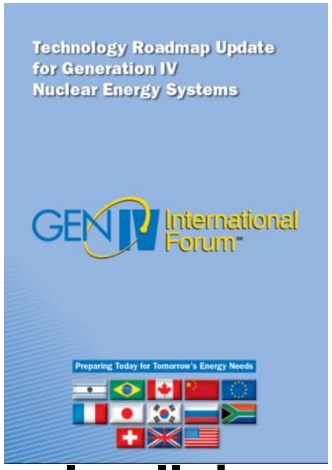
- Enhanced safety
- Minimisation of waste and better use of natural resources
- More economical
- Improved proliferation resistance and physical protection

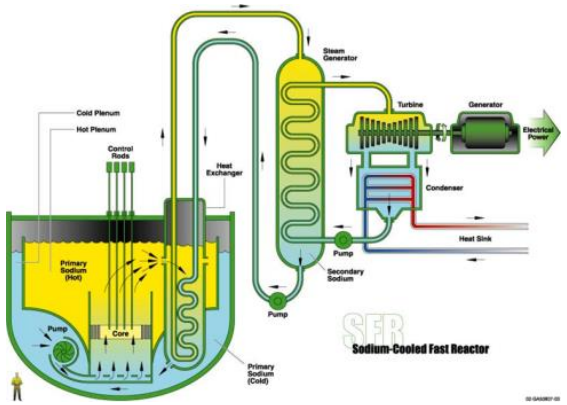
SMRs



Nuclear essentially to produce low-carbon electricity. Only a fraction of today's 450 reactors operate in cogeneration mode (essentially district heating) (1% of total nuclear heat used to produce non-el. applications)

Advanced Reactor Technologies: Gen IV





6 designs developed in an international collaborative framework

- "Fast Reactors":
  - Sodium-cooled fast reactor (SFR)
  - Lead-cooled fast reactor (LFR)
  - Gas-cooled fast reactor (GFR)
- "Thermal Reactors":
  - Super-critical water-cooled reactor (SCWR)
  - **Very high temperature reactor (VHTR)**
- "Thermal/Fast Reactor":
  - Molten Salt Reactor (MSR)

Goals

- Sustainability
- Economics
- Safety and Reliability
- Proliferation Resistance & Physical Protection

At R&D level today (GIF). Prototypes of some of these technologies planned over the period 2030/2040. **Commercialisation beyond 2040**, alongside further evolutions of LWRs. Earlier deployment of Gen IV SMRs possible, especially if addressing specific market needs.

Challenges: new build (Gen III/III+)

	Nuclear	Coal steam	Gas CCGT	Wind onshore and solar PV
Investment cost	Very High	Moderate	Low	Moderate - high
Construction time	4-10 years	4-5 years	2-3 years	0.5 – 2 years
Operational cost	Low	Low-moderate	Low-high	Very low
Operational characteristics	Mid to large scale production, baseload, limited flexibility	Baseload, moderate flexibility	Mid-load, high flexibility	Variable output, low load factor, seasonality (solar PV)
CO_2 emissions	Negligible	High- very high	Moderate	Negligible
Key risks	Regulatory (policy changes), public acceptance, market	Regulatory (CO_2 and pollution*), public acceptance, market	Regulatory (CO_2), market	Regulatory (policy changes)
Other features	Low sensitivity to fuel prices (stable production costs), contributes to security of energy supply	Sensitivity to fuel prices	Very high sensitivity to fuel prices, security of energy supply issues	Integration costs, need for back-up in absence of sufficient storage

* Around 18 000 people die each day as a result of air pollution from fossil fuel combustion (heating, transport, power) ((IEA, 2016)

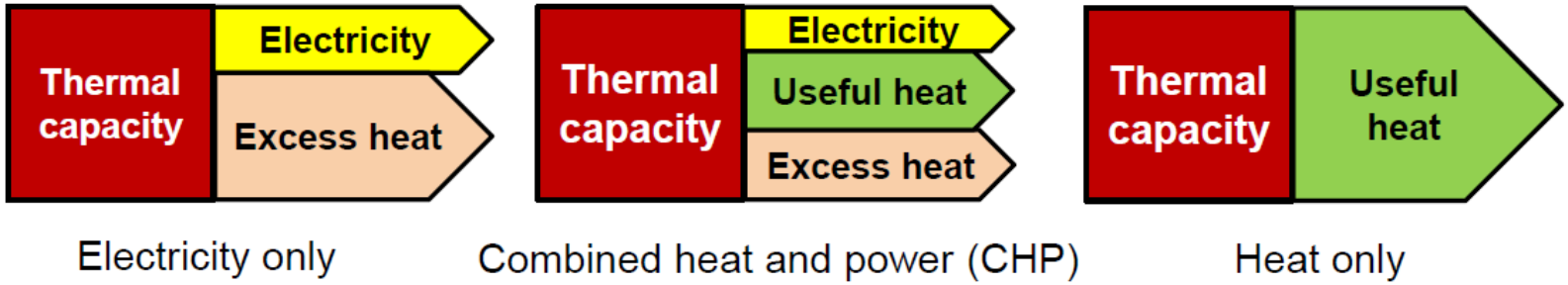
Source: IEA WEO (2014), NEA analysis

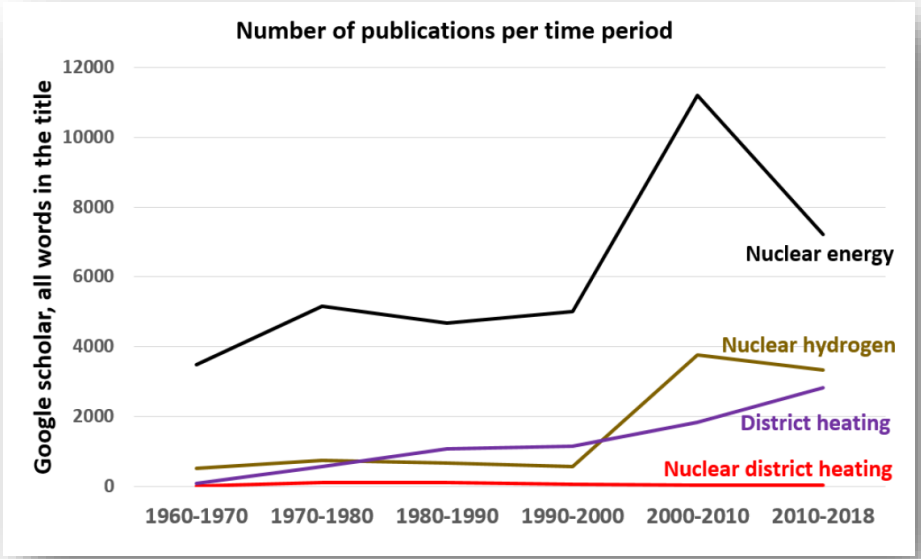
Why nuclear cogeneration?

- **Minimize heat losses** (2/3 heat wasted in current nuclear steam cycles)
- **Improve energy (fuel) efficiencies & economics**
- **Reduce CO_2 emissions and air pollution**
- **Enhance security of energy supply**
- **(non-nuclear) CHP since long applied in many industrial sectors**
- **Potential in 4 areas:** (i) desalination (ii) district heating in residential/commercial areas **(iii) industrial process heat (iv) fuel synthesis (e.g. Hydrogen)**

A growing interest in non-electric applications of nuclear energy

Any thermal plant can be operated in three archetypal modes:





From Martin LEURENT's PhD at CEA (2018)

Also discussed recently in IFNEC conference, Tokyo, Nov 2018!

PANEL SESSION 4: NUCLEAR TECHNOLOGY BEYOND ELECTRICITY GENERATION, HYBRID ENERGY SYSTEMS

Objectives: Increase awareness of the role of nuclear energy in non-electric applications, such as process heat, desalination, district heating and hydrogen production to help decarbonise sectors other than the power sector. The session will also discuss the integration of advanced reactors to provide both electricity and heat in future low-carbon energy systems (hybrid energy systems), and their potential to shift economic paradigms.

Moderator: Henri Paillere[33] – Deputy Head, Division of Nuclear Technology Development and Economics, Head of IFNEC Technical Secretariat, OECD/NEA

Speakers:

- Josef Sobolewski[38] – Director of the Department of Nuclear Energy at the Ministry of Energy, Poland
- Dohee Hahn[12] – Director of the Division of Nuclear Power at the International Atomic Energy Agency (IAEA)
- Shannon M. Bragg-Sitton[6] – Manager of the Systems Integration Department in the Nuclear Systems Design & Analysis Division at Idaho National Laboratory
- David Blee[4] – President & CEO of the US Nuclear Industry Council
- Juan Pablo Ordoñez[32] – Deputy Director General at INVAP Applied Research
- Akira Omoto[31] – Project professor at the Tokyo Institute of Technology, Japan
- Xingmin Liu[25] – Deputy Chief Engineer of Deep Pool Low Temperature Heating Reactor (DHR, Yanlong), China
- Zhi Gang[10] – State Power Investment Corporation Central Research Institute, China

https://www.ifnec.org/ifnec/jcms/g_11187/ifnec-nice-future-initiative-conference

District Heating

CASE DESCRIPTION : ACTUAL SITUATION

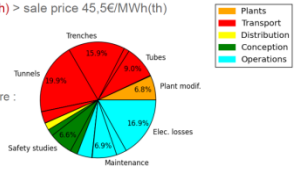
- Lyon agglomeration:
  - 1.5 M inhabitants
  - 9 DH networks delivering 1 TWh/a (15% of the population)
  - Price of heat ~70€/MWh
  - Mean carbon prod. 0,18 t_{CO2}/MWh

- Surrounded by 2
  - St Alban : 35
  - (Bugey : 25km

RESULTS : ECONOMIC INDICATORS

- NPV = +145M€
- LCOH = 48€/MWh(th) > sale price 45,5€/MWh(th)

LCOH structure :

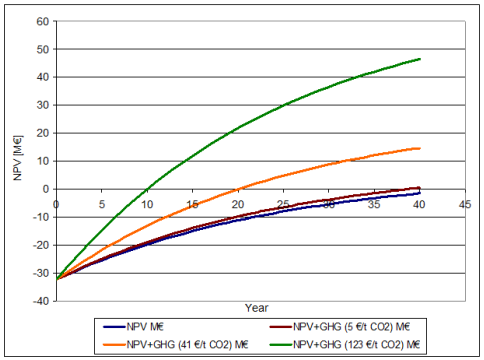


- IRR = 5.3%
- Payback period= 15 years
- Saved CO_2 emissions : 0,180 Mt_{CO2}

Nuclear heat transit pipeline to Szekszárd

NPV of investment reaches zero only in 38 years considering the present carbon emission price.

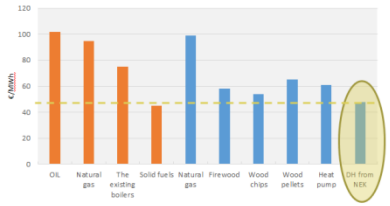
In order to shorten the payback period to 20 years, 41 €/t carbon emission price is sufficient



Time evolution of NPV for nuclear energy based district heating at Szekszárd with different carbon prices

Economic analysis - a comparison with the current situation

The cost of unit of thermal energy produced by individual heating systems in Krško and Brežice



Competitive prices!

Average SLO heat price:
- 66 EUR/MWh (2013)

- a high proportion of appliances running on Oil and Natural gas
- many devices are at the end of their life
- poor efficiencies of devices, high emission discharges into the environment
- DH is economically much cheaper than the (large) majority of existing and new systems

Nuclear DH in Poland

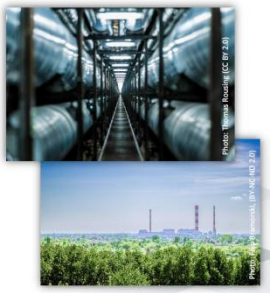
MINISTRY OF ENERGY

Current plans for nuclear CHP in Poland

CHP mode for NPP is suggested in the Polish Nuclear Power Programme document.

Ministry of Energy is considering this option due to:
- EU climate policy and environmental requirements
- Low level emission problem (requires general policy on DH expansion in urban areas, regardless of fuel type)

Decision will depend on final scheme of new cogeneration support mechanism which is currently being reviewed by the Ministry. However, the future of coal-based CHPs is unknown due to the BREF/BAT regulations.



swissnuclear
Nuclear Energy Section of swisselectric

Steam extraction from NPP Beznau

- Max. connection load 76 MW_{th}
- Length: 146 km (total 290 km)
- Heat sold: 150 GWh per year
- Grid connection to 11 communities
- Thermal power for 2600 connections (households, commerce and industry)
- Five backup heating plants (oil and waste)
- Set up end of 1970s to beginning of 1980s (oil crisis)

From NEA study to be published (2020)

Process Heat (chemical, oil, bio-refineries, H2)

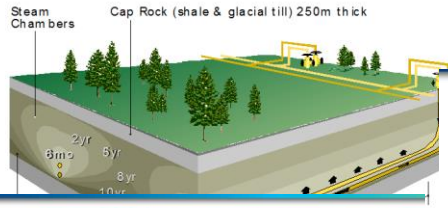
INDUSTRIAL HEAT DEMAN

- 13 LARGEST CHEMICAL PLANTS NEED 6500 MW OF HEAT AT T=400-550°C
- THEY USE 200 TJ / YEAR, EQUIVALENT TO BURNING OF >5 MLN T OF NATURAL GAS OR OIL
- REPLACING BY HTGR WOULD REDUCE CO_2 EMISSION BY 14-17 MLN T / YEAR

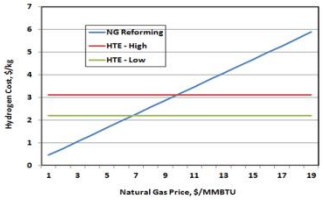
Plant	Boilers	MW
ZE PKN Orlen S.A.Plock	8	2140
Arcelor Mittal Poland S.A.	8	1273
Zaklady Azotowe "Pulawy" S.A.	5	850
Zaklady Azotowe ANWIL SA	3	580
Zaklady Chemiczne "Police" S.A.	8	566
Energetyka Dwory	5	538
International Paper - Kwidzyn	5	538
Grupa LOTOS S.A. Gdańsk	4	518
ZAK S.A. Kędzierzyn	6	474
Zakl. Azotowe w Tarnowie Moscicach S.A.	4	430
MICHELIN POLSKA S.A.	9	384
PCC Rokita SA	7	368
MONDI ŚWIECIE S.A.	3	313

Oil Sands Extraction - In Situ Steam Assisted Gravity Drainage

- Surface area disturbance <10%
- 90 % of water is recycled
- Energy



Economics of High Temperature Electrolysis for H2 Production with 1200 MWe SCWR



Considerations of Using Nuclear Steam for SAGD

Large reactors

- Current generation reactors may be used
- NP capacity far exceeds phased implementation of SAGD field (~70,000 bpd requiring ~ 800 MWth)
- Supply of steam over large distances (>10 km) is challenging
- Electric boilers instead of steam may be technically feasible; subject to economics

SMRs

- High pressure steam – possible to transport longer distances
- NP capacity (500 MWth) suitable for phased implementation of SAGD
- SMRs can be implemented in modules for increase in SAGD capacity

INTEGRATION OF NUCLEAR COGENERATION AND BIOREFENIRIES: ENVIRONEMENTAL BENEFITS

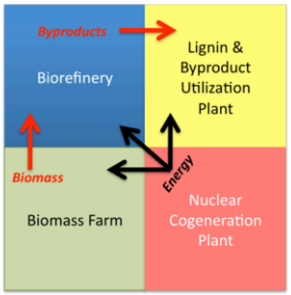


Figure 2: Integrated system of a Bio-Nuclear refinery, a Biomass farm and industries that can use the lignin to produce valuable good and services

Benefits from regional symbiosis between nuclear cogeneration plant, biorefinery and biofarm are threefold:

1) Higher efficiency of the overall system
2) Low carbon process heat for biofarms & biorefineries
3) Recovery of valuable bio-products (mainly lignin)

For a « typical sized » biochemical refinery, nuclear steam would replace the burning of 200 000 tons of wood-crop residues every year

This is equivalent to the saving of:
- 300 000 tCO2
- 1000 tCH4

Hydrogen System : Economics Analysis

Benefits Analysis

	Hydrogen Sales Price (KRW/kg)	IRR (%)	B/C	Hydrogen Production Cost (KRW/kg)	Payback Period (yr)
Without taxation	55,000	28.27	2.62	2442	5
With taxation	65,000	28.09	2.07		6

- **O_2 Benefits**
  - ✓ POSCO consumption of of O_2 : 3,504MNm³/yr at 40 KRW/m³
  - ✓ 4 x 600MWth NuH2-HPS production : 1,344 MNm3/yr
  - ✓ Benefits : 53.76 Billion KRW/yr.
- **CO_2 Emission Reduction**
  - ✓ CO_2 Emission for Carbon Monoxide Reduction = 1.86t per 1t of steel
  - ✓ CO_2 Emission Reduction by Hydrogen Reduction = 1.06t per 1t of steel (57%)
  - Further reduction expected if nuclear electricity is supplied.
  - ✓ 4.1 Mt/yr FINEX facilities = 4.35 Mt/yr
  - ✓ 40 Mt/yr in Korea = 42.4 Mt/yr
  - ✓ 4 x 600 MWth NuH2-HPS = 3.5 Mt/yr

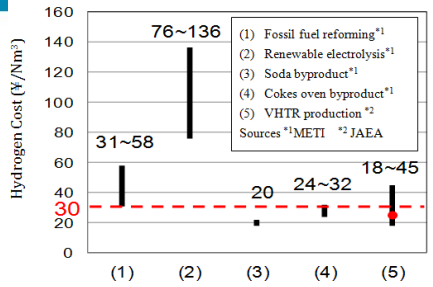


Figure 8. Competitiveness of VHTR hydrogen production cost

From NEA study to be published (2020)

Desalination

Economic Assessment

- **Plant Cost Estimates and Assumptions**
  - Equipment Lists and Price Quotation based on Single Unit SDA Design
  - Labor hours, rates are based on Korean project experience
  - Indirect costs based on estimated staffing plan, construction schedule and facility plan
  - Construction schedule based on 50 months – first concrete to O/L
  - Assumptions similar to AACE Class 4 estimates with uncertainty of 25%
- **LCOE and Water Cost results of $94.5~$111.3/MWh and $0.95~$1.02/m³ based on DEEP5.0 Analysis**
  - Two specific plant construction costs ($8,000~$10,000/kWe)
  - Financing of 45% Debt (@5.5%), 55% Equity (@10% Expected)
  - Plant Operation of 50 years (20 years for Desal. Units)

SMART System-integrated Modular Advanced ReacTor 24 KAERI 한국원자력연구원

Case study I: Desalination cogeneration with the use of GTHTR300C waste heat

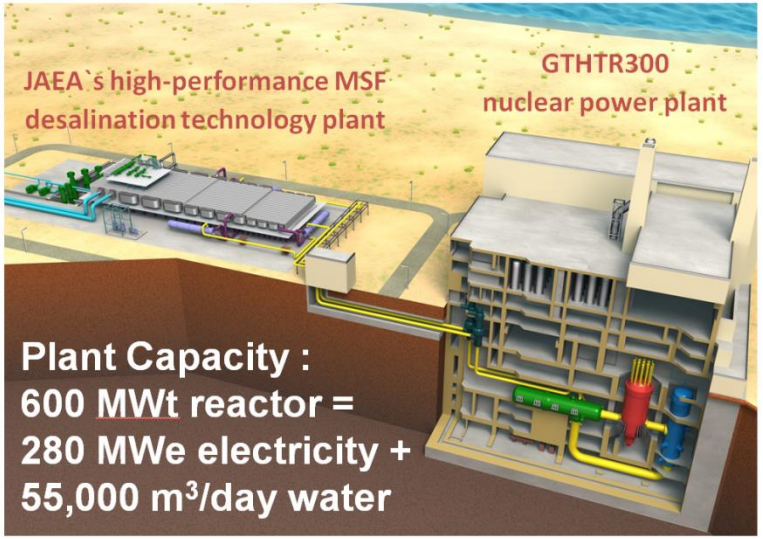


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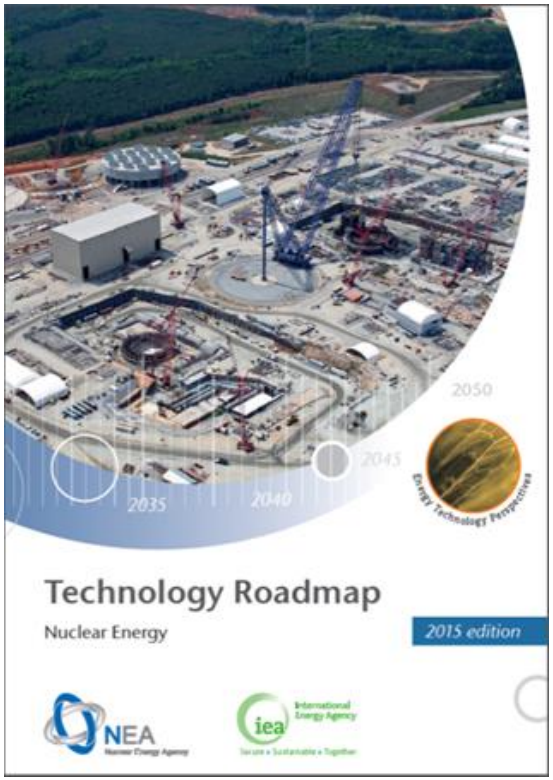
Table 3. Desalination cost comparison

Plant ->	CCGT desalination plant		GTHTR300C desalination plant
	Oil-fired	Gas-fired	
Capital (US$/m³)	0.29	0.29	0.39
Energy (US$/m³)			
Heat	1.65	0.67	0.04
Electricity	0.13	0.13	0.09
Operation (US$/m³)			
Consumables	0.02	0.02	0.02
O&M	0.03	0.03	0.03
Water cost (US$/m³)	**2.13**	**1.14**	**0.57**

From NEA study to be published (2020)

Application	Level of maturity	Possible new projects & recent activity	Challenges
District Heating	Demonstrated at industrial scale & currently operating (Russia, Switzerland, …)	Option for future new build in Finland or Poland, feasibility studies in France for coupling existing NPPs to DH systems	Differences between electricity & heat markets. Economic assessment.
Desalination	Tested at industrial scale in the past (BN-350) Small small scale applications in NPPs to supply fresh water to plant	Huge needs in the future (projects in the MENA region: Egypt, Jordan, Saudi Arabia)	Complexity and scale of investments in water infrastructures. Public acceptance? Long term?
High temperature process heat	Demonstrated at industrial scale for low temp. steam applications. R&D HTR and cogeneration	NHDD project in Korea “clean steel”, NGNP Alliance & EU’s NC2I/GEMINI+ collaboration, Poland HTR Programme	Business model (nuclear operator ≠ industrial application operator) Licensing, safety, public acceptance, Long term
Hydrogen production	Demonstrated at lab scale for thermochemical cycles (HTTR) and HTE	HTTR in Japan, on-going R&D (Gen IV), NEA reports on nuclear H2 production (2000-2009)	Hydrogen economy? Competition with electric mobility? Role in energy storage
Nuclear hybrid energy system	R&D on low carbon energy systems involving nuclear & variable renewables	Assessment of services provided by nuclear (electricity, storage, heat)	Economic assessment Long term prospects

IEA/NEA Nuclear Technology Roadmap on nuclear cogeneration



Nuclear energy technology development: Actions and milestones

Reactor technology

This Roadmap recommends the following actions:	*Proposed timeline*
Governments to recognise the value of long-term operation to maintain low-carbon generation capacity and security of energy supply, provided safety requirements are met. Clearer policies are needed to encourage operators to invest in both long-term operation and new build so as to replace retiring units.	2015-30
R&D in ageing of systems and materials is needed to support safe, long-term operation of existing nuclear power plants (NPPs) for 60 years operation or more.	Ongoing
Vendors to optimise Gen III designs to improve constructability and reduce costs. The learning rate from new build construction needs to be accelerated by rapidly integrating lessons learnt from FOAK projects (design optimisation, project management, supply chain, interactions with regulators) to ensure that NOAK plants are built on time and to budget.	Ongoing
To open up the market for small modular reactors (SMRs), governments and industry should work together to accelerate the development of SMR prototypes and the launch of construction projects (about 5 projects per design) needed to demonstrate the benefits of modular design and factory assembly.	2015-25
Governments to recognise the long-term benefits of developing Generation IV (Gen IV) systems in terms of resource utilisation and waste management, and support R&D and development of at least one or two Fast Breeder Reactor Gen IV prototypes.	2015-30
Public-private partnerships need to be put in place between governments and	

Public-private partnerships need to be put in place between governments and industry in order to develop demonstration projects for nuclear cogeneration in the area of desalination or hydrogen production.	2015-30

NEA's Nuclear Innovation 2050 "HTR cogeneration"

Towards a Joint Project to accelerate the demonstration of the coupling of an HTR and a non-electric application?

See presentation from Prof. Wrochna in this workshop

Flexibility, a key asset for tomorrow's nuclear energy systems

Expanded Flexibility Adds Value and Supports Reliability, Resilience

Attribute	Sub-Attribute	Benefits
Operational Flexibility	Maneuverability	Load following ✓
	Compatibility with Hybrid Energy Systems and Polygeneration	Economic operation with increasing penetration of intermittent generation, alternative missions ✓
	Diversified Fuel Use	Economics and security of fuel supply ✓
	Island Operation	System resiliency, remote power, micro-grid, emergency power applications ✓
Deployment Flexibility	Scalability	Ability to deploy at scale needed ✓
	Siting	Ability to deploy where needed ✓
	Constructability	Ability to deploy on schedule and on budget
Product Flexibility	Electricity	Reliable, dispatchable power supply ✓
	Process Heat	Reliable, dispatchable process heat supply ✓
	Radioisotopes	Unique or high demand isotopes supply

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From A. Sowder (EPRI), NEA workshop Advanced Reactors and Future Energy Market Needs (ARFEM), 4 Sept 2019, https://www.oecd-nea.org/download/nssnexus/WorkshopARFEM4September2019.html

Nuclear Innovation Clean Energy Future - NICE Future

CLEAN ENERGY MINISTERIAL
Advancing Clean Energy Together

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NUCLEAR INNOVATION: CLEAN ENERGY FUTURE (NICE FUTURE)
A CLEAN ENERGY MINISTERIAL INITIATIVE

Countries Launch a Nuclear Innovation Initiative under the Clean Energy Ministerial

24 May 2018

- Technology evaluations of innovative energy systems and uses
- Engagement of policy makers and stakeholders in future energy choices
- Valuation, market structure, and ability to finance
- Communicating nuclear energy's role in clean, integrated energy systems

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https://www.nice-future.org

Key factors for nuclear cogeneration success