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Prospects for Nuclear Hybrid Systems

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Scientific Direction

Nuclear Cogeneration: Electricity & Heat

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 & Biofuels

High temperatures

550°C to 900°C

- Hydrogen Production

HYFRANCE3 : Development of hydrogen markets

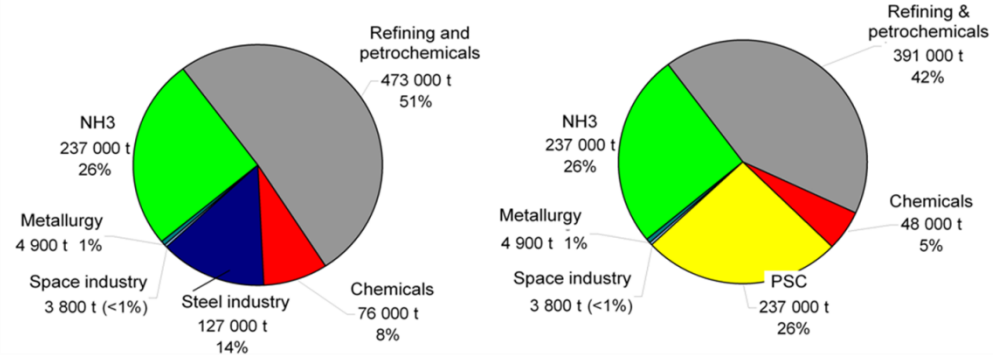
Prospective demand in industry, Production using wind energy, Mass storage and distribution to regional vehicles

Partners: Air Liquide, Total, EdF R&D, GdF, Renault, PSA / CEA (coordinator), ADEME, BRGM, CNRS, IFP / AFH2, ALPHEA Hydrogène / Government (Research, DGEMP)

Prospective demand in industry

(chemistry, fuels, BtL, iron and steel, coproduction – present situation and future prospects)

Demand from French industries



At least 1Mt/y by 2030 – a huge potential market for reduction process in iron and steel industry

Focus on refining market

2 Scenarii : "trend-setting" (10% bio-fuel use, 7.5% EV ➔ - 20% fuel consumption / 2005) and "environmentally friendly" (-20% consumptions trucks, 95gCO2/km, - 10% km cars, increase in combined rail and road transport (20%), 15% EV and 6% FCV ➔ - 40% fuel consumption / 2005)

Avoid hydrogen losses in refineries, cost effective for fuel cells uses

BtL production case: break-even price at 2-2.5 €/kg for wind energy only or grid connected H_2 production

Production costs using wind energy vs. demand

(decentralized production for a motorway refuelling station, a BtL station and a Hythane® bus fleet)

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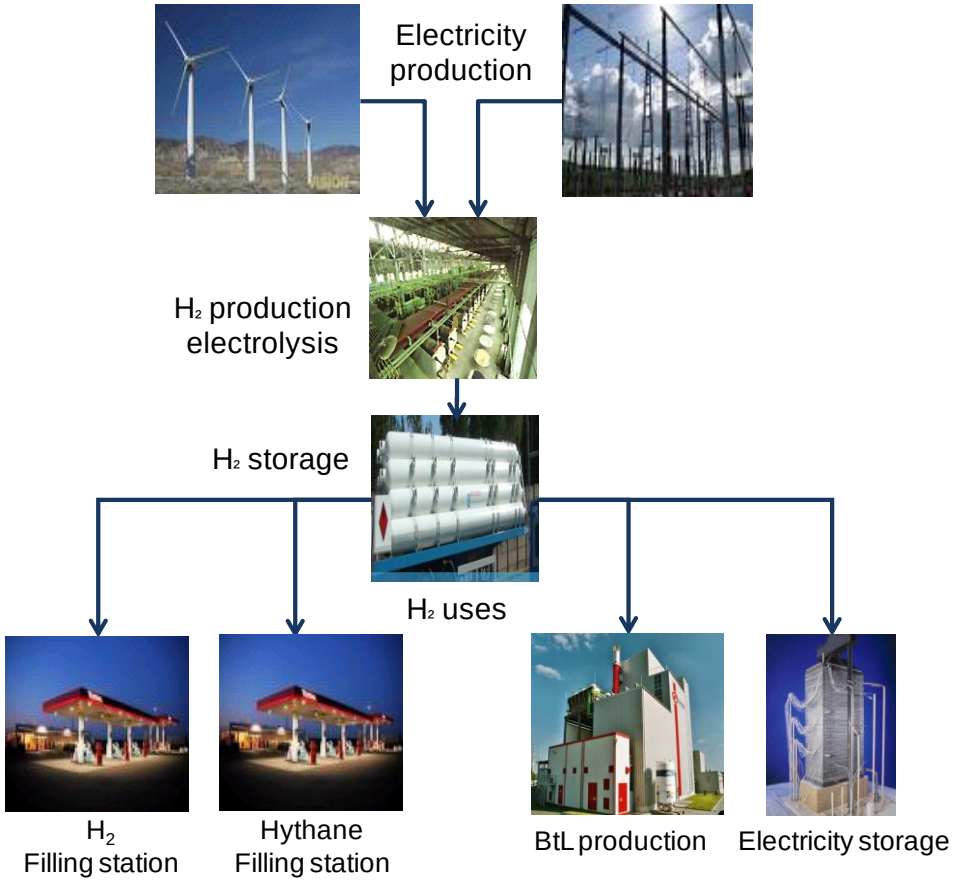
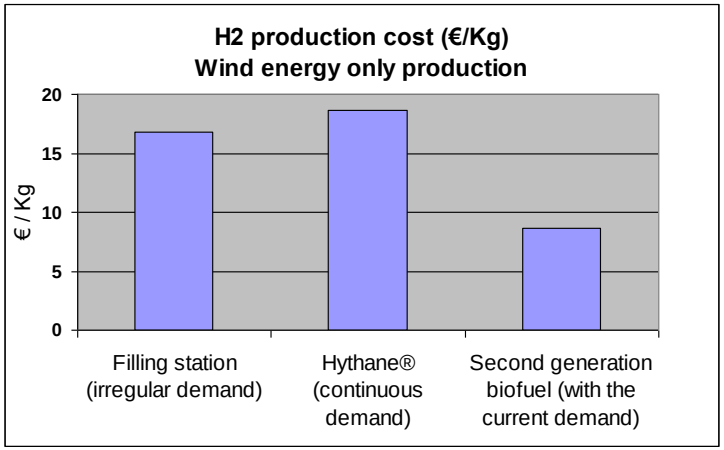
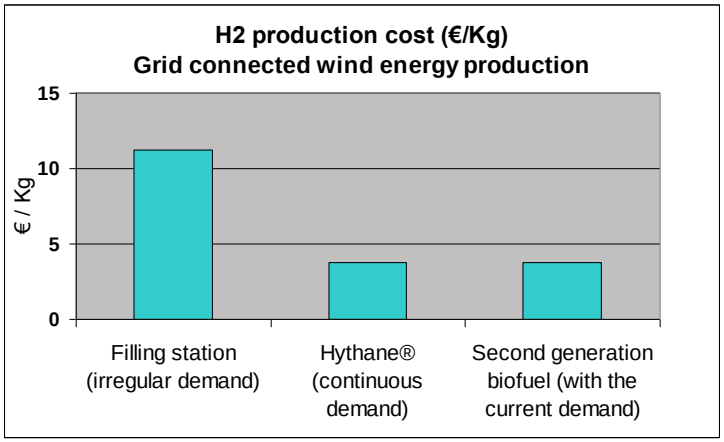
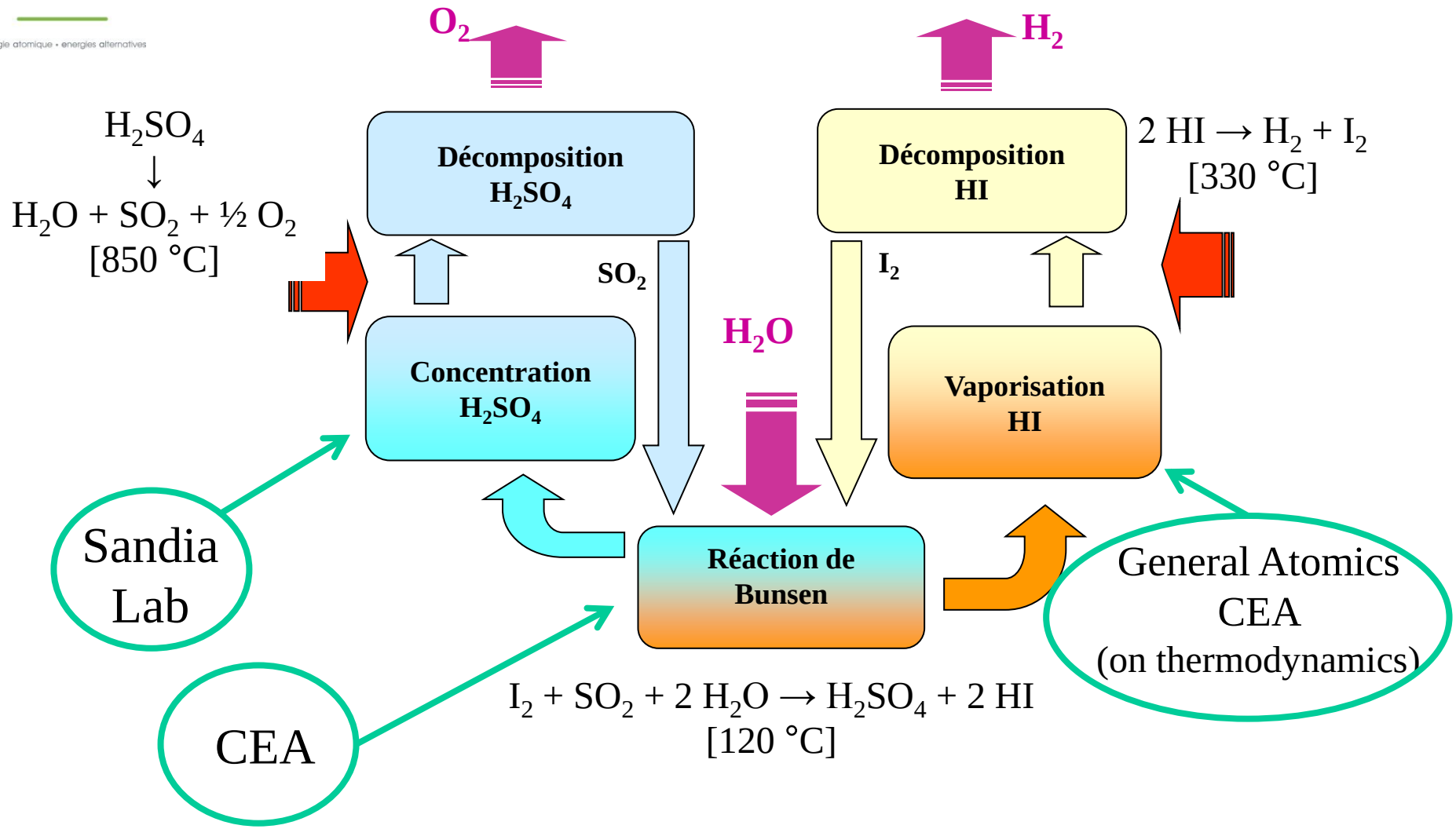




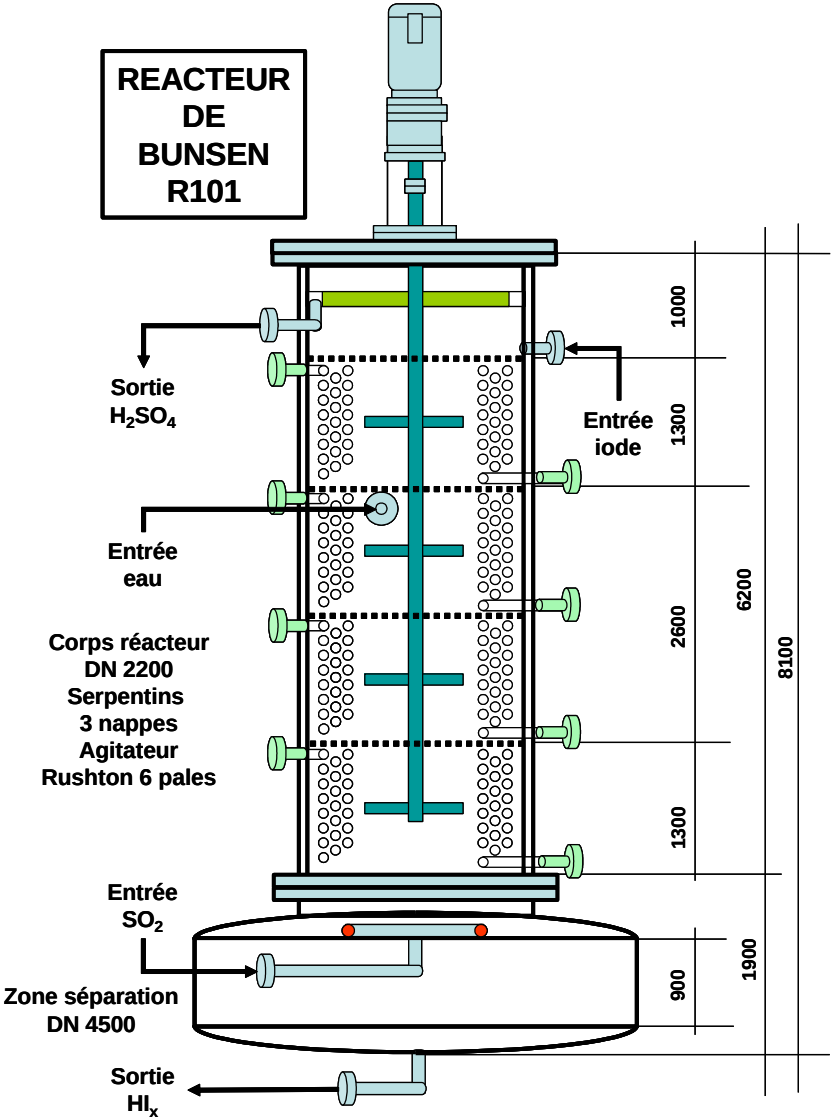


The Sulfur/Iodine thermochemical cycle

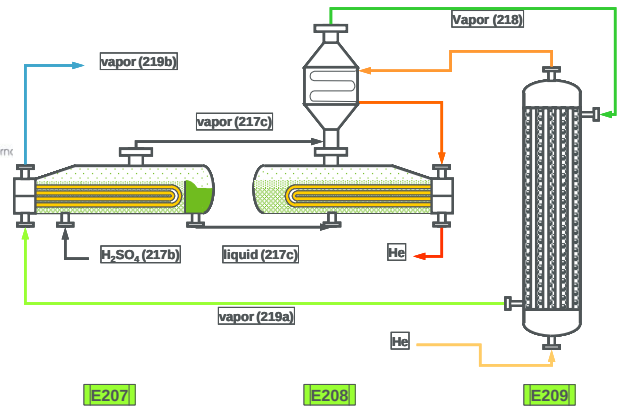


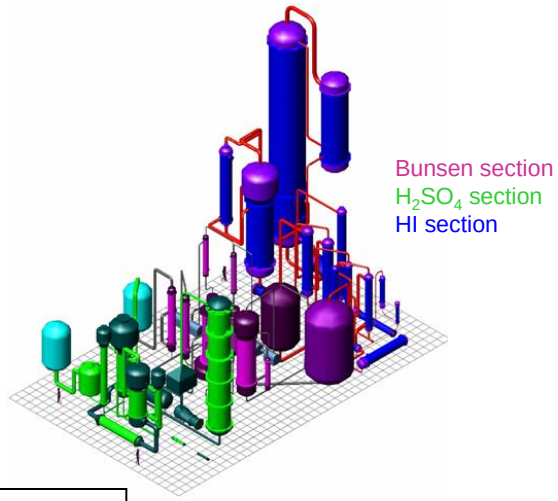
Nuclear & Hydrogen Production

The Bunsen Pilot installed in San Diego



Nuclear & Hydrogen Production: System Analysis





Component design

Plant layout

Flowsheet

Thermo-dynamic data

Materials

Investment cost

Efficiency

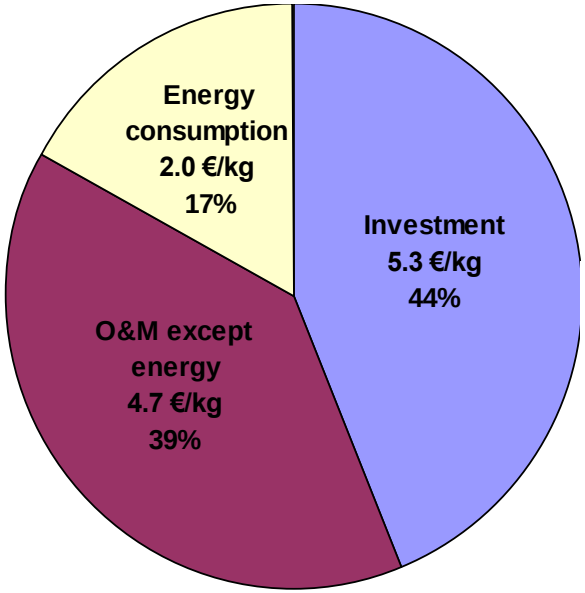
Energy cost

Hydrogen Production Cost

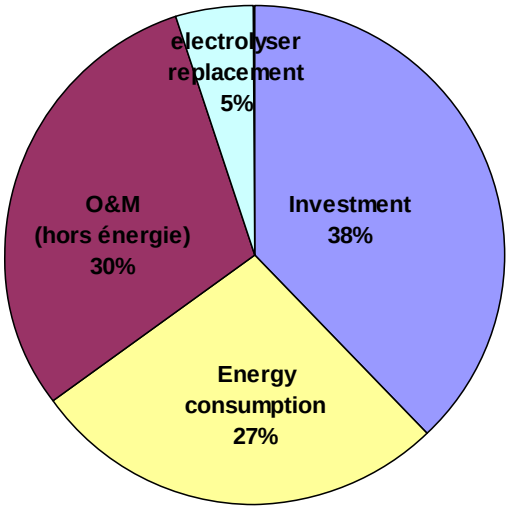
Final estimation : ~12 €/kg H_2

Nuclear & Hydrogen Production: Cost Assessment

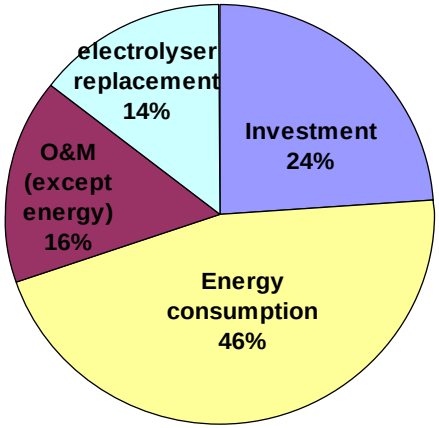
Results from I-tésé



S/I Cycle 12 €/kg



HyS Cycle 6.6 €/kg

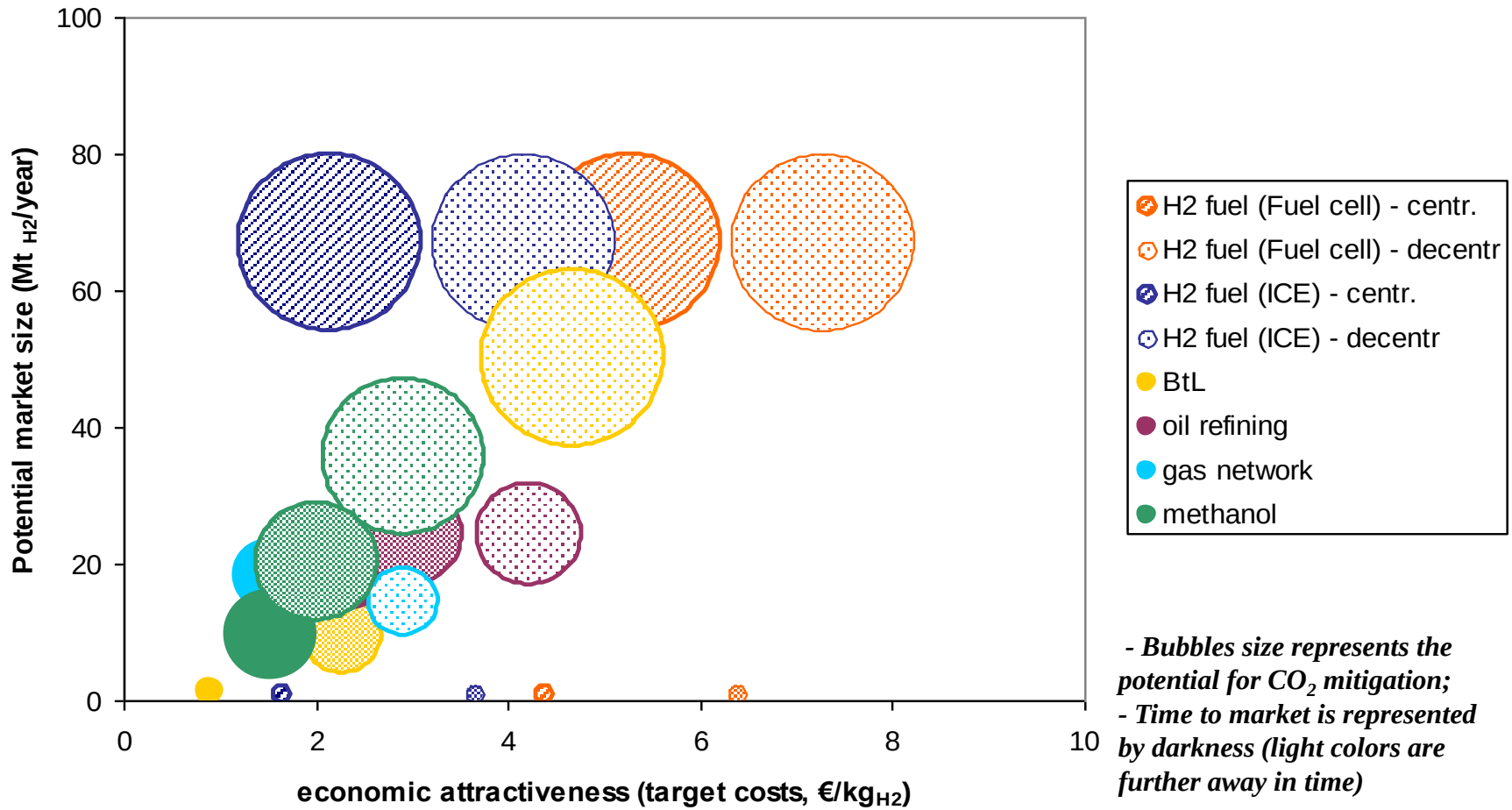


HTSE 3.6 €/kg

J. Leybros, T. Gilardi, A. Saturnin, C. Mansilla, P. Carles, Plant sizing and evaluation of hydrogen production costs from advanced processes coupled to a nuclear heat source. Part I: Sulphur-Iodine cycle – Part II: Hybrid-sulphur cycle. International Journal of Hydrogen Energy 35(3) 1008-1018 ; 1019-1028

Nuclear & Hydrogen Production: Market Attractiveness

Study from I-tésé



- Bubbles size represents the potential for CO_2 mitigation;
- Time to market is represented by darkness (light colors are further away in time)

C. Mansilla, S. Avril, J. Imbach, A. Le Duigou, Hydrogen as a substitute to fossil fuels: what are the targets? Prospective assessment of the hydrogen market attractiveness, Submitted to the International Journal of Hydrogen Energy

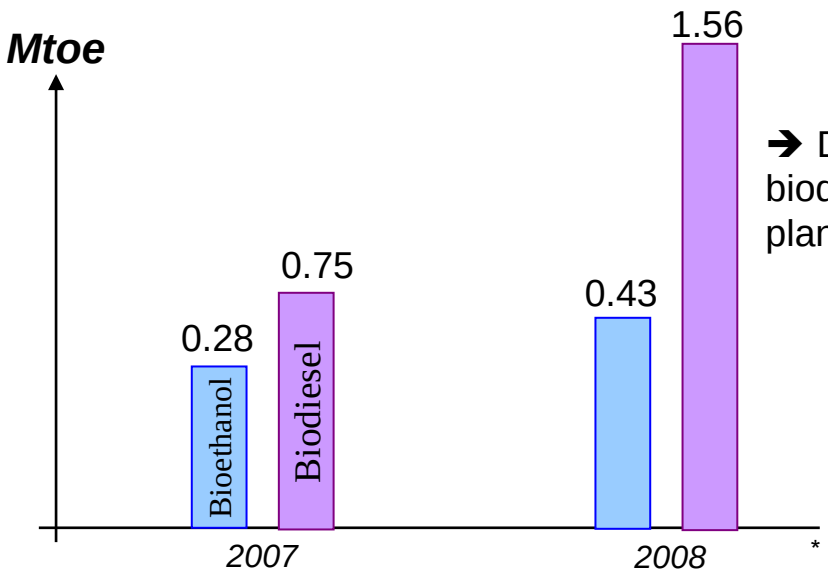
II. Biofuels Prospects

First generation biofuel consumption and production in France

➲**Consumption**

- In 2009, 1st generation biofuel consumption is 2.5 Mtoe (increase by 10.4% with regard to 2008)
- In 2009, the incorporation rate is equal to the French regulatory objective: 6.25%* (European incorporation rate: 4%).

➲ **Production**: as for the consumption, most of 1st gen. biofuel production is biodiesel with a worldwide key player, Diester Industrie



➔ Diester Industrie, first worldwide biodiesel producer, opened 3 new plants in 2005 (~250 kt/y each)

* EurObserv'ER 2009, UEPA 2009, EBB 2009

Second Generation Biofuels projects in France

① Biological process: Futurol

R&D demonstrator, development

- *Location*: Champagne-Ardenne region, located in an industrial site
- *A duration* of 8 years:
  - By 2008 to 2010 : pilot plant construction (~ 1000 tons dry biomass / year)
  - Prototype construction (~ 20 000 dry tons/year)
  - By 2015: industrialization by selling licenses
- *Budget*: 74 M€
- *Partnerships*: farmers, cooperatives, public and private research organizations.

② Thermochemical process: Bio T Fuel

R&D demonstrator, separated production steps

- *Location*: 2 different industrial sites, one for the torrefaction, one for the gasification
- *A duration* of 7 years, from 2009 to 2015:
  - Pilot plant construction (~ 25 000 tons dry biomass / year for the torrefaction plant, 15 MW_{th} for the gasification plant, R&D Fischer-Tropsch plant)
  - By 2015, industrialization by selling licenses
- *Budget*: 112,7 M€
- *Partnerships*: Sofipreoteol, IFP, CEA, Axens, Total, Uhde

② Thermochemical process: Bure-Saudron

Pre-industrial demonstrator, whole production chain

- *Location*: Champagne-Ardenne-Lorraine region
- *A duration* of more than 20 years:
  - Until 2015: plant construction and start up of the pre-industrial plant (~ 75 000 dry biomass tons/year)
  - Operation: from 2015 to 2034
- *Budget*: in progress
- *Partnerships*: industrial companies positioned on the whole BtL value chain

SYNDIESE Project: from Nuclear to Biomass

Bure-Saudron BtL demonstrator,

located in the East of France, between Meuse & Haute-Marne departments,

is involved in a twofold national strategy

Economic accompanying program

Reinforce the economic measures linked to Bure-Saudron's research laboratory on long lived radioactive waste in deep geological formation (06/28/2006 law)

Start the industrial development of the Second generation biofuels
(Environment Round Table)

- Reduce French fossil fuels energy dependence
- Not in competition with food
- Relying on additional biomass resources, not in competition with existing wood industries in the region
- Reduced GHG emissions compared to fossil fuels
- High quality, use in a classical diesel engine, acceptance in current fueling stations

SYNDIESE Project Objectives

① First Demonstration in France of a complete BTL chain

- ❑ Technological demonstration
  - Integration of the most efficient technologies
  - Biomass conversion efficiency improvement through the addition of hydrogen into the process (world first)
- ❑ Pre-industrial demonstration (estimated rate 30%, target 40%)
  - 75 000 t/y of dry biomass implying the set up of a specific supply
  - 23 to 30 000 t/y of naphta, biodiesel and biokerosene
  - 5 100 t/y of hydrogen, 41 000 t/y of oxygen
- ❑ Economic demonstration
  - Profitability of the economic model at a local level

② The regional impact

- ❑ Work involving over 200 people during 2 years
- ❑ Creation of 100 jobs (plant, biomass harvesting and transport, biofuels distribution,…)
- ❑ Regional assets by valorization of ligno-cellulosic forest-based resources
- ❑ Contribution to the development of a new industrial scheme: visibility at a national, European and international level

Nuclear & Biofuels

SYNDIESE PLANT'S PROJECT OWNER: CEA

$$C_6H_9O_4 + 2\,H_2O \rightarrow CO + H_2 \rightarrow (-CH_2-) + H_2O$$

H_2

Pre-treatment	Gasification Syngas CO, H_2 $H_2/CO \sim 1$	Purification	Fischer – Tropsch synthesis	Hydro-cracking

β-plant (Choren)

Rectisol (AirLiquide/Lürgi)

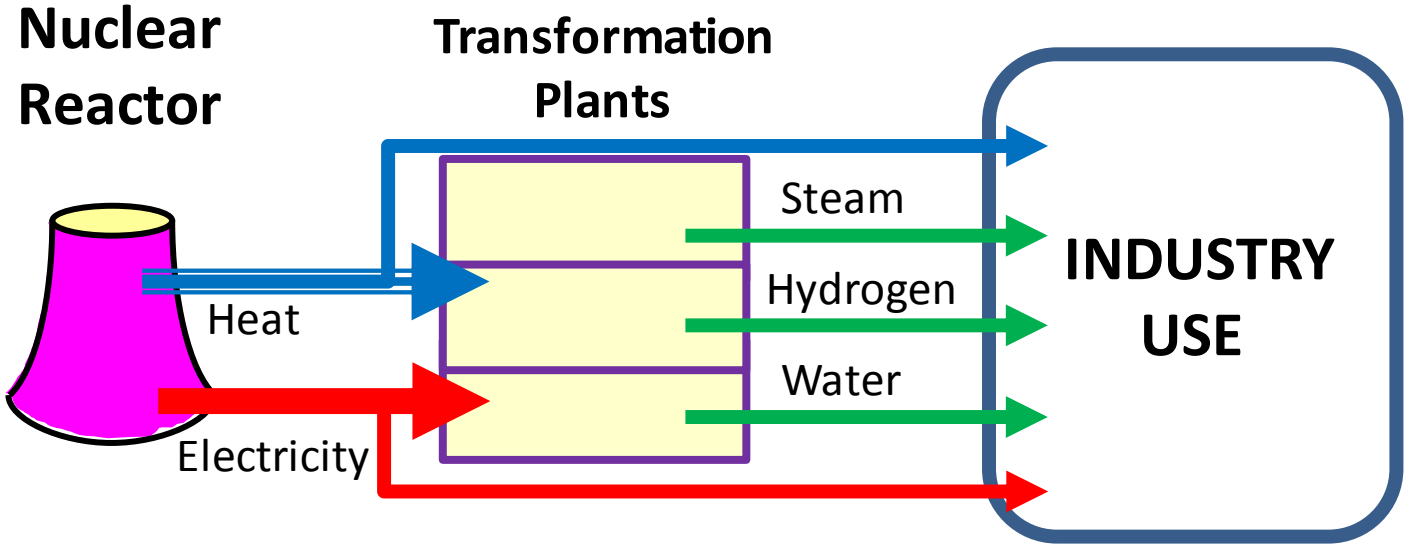
Sasol (AirLiquide/Lürgi)

UOP

CNIM: project management
GTL.F1: Fischer-Tropsch synthesis, hydrocracking, catalysts
SNC-Lavallin, Foster Wheeler France, Bertin Technologie: engineering

III – Industrial Nuclear Hybrid Prospects

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

One example: Oil Refinery

Energy needs

Electricity	**117**	kWhe/t
Heat	**551**	kWh/t
Hydrogen	**5.9**	kg/t
Water	**1.0**	m3/t

TOTAL Oil Refinery in Gonfreville (Normandy, France)

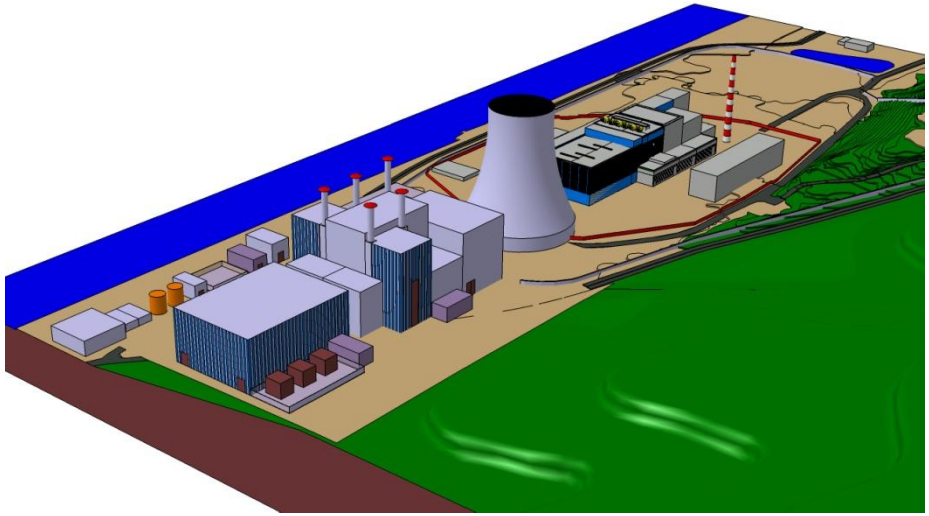
Annual capacity of **16 Mtons** of refined gasoline

(uses **10%** of output products to generate electricity, steam and hydrogen for its own needs)

Requires a cogeneration plant and a SMR plant built on site

One example: Oil Refinery

A single Sodium Fast Reactor (600 MWe) can provide all the needed inputs to feed the oil refinery plant

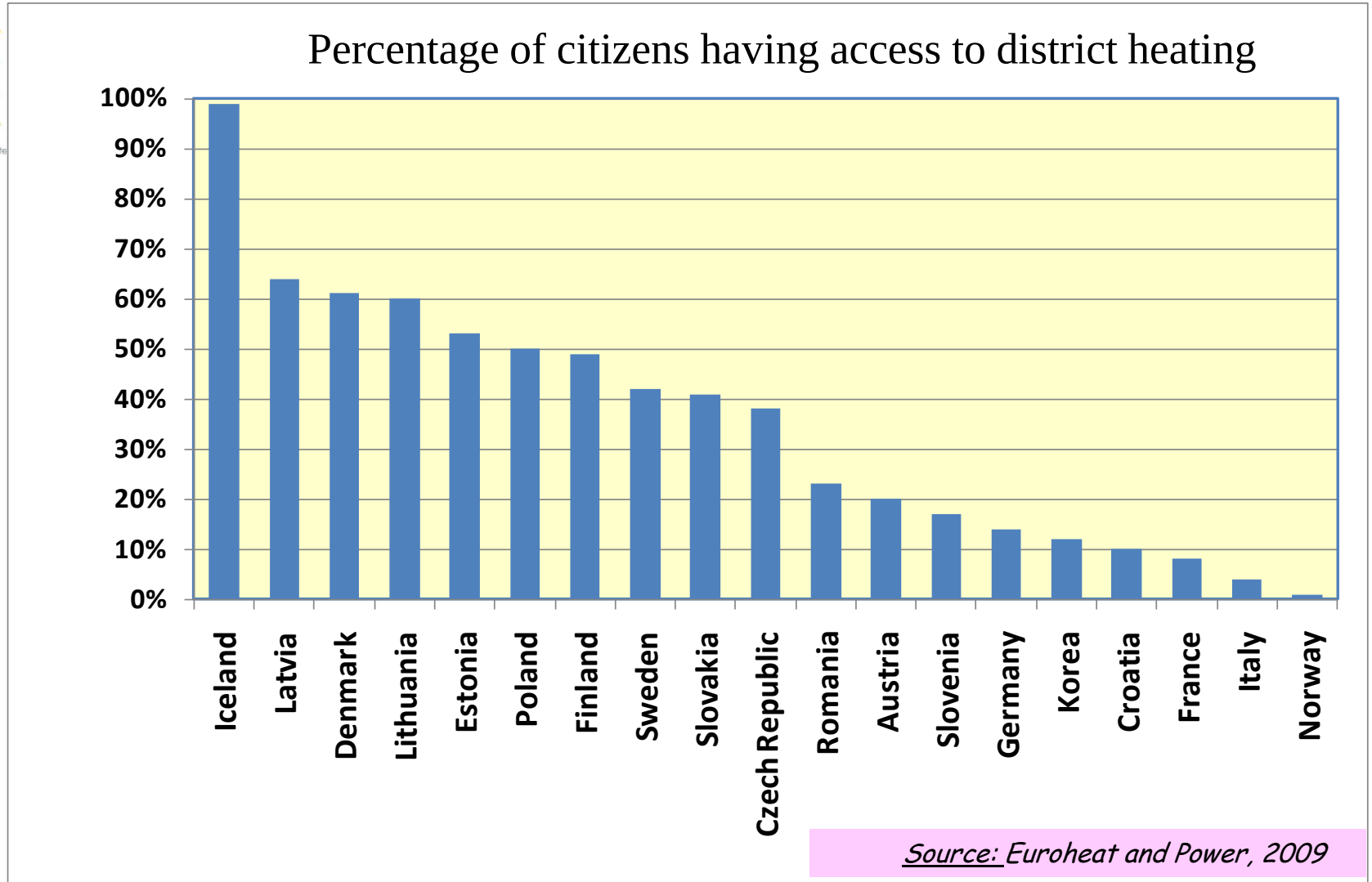


Outputs of the plant

Electric power	**250**	MWhe
Steam at 400°C	**450**	t/h
Hydrogen	**13**	t/h
Water	**2300**	m3/h

Can save about **1.5 Mtons/y of refined gasoline** (worth 1 G€/year) and reduce annual GHG emissions by **4 Mtons of CO_2**

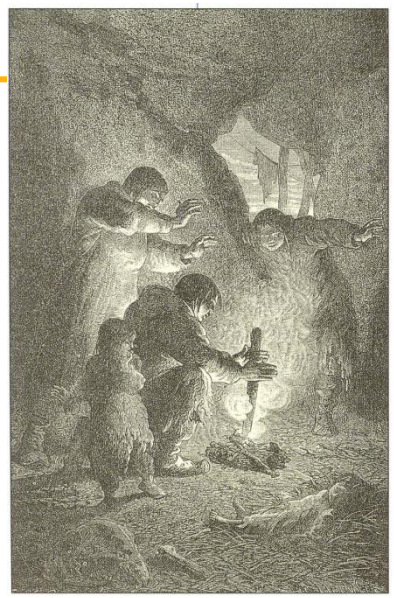
IV - District Heating Prospects



Source: Euroheat and Power, 2009

District Heating is developed in northern European countries

Energy and Heat



Heat has always been an issue for mankind

In 2008, the total world energy production amounted to **12000 Mtoe**

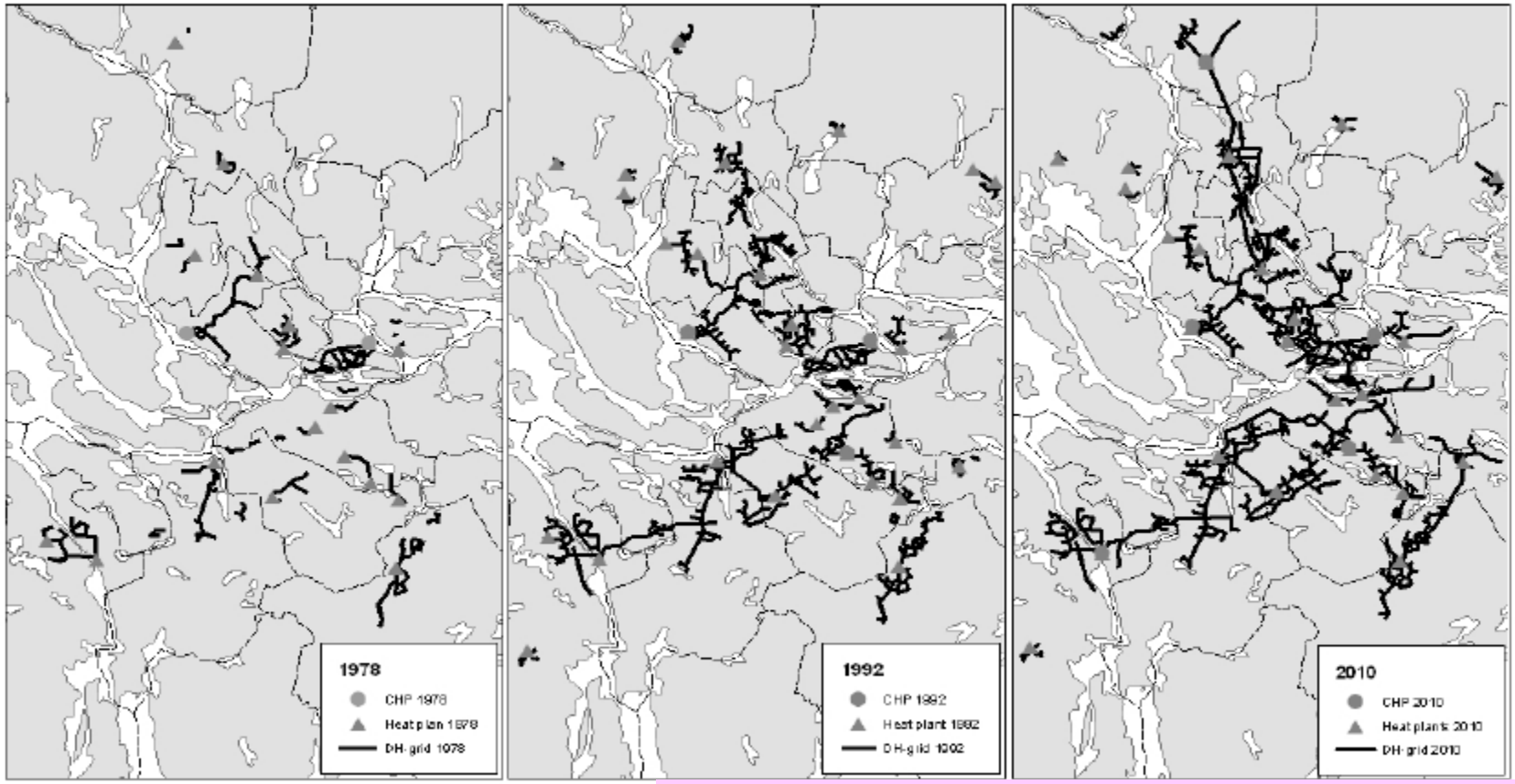
Approximately one third of it (4000 Mtoe) was used as **heat.**
50% of this heat was for residential homes, commercial businesses and public services (hospitals, schools, universities, offices)

Total space heating and cooling demand **~ 20000 TWh**
World District Heating and Cooling **~ 2500 TWh**

The potential of DHC increase is very large

District Heating

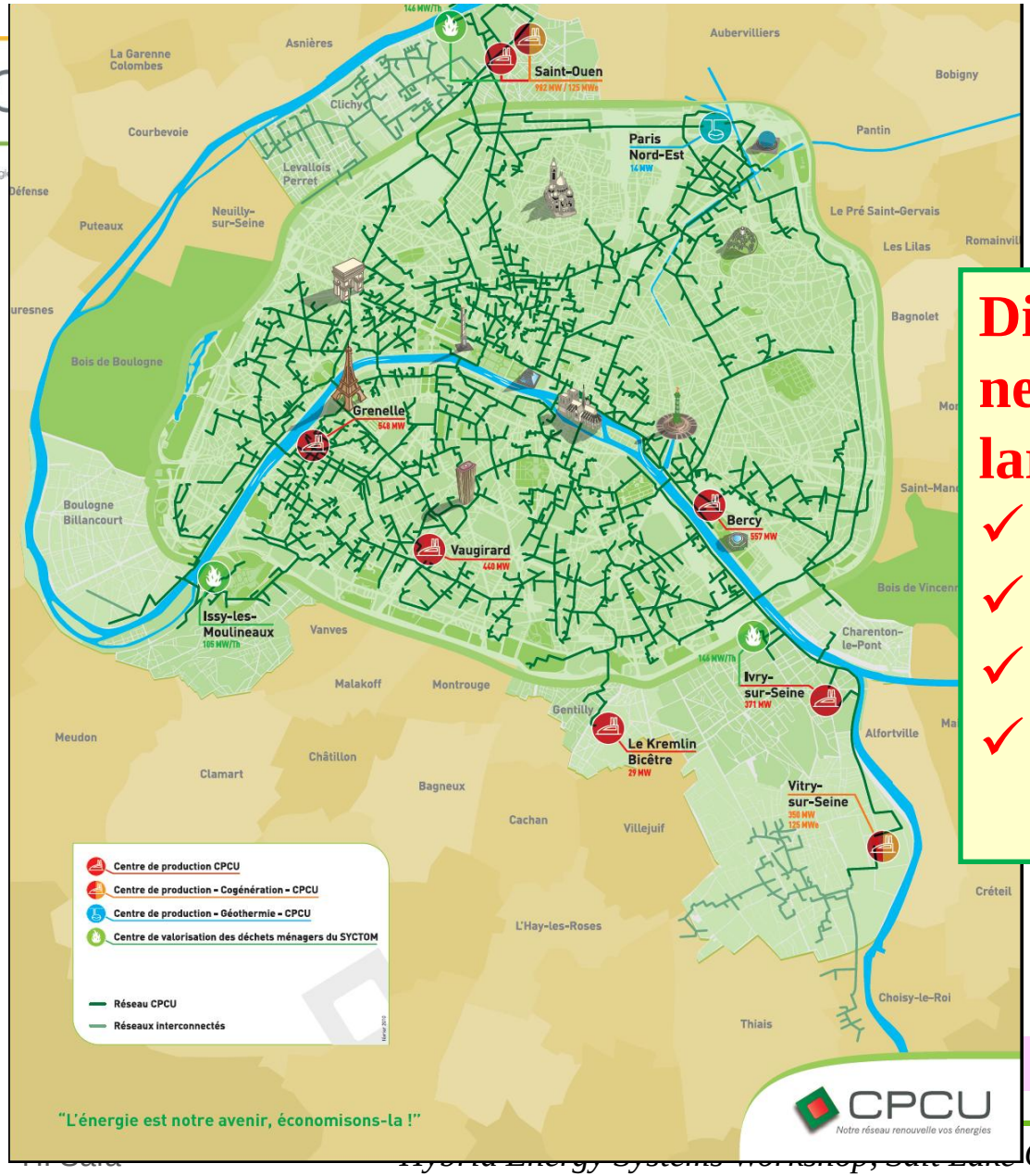
The Development of the District Heating Systems
in Stockholm County - Networks of Heating



Source: D. Magnusson, Linköping University, Sweden

District Heating networks are expanding

District Heating in large cities



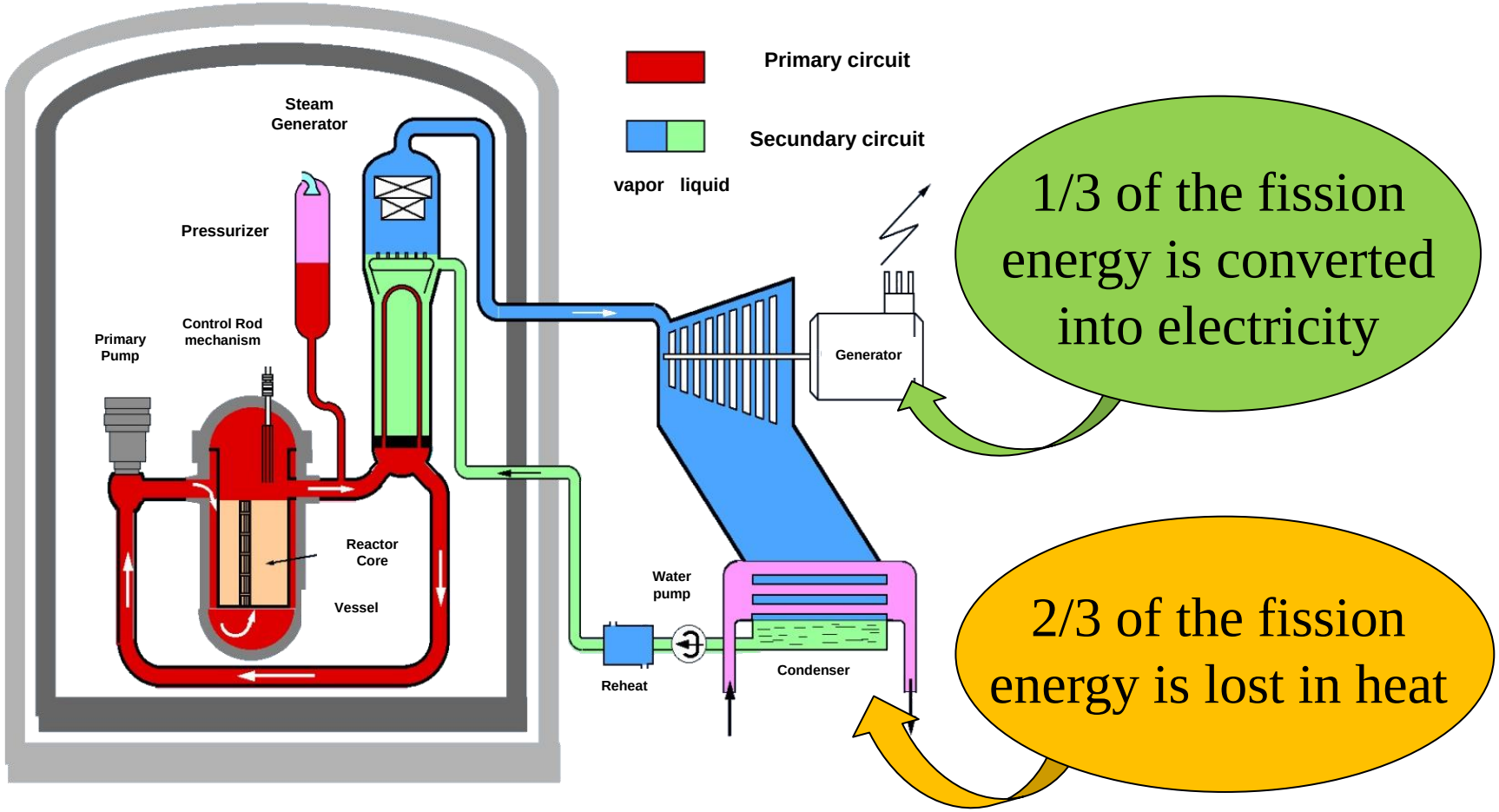
District Heating network in Paris is the largest in France:

- ✓ **2 x 440 km**
- ✓ **5700 GWh**
- ✓ **25% of total heating**
- ✓ **8 production sites**

Source: CPCU at www.cpcu.fr

Recovery of Nuclear Heat

Nuclear Power Plant



Exergy

- Ambient temperature heat is of no use
- The **Exergy** concept allows to also valuate the temperature at which the heat is produced.

$$E = H - T_0 . S$$

Exergy of a quantity of heat Q at a temperature T $\longrightarrow$ $E = Q.(1 - \frac{T_0}{T})$

Case of 1300 MWe Nuclear Power Plant

T hot	T cold	Wp	Qi	W_{HP}	W_{BP}	W_{gross}	Qs	η carnot	η
(°C)	(°C)	(MW)	(MW)	(MW)	(MW)	(MWe)	(MW)	(%)	(%)
288	**39**	**9**	**3 920**	**-417**	**-936**	**1 353**	**-2 562**	**44.4%**	**34.3%**

Exergy: Electrical Efficiency

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

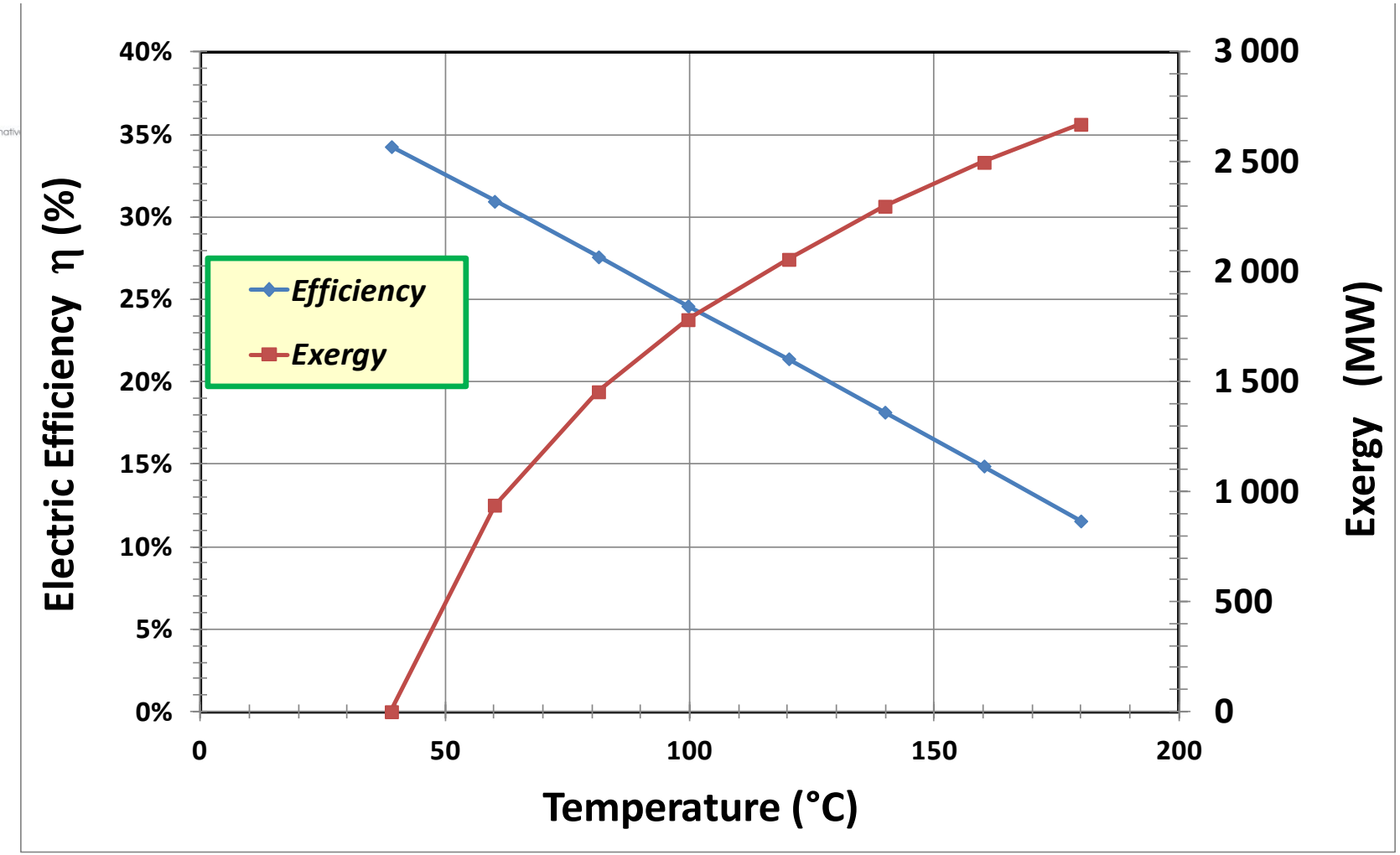
- W_{BP} on the Low Pressure Turbine decreases with increasing temperature

$$Q_{out} \approx Q_i - |W_{HP} + W_{BP}|$$

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

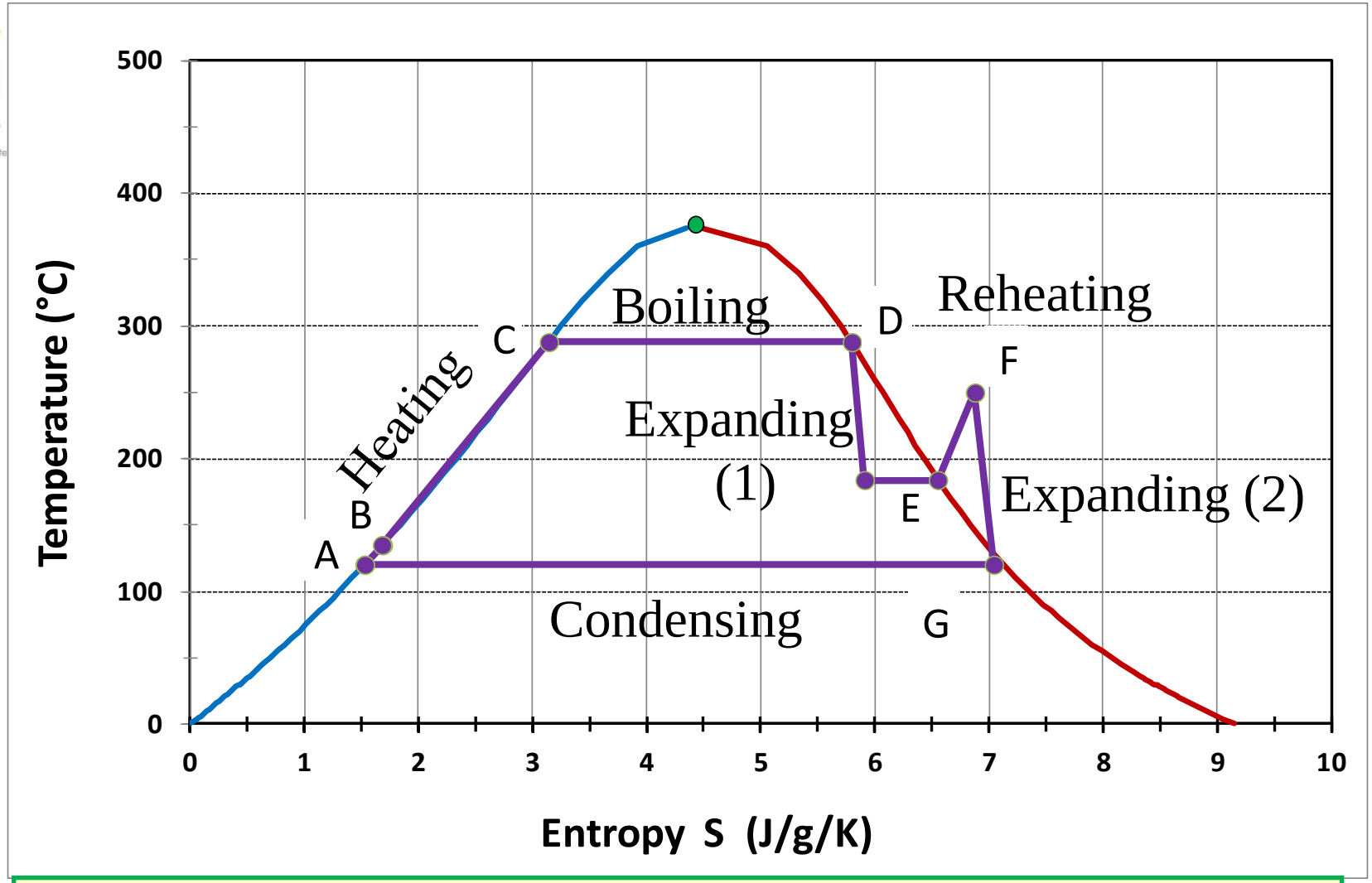
- The output exergy increases with increasing temperature

Electrical Efficiency



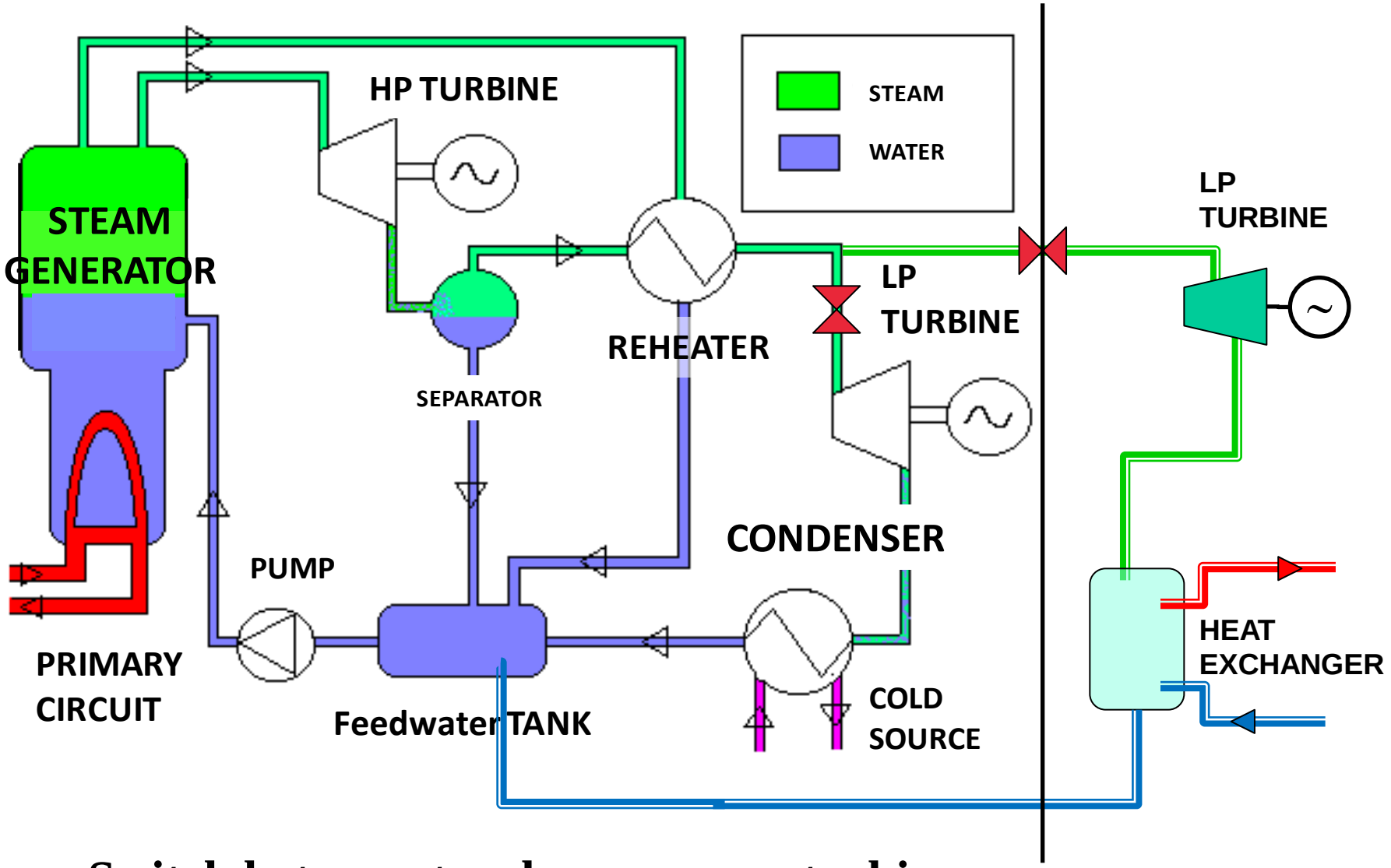
Trade-off between electric output and Exergy

Thermodynamics: The Rankine cycle



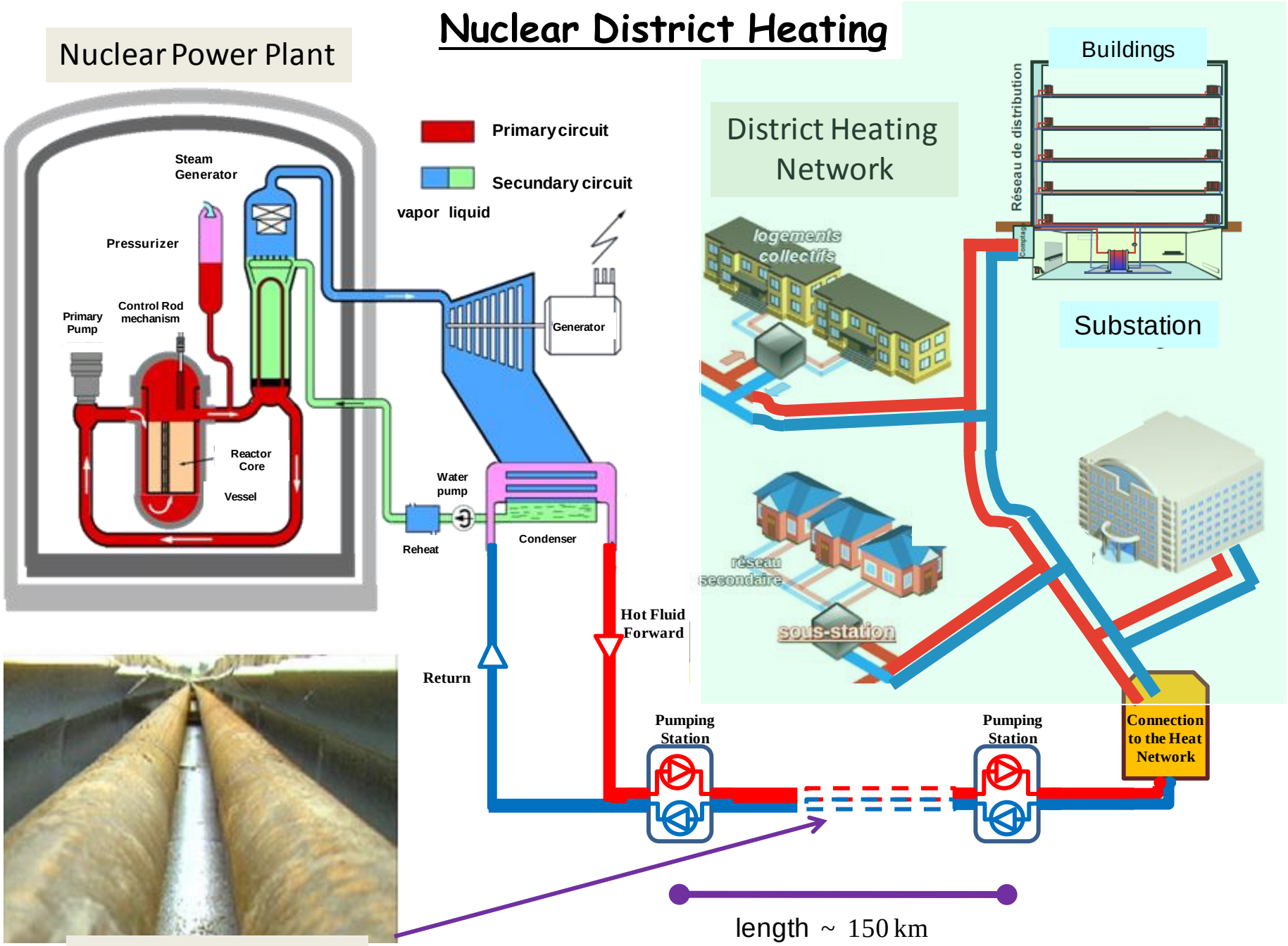
Modify the low pressure turbine: outlet at 2 bars

Thermodynamics: The secondary circuit

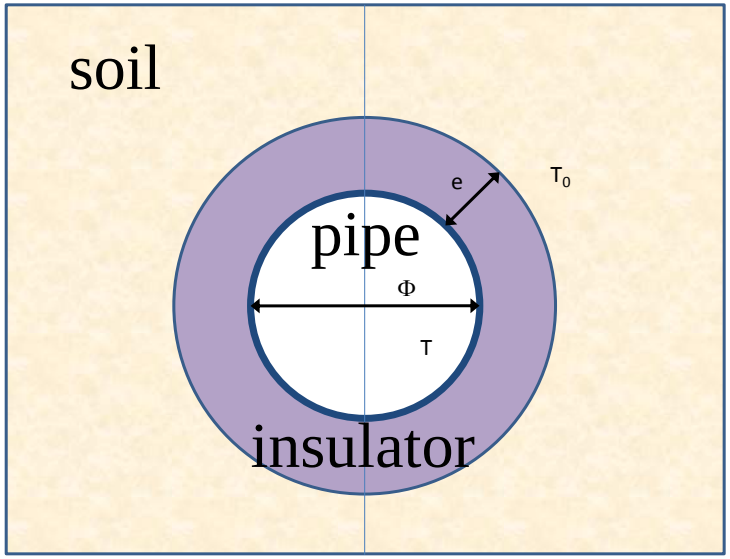


Switch between two low pressure turbines

Nuclear District Heating



The Main Transport Line: Thermal Losses



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

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

Total heat loss ~ 2% of the transported power!

Loviisa 3 Nuclear Power Plant Project in Finland

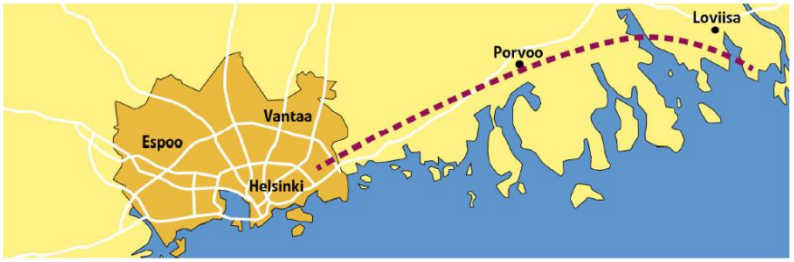
Loviisa 3 CHP – heat transport on a long distance

Heat transport in pipes

- Mounting in a rock tunnel, cross section 30 m^2
  - stable conditions
  - positive maintenance aspects
- Near surface installation
  - lower costs
  - environmentally more challenging

District heat transport system

- Distance over 75 km (Loviisa – eastern Helsinki)
  - 2 x Ø 1200 mm pipes, PN25 bar, Q = 4 - 5 m^3/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



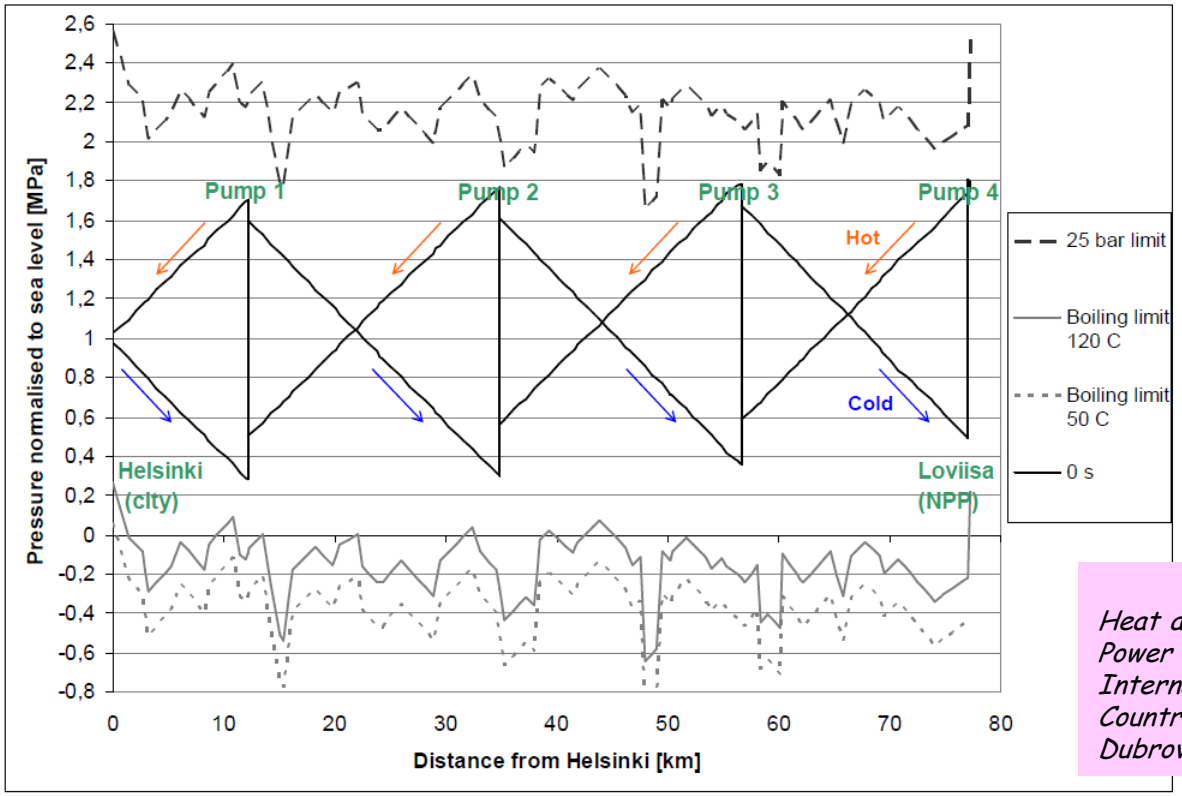
Source: Harri Tuomisto, FORTUM, Finland , October 2010

The Main Transport Line : Pumping Power

Pressure drop along the pipe

$$\left(\frac{dH}{dz}\right) = C.\ \frac{8\,P^2}{\pi^2\,\rho c_p^2\,\Delta T^2\,\Phi^5}$$

- Diameter Φ
- Heat power P



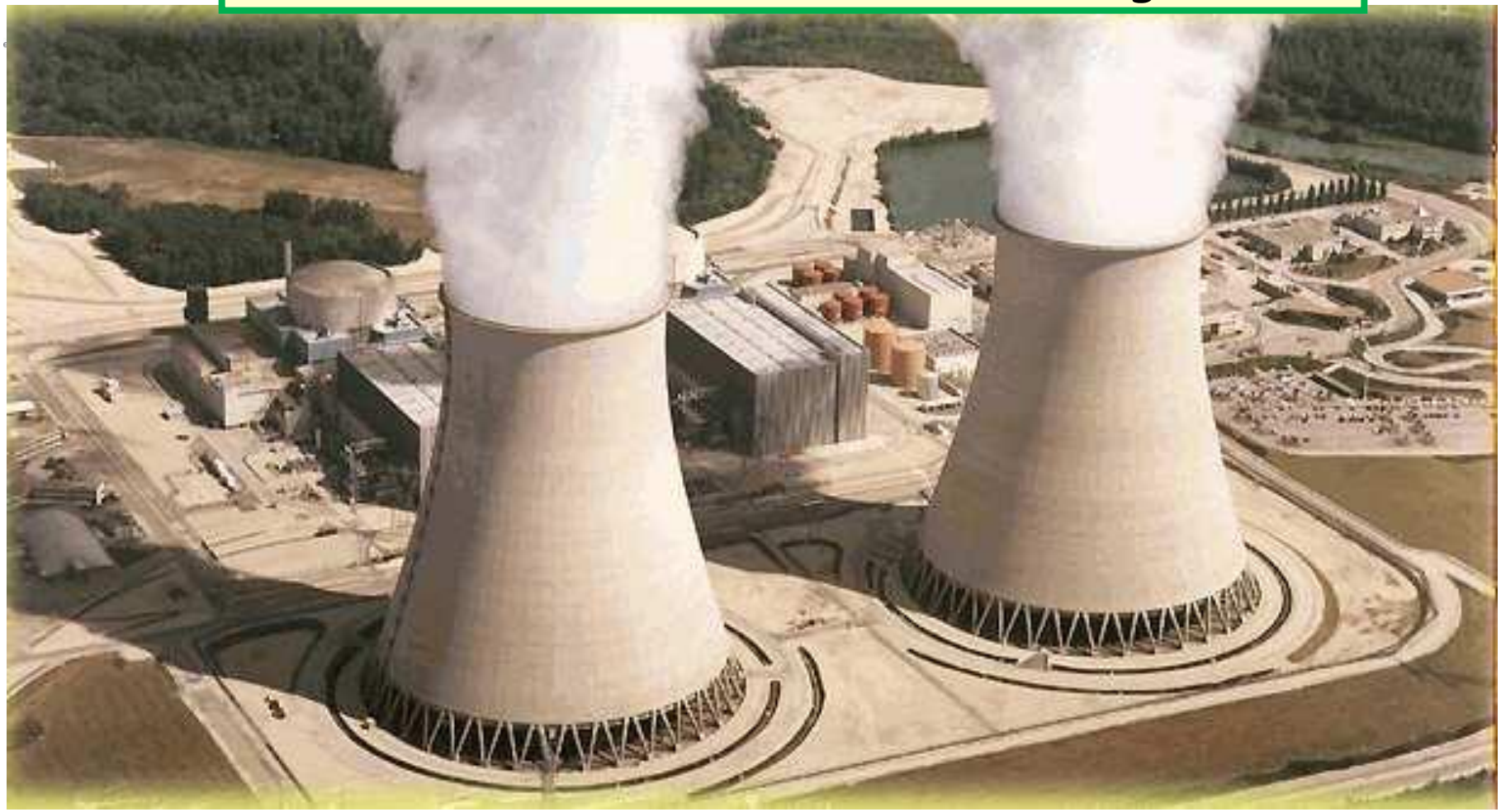
Loviisa 3 Nuclear Power Plant Project in Finland

Source: N. Bergroth, "Large-Scale Combined Heat and Power (CHP) Generation at Loviisa Nuclear Power Plant Unit 3", Proceedings of the 8th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids, Dubrovnik, Croatia, (16-20 May 2010)

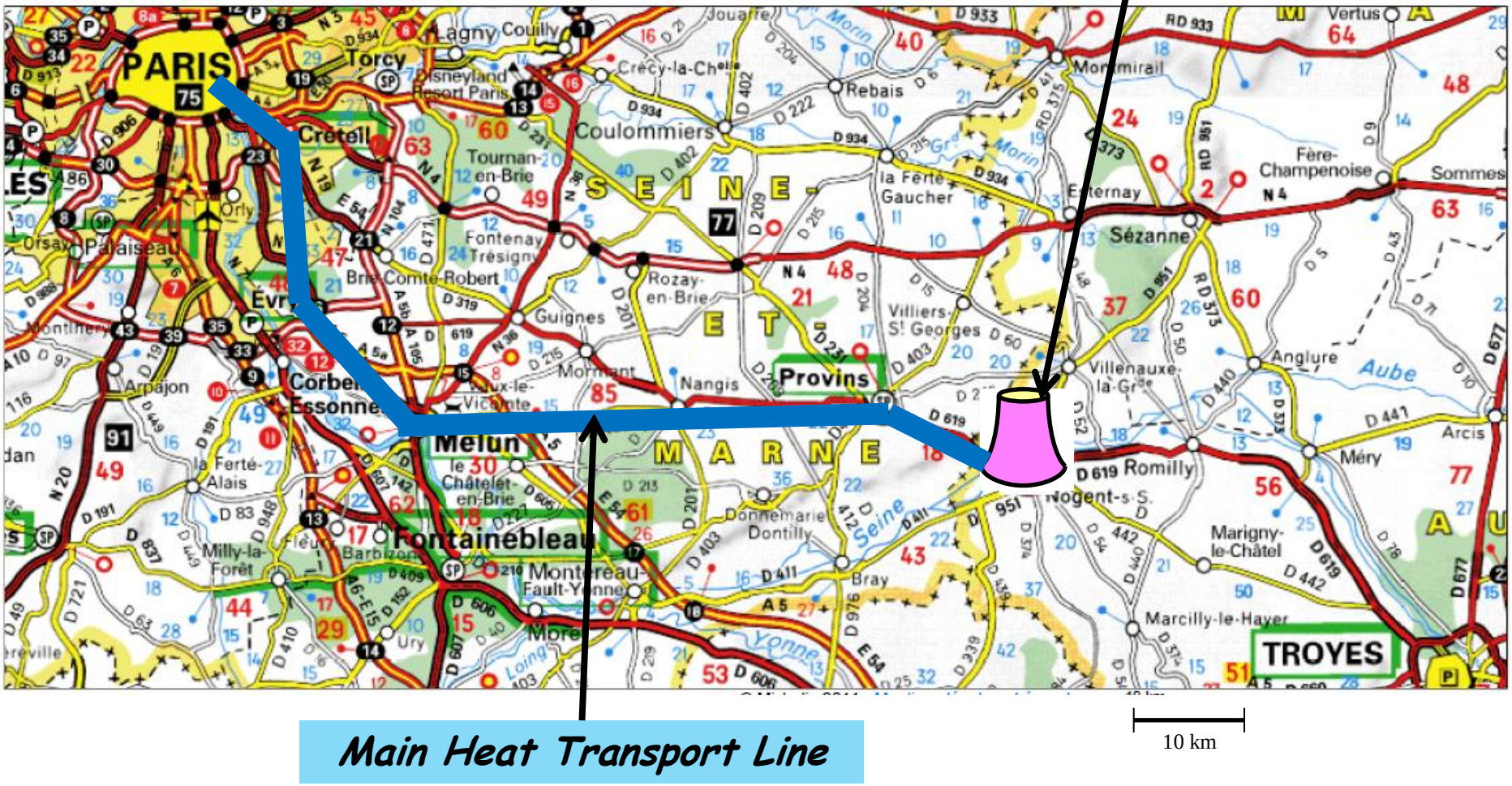
Install pumping stations every ~ 20 km

The Nogent-sur-Seine Power Plant

Two 1300 MWe reactors with cooling towers



The Main Transport Line: An example



Design Calculation

Need to optimize the whole system:
(NPP + Main Transport Line + District Heating Network)

Two major parameters

1. The Temperature T of the fluid

   Electric Efficiency, Heat Losses

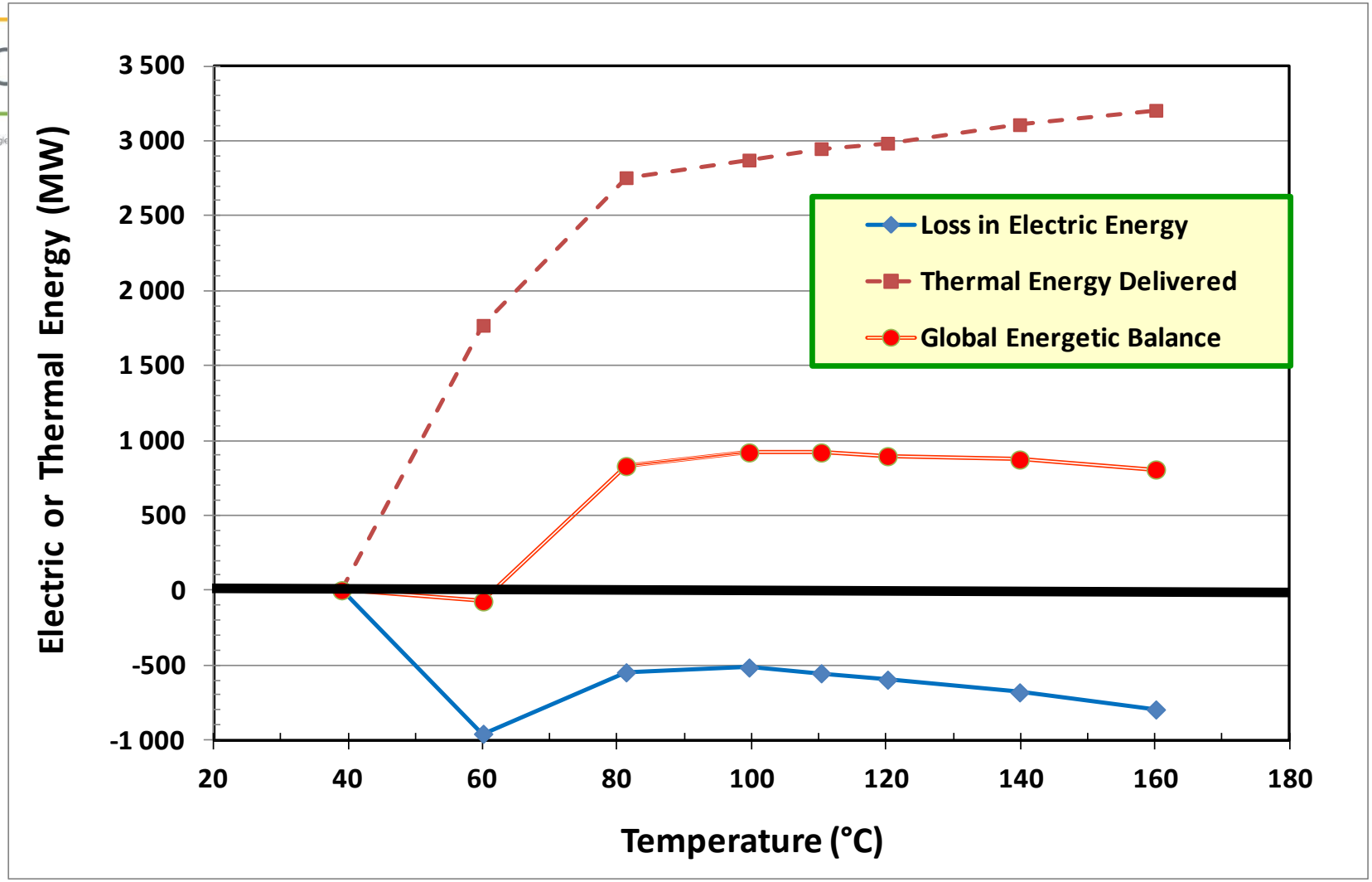
2. The Piping Size Φ

   Pumping Power

<u>Hypothesis:</u>

- Operation time: 1/3 cogeneration, 2/3 electric
- Value of 1 MW thermal = 50% of 1 MW electric
- 2 lines of 1500 MW capacity each

Optimization Results



A gain equivalent to 920 MWe (+70%) can be achieved !!

Economics and CO2 emissions

Implementation on Nogent-sur-Seine reactor (1300 MWe)

150 km long main heat transport line

- Additional heat production of 9 TWh
  Gain of +540 M€/year
- Reduction of electric production -1.8 TWhe
  Loss of -180 M€/year

Gain of +360 M€/year

Large reduction in CO_2 emissions

CO_2 emissions from district heating in Paris

60% fossil fuels (gas boilers, coal, oil)

40% waste incineration

Average of 195 gCO_2/kWh

Huge savings in CO_2 emissions

Avoid 1.7 Million tons of CO_2/year

Conclusions

- There is a lot of prospects for hybrid applications of nuclear energy including **district heating, industrial steam, hydrogen production and biofuels.**

- A large scale demonstration of **second generation biofuels** is undertaken in France in the frame of the SYNDIESE project.

- **Fast reactors** have a potential to provide **industrial steam** at the needed required temperatures (e.g. oil refinery)

- Heat recovery from **existing Nuclear Power Plants** appears to be extremely attractive for **District Heating**

- The primary heat transport line can be designed with low thermal losses (a few percents) even for **long distances** (> 100km)

- NPP heat recovery provides a **high energetic gain** (+70%), is economically competitive and offers large **reduction in CO_2 emissions**