LOW-TEMPERATURE HEAT APPLICATIONS OF NUCLEAR ENERGY IMPACT ON CLIMATE CHANGE

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OUTLINE

1. Nuclear & Climate Change
2. Nuclear Power Plant for Cogeneration
3. District Heating
4. Low Temperature Applications
5. Conclusions
ENERGY & CLIMATE CHANGE

Primary Energy (in Gtoe)

1990 2000 2010 2020 2030 2040 2050

Scenario A
Scenario B
Scenario C

We are here

A: Business as usual
B: Medium or Moderate
C: Ecological
Actual
Thanks to nuclear energy, France is emitting 6 time less GHG than average EU countries for electricity generation.
CO\textsubscript{2} EMISSIONS BY ENERGY SOURCE

Electricity Generation: CO\textsubscript{2} emissions (in g/kWhe)

- Coal: 950 g/kWhe (50 g/kWhe indirect emissions)
- Oil: 750 g/kWhe (150 g/kWhe indirect emissions)
- Gas: 400 g/kWhe (100 g/kWhe indirect emissions)
- Photovoltaic: 70 g/kWhe
- Wind: 18 g/kWhe
- Hydraulic: 7 g/kWhe
- Nuclear: 2 g/kWhe

Not accounting for fugitive emissions

Direct Emissions

Indirect Emissions
Thanks to nuclear energy, electricity generation is almost fully decarbonized in France. Main GHG emitters are transport and heat production (residential, commercial and industry).
We need to decarbonize the non-electric uses of energy:

1. Transportation (electric cars)
2. Heat in Residential and Commercial sectors
3. Industry
**ENERGY AND HEAT**

**Heat** has always been an issue for mankind.

In 2017, the total world energy production amounted to $\sim 15\,000\,\text{Mtoe} = 15\,\text{Gtoe}$

Over 38% of it ($5\,700\,\text{Mtoe}$) is ultimately used as heat. 50% of this heat is feeding residential homes, commercial businesses and public services (hospitals, schools, universities, offices, etc)

Potential space heating and cooling demand $>20\,000\,\text{TWh}$
Actual world District Heating and Cooling delivery $\sim 2500\,\text{TWh}$

**The primary use of energy is for heating purposes**
ENERGY AND HEAT IN THE WORLD

Wasted Heat ≈ 4.2 Gtoe

Produced Energy 14.7 Gtoe

Final Energy + Own use 10.5 Gtoe

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ENERGY AND HEAT

**SOURCES**
- Oil \(\approx 15\, \text{Gtoe}\)
- Gas
- Coal
- Nuclear
- Hydro
- Renewables

**ENERGETIC PRODUCTS**
- Liquid Fuels
- Gaseous Fuels
- Solid Fuels
- Electricity
- Heat

\(\approx 10.5\, \text{Gtoe}\)

**Heat Use** \(\approx 4.5\, \text{Gtoe}\)

**Losses** \(\approx 4.5\, \text{Gtoe}\)

**Heat Recovery ?**

**Energy sector** \(\approx 1\, \text{Gtoe}\)

**Final Use in Industry, Residential, Commercial, Transportation, Agriculture** \(\approx 9.5\, \text{Gtoe}\)
SPACE HEATING IN EUROPE

Heat Use in Europe

Annual Heat Consumption (PJ)

13000 PJ = 3600 TWh

- > 400°C
- <400°C
- <120°C

Data from Euroheatcool, 2006

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One third of the primary energy is dedicated to heat
HEAT IN FRANCE

In France, heat represents

- **80%** of all energy consumption in the residential and service sectors
- **40%** of all industrial energy needs

Domestic uses: heat, sanitary hot water,…
Industry uses: Drying, chemistry, oil refinery, matter transformation, fusion, boiling, sterilization,…

- **80%** of heat uses are at temperatures **below 400°C**
- **65%** of heat uses are at temperatures **below 120°C**

Most of Heat requirements stand at low temperatures
Residential heating represents by far the larger consumption amount.
1. Nuclear & Climate Change
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WHAT IS COGENERATION?

Cogeneration Mode
- Reduced electrical efficiency (condensation at higher temperature)
- Better overall energy efficiency (from 34% up to 90%)

Electric only Mode
- Electrical efficiency from 34% (Nuclear) to 56% (Gas in CCGT)

Other energetic Product
- (Heat, Fuels, Steam, Water...)

ELECTRIC POWER PLANT

Electricity

Cooling (Heat Loss)

Cogeneration Mode

Cooling (Heat Loss)

Other energetic Product

(Electricity)
A Pressurized Water Reactor (PWR)

1/3 of fission energy is converted into electricity

2/3 of energy is dumped in the environment
COGENERATION LEADS TO...

1. Better Efficiency
   ✓ Over 80% energy efficiency
   ✓ Open new sectors for nuclear power

2. Better Use of energy
   ✓ Make best use of heat at the right temperature
   ✓ Match industrial applications needs

3. Better Flexibility
   ✓ Allow flexible operation of the NPP
   ✓ Diversify energy outputs

4. Lower Environmental impacts
   ✓ Lower dumped heat in the environment
   ✓ Additional heat sink
Some facts and figures on Nuclear Cogeneration

- **74** reactors worldwide are being used in a cogeneration mode (heat, industrial steam, water desalination)

- **700** reactors-years of accumulated experience

- The thermal power extraction vary from **5 to 240 MW**

- The maximum length for the heat transport line is **64 km** (Kola, Russia)
NUCLEAR COGENERATION: A REALITY FOR 74 NPP

Source: I. Khamis, IAEA Technical Meeting, Prague, October 2010
**District Heating Using Nuclear**

- 18 nuclear sites
- 51 reactors
- 110 GWh thermal of Heat delivered in DH networks
- 0.17% of the District Heating deliveries in the European Union

*Source: Energy Technology Institute, 2016*
A NUCLEAR POWER PLANT

Two 1300 MWe reactors with cooling towers
THE SECONDARY LOOP OF A PWR

STEAM GENERATOR

HP TURBINE

REHEATER

CONDENSER

COLD SOURCE

PRIMARY CIRCUIT

Feedwater TANK

PUMP

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The turbine hall of a NPP showing the major components

Source: EDF

The ALSTOM Low Pressure Turbine

Courtesy of http://www.power.alstom.com
The condenser is located below the LP turbines
A two-stage process: High Pressure then Low Pressure turbine
THERMODYNAMICS

Theoretical efficiency

$$\eta_{\text{carnot}} = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}$$

max of 340°C in PWR

If $T_{\text{hot}} = 288^\circ\text{C}$ and $T_{\text{cold}} = 39^\circ\text{C}$, $\eta_{\text{carnot}} = 44.4\%$

In an electric transformation, heat is unavoidable
EXERGY & ELECTRICAL EFFICIENCY

\[ \eta = \frac{|W_{HP} + W_{BP}| - W_P}{Q_i} \]

➢ \( W_{BP} \) on the Low Pressure Turbine decreases with increasing output temperature

\[ E_{out} = Q_{out} \cdot (1 - \frac{T_0}{T}) \]

➢ The output exergy increases with increasing temperature
EXERGY

➢ Heat at ambient temperature has no value
➢ Exergy is more appropriate to taken into account the temperature at which the heat is produced

\[ E = H - T_0 \cdot S \]

*Exergetic* value of a heat quantity \( Q \) generated at a temperature \( T \)

\[ E = Q \cdot \left(1 - \frac{T_0}{T}\right) \]

Example of a 1300 MWe PWR reactor

<table>
<thead>
<tr>
<th>T hot (°C)</th>
<th>T cold (°C)</th>
<th>Wp (MW)</th>
<th>Qi (MW)</th>
<th>W_{HP} (MW)</th>
<th>W_{BP} (MW)</th>
<th>W_{gross} (MW)</th>
<th>Qs (MW)</th>
<th>η carnот (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>288</td>
<td>39</td>
<td>9</td>
<td>3 920</td>
<td>-417</td>
<td>-936</td>
<td>1 353</td>
<td>-2 562</td>
<td>44.4%</td>
<td>34.3%</td>
</tr>
</tbody>
</table>
THE SECONDARY LOOP OF A PWR

HP TURBINE
SEPARATOR
REHEATER
CONDENSER
COLD SOURCE
HEAT EXCHANGER
LP TURBINE
STEAM GENERATOR

Feedwater TANK
PUMP
PRIMARY CIRCUIT

PUMP

STEAM
WATER

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Modify the low pressure turbine: outlet at 2 bars
ELECTRICAL EFFICIENCY

Trade-off between electric output and Exergy

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NUCLEAR COGENERATION & DISTRICT HEATING

Nuclear District Heating

Nuclear Power Plant

District Heating Network

Main Transport Line

length ~ 100 km

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ONE TYPICAL CONFIGURATION

➢ A 100 km long Heat Transport Line delivering energy in the form of hot water to a large urban city, one airport and industrial areas.
THE MAIN TRANSPORT LINE
THERMAL LOSSES

- Diameter $\Phi$
- Insulator thickness $e$
- Insulator conductivity $\lambda < 0.04$ W/m.K

\[ \left( \frac{dQ}{dz} \right) = \frac{2\pi \lambda}{\ln\left(1 + \frac{2e}{\Phi}\right)} (T - T_0) < 120 \text{ W/m} \]

Total heat loss ~ 2% of the transported power!
OPTIMIZATION RESULTS

A gain equivalent to 920 MWe (+70%) can be achieved!!
➢ One Heat Transport Line 100 km long
   ✓ Buy heat from the NPP production site
   ✓ Sell heat to the District Heating Network Company

➢ Assume an annual production of 9 TWh
   → Annual heat sales value of +540 M€

➢ Loss of electrical production of -1.8 TWh
   → Electric loss value cost of -180 M€

Overall annual gain of +360 M€
Greenhouse gas reduction

Large reduction in CO\textsubscript{2} emissions

- CO\textsubscript{2} emissions from district heating
- 60% fossil fuels
- 40% waste incineration
- Average of 200 gCO\textsubscript{2}/kWh

Zero GHG emissions from nuclear cogeneration

Huge savings in CO\textsubscript{2} emissions

Avoid 0.2 Million ton of CO\textsubscript{2} per TWh

\[ \Delta C_t = p_{GHG} \cdot \gamma \cdot H_t \]

If \( p_{GHG} = 50 \, \text{€/ton} \), \( \gamma = 0.2 \, \text{ton CO}_2/\text{MWh} \)

Additional financial gain of \( \Delta C_t = 10 \, \text{M€/TWh} \)
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District Heating is developed in northern European countries
DEVELOPMENT OF DH NETWORKS

The Development of the District Heating Systems in Stockholm County - Networks of Heating

Source: D. Magnusson, Linköping University, Sweden

District Heating networks are expanding
In a tunnel...

(maybe shared with other utilities)

...or in a trench
A major cost issue: Construction and installation of piping.

Source: Urecon

Source: R. Narjot, Techniques de l’ingénieur
New generation of DH work at very low temperatures (< 80°C)


favours the development of Nuclear Heat
COST OF HEAT PRODUCTION

\[ C' = c_0 \cdot E' + c \cdot H \]

- \( C' \) = Annual cost of the plant in the cogeneration mode
- \( E' \) = Electrical energy annual production in the cogeneration mode
- \( H \) = Annual production of the cogenerated product
- \( c \) = Cost of the cogenerated product

\[ c \cdot H = \Delta C + c_0 \cdot \Delta E \]

- \( c_0 \) = Cost of electric power
- \( \Delta C \) = Increase in annual costs due to cogeneration
- \( \Delta E \) = Loss in electricity production due to cogeneration
\[ c \cdot H = \Delta C + c_0 \cdot \Delta E \]

- \( c_0 = 50 \$/MWh \) (average actual cost of nuclear electricity)
- \( \Delta C = 24 \text{ M$/y} \) (200 M$ at 5\% interest rate over 20 years plus additional operating costs)
- \( \Delta E = 1.5 \text{ TWh} \) (loss of 500 MWe for 3000 h/y)
- \( H = 9 \text{ TWh} \) (production of 2000 MW thermal for 4500 h/y)

\[ c = 11 \$/MWh \]

Production cost is very competitive
## NUCLEAR HEAT COST

### Splitting of Heat costs

<table>
<thead>
<tr>
<th></th>
<th>LCOH: €/MWh(th)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small DH network</td>
<td></td>
</tr>
<tr>
<td>DH distribution capital cost*</td>
<td>9,3</td>
</tr>
<tr>
<td>DH distribution electricity consumption</td>
<td>0,6</td>
</tr>
<tr>
<td>DH distribution fixed O&amp;M</td>
<td>8,9</td>
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<tr>
<td>GHOB + WTES capital cost*</td>
<td>0,5</td>
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<tr>
<td>GHOB + WTES electricity consumption</td>
<td>1,0</td>
</tr>
<tr>
<td>GHOB gas consumption</td>
<td>7,0</td>
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<tr>
<td>GHOB + WTES fixed O&amp;M</td>
<td>0,3</td>
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<tr>
<td>HTS capital cost*</td>
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<td>HTS electricity consumption</td>
<td>12,4</td>
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<tr>
<td>HTS fixed O&amp;M</td>
<td>1,4</td>
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<tr>
<td>NCHP heat generation capital cost**</td>
<td>1,5</td>
</tr>
<tr>
<td>NCHP opportunity cost (electric output reduction)</td>
<td>6,6</td>
</tr>
<tr>
<td>NCHP fixed O&amp;M</td>
<td>0,0</td>
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<tr>
<td>Large DH network</td>
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</tr>
<tr>
<td>DH distribution capital cost*</td>
<td>14,6</td>
</tr>
<tr>
<td>DH distribution electricity consumption</td>
<td>0,3</td>
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<tr>
<td>DH distribution fixed O&amp;M</td>
<td>13,9</td>
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<tr>
<td>GHOB + WTES capital cost*</td>
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<tr>
<td>GHOB + WTES electricity consumption</td>
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<tr>
<td>GHOB gas consumption</td>
<td>7,0</td>
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<td>GHOB + WTES fixed O&amp;M</td>
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<tr>
<td>HTS capital cost*</td>
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<td>HTS electricity consumption</td>
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<td>HTS fixed O&amp;M</td>
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<tr>
<td>NCHP heat generation capital cost**</td>
<td>1,5</td>
</tr>
<tr>
<td>NCHP opportunity cost (electric output reduction)</td>
<td>6,6</td>
</tr>
<tr>
<td>NCHP fixed O&amp;M</td>
<td>0,0</td>
</tr>
</tbody>
</table>

Source: Martin Leurent, PhD thesis, 2018
≪ Nuclear plants as an option to help decarbonizing the European and French heat sectors ≫
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APPLICATIONS FOR ENERGY

➢ DISTRICT HEATING
➢ DESALINATION
➢ INDUSTRIAL STEAM
➢ SYNTHETIC FUELS PRODUCTION
➢ OIL & TAR SANDS EXTRACTION
➢ COAL LIQUEFACTION & GASIFICATION
➢ HYDROGEN PRODUCTION
NUCLEAR COGENERATION
ELECTRICITY & HEAT APPLICATIONS

Low temperatures
40°C to 250°C

District Heating
Water Desalination

Medium temperatures
250°C to 550°C

Industrial Steam
Coal Liquefaction and Gasification
Oil Shale
Tar Sands
Biomass
Synthetic Fuels

High temperatures
550°C to 900°C

Hydrogen Production
Many industries require steam or heat at moderate temperatures (from 60°C to 400°C)

About 40% of energy consumption in industry is heat < 400°C
SCHEMATIC DIAGRAM OF LTE DESALINATION PLANT COUPLED TO A REACTOR TO USE WASTE HEAT

Source: V. Srivastava & P. Tewari, BARC, IAEA Technical Meeting, Prague, October 2010
SYNTHETIC FUELS

\[ C_xH_yO_z + 2\ H_2O + O_2 \rightarrow CO + H_2 \rightarrow (-CH_2-) + H_2O \]

Gasification

Purification

Fischer-Tropsch

Pre-treatment

Biomass

Cogeneration

Heat

Grinding, Drying, Pyrolysis

Hydrogen

H_2/CO ~ 1

H_2/CO ~ 2

Oxygen

Water

Upgrading

Diesel Oil

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2156 industrial sites identified as large low-temperature heat consumers and located less than 100 km away from nuclear sites

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WORLD ENERGY PROJECTIONS

(Mtoe) Comparison of Future World Energy Consumption in 2040

<table>
<thead>
<tr>
<th>Institution</th>
<th>WEO Reference</th>
<th>WEO New Policies Scenario</th>
<th>WEO Sustainable Development Scenario</th>
<th>BP*</th>
<th>Exxon</th>
<th>Shell</th>
<th>EIA</th>
<th>IEEJ Reference</th>
<th>IEEJ ATS</th>
<th>Average</th>
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<tbody>
<tr>
<td>Coal</td>
<td>4 769</td>
<td>3 809</td>
<td>1 597</td>
<td>3 762</td>
<td>3 890</td>
<td>3 101</td>
<td>4 045</td>
<td>4 352</td>
<td>3 391</td>
<td>3 635</td>
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<tr>
<td>Oil</td>
<td>5 570</td>
<td>4 894</td>
<td>3 156</td>
<td>4 836</td>
<td>5 617</td>
<td>4 291</td>
<td>5 695</td>
<td>5 416</td>
<td>4 662</td>
<td>4 904</td>
</tr>
<tr>
<td>Gas</td>
<td>4 804</td>
<td>4 436</td>
<td>3 438</td>
<td>4 707</td>
<td>4 670</td>
<td>3 601</td>
<td>4 637</td>
<td>4 628</td>
<td>4 140</td>
<td>4 340</td>
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<tr>
<td>Nuclear</td>
<td>951</td>
<td>971</td>
<td>1 293</td>
<td>912</td>
<td>1 028</td>
<td>1 525</td>
<td>955</td>
<td>856</td>
<td>1 246</td>
<td>1 082</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>514</td>
<td>531</td>
<td>601</td>
<td>1 241</td>
<td>482</td>
<td>419</td>
<td>3 226</td>
<td>466</td>
<td>466</td>
<td>494</td>
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<tr>
<td>Biomass &amp; Waste</td>
<td>1 772</td>
<td>1 851</td>
<td>1 504</td>
<td>1 521</td>
<td>1 995</td>
<td>1 525</td>
<td>3 226</td>
<td>1 640</td>
<td>1 595</td>
<td>1 647</td>
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<tr>
<td>Renewables</td>
<td>948</td>
<td>1 223</td>
<td>2 132</td>
<td>2 527</td>
<td>880</td>
<td>2 979</td>
<td>806</td>
<td>1 149</td>
<td>1 381</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>19 328</td>
<td>17 715</td>
<td>13 720</td>
<td>17 983</td>
<td>18 088</td>
<td>17 910</td>
<td>18 557</td>
<td>18 164</td>
<td>16 649</td>
<td>17 483</td>
</tr>
</tbody>
</table>

*BP values Hydro in equivalent primary energy and does not evaluate Biomass

Nuclear energy is projected to increase +60% by 2040 avoiding the emissions of 1.8 Gt of CO\textsubscript{2}

All these projections do not take in consideration nuclear heat!

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ADVANTAGES OF NUCLEAR HEAT

1. **Save Energy**
   - ✓ Recover waste heat
   - ✓ Open new utilization of nuclear power

2. **Save Environment**
   - ✓ Drastically reduce CO₂ emissions
   - ✓ Reduce nuclear waste

3. **Save Money**
   - ✓ Get cheaper energy
   - ✓ Reduce the need for fossil fuels
CONCLUSIONS

➢ Heat recovery from a Nuclear Power Plant for District Heating or industrial applications is technically at hand

➢ Nuclear Cogeneration improves the overall energy efficiency of the Power Plant (from 33% to over 90%)

➢ The Main Heat Transport line is a key economic issue for competitiveness. Heat can be transported with low thermal losses (a few %) at long distances (> 100 km)

➢ The use of nuclear energy for District Heating and other Low-temperature applications allows large reduction of CO$_2$ emissions and could significantly contributes to fight climate change.