Nuclear Energy for Decarbonization of Industry

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Summary

Nuclear in the Energy Mix

Envisaged Non-Electric Applications

Market and Economics

Potential Impact

Examples for Decarbonization in Industry

Outlook

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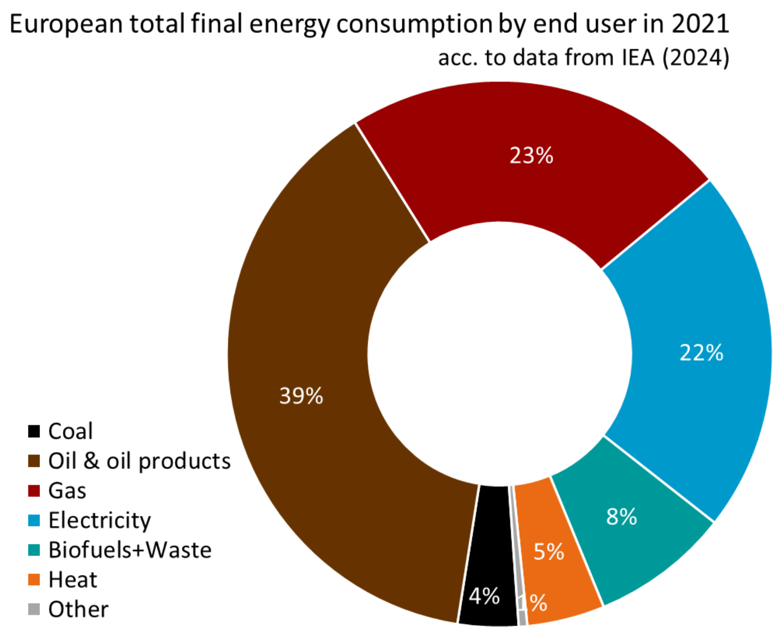
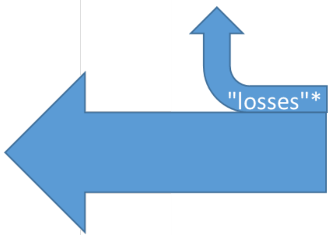
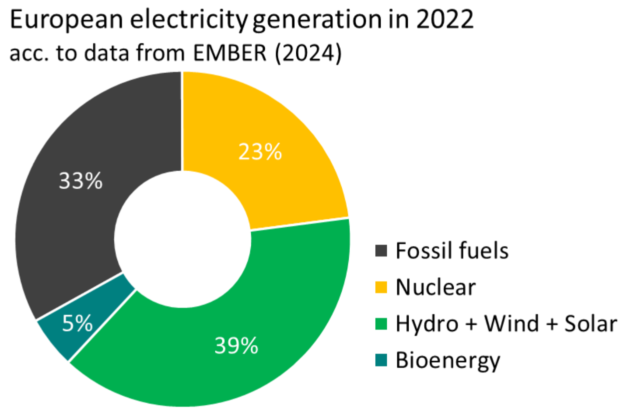
Nuclear in the European Energy Mix



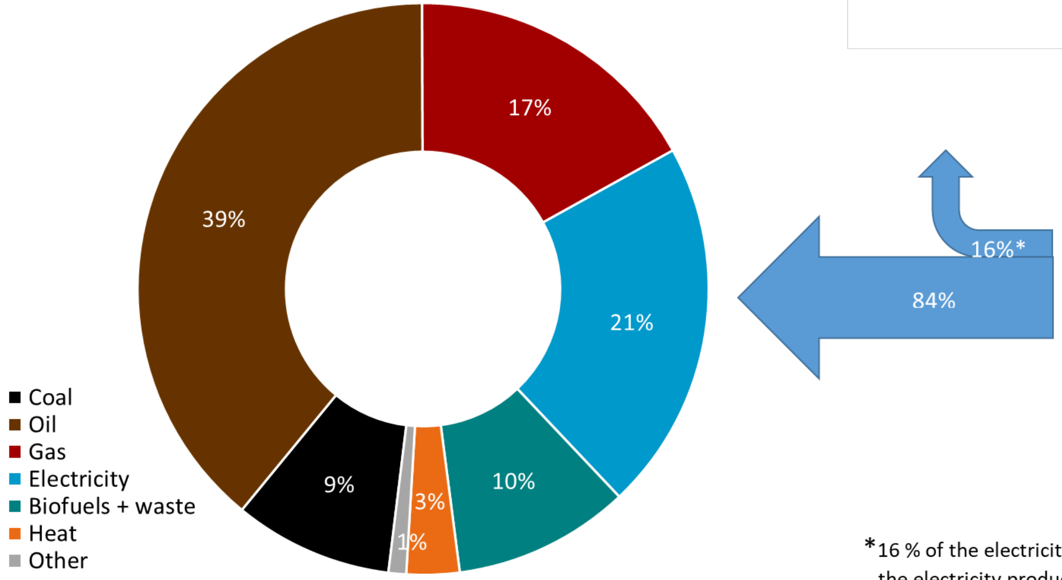




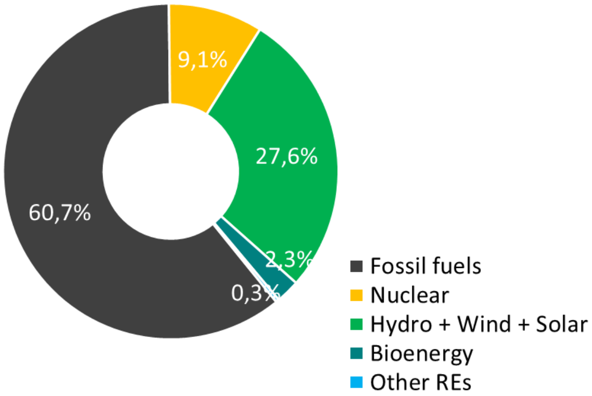
*A part of the electricity produced does not arrive at the end users, as the electricity producing industry needs a fraction for their own needs and there are losses during transport and distribution

Nuclear in the Global Energy Mix

World total final energy consumption by end users in 2021
acc. to data from IEA (2023)

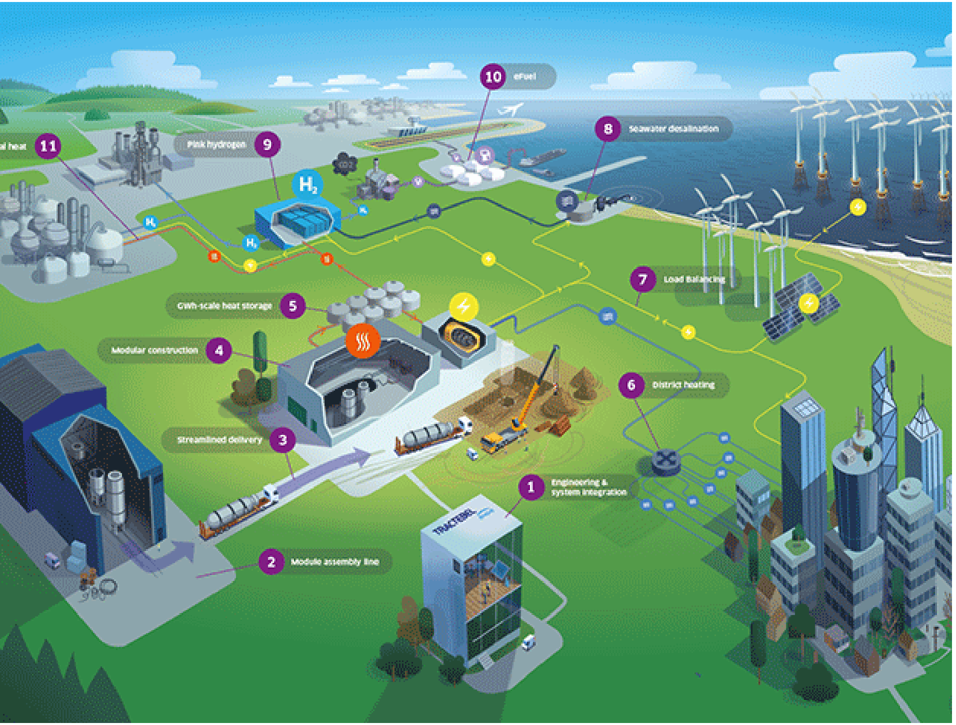


World Electricity generation in 2023
acc. to data from EMBER(2024)



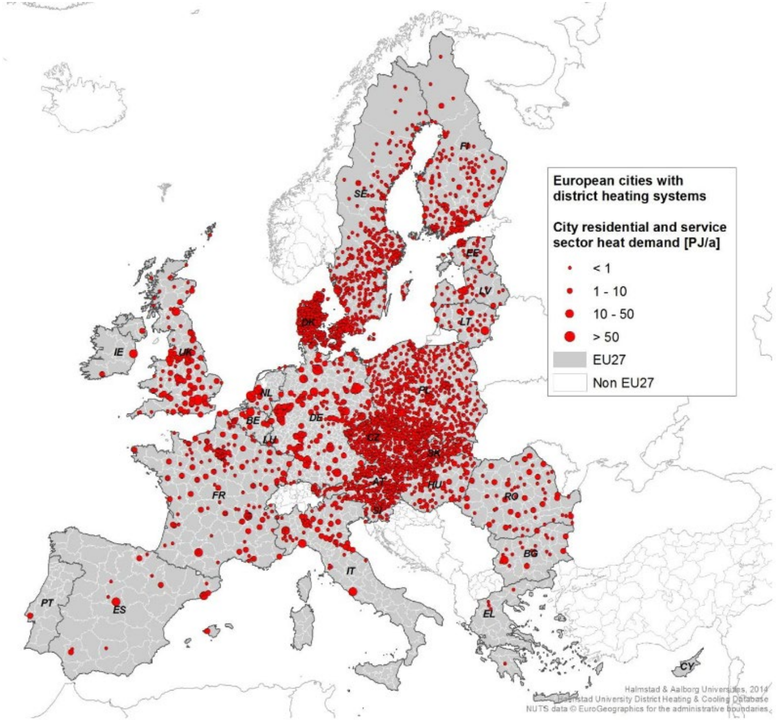
*16 % of the electricity produced do not arrive at the end users, as the electricity producing industry needs 9 % for their own needs and as 7 % are lost during transport and distribution

Envisaged Applications



Energy Hubs:
Multiple energy products,
integration with renewables
(heat, electricity, H_2, desalination, etc.)

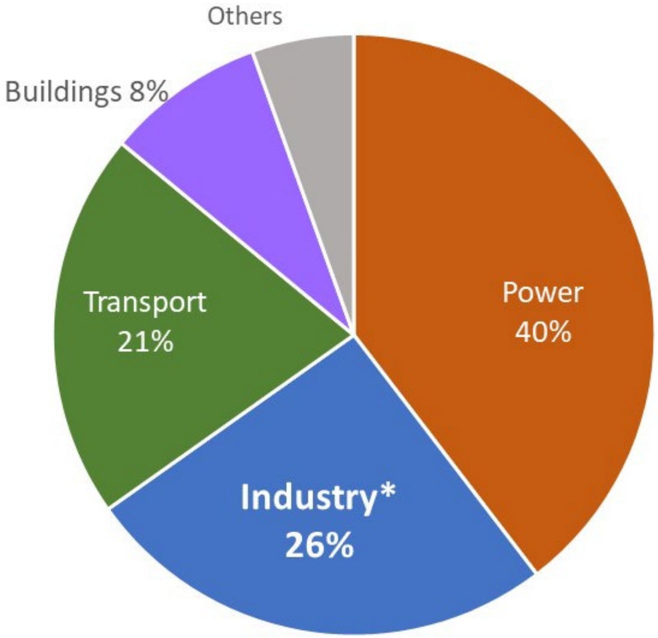
Envisaged Applications



District Heating:
3500 networks across Europe,
serving 60 million people,
75% fossil

Why Decarbonization of Industry?

Global energy-related CO_2 emissions by sector, 2020



* Emissions from industry sector include process emissions
Source IEA (2021)

Industry generates about ¼ of global energy-related CO_2 emissions

- ➔ **Decarbonization of power and transport alone would be insufficient**
- ➔ **Competitors are fossil fuels**
- ➔ **Few low-carbon alternatives commercially available so far**

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Market Studies and Economics

Very significant information compiled and analyzed by:

- IAEA TECDOCS, Technical Meetings etc.
- OECD/NEA publications
- German HTR Program (PNP for coal refining) in 1970-1989, especially after oil crises
- South Africa: Techno-economics of use of process heat from HTGR for CTL
- Europe: Nuclear Cogeneration Industrial Initiative

Focus here on (process heat, H_2, electricity):

- EU: SNETP/NC2I (MICANET, Europairs, ARCHER, NC2I-R, GEMINI+), TANDEM, NPHyCo, GEMINI 4.0
- US/Canada: NIA (Wyoming, Kentucky, Texas, oil sand recovery)
- China: electricity and process heat
- South Korea: process heat and H_2

Market Studies

Region	Plug-in market	Total market	GDP 2011 (approx.)
Europe	~ 800 TWh/y *(EUROPAIRS)*	~ 3,000 TWh/y *(EUROPAIRS)*	17,000 bn€ / 25% of world
USA	~ 1,100 TWh/y *(MPR Associates)*	~ 3,600 TWh/y *(MPR Associates)*	15,000 bn€ / 22% of world
Japan		*1,000 – 1,400 TWh/y (est.)*	5,900 bn€ / 8% of world
China		*1,200 – 1,700 TWh/y (est.)*	7,000 bn€ / 10% of world
India		*300 – 500 TWh/y (est.)*	2,000 bn€ / 3% of world
Russia		*300 – 500 TWh/y (est.)*	2,000 bn€ / 3% of world
World total	***3,000 – 5,000 TWh/y ~ 370 – 630 GWth***	***11,000 – 16,000 TWh/y***	**69,000 bn€**

Not a niche market, but space for several hundred reactors!

Source: Bredimas

Market Studies: Europe

EU projects:
MICANET, Europairs, NC2I-R, GEMINI+

NC2I
Nuclear Cogeneration Industrial Initiative

Drivers:
- Security of supply (oil crisis in 1970s, now vulnerable gas/oil imports)
- Price predictability and stability
- CO_2 and air quality: one 600 MWth HTGR can save 1 Mt/yr CO_2 if replacing natural gas and 1.8 Mt/yr if replacing coal (2022: 3138 Mt/yr)
- Re-industrialization ("carbon leakage" to SE Asia)
- Largest market: process steam < 600°C, “low-hanging fruit”
- Very significant H_2 market and existing pipelines, no need to wait for a “Hydrogen Economy” to justify alternative H_2 production at large scale

Market Studies: Europe

Hurdles:

- Industrial process heat: little noticed by decision makers and public
- Natural gas is relatively cheap and abundant – until recently
- No sufficiently stringent CO_2 cap
- High initial investment, slow return
- Unrealistically high investor expectations
- Power generation currently unattractive for investors (consequence of market liberalization. Excess generation capacity due to preferential feed-in of subsidized RES and keeping alive ageing fossil plants to balance RES variability)
- Need to fit in right window of industrial investment cycle

Which Industries can be decarbonized? Haber-Bosch Process for Ammonia production

source: linde-engineering.com

Example for a big industrial CO_2 emitter and energy consumer:

1. Steam Methane Reforming

$CH_4 + 2H_2O \rightarrow 3H_2 + CO_2$ endothermic 3-25 bar, 700-1000°C

pumping, compression, steam generation, heating, purification

2. Haber-Bosch Synthesis

$3H_2 + N_2 \rightarrow 2NH_3$ exothermic 200 bar, 400-500°C

air separation, compression, heating, cooling for liquefaction

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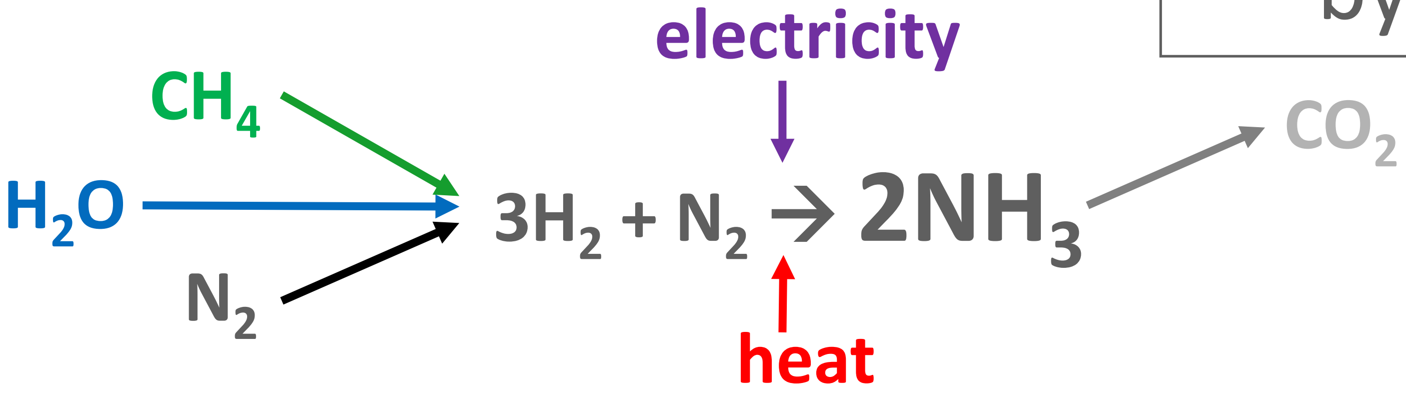
(Nuclear) Cogeneration makes sense

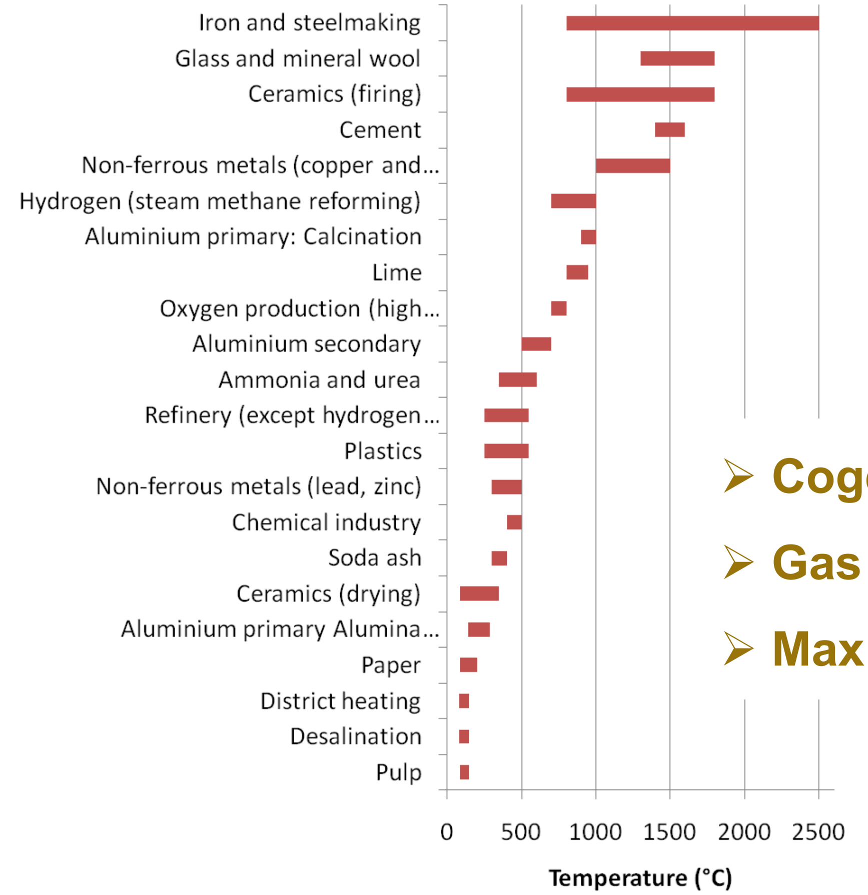
Replace SMR by SMR



Pathways to decarbonization:

- produce heat, steam, electricity for the processes with low-C energy
- produce H_2 to eliminate Steam Methane Reforming

From low-hanging fruit to hard to abate



NC2I Nuclear Cogeneration Industrial Initiative

- Cogeneration is a mature technology
- Gas is still the reference/competitor
- Max process temperature ~ 550°C

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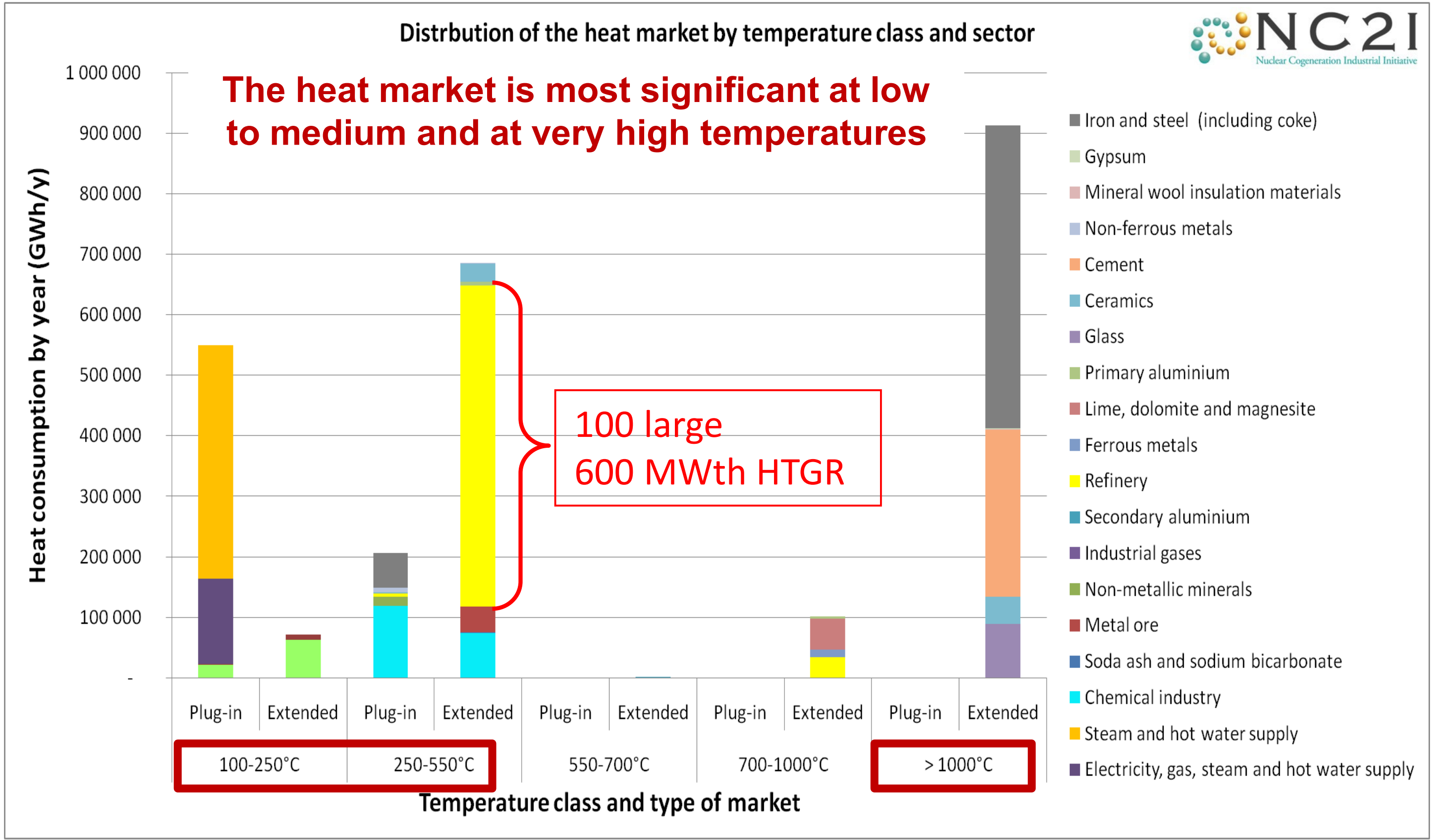
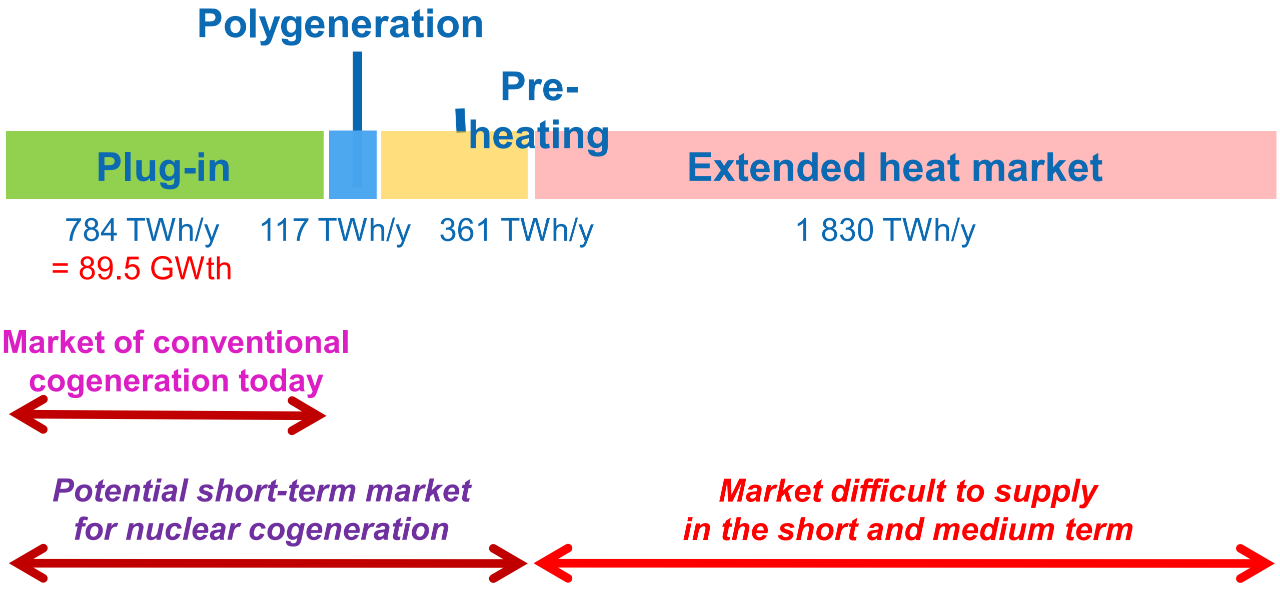
Distribution by Temperature/Sector



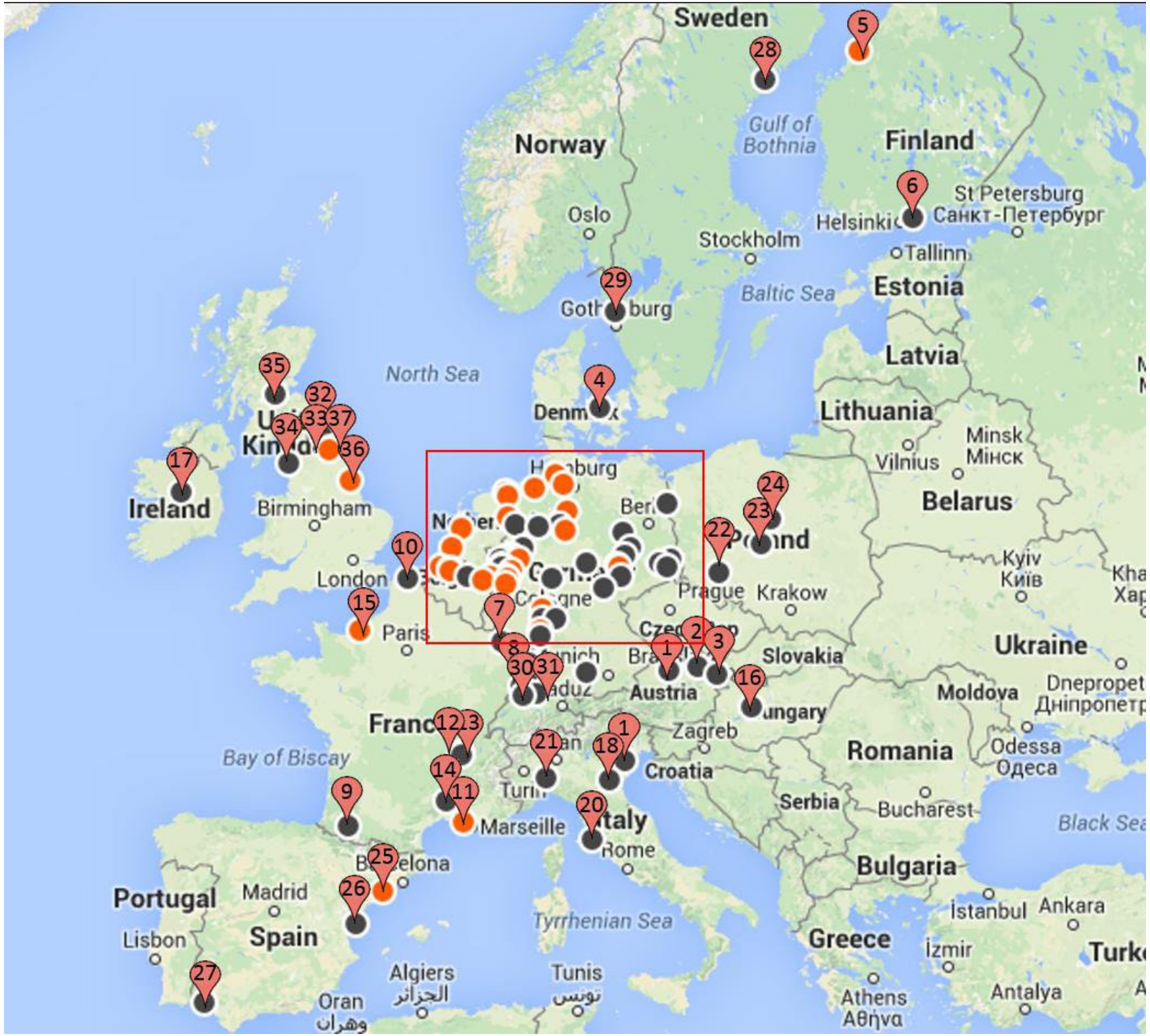
Market Size in EU28



Alexandre Bredimas, Market study on energy usage in European heat intensive industries, Deliverable D131, EUROPAIRS project, 27/05/2011.

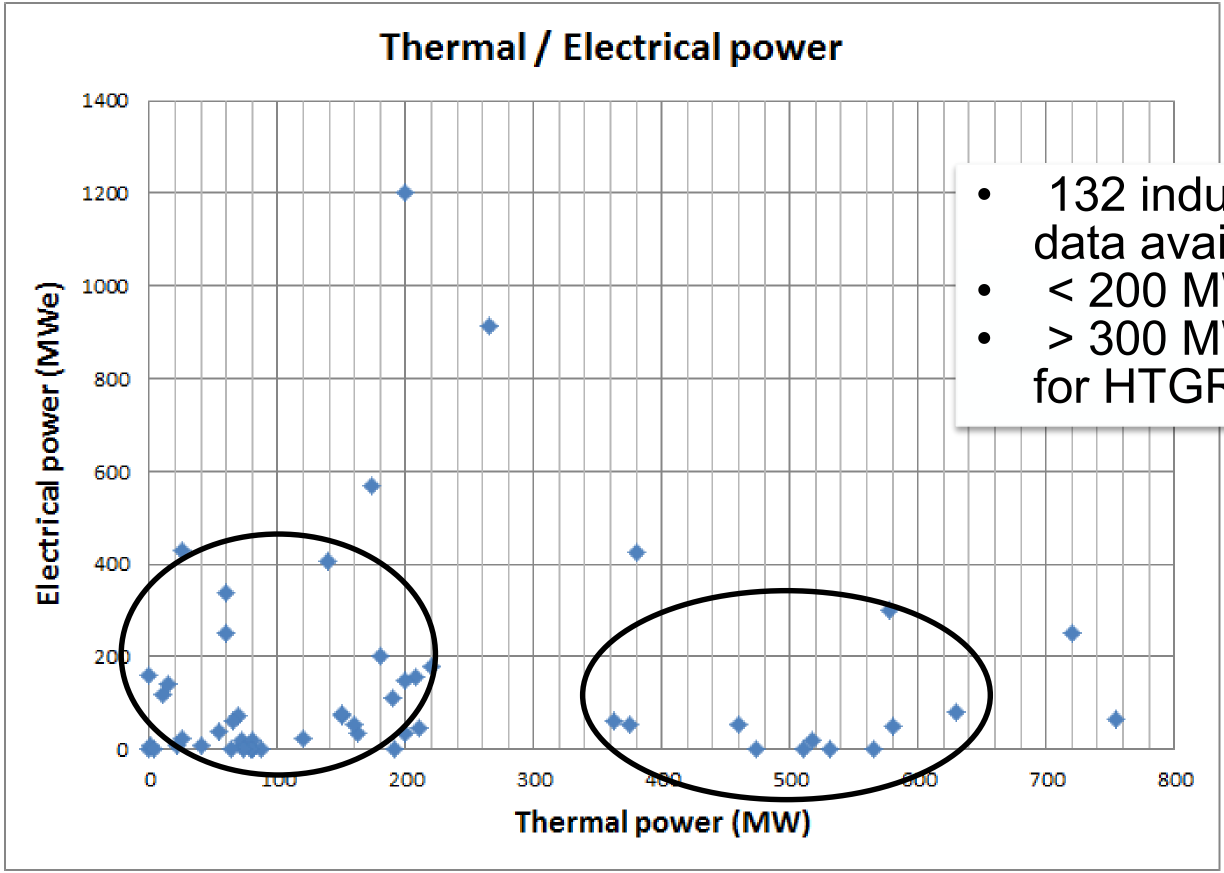
EU sites (NC2I-R)

- 132 chemical sites identified
- Concentration in Germany, Belgium and Netherlands
- Big demand also in France, UK



Nuclear Cogeneration Industrial Initiative

EU28 Site Mapping



- 132 industrial sites identified, data available for 57 sites
- < 200 MWth: mostly NG fired CHP
- > 300 MWth: market opportunities for HTGR at chemical plants

Potential Market

- The potential market is not the limit: room for 100s of nuclear cogen plants:
  - Very large confirmed **steam** market in most industrialized countries
  - **H_2** production as the initial driver of the VHTR is in the focus in countries with high natural gas prices and CO_2 taxes
- Heat, hydrogen, electricity and other energy products (e.g. compressed air, chilled water) are often consumed in combination on large industry complexes → cogeneration
- Local heat consumption is very often compatible with possible output from MMR or SMR
- The market is by far large enough to accommodate several different types and sizes of MMR and SMR
- In Europe, SNETP and its NC2I branch are supporting action towards development and deployment of nuclear cogeneration

NC2I
Nuclear Cogeneration Industrial Initiative

Potential Impact

source: www.nato.int

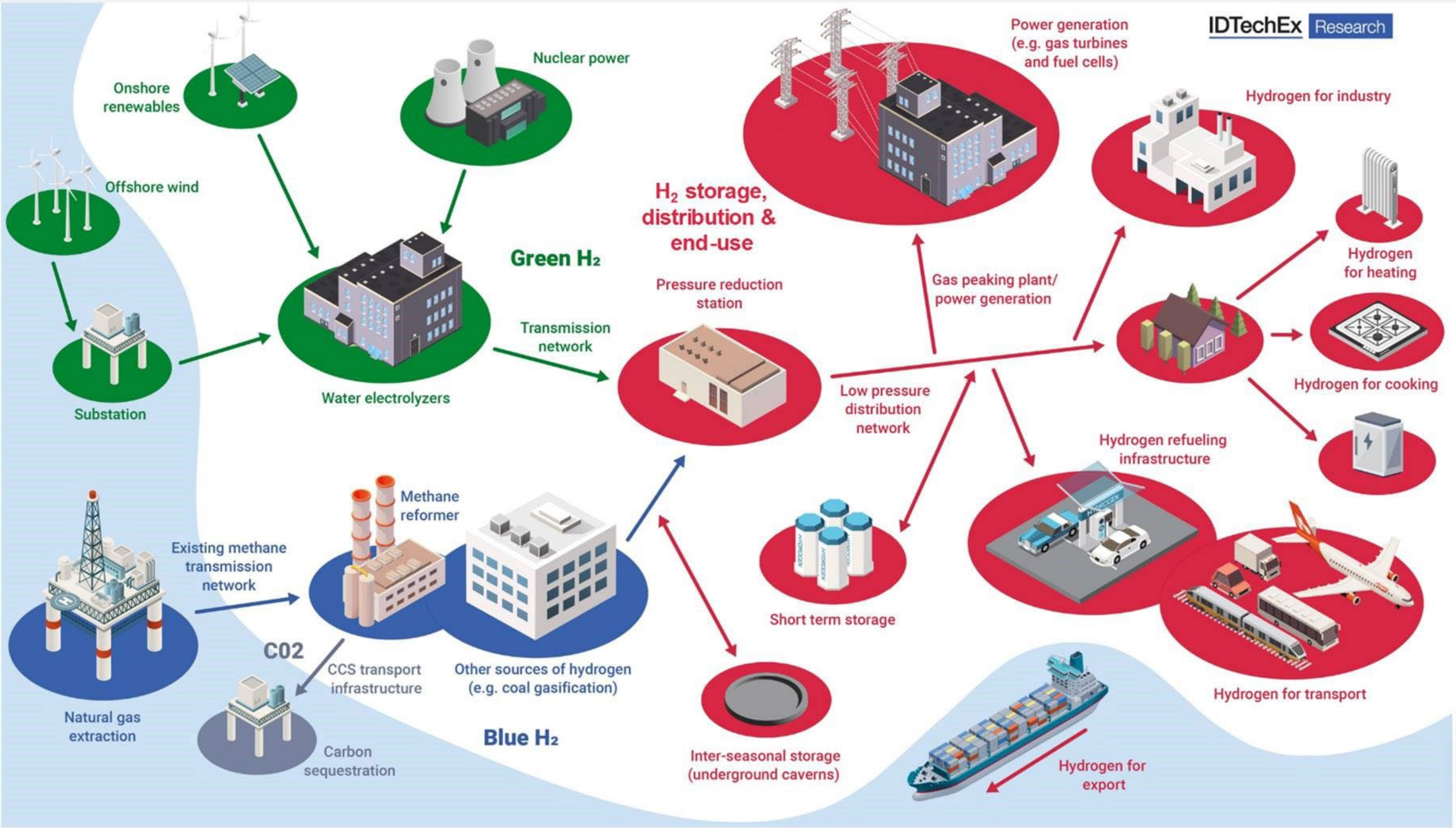
- Nuclear Cogeneration of Heat and Power is a known but little used technology: **750 reactor-years experience** (IAEA TECDOC)
- Certain markets, which would benefit most, pursue an anti-nuclear policy
- Several energy-intensive applications cannot be easily supplied with RES alone;
- Nuclear cogeneration can facilitate (technically and economically) energy system integration with RES;
- High **CO_2 savings** impact;
- EU does not have the luxury to choose between RES and nuclear, it needs both;
- Natural **gas is dominating the market**, gas prices are high and fickle, energy security aspects and emissions will gradually disqualify it as an economic competitor
- **Energy security** for this market is a strong driver in certain countries
- Acceleration of deployment needs **enhanced "certainty"** and reduced risk (financial, industrial, regulatory…) and a more favorable investment climate;
- If nuclear cogeneration takes off significantly, pressure on **uranium prices** will increase and breeding would become attractive earlier than at the end of the century;

H_2 market and outlook in EU

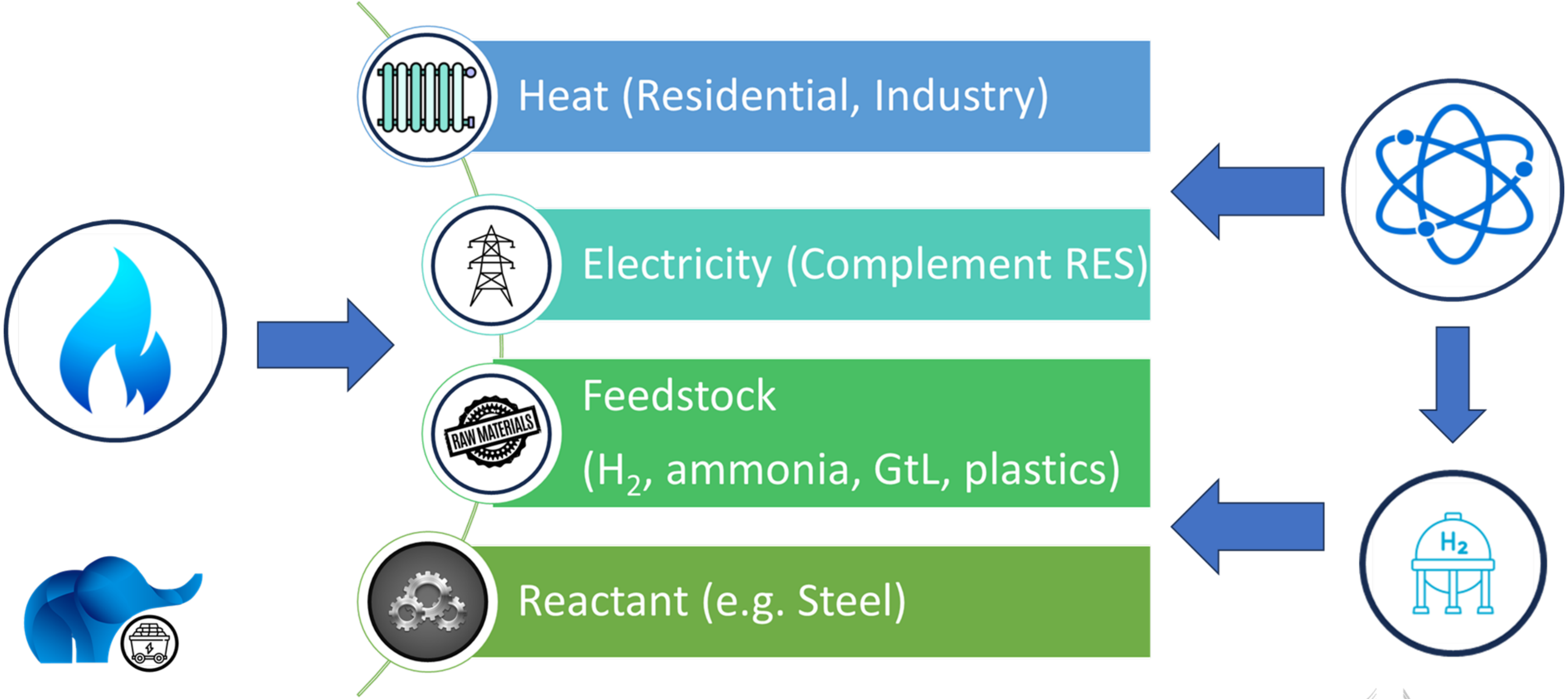
8.2 - 9.7 Mt/year mainly for

- fertilizers (ammonia)
- synthetic hydrocarbons from synthesis gas (syngas)
- metallurgy (reduction of ores and metal purification)
- electronics
- power generation (generator cooling)
- petrochemicals (crude oil refining)
- transportation (fuel cells or synthetic fuels)

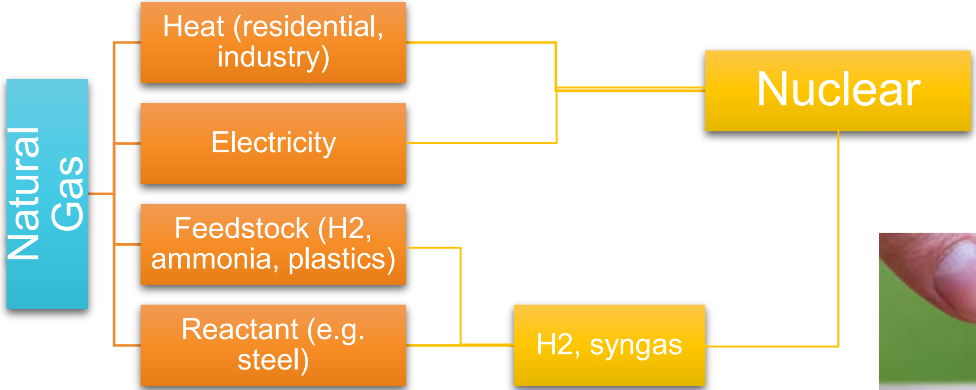
For decarbonization in industry, H_2 will be increasingly used not only as energy carrier (storage), but as reactant and as feedstock


IDTechEx Research
Onshore renewables
Nuclear power
Offshore wind
Substation
Water electrolyzers
Green H2
Transmission network
H2 storage, distribution & end-use
Pressure reduction station
Power generation (e.g. gas turbines and fuel cells)
Gas peaking plant/ power generation
Hydrogen for industry
Hydrogen for heating
Hydrogen for cooking
Low pressure distribution network
Hydrogen refueling infrastructure
Short term storage
Hydrogen for transport
Methane reformer
Existing methane transmission network
C02
CCS transport infrastructure
Other sources of hydrogen (e.g. coal gasification)
Natural gas extraction
Carbon sequestration
Blue H2
Inter-seasonal storage (underground caverns)
Hydrogen for export

How can Nuclear replace Natural Gas ?



Can nuclear replace natural gas?



Substitution of natural gas

- NG consumption in EU (2019) 16×10^{18} J/yr → 900 Mt/yr CO_2
- Equivalent hydrogen: 113 Mt/yr
- Using alkaline electrolysis, this would require a constant power of **574 GWe**

European Commission

H_2: Scale is the issue!

current nuclear capacity in EU-27: 104 GWe
current H_2 use: 9.7 Mt/yr

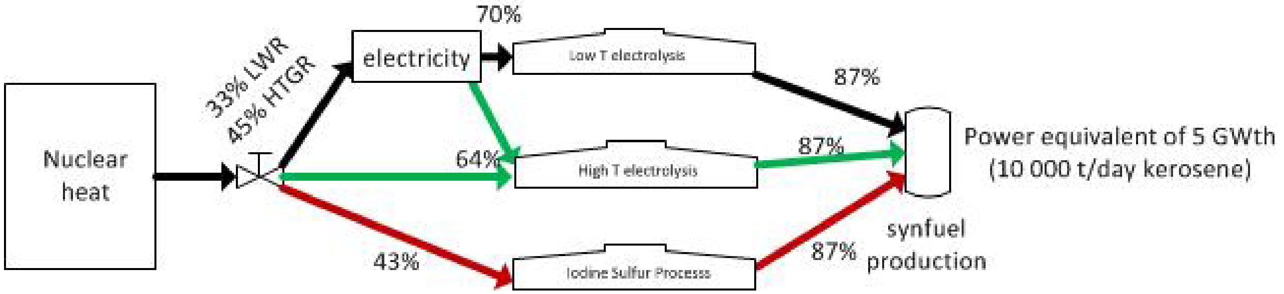
Steel:

- EU steel production: **159 Mt/yr** (factor 7 lower than China)
- Carbon intensity: 1.15 kg CO_2/kg steel → 183 Mt/yr CO_2 emissions, would be almost double without recycling
- Decarbonization of steel requires: 5.7 Mt/yr H_2 (+ additional heat)
- Using alkaline electrolysis, this would require a constant power of **33 GWe** + low carbon heat + low carbon electricity for recycling

Jetfuel (P2L):

- EU kerosene consumption: **62.8 Mt/yr** (2018) → 203 Mt/yr CO_2 emissions
- Minimum hydrogen needs >> 24.5 Mt/yr (+ conversion losses H_2 → synfuel)
- Using alkaline electrolysis, this would require a constant power of **124 GWe**

Efficiency Chain for Synfuel (e.g. SAF)



Efficiency Assumptions:

Heat to electricity LWR	33%
Heat to electricity HTGR	45%
Electricity to hydrogen (low T electrolysis)	70%
Heat + electricity to hydrogen (high T electrolysis)	64%
Heat to hydrogen (Iodine Sulfur process)	43%
Hydrogen to synfuel	87%

To produce 5 GWth synfuel equivalent requires:

→ 9 GWth (nuclear) using HTGR + HTSE

→ 13.3 GWth (nuclear) using HTGR + IS

→ 25 GWth (nuclear) using LWR + low T electrolysis

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H_2: Scale is the issue!

current nuclear capacity in EU-27: 104 GWe
current H_2 use: 9.7 Mt/yr

Fertilizer (NH_3):

- EU27: 13 billion m^3/yr of natural gas, 1/3 for heating, 2/3 for feedstock, 8.84 Mt/yr NG → 24.3 Mt CO_2/yr
  carbon intensity about ~ 2 t CO_2 per t NH_3, similar to new steel
- supplying constant low-carbon heat **4.7 GWth** could save emissions of approx. 8 Mt/yr of CO_2
- replacing the CH_4 feedstock would require 1.47 Mt/yr H_2
- supplying low-carbon H_2 in addition could save another 16 Mt/yr of CO_2 requiring an additional constant power of **7.5 GWe**

Power and Investment Requirements

- Power requirements indicated as "constant power" in MWth and MWe
- this has to be corrected for **availability** factors of different energy sources, e.g. 0.9 for nuclear and 0.3 for off-shore wind (FACTOR 3)

- economic assessments need to consider **lifetime**:
  e.g. nuclear reactor 60 years, wind turbine 20 years (FACTOR 3)

➔ for the same decarbonizing effect over a period of 60 years, one would need to invest into 9 times more wind power (+ externalities) than into nuclear power;

Is all this correctly reflected in comparative economic assessments?

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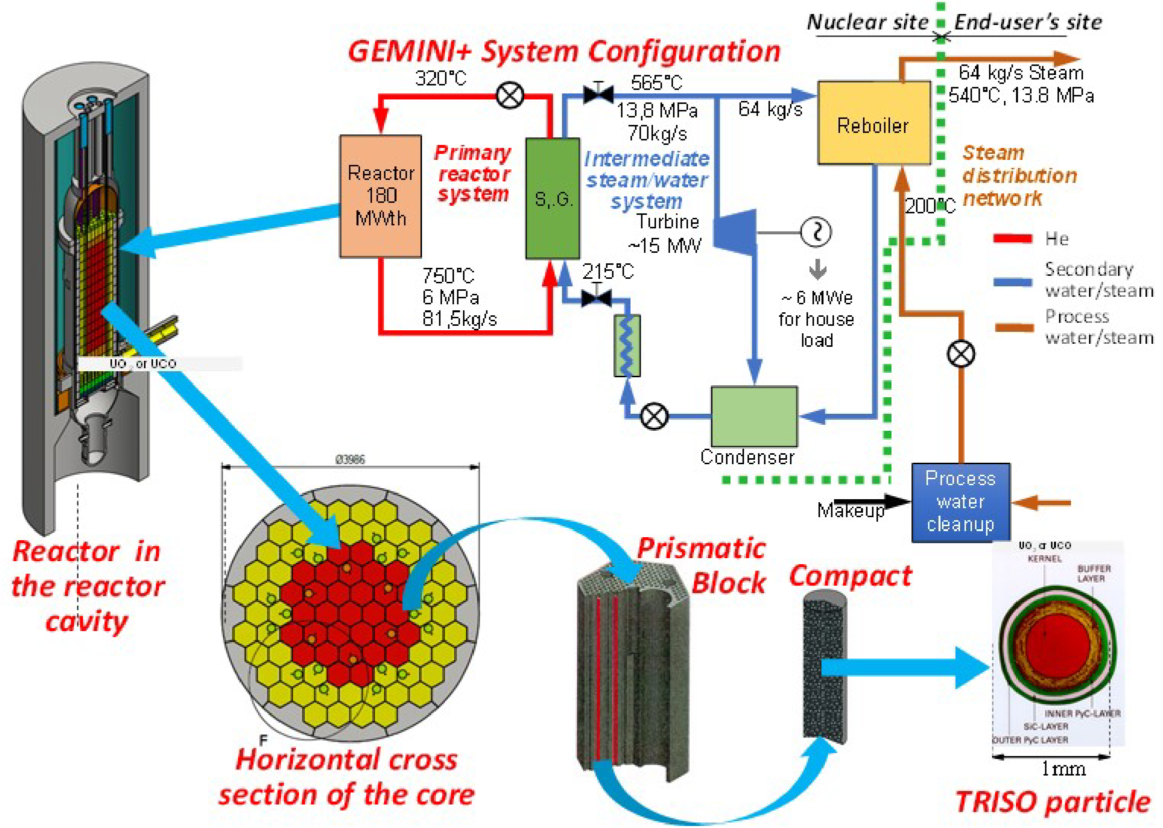
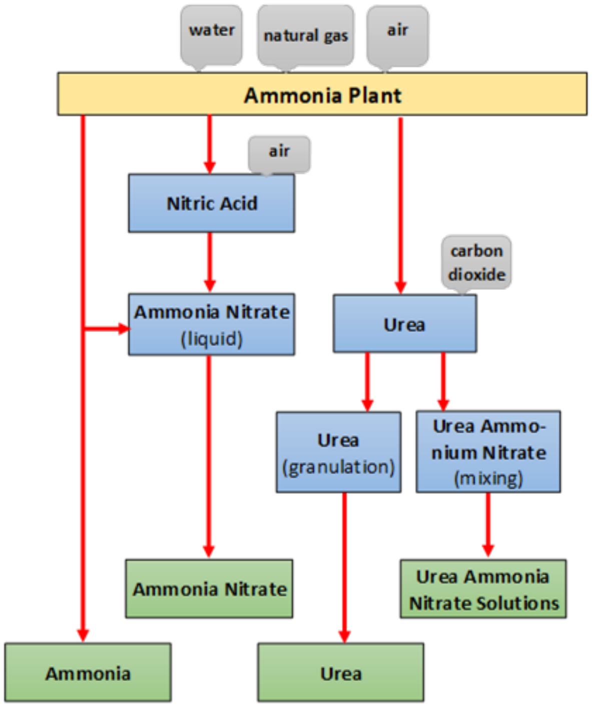
GEMINI+ Applications

GEMINI+ HTGR



- HTGR is a suitable near-term technology
- Excellent demonstrated safety performance of HTGR (paid by low power density and thus higher cost)
- HTGR can supply applications with highest carbon intensity → strongest effect

Fertilizer production (w/ LEI)

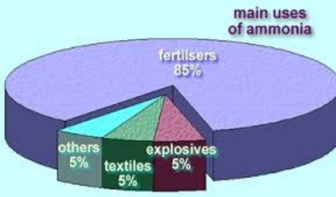


$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$ (endothermic >750°C)

$N_2 + 3H_2 \rightarrow 2NH_3$ (endothermic, 350-500°C)

- NH_3: Energy-intensive, strategically important commodity
- Highly dependent on NG (energy + feedstock)
- Fertilizer production: 1.2% of world energy consumption, 90% for nitrogen-based fertilizers

Fertilizer production



- Emissions from ammonia production: ~2 t CO_2/t NH_3 (2011)
- EU fertilizer manufacturers 13 billion m^3/yr of NG (25 Mt CO_2/yr) (1/3 for heat, 2/3 for feedstock) (1 m^3 NG → 1.9 kg CO_2)
- Integration of nuclear possible via electricity, steam, heat, H_2

→ 1/3 NG and concomitant emissions from using it for **energy** could be eliminated with steam-generating HTGR: approx. 8 Mt/yr of CO_2

→ An additional 2/3 could be saved with HTGR used for bulk H_2 production as **feedstock** for NH_3 instead of SMR: approx. 16 Mt/yr of CO_2

Gain also regarding NG imports (energy security)

Development hindered by cheap NG and relatively low CO_2 taxes.

Fertilizer production

Type of product, chemical formula	Reaction	Process parameters		Net energy efficiency (average with BAT **) [GJ/t of product]	Heat demand [% of total energy]
		T [^oC]	p [MPa]		
Ammonia (Am), NH_3	Haber-Bosch process $N_2 + 3H_2 \rightarrow 2NH_3$	(350 – 500)*	(10 – 25)*	~37 / 29 [10]	90
Urea (U), $CO(NH_2)_2$	$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow H_2O + NH_2CONH_2$	190	14 - 17	3.7 /3.2 [11]	9
Ammonium Nitrate (AN), NH_4NO_3	$HNO_3 + NH_3 \rightarrow NH_4NO_3$	100 - 180	~0.4	0.5 / 0 [12]	1
Urea Ammonium Nitrate (UAN)	mixing (U + AN)	ambient	0.1	0.04 / 0 [11]	~0
Nitric Acid (NA), HNO_3	Ostwald Process (not stoichiometric here) $NH_3+O_2 \rightarrow NO_x(N_2O)+H_2O \rightarrow NO+O_2 \rightarrow NO_2+H_2O \rightarrow HNO_3 + NO$	~230	1	-2.3 / -3.1 [13]	exothermic reaction

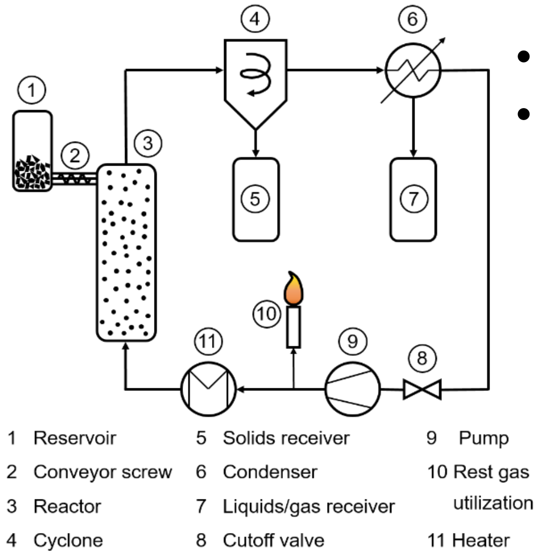
Table 1: Main process parameters for production of nitrogen fertilizers.
* high temperature and low pressure in optimum mode are favorable for ammonia synthesis
** *Best* Available Techniques

Plastics Recycling with Polymer Cracking Process (PCP) w/ TU Dresden

GEMINI+

Objective: replace thermo-mechanical recycling by PCP to:

- Expand the range of recyclable plastics beyond thermoplastics, which represent only 50% of the EU plastics waste;
- Allow mixed plastics and reduce need for cleaning;
- Enable recycling to a much larger product range.



The shredded educt is transported from the **reservoir (1)** with a heated **conveyor screw (2)** into the **reactor (3)**.
The reactor contains fluidization particles, e.g. sand, and is fluidized by inert gas or steam.
The pyrolyzed products are separated and withdrawn from the process via a **cyclone (4, 5)**, a **condenser (6, 7)** and a **membrane separator (10)**, respectively for solids, liquids or gas. The energy for the process is provided by a **pump (9)** and a **heater (11)**.

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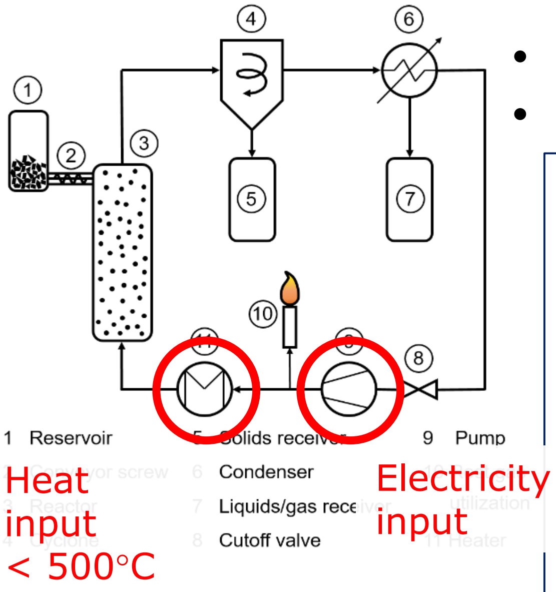

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Plastics Recycling with PCP

GEMINI+

- Polymethyl-Methacrylate (PMMA): valuable transparent polymer, widely used in construction, car industry, computer screens, optics, medicine…
- Production generates 3.75-4.78 kg CO_2 per kg of PMMA
  ➔ PMMA recycling saves much CO_2
- Pyrolysis of PMMA requires heat (450-490°C), doable with HTGR steam
- High conversion rates (up to 97 %) from PMMA to Methyl Methacrylate (MMA).

➔ one GEMINI+ reactor could process 120 t/h of PMMA waste.
➔ triple the currently recycled PMMA waste in the EU
➔ save 3-4 Mt CO_2/yr compared to virgin PMMA

This is one example where the use of nuclear process heat in a specialized niche application could save significantly more CO_2 than for generating electricity.

Efficiency, Land Use, Economy

Work in Progress
(cooperation TANDEM – GEMINI 4.0 – NPHyCo)

Examples from UK and Japan

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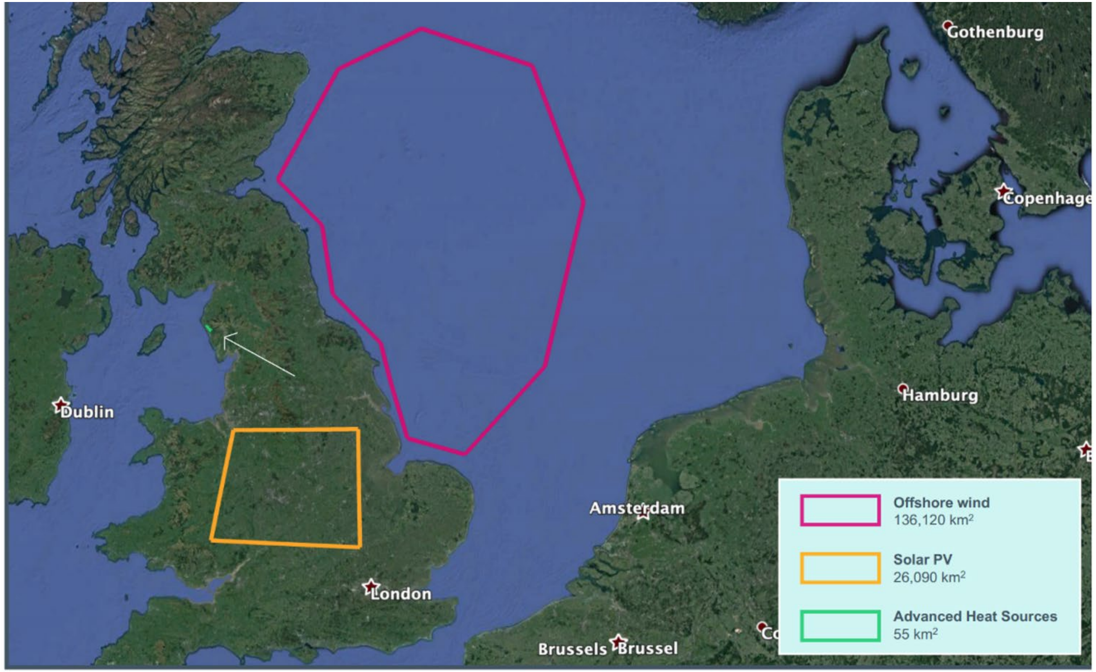
Land Area Requirements for Meeting Current UK Oil Consumption with Hydrogen

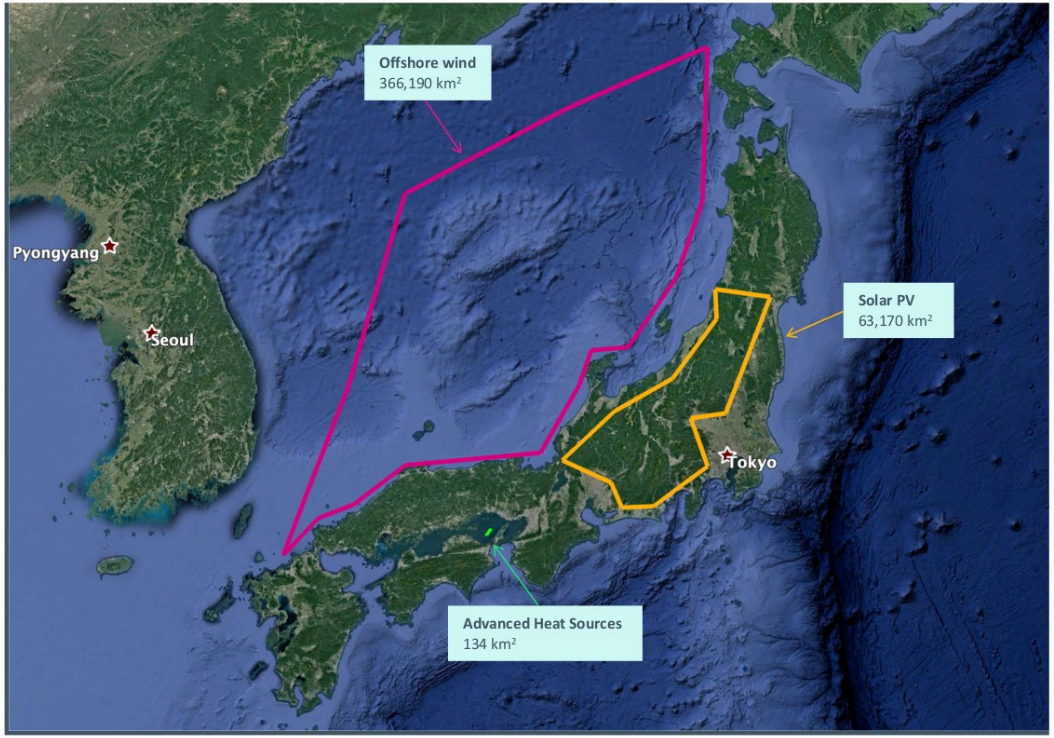


Each colored outline represents the total area that would be required for the siting of each type of resource if it were to be the only one used to generate enough hydrogen to replace current oil consumption in the UK.

Comparing area required to replace the UK's current oil consumption with hydrogen generated from either wind, solar, or advanced heat sources.

Source: *Missing Link to a Livable Climate*

Japan Hydrogen Production Geographic Area Requirements



Comparing the total area required to replace Japan's current oil consumption with hydrogen generated from either wind, solar, or advanced heat sources

Source: *Missing Link to a Livable Climate*

Outlook

Use of nuclear for more than just electricity is a very realistic and attractive option to help with decarbonization, energy security, technological autonomy… especially in those industries, where RES are not a good choice.

Thousands of new multi-disciplinary engineers in different regions and countries required.

Mid- and long-term technical and societal benefits of nuclear cogeneration need to be made compatible with short-term ROI expectations.

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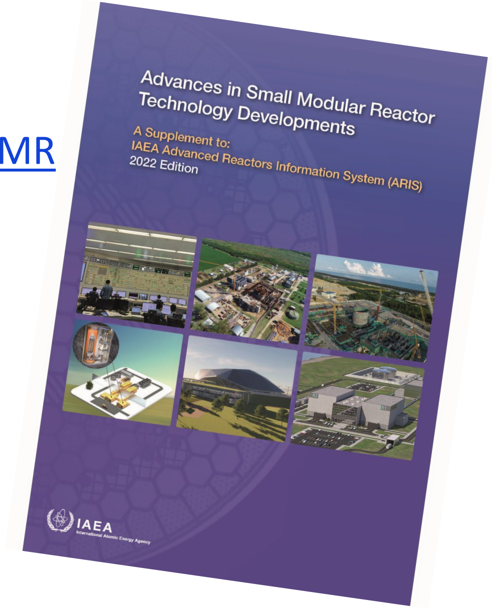
A few links

Most SMR concepts now with Cogen option

https://nucleus.iaea.org/sites/smr/Shared%20Documents/2022%20IAEA%20SMR%20ARIS%20Booklet.pdf



European SMR Industrial Alliance

https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en

SNETP Nuclear Cogeneration Industrial Initiative

https://snetp.eu/nc2i/

NC2I
Nuclear Cogeneration Industrial Initiative

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