Decarbonization Wedges Exercise

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NUCLEAR COGENERATION AND NON-ELECTRIC APPLICATIONS

1. State of the art and current development in different world regions

As of today nuclear cogeneration —i.e. using nuclear reactor thermal power for other applications than solely generating electricity— was implemented in the 1960s mainly for district heating in the countries of the Soviet Union. Today some 70 reactors supply electricity and heat essentially for district heating and seawater desalination, and an cumulative experience of nuclear cogeneration of about 1,800 reactor.years has been gained. Furthermore improvement in heat transport technologies on a large scale spurs a new interest in nuclear heat, hydrogen and derivatives as possible substitutes for fossil fuels that are currently used for transportation and industrial processes. Heat demands below 250°C fall within the theoretical range of capabilities of light water reactors and could be met by the current reactor technology in the coming decades for applications that are economically viable. Demands above 300°C require higher temperature reactors that will likely not be deployed on the large scale before 2040 owing to their specific technological requirements — materials, fuel, etc. — and to the licensing framework.

Prospects for non-electric nuclear production to cut CO_2 emissions by 2050 are low compared to those offered by power generation. They will depend on applications that can be made economically viable with light water reactors in an unforeseeable context of fossil fuel prices, carbon tax and desirable investment incentives in low carbon technologies (like those applicable to renewable energies).

However research has to harness all types of nuclear production that can replace fossil fuels when those nuclear technologies become commercially viable.

There are several non-electric nuclear applications that may arise and begin to develop by 2050:

1. **District heating:** deployed in central and Eastern Europe during the 1980s. Most of the plants producing heat for district heating deliver small amounts of heat over short distances. Even if no large-scale project exists yet, district heating is considered mature from a technological point of view. Should a large-scale project be decided, the technology could rapidly become more mature than the current readiness ranking at level TRL 6. Nuclear cogeneration may be encouraged by an energy efficiency policy that would support the development of heating networks in urban and industrial areas.

2. **Desalination:** different technologies (Multiple-Effect Distillation MED, Reverse Osmosis RO, Multiple-Stage Flash MSF, Vapor Compression VC, etc.) are employed at industrial scale since the 1980s, mainly in Japan. However the power dedicated to desalination remains low and the ~15 reactors involved in this mission currently produce about 0.1% only of the needs of desalinated water worldwide (IAEA, 2015)[1]. Several studies state that nuclear desalination is more economically competitive than desalination based on fossil fuels but the investment cost of nuclear plants limits the deployment of this technology in many countries. The technology readiness of nuclear desalination is ranks at level TRL 7.

3. **Hydrogen production**: with an annual consumption of about 60 Mtons, hydrogen is currently used extensively in the oil industry, mainly to optimize the refining of heavy crude oil, as well as in the chemical industry, especially to produce ammonia-based fertilizers. Future uses as energy carrier open prospects of fast growth of the demand, and concerns about greenhouse gas emissions should progressively replace steam-methane reforming as an industrial production means as it generates 5.5 tons of CO_2 per ton of hydrogen. Low-carbon substitute production processes include low- or high-temperature electrolysis powered with a low-carbon electricity, and electrochemical water splitting methods that require a high temperature (well above 500°C); Energy-based uses of Hydrogen include use in fuel cells to generate electricity, mixing with natural gas (<20%) to make a substitute fuel gas called hythane, storing energy,

[1] Source: IAEA (20015), "*Opportunities for cogeneration with nuclear power*", to be edited.

manufacturing synthetic hydrocarbon fuels from coal or biomass: methane, liquids from coal or biomass, etc. Except for specific conditions that allow for very low electricity prices, clean hydrogen generation by electrolysis is not competitive with steam-methane reforming, by a factor of 2.

4. **Other industrial uses:** several nuclear plants contributed to supply heat and/or steam for industrial processes from the 1970s and throughout the 1990s: Bruce power plant in Canada (4x825 MWe + heat, 1987-1997) for the production of heavy water; Stade power plant in Germany (630 MWe + heat, 1972-2003) for a salt refinery, etc. Other considered uses include extraction of bitumen and production of synthetic hydrocarbon fuels, but their implementation and development is uncertain. Owing to prior successful uses of nuclear heat or steam for industrial processes, related technologies readiness is rated at levels 7 and 8.

2. Maturity level and technological perspectives

Maturity of technologies associated with nuclear cogeneration and non-electric applications

Methodological information:

The maturity level is the TRL, reduced to 5 levels with market deployment enclosed in the higher TRL classes; maturity level scaling: 0 = none; 1 = fundamental research; 2 = R&D; 3 = demonstrator; 4 = low deployment; 5 = large deployment.

	2015	2020	2030	2040	2050
1 – District heating	3	3	4	5	5
2 - Desalination	4	5	5	5	5
3 – Hydrogen production	3	3	3	3	4
4 – Process heat for the industry	3	3	3	4	4

1 – District heating

The scientific community acknowledges the fact that there is no technological obstacle to further deployment. The main barriers are linked to financing the heating network and to social acceptance.

Reducing global GHG emissions significantly involves both extending heating networks and replacing fossil fuels in the energy mix (gas, oil, coal, etc.), as well as being competitive with other low-carbon energies (e.g. biomass) that are actively developed. In 2010 Europe consumed 3,300 TWh of heat, 13% of which were for district heating mainly fueled with natural gas —with an average emission rate of GHG of 70 to 180 tCO_2/GWh.

The project of the third reactor on the site of Loviisa, Finland —which is currently in the project phase— is designed to operate in cogeneration mode to supply heat Helsinki's heating network, some 80 km away.

2 – Desalination

Desalination technologies are mature and nuclear desalination became an industrial reality with BN350 (Kazakhstan, 1973-1999) and several nuclear plants in Japan (Ikata, Ohi, Genkai, Takahama, Kashiwasaki, etc.). Increasing needs in fresh water should create new opportunities (AIEA, 2015). These developments will happen first in Middle-East and Asia, which are the regions most affected by fresh water shortage. Africa might follow when nuclear power will develop primarily for electricity generation.

3 – Hydrogen production

Light Water Reactors (PWR and BWR) are readily available for hydrogen production by alkaline or proton-membrane electrolysis, however with a cost that is about twice that of hydrogen generated by steam methane reforming with prices of electricity around €50/MWh.

High Temperature Reactors should be more efficient while supplying high temperature heat as additional energy to electricity to split the water molecule. However current estimated production costs still exceed those for alkaline or proton-membrane electrolysis. Nuclear hydrogen generated by high temperature electrolysis are far from being competitive and their development is currently subject to bridging technology gaps in materials and in high temperature technologies, as well as to identifying conditions for very low electricity price (that is responsible for more than half of the cost of the hydrogen produced).

Potential development of technologies related to nuclear cogeneration and non-electric applications

Methodological information:

Potential development is measured as the percentage of the technology's contribution to environmental protection. This means evaluating, in terms of carbon emissions and of carbon emissions reduction, to what extent this new technology can contribute to limiting temperature increase to 2°C above pre-industrial level according to the time horizon considered in this study. Potential development scaling: 0 = not significant; 1 = significant (i.e. more than 1% of global emissions reduction) in some countries; 2 = significant on the global scale; 3 = very significant on the global scale (i.e. up to 3% of global emissions reduction); 4 = major technology vs. climate change (i.e. more than 3% of global emissions reduction).

	2015	2020	2030	2040	2050
All technologies	-	0	0-1	1	1-2
1 – District heating	-	0	0	<1	1
2 - Desalination	-	0	0	<1	<1
3 – Hydrogen production	-	0	0	0	0
4 – Process heat for the industry	-	0	0	1	1

The line "all technologies" represents: cumulative effects of all the cogeneration types.

1 – District heating

The use of district heating is currently limited to areas with cold winters —Northern or Eastern Europe, North Asia, North America. However, it is used in some temperate countries like Switzerland and could well be implemented in similar countries equipped with district heating networks, such as France. Heat networks account for most infrastructures investments required to implement nuclear cogeneration.

Currently each of the nuclear plants supplying heat to heating networks, especially in Europe, deliver a few percent only of the plant thermal output. Most of these cogeneration applications have been implemented in the 1980s and could probably not be launched today with the current economic situation, unless they could benefit from investment incentives in low-carbon technologies like renewable energies.

2 - Desalination

For an annual production of 47 Mm^3/day of fresh water, fossil fuels would emit from 25 to 600 Mt_{CO2}/y, i.e. up to 0.2% of the total world emissions. Thus increasing the use of nuclear cogeneration from 0.1% to 10% for desalination needs should only has a modest impact on the world greenhouse emissions.

3 – Hydrogen production

Finally the potential use of hydrogen production by nuclear cogeneration will be strictly connected to future uses of hydrogen —Industrial reactant, Hythane, Energy storage, Fuel cells, Synthetic Hydrocarbon fuels, etc. All types of cogeneration will have to overcome safety and social acceptance issues in a large development scenario.

4 – Process heat for the industry Many industries are using process heat below 250°C —e.g. the agri-food sector, the paper industry, plastics industries and some sections of the chemical industry— and at higher temperatures —e.g. petrochemistry, oil industry, hydrogen production—, or even at very high temperature —e.g. the cement industry, the glass industry. Main issues for the deployment nuclear cogeneration of process heat for the industry relate to the economic competitiveness of nuclear heat, to specific safety issues when the nuclear plant and the user industry are collocated, and to social acceptance. Orders of magnitude include: France's total needs of process heat amount to ~280 TWh/year, 103 TWh/year of which are below 250°C (i.e. ~6% of France's final energy consumption). It is estimated that ~22 TWh/year (~20% of needs) could be met with nuclear cogeneration, thus reducing CO_2 emissions by 6 Mtons (i.e. ~7.4% of total industry-related emissions or ~0.8% of France's total emissions).

3. Technological, economic and social bottlenecks

Methodological information:

The following table ranks the bottlenecks according to their impact on the development of the technology. A bottleneck ranking at 6 on the scale will hinder or stall the deployment of the technology compared with bottlenecks ranking at 1; conversely, a bottleneck ranking at 1 will hinder the deployment of the technology much less than bottlenecks ranking at 6. Note that the ranking is relative, meaning that a bottleneck ranking at 6 is not necessarily hard to remove; conversely, a bottleneck ranking at 1 is not necessarily easy to remove. Technologies rank according to: research, finance, regulations, resources & environment, security and acceptability. The table also contains keywords associated with each bottleneck.

It must be stressed that the ranking of such different factors must be considered with caution; as an expert's judgement, not a quantitative assessment.

Technology		**Research & technological bottlenecks**	**Economy and financial bottlenecks** (investment, risks)	**Regulation & institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
Urban district	Rank	3	6	5	1	2	4
	Key-words	Improvement in heat transport (losses…)	High investments (nuclear plant+heat transport and distribution network)	Need for a carbon tax and regulation mechanism for CO_2 price			
Desalination	Rank	4	6	2	1	3	5
	Key-words	Nuclear plant adapted to conditions of countries experiencing water shortage	High investments in the nuclear power plant				
Hydrogen production	Rank						
	Key-words						
Heat for industrial applications	Rank						
	Key-words						

Whichever cogeneration technology is considered, it has to face the specific issues of nuclear power that include high investment costs, social acceptance, safety, etc. Thus the development of nuclear cogeneration needs to be strongly supported by an incentive policy that would implement a carbon tax and investment incentives in low carbon technologies, like those already adopted for renewable energies.

Hydrogen production and industrial uses of heat remain very prospective and it is thus difficult to make predictions for their deployment for the moment. For industrial heat the main bottlenecks should be regulation, safety and social acceptance, while research, financing and resources are of less importance.

4. Potential radical and incremental innovations

Methodological information:

The following table lists the nature of innovations needed to overcome the bottlenecks mentioned earlier. There are two types of innovations: I stands for 'incremental innovation' (i.e. improving existing products and processes) and R stands for 'radical innovation' (i.e. developing new products and processes).

Technology		**Research & technological bottlenecks**	**Economy and financial bottlenecks** (investment, risks)	**Regulation & institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
District Heating	I or R	I	R	R			I
	Key-words	Transport pipes Branching on the power conversion system	Financing	Policy encouraging the deployment of district networks			Better acceptance of nuclear power
Desalination	I or R						I
	Key-words						Better acceptance of nuclear power
Hydrogen production	I or R	I					R
	Key-words	Production yields improvements					No actual place for hydrogen in the energy mix
Heat for industrial applications	I or R	I				R	I
	Key-words	Best synergies yet to be found				Colocation of nuclear and industrial plants	Better acceptance of nuclear power

All technologies described above have the potential for a wider use. However their development is currently limited by hesitations about nuclear power linked to social acceptance and to financing the building of reactors. However there are already conditions for low-carbon nuclear heat to be competitive for district heating and industrial process heat. Furthermore, even though, nuclear-based hydrogen is not competitive yet costs for this technology are largely driven by the price of electricity. Nuclear-based hydrogen could become more attractive in the future as a by-product: in that context, it could be produced at marginal electricity cost during the time nuclear power plants do not need to counterweigh intermittent energies.