MICHELANGELO NETWORK

Competitiveness and sustainability of nuclear energy in the European Union

(MICANET)

EU-funded Project FIKW-CT-2001-20180

Work Package 4

NON-ELECTRICITY APPLICATIONS OF NUCLEAR ENERGY

Synthesis of information on non-electricity applications of nuclear energy:

Data collection on available non-nuclear processes and coupling with nuclear reactors

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FOREWORD

This data collection is used as working material for the Work Package 4 in the MICHELANGELO-Network.

It is not intended to have a complete dataset for the selected non-electricity applications but to compile step-by-step interesting background information which might be used in the final reports and has already been in part supplied for Gen IV technical groups on the Very High Temperature Reactor and the Energy Product Cross Cut Group.

The material collects general aspects on non-electricity markets as well as more detailed information on specific processes including the coupling of a nuclear reactor.

Valuable information could be taken from the very detailed study ‘Utilization of Process Heat in the Chemical and Related Industries’ produced by the process engineering company LURGI which provides detailed data on nuclear process heat applications and has been made available to MICANET on SINTER (Doc. No.: MICANET-02/04-D-4.2.1).

Another interesting background paper on ‘The Market Potential of Modular High-Temperature Reactors’ from INTERATOM/EST [14] gives a survey on industrial applications beyond dedicated electricity generation as expected Mid of the 1980 but partially still valid today. This report has also been scanned and can be downloaded from SINTER (Doc. No.: MICANET-02/04-D-4.3.1)

Recent information from the European High Level Group on Hydrogen and from the EC Green Paper on security of energy supply have also been included with regard to the long-term market perspectives.

Diverse other publications on nuclear and conventional technologies have been analyzed for extracting and compiling relevant information.

Acknowledgements

The authors like to thank all contributors to this data collection and especially Dr. Schad, formerly Lurgi, Mr. Weisbrodt and Dr. Jaegers, both formerly INTERATOM, to provide detailed information from former and actual studies and to give valuable advice for future R&D activities.

Further valuable information has been elaborated together with the ‘Energy Product Cross-Cut Group’ allowing for mutual benefit during the intensive collaboration under the Gen IV Road Map activities.

Executive Summary

Due to the fact that about two thirds of the final energy consumption are used as heat for different purposes and on different temperature levels, a considerable potential market may exist for nuclear energy beyond dedicated electricity generation. However, the penetration of the non-electricity applications by nuclear energy has only been done on a very low level, despite rather good experiences in the few examples on the Western hemisphere (e.g. district heating from Beznau plant, CH; process steam for aluminum oxide production in Stade, D; heat for D_2O production at Bruce, CAN; desalination in Japanese LWR). Some more extended use of nuclear power plants for district heating has been made in the Eastern European Countries and in the former Soviet Union. De-facto, nuclear energy has been only focused on electricity production and its capabilities for CO_2 reduction in the industrial and private heat consumption sector have nearly not yet seriously been taken into account or implemented..

Reasons for this situation can be assumed in technical and psychological barriers as heat applications cannot be done in remote places but have to be situated near to the consumers and are associated with the additional risk of contamination transported from the nuclear heat source to the consumer. This is different in case of electricity consumption which does not imply transport of a medium. The technical consequence from this perception is that non-electricity applications of nuclear energy will not only need a very high safety level with regard to the exclusion of massive release of radioactivity to be a ‘good neighbor’ but also has to show an exclusion of contamination of products and heat transfer media.

An example for these problems is the use of nuclear energy for sea water desalination which is technically and economically feasible (see EURODESAL project) but is not yet demonstrated in industrial scale and accepted by the public despite growing drinking water shortage in many arid areas. Nevertheless, simple non-electric applications like district heating and desalination may provide a psychological break-through, open new markets and contribute significantly to CO_2 reduction, too.

Additionally, the First-of-A-Kind problematic for a new nuclear system in a new application area will raise considerable impediments for a market introduction and will need international support and consortia.

Although still preliminary, the literature search on potential non-electricity applications clearly showed that neither dedicated electricity production nor dedicated heat generation will be a sustainable approach for the future under economic and environmental aspects.

This is especially true for low temperature reactor concepts only dedicated to desalination and district heat supply, despite their simplicity, as they cannot compete to Combined Heat and Power (CHP) generation which takes benefit from the added value of electricity sales. This may also apply to other applications where electricity will be an essential by-product to improve economics and to provide electricity for industrial sites.

A first conclusion from these facts is that “Non-Electricity Applications” might be the wrong target for the Work Package 4. However, the symbiosis of electricity generation combined with the use of the heat on different levels especially of waste heat is a more promising objective than ‘non-electricity’ applications, only.

Therefore, it is strongly recommended to investigate in more detail the CHP options and market requirements for nuclear CHP as it offers a considerable potential for fuel resource saving due to high overall efficiencies, improved economics and reduction of CO_2 emissions, already in the near and medium term.

A detailed analysis will be necessary why this option is not yet applied in large industrial scale although the basic technology seems to be available. It can be expected that a nearly 'zero-release' safety and operation approach will be a precondition to explore the CHP market. These industrial and public requirements may be much more stringent and beyond the present state of the art for dedicated and remote electricity producing nuclear reactors. Thus, CHP represents a challenging R&D target even if very robust technology and wide safety margins will have to be addressed.

From an economical and thermal efficiency point of view, high operational temperatures are the key for CHP because electricity generation losses can be reduced when increasing operational temperatures. In principle, this can in future also be done by reactors with liquid metal, super-critical water or super-critical CO_2 coolant, but it appears reasonable to focus on HTR, in the near and medium term, because this technology is rather advanced and temperature levels as well as safety features seem to favor HTR for CHP applications. A more detailed evaluation for this assumption is given in deliverable 4.1. Anyhow, most of the results elaborated for HTR can be back-extrapolated to other reactor concepts, too.

Although large LWR could already be applied for CHP, the low operational temperatures will degrade the efficiency for electricity production in case of significant extraction of high quality steam or heat for non-electric purposes. On the other hand, the thermal power levels of LWR are much too large to be consumed by any CHP application. Thus, the power size of a nuclear heat source has to be adopted to the heat requirements to reach high thermal efficiencies [13].

The data elaborated for different CHP applications in EU clearly show that unit sizes of some hundred MW are sufficient. A modular arrangement (2-6 units) will be necessary for redundancy, reliability and reserve capacity reasons which again reduces power size per modular unit. However, smaller power size allows for simplicity and robustness by higher safety margins even at higher operational temperatures if necessary at all. Under this background, it should be investigated whether steady increase of power for modular reactors being deployed for electricity generation is the correct approach for CHP applications which might need a special reactor design and system lay-out e.g. with combined gas and steam turbine cycle as applied in the steadily growing conventional CHP market.

Different 'non-electricity' applications beyond classical CHP have been addressed in former studies and within Work Package 4:

- Mineral Oil Technology (Heavy Oil Recovery, Crude Oil Refinery, Crude Oil Recovery from Oil Shale, Crude Oil Recovery from Oil Sand)
- Synthesis Gas from Hydrocarbon (Methanol Production, Ammonia / Fertilizer)
- Petrol Chemistry (Naphtha Cracking)
- Gas Production (Hydrogen Production, Coal Gasification in a Circulating Fluidized Bed)
- Iron Production (Pelletizing of Iron Ore, Sintering of Iron Ore; Direct Reduction)
- Non-Ferrous Metals (Alumina Oxide Production, Copper , Zinc , Lead)
- Miscellaneous (Cement Production, Coarse Ceramic Industry)

A first screening identified the most promising additional applications, such as

- Crude oil refineries and petrochemistry
- Hydrogen production for present and future markets
- Alumina Oxide Production

The collected data shows that there is already a huge potential market in this area without waiting for a future 'hydrogen economy'. Substitution of process heat can be done by use of steam and heat over a wide temperature range. Special components for the necessary chemical processes as illustrated in this paper have to be developed as pressures and temperatures of the nuclear heat supply source have to be matched to the conventional processes which – in part – are operated at lower pressures (e.g. steam reformers).

It should be noted that any use of nuclear process heat directly reduces the significant CO_2 emissions from the above mentioned processes even if not that spectacular as a pure hydrogen economy!

Data from the EU High Level Group show that the projection of hydrogen demands stay on a rather high level for refineries, petrochemicals, ammonia, steel etc. even beyond the scope of the forecast whereas the niches and additional markets for hydrogen are slowly developing with an uncertain slope not before some decades from now. The indicated 'tensions due to oil price increase' might not only favor hydrogen technologies but also other technologies to prolong oil resources by tertiary oil recovery, oil shale processing or coal gasification. This trend was already experienced in the past oil crises showing that these technologies are near to competitiveness if the oil price stabilizes on a slightly higher level. In addition, any progress in CO_2 sequestration will at least prolong the 'fossil era' for many decades.

Consequently, it is highly recommended not only to focus on the 'ideal' CO_2–free hydrogen economy but to follow in parallel a more pragmatic approach to reduce CO_2 by providing CO_2 – free process heat to crude oil processing (> 200GW), to present hydrogen production (> 60 GW) by natural gas reforming. to aluminum oxide production (>14 GW), production of petrochemicals and CHP. The power figures indicated above represent the worldwide process heat consumption in the selected areas and clearly show the considerable potential for nuclear process heat in an already existing market and the chances for CO_2 reduction in addition to the envisaged hydrogen economy. It has to be noted that the tables on process heat demands in refineries clearly show that most of the process heat is consumed as steam and at moderate temperatures and that the hydrogen needs are not dominant even though they will be growing with ongoing degradation of oil qualities.

Concerning hydrogen production, all technologies starting from electrolysis using (cheap) surplus power from existing LWR via allothermal steam reforming using heat from HTR towards high temperature electrolysis and thermochemical cycles have to be taken into account to have a more robust approach on CO_2-reduction not relying only on very ambitious developments of new technologies and uncertain implementation of new markets. Synergies between hydrogen (protons) and electricity (electrons) have to be used (HYDRICITY) for optimized energy supply systems due to the mutual re-conversabilities (e.g. electrolysis vs. fuel cells).

Combined Heat and Power by modular nuclear reactors for various industrial purposes is another important field where nuclear energy can reduce CO_2 emissions at competitive conditions already in the near and medium term.

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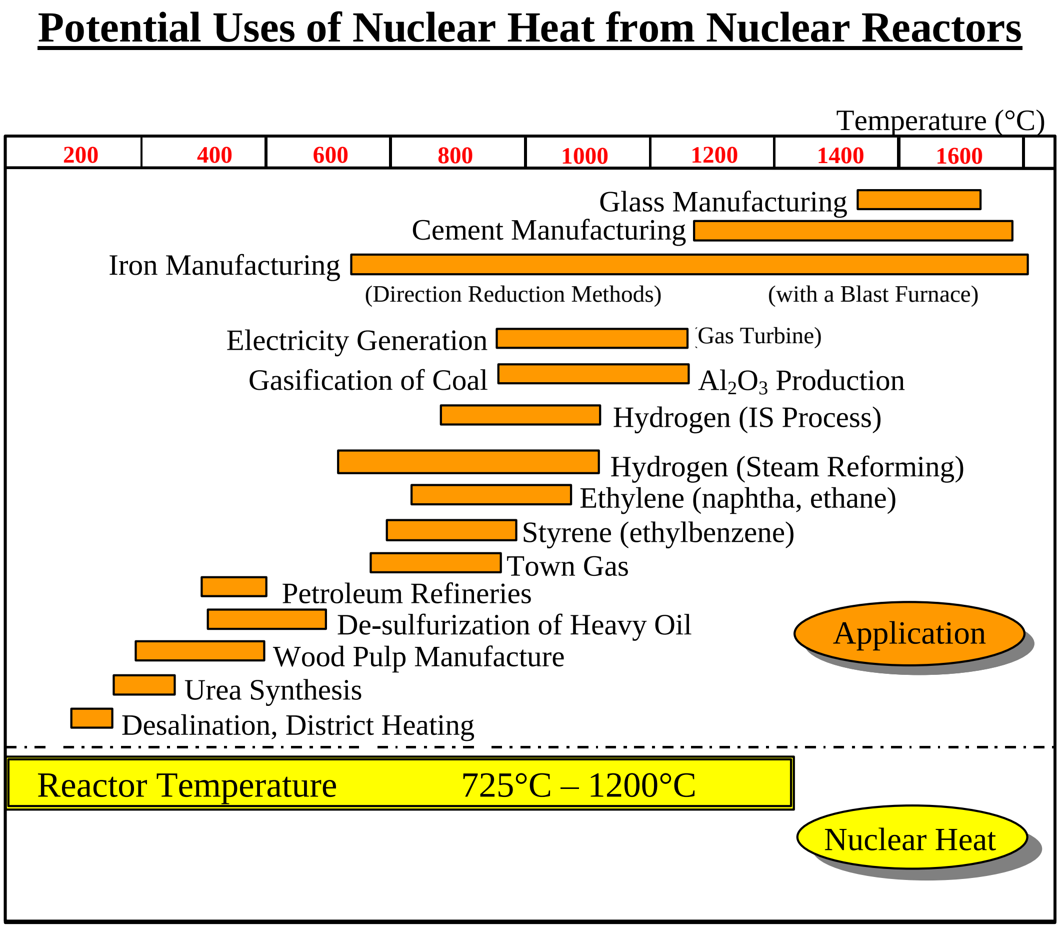
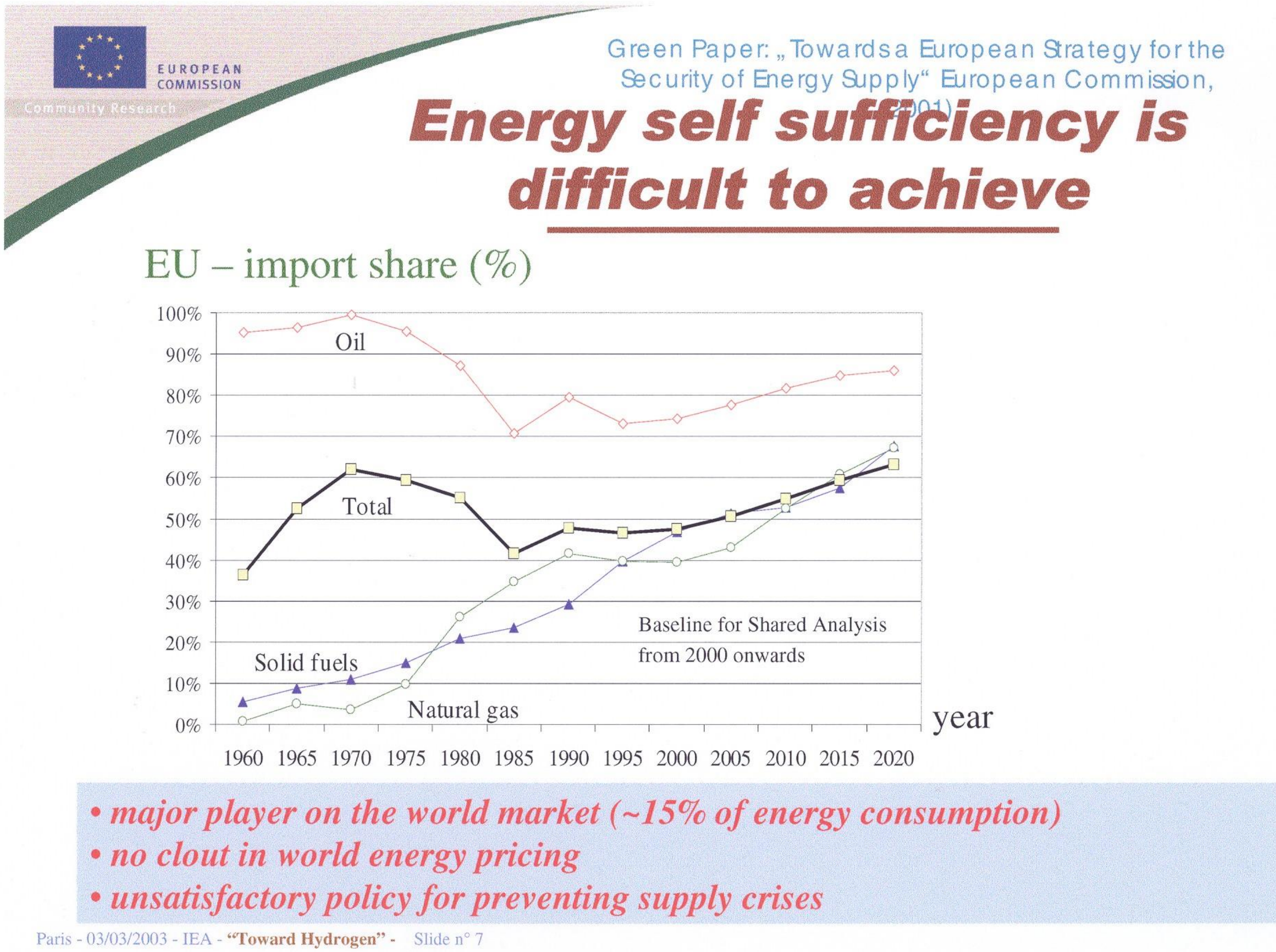
1. GENERAL ASPECTS OF NON-ELECTRICITY APPLICATIONS




EUROPEAN
COMMISSION
Community Research
Green Paper: „Towards a European Strategy for the Security of Energy Supply“ European Commission, 2001)
Energy self sufficiency is difficult to achieve
EU – import share (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Oil
Total
Solid fuels
Natural gas
Baseline for Shared Analysis from 2000 onwards
year
1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020
• major player on the world market (~15% of energy consumption)
• no clout in world energy pricing
• unsatisfactory policy for preventing supply crises
Paris - 03/03/2003 - IEA - "Toward Hydrogen" - Slide n° 7

Market Size for Non-Electric Energy Services (low/high)

Application / *Region*	District heating, GW(th)	Desalination	Process heat supply, GW(th)	Ship propulsion, million gross tonnes	Other applications
1. North America	7 / 1500	not estimated	9 / 500	4 / 11	not estimated
2. Latin America and the Caribbean	0 / 320		0 / 210	0 / 100	
3. Sub-Saharan Africa	0 / 400		0 / 50	0 / 50	
4. Middle East and North Africa	0 / 330		0 / 110	0 / 6	
5. Western Europe	50 / 1200		8 / 390	7 / 120	
6. Central and Eastern Europe	50 / 220		14 / 110	0.3 / 5	
7. Newly independent states of the former Soviet Union	230 / 1000		170 / 340	5 / 14	
8. Centrally planned Asia and China	0 / 1100		34 / 630	7 / 24	
9. South Asia	0 / 700		0 / 180	2 / 6	
10. Other Pacific Asia	0 / 410		2 / 180	5 / 44	
11. Pacific OECD	1 / 340		0 / 190	5 / 17	
World on average	340 / 7600		240 / 2900	35 / 400	

from [1]

Investigated Processes in LURGI Study

Mineral Oil Technology

Heavy Oil Recovery
Crude Oil Refinery
Crude Oil Recovery from Oil Shale
Crude Oil Recovery from Oil Sand

Synthesis Gas from Hydrocarbon

Methanol Production
Ammonia / Fertilizer

Petrol Chemistry

Naphtha Cracking

Gas Production

Coal Gasification in a Circulating Fluid Bed
Hydrogen Production

Iron Production

Pelletizing of Iron Ore
Sintering of Iron Ore
Direct Reduction
Blast Furnaces

Non-Ferrous Metals

Alumina Oxide Production
Copper , Zinc , Lead

Miscellaneous

Sea-Water Desalination
Cement Production
Coarse Ceramic Industry

from [2]

HTR - Module Potential 1992 (2001)

(HTR-Module 170 MW or 200 MW as suitable)

	World Production (Mio. TPY)	Number of Plants in the World	Process Heat required in HTR-Ms
Heavy Oil Recovery	25		40
Refinery	3000 (4.474)	732	850*(1492)*
Oil Sand - Retorting Oil Shale -	42		40
Sea Water Desalination			
Alumina Oxide Production	41 (56)	70	104*(187)*
Naphtha Processing	46 (93)	231	(62)*
Methanol Production	25		50
Ammonia Production	100		270
Iron Ore Sintering	400		80
Iron Ore Pelletizing	350		47
Coal Gasification			
Cement Production	1000		450
Heavy Ceramic Industry			

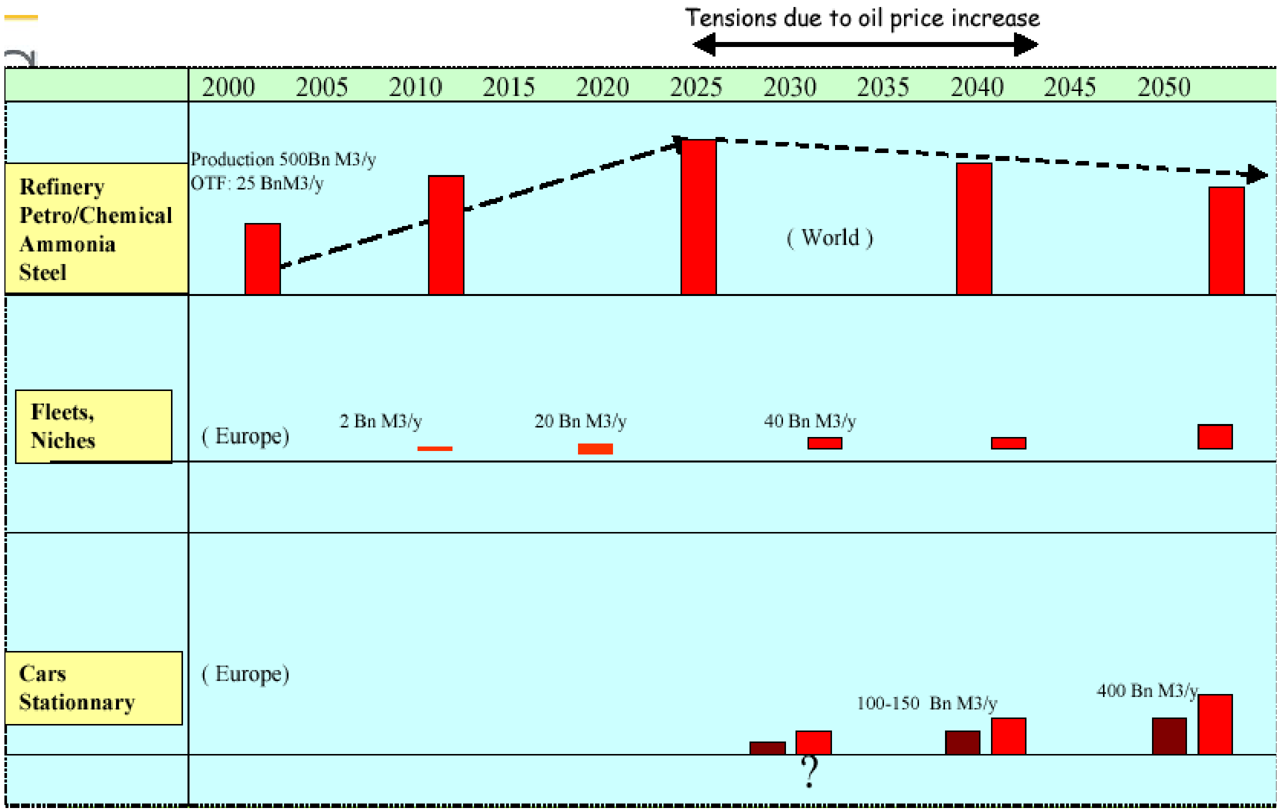
			2043 (2718)

Increase : 1991 - 2001 ~ 30 %

* Sum over 60% of Total Number HTRs

from [2]

Projection of Hydrogen Market from EC High Level Group



2. APPLICABLE NUCLEAR ENERGY SYSTEMS

Potential for Energy Products Applications of the Most Promising Generation IV Water Cooled Reactor Systems

Reactor		SCWR	IPSR	CANDU-NG
Thermal power	MW	900 - 3800	100 - 900	1100 - 3300
Electric power	MW	200 - 1700	30 - 300	400 - 1200
Outlet temperature	°C	400 - 625	230 - 330	330
Primary pressure	MPa	22	3 - 15	13
Hydrogen production		• Naphtha • CH_4	no	no
Desalination of water		yes	yes	yes
High temperature process heat		• Petroleum refineries • Desulfurization of heavy oil	no	no
District heating		yes	yes	yes

SCWR: Super Critical Water Reactor
IPSR: Integral Primary System Reactor
CANDU-NG: Next Generation Candu

from [9]

Potential for Energy Products Applications of the Most Promising Generation IV Gas Cooled Reactor Systems

Reactor		PBR	PMR	GFR	VHTR
Thermal power	MW	250	600	600	600
Electric power	MW	110	286	288	300 - 360
Outlet temperature	°C	850	850	850	950 - 1300
Primary pressure	MPa	7.75	7.07	7.0	6.8 – 8.0
Hydrogen production		• Naphtha • CH_4	yes yes	yes yes	yes yes
Desalination of water		yes	yes	yes	yes
High temperature process heat		• Petroleum refineries • Desulfurization of heavy oil	yes	yes	yes
District heating		yes	yes	yes	yes

PBR: Pebble Bed Reactor
PMR: Prismatic Reactor
GFR: Gas Cooled Fast Reactor
VHTR: Very High Temperature Reactor

from [9]

Potential for Energy Products Applications of the Most Promising Generation IV Liquid Metal Cooled Reactor Systems

Reactor		L1	L2	L4	L6
Thermal power	MW	2000 - 4000	400 - 1200	~1000	125 - 1000
Electric power	MW	800 - 1500	150 - 500	2400	50 - 350
Outlet temperature	°C	550	530	540	540 - 780
Primary pressure	MPa	0.1	0.1	0.1	0.1
Hydrogen production		yes*	yes*	yes*	yes
Desalination of water		yes	yes	yes	yes
High temperature process heat		no	no	depending on requirements	depending on requirements
District heating		yes	yes	yes	yes

(*) The medium temperature liquid metal systems may contribute to hydrogen production the so-called “symbiotic” approaches through nuclear-assisted steam reforming of natural gas and the membrane reformer

from [9]

Potential for Energy Products Applications of the Most Promising Generation IV Non-Classical Reactor Systems

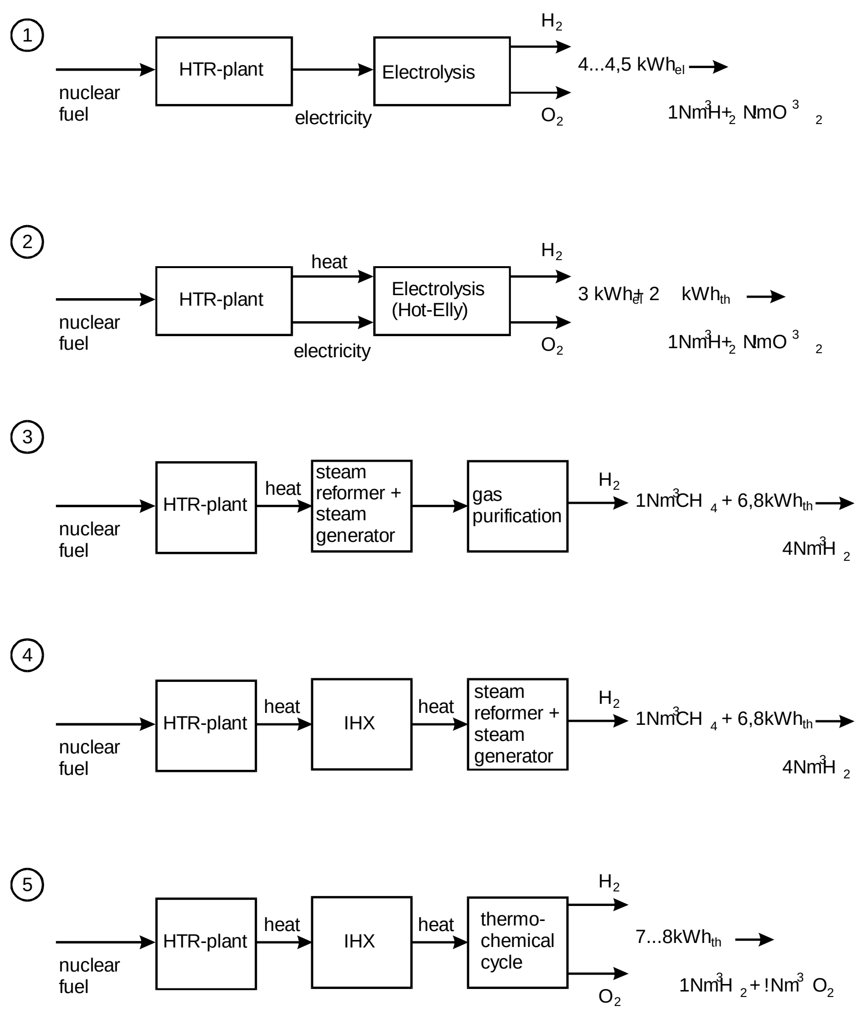
Reactor		Molten Salt Reactor	Gas Core Reactor	Advanced HTR
Thermal power	MW	2250	1675	300 - 2000
Electric power	MW	1000	1000	150 - 900
Outlet temperature	°C	704	1527	1000
Primary pressure	MPa	0.520	5.00	0.5
Hydrogen production		• Ca-Br • HT electrolytic	• All thermo-chemical	• S-I • UT-3
Desalination of water		yes	yes	yes
High temperature process heat		• Petroleum refineries • Desulfurization of heavy oil • Concern for tritium migration	Temperature is certainly high enough. Concern for materials and FP/T migration into secondary	yes salt is attractive heat transport medium
District heating		yes as a bottoming application	yes but a poor use of the heat	yes though distribution is an obstacle

from [9]

3. HYDROGEN PRODUCTION PROCESSES

3.1. General Data

<u>Various Processes to Produce Hydrogen</u>



from [10]

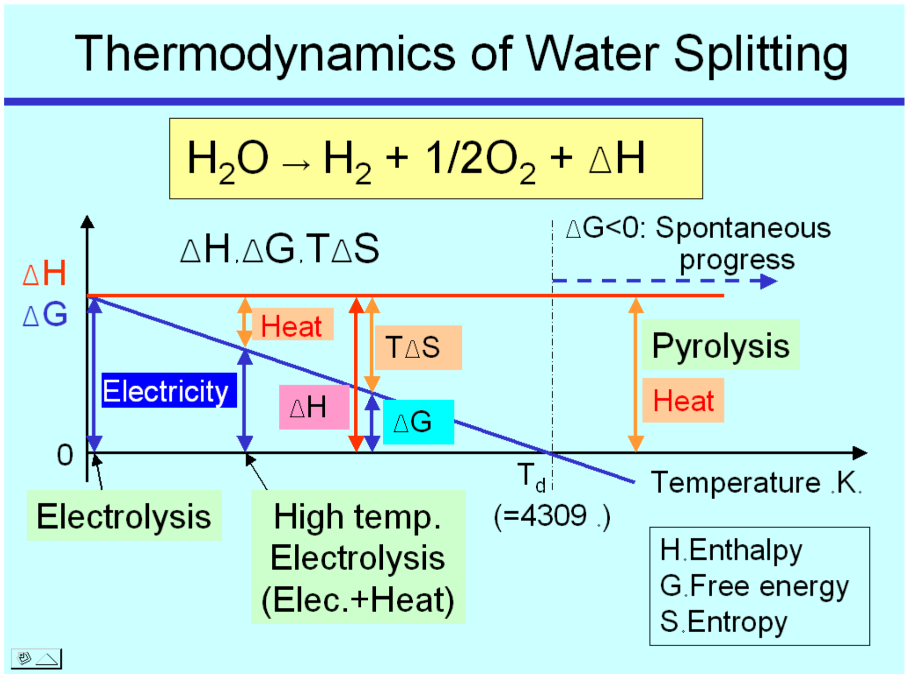
Benefits and Barriers of Hydrogen Production Technologies

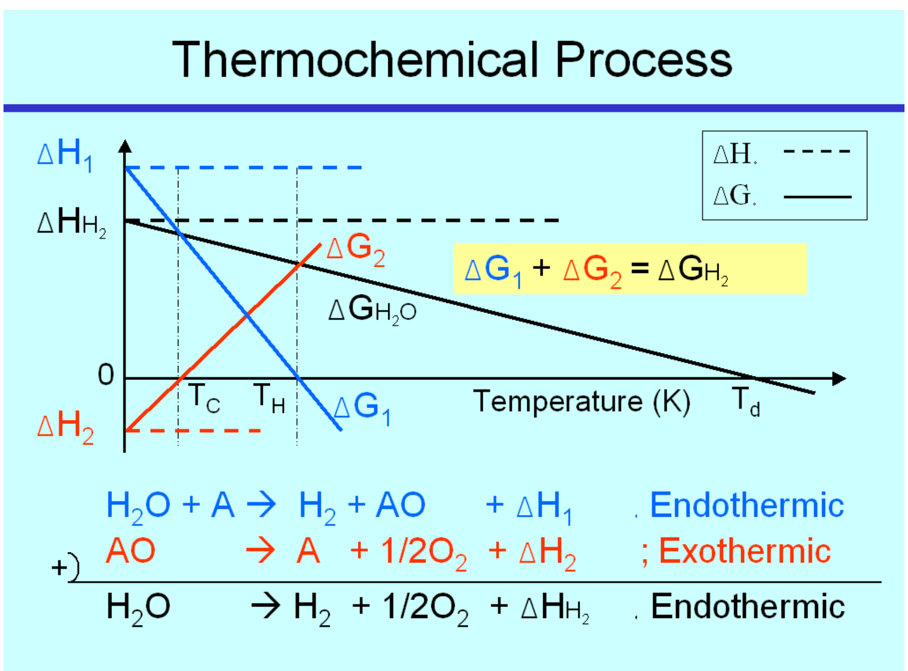
Technology	Benefits	Barriers
Electrolysis: splitting water using electricity.	Commercially available with proven technology; well understood industrial process; modular; high purity hydrogen; convenient for producing H_2 from renewable electricity; compensates for intermittent nature of some renewables.	Electricity price strongly impacts cost of H_2 produced; efficiency of whole chain; competition with direct use of renewable electricity.
Steam Reforming: splitting hydrocarbon gases with heat and steam.	Well understood at large scale; widespread; low-cost hydrogen; CO_2 sequestration at large scale.	Small-scale units not commercial; hydrogen contains some impurities; CO_2 emissions; primary fuel may be used directly.
Gasification: splitting heavy hydrocarbons and biomass into hydrogen and gases for reforming.	Well understood at large scale; can be used for solids and liquids.	Small units very rare; hydrogen usually requires extensive cleaning before use; biomass gasification still under research; in competition with synthetic fuels from biomass.
Thermochemical Cycles: using cheap high temperature heat from nuclear or concentrated solar energy.	Potentially massive production at low cost and without GHG emission for big industry or transportation; high-efficiency process (near 50% from total primary heat); international collaboration (USA, Europe, Japan) on R&D and deployment.	Not commercial; R&D needed over 10 years on the process, materials, and chemistry technology; high temperature nuclear reactor deployment needed; hydrogen infrastructure needed for transportation application.
Biological Production: algae and bacteria produce hydrogen directly under certain conditions.	Potentially large resource; no feedstock required.	Slow hydrogen production rates; large area needed; most appropriate organisms not yet found; still under research.

from [3]

3.2. Thermochemical Cycles

Analysis of Hydrogen Production by Electrolysis and Thermochemical Processes





from [4]

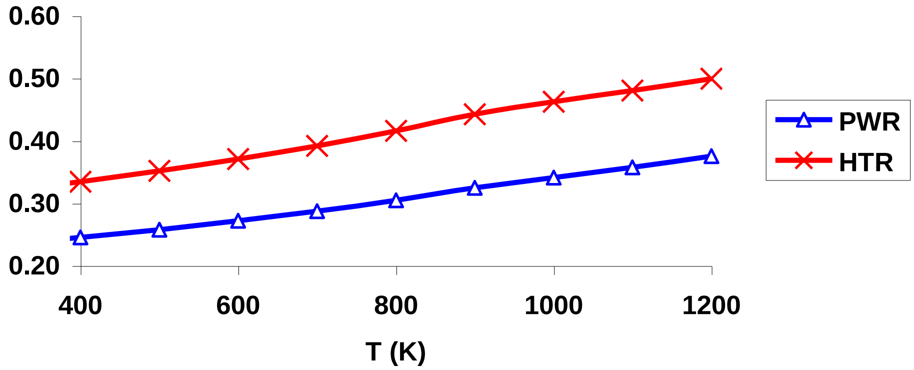
3.3. Electrolysis

Hydrogen Production by High Pressure Electrolysis

		State of the Art	Scenario 2025
Technical Data			
Rated power	kW	2000	2000
Hydrogen production	Nm^3/h	485	515
System pressure	MPa	3.0	10.0
Water demand	m^3/h	0.412	0.436
Life time	a	20	20
Efficiency	%	73	77
KEA (without electricity)			
Plant construction	$kWh/kWh(H_2)$	0.022	0.021
Deionized water consumption	$kWh/kWh(H_2)$	0.016	0.016
Emissions (without electricity)			
CO_2 from plant construction	$g/kWh(H_2)$	6	6
Cost (without electricity)			
Investition	$€/kW(H_2)$	1250	1175
Specific total cost	$Ct/kWh(H_2)$	5.5	5.2

from [5]

Efficiency of Hot Electrolysis Using Electricity from HTR's or LWR's



from [11]

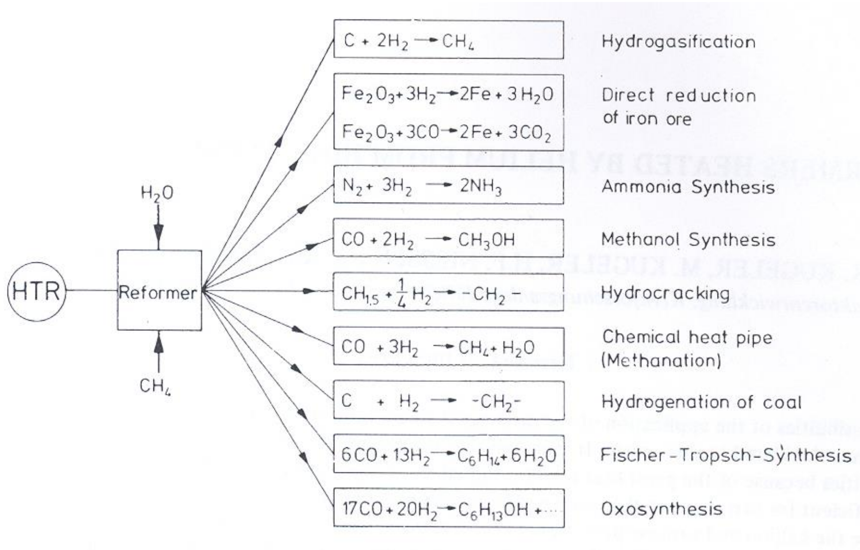
3.4. Steam Reforming of Methane

<u>Hydrogen Production by Steam Reforming of Natural Gas</u>

		State of the Art		**Scenario 2025**	
Technical Data					
Rated power natural gas	kW	4500	405,000	4275	385,000
Hydrogen production	Nm^3/h	1000	100,000	1000	100,000
System pressure	MPa	1.6	3.0	1.6	3.0
Water demand	m^3/h	2.1	58	2.1	58
Efficiency	%	67	74	70	78
Life time	a	20	20	20	20
Utilization	h/a	8000	8000	8000	8000
KEA					
Provision efficiency	%	59	66	63	70
Emissions					
CO_2	g/kWh(H_2)	334	290	306	275
Cost					
Investition	€/kW(H_2)	675	335	675	335
Specific total cost	Ct/kWh(H_2)	3.2	2.3	3.1	2.2

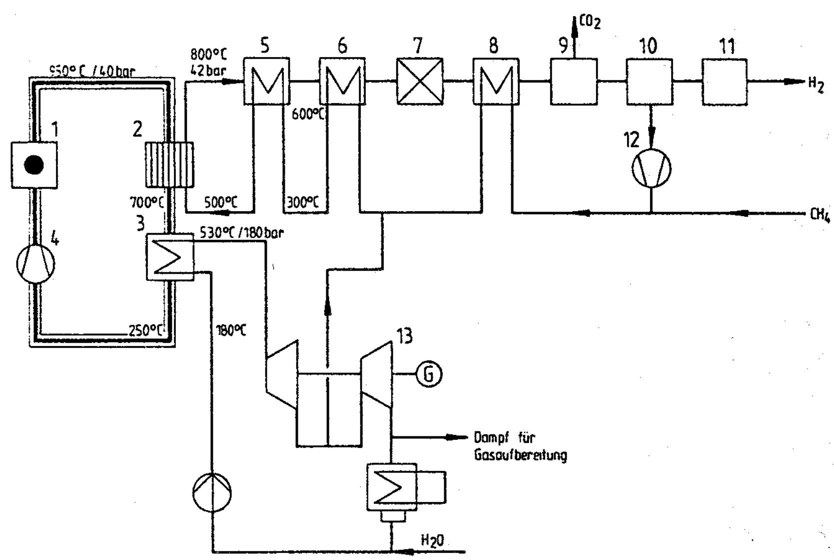
from [5]

Application of steam reformers



from [6]

Flow Sheet for Steam Reforming of Methane Using Nuclear Heat



1-HTR, 2-steam reformer, 3-steam generator, 4-He-blower, 5-preheater gas, 6-preheater gas, 7-shift-conversion, 8-CH_4–pre-heater, 9-CO_2–washer, 10-H_2/CH_4–separation, 11-methanation, 12-CH_4 –compressor, 13-steam turbine plant

from [10]

Steam Reformer Gas Requirements

Process	Ammonia synthesis	Methanol synthesis	Hydro-Gasification	Coal hydrogenation	Hydro-Cracking	Direct reduction of iron	Chemical heat pipe
Reaction	$N_2 + 3H_2 \rightarrow 2NH_3$	$2H_2 + CO \rightarrow CH_3OH$	$C + 2H_2 \rightarrow CH_4$	$C + H_2 \rightarrow –CH_2–$	$CH_{1,2} + nH_2 \rightarrow CH_2$	(a) $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$ (b) $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$	$CO + 3H_2 \rightarrow CH_4 + H_2O$ + heat
Input	$N_2 + H_2$	$CO + H_2$	Coal	Coal	Distillate residue	Iron ore	$CO + H_2$
Temperature [°C]	400	250 - 300	800	500	350 - 450	(a) 500 (b) 800	20
Pressure [MPa]	50	5 - 20	5 - 10	30 - 70	5 - 15	(a) 3 - 4 (b) 0.3	7
Desired gas analysis	$H_2/N_2 = 3/1$	$H_2/CO = 2/1$	95% H_2	98% H_2	98% H_2	(a) 98% H_2 (b) $H_2O + CO_2 < 5\%$ CH4 < 3% $H_2/CO \sim 2/1$	not specified
Feed material to steam reformer	CH_4, C_nH_m	CH_4, C_nH_m	CH_4	C_1 - C_4	C_1 - C_4, C_nH_m	CH_4, C_nH_m	CH_4
Temperature in steam reformer [°C]	850	850	800 - 850	800 - 850	800 - 850	(a) 800 - 850 (b) 850	800 - 850
Pressure in steam reformer [MPa]	3 - 4	3 - 4	3 - 4	3 - 4	3 - 4	(a) 3 - 4 (b) 0.5	3 - 4
H_2O / CH_4 ratio	4/1 - 5/1	4/1 - 5/1	4/1 - 5/1	4/1 - 5/1	3/1 - 4/1	(a) 4/1 (b) 1.2/1 - 1.5/1	1.5/1 - 3/1
Specific gas production	2200 Nm^3 H_2 per t NH_3	2300 Nm^3 $(CO+H_2)$ per t CH_3OH	1.5 Nm^3 H_2 per Nm^3 CH_4	2000-2600 Nm^3 H_2 per t gasoline	400-500 Nm^3 H_2 per t distillate residue	600-700 Nm^3 $(CO+H_2)$ per t Fe	500 Nm^3 $(CO+H_2)$ per GJ heat

from [6]

Thermodynamic Data of a Single Reformer Tube

Helium Side		
Inlet temperature	°C	950
Outlet temperature	°C	700
Inlet pressue	MPa	3.94
Outlet pressure	MPa	3.92
Mass flow rate	kg/s	0.1846
Heat available	kW	239
Process side		
Inlet temperature	°C	450
Reforming temperature	°C	825
Outlet temperature (pigtail)	°C	600
Inlet pressure	MPa	4.6
Outlet pressure	MPa	4.0
Methane mass flow rate	Nm^3/h	125.1
Steam mass flow rate	kg/h	290
Total amount of product gas	Nm^3/h	640
Gas production	$Nm^3(CO+H_2)/h$	314
Amount of heat required	kW	239
Reformer tube data		
Inner diameter of tube	mm	100
Outer diameter of tube	mm	130
Length of chemically active tube section	m	10
Length of chemically inactive tube section	m	1
Helium velocity in tube bundle	m/s	13.5
Film coefficient of heat transfer on He side (with baffles)	$kW/(m^2 K)$	0.94
Film coefficient on product side	$kW/(m^2 K)$	1.16
Thermal conductivity of tube wall	kW/(m K)	0.027
Overall heat transfer coefficient	$kW/(m^2 K)$	0.35
Average temperature difference	K	180
Heat flux	kW/m^2	0.064
Effective heat transfer area	m^2	4.08
Transferable heat per tube	kW/tube	259.7
Maximum tube wall temperature	°C	900
Pressure drop at max. tube wall temperature	MPa	0.1

from [6]

3.5. Coal Gasification

Hydrogen Production by Coal Gasification

		State of the Art	Scenario 2025
Technical Data			
Rated power hard coal	MW	486	413
Electricity demand	MW	25	22
Hydrogen production	Nm^3/h	100,000	100,000
System pressure	MPa	5.0	5.0
Water demand	m^3/h	84	84
Efficiency	%	59	69
Life time	a	20	20
Utilization	h/a	8000	8000
KEA			
Provision efficiency	%	51	59
Emissions			
CO_2	g/kWh(H_2)	614	522
Cost			
Investition	€/kW(H_2)	700	1400
Specific total cost	Ct/kWh(H_2)	3.9	3.5

from [5]

3.6. Biological Systems

Hydrogen Production in Biological Systems

Metabolism Process	Micro-Organisms	Light Demand	Starting Material, Electron Donor	Products
Biophotolysis (oxygenic photo synthesis)	Green algae, cyano bacteria	Yes	H_2O	H_2, O_2
Photo production (anoxygenic photo synthesis)	Phototrophic bacteria (purpur bacteria)	Yes	Organic materials, reduced S-compounds	H_2, CO_2
Fermentation	Fermenting bacteria	No	Organic compounds	H_2, O_2, organic compounds

from [5]

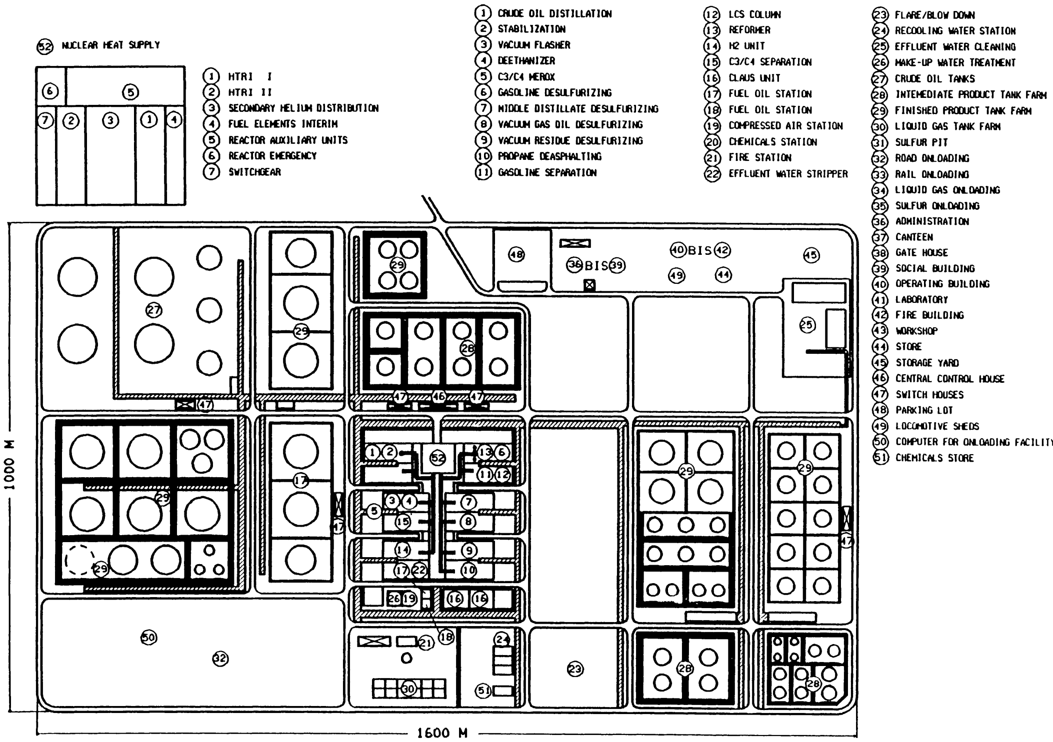
4. REFINING OF CRUDE OIL

Thermal Power Demand of a Refinery (6 million t/y)

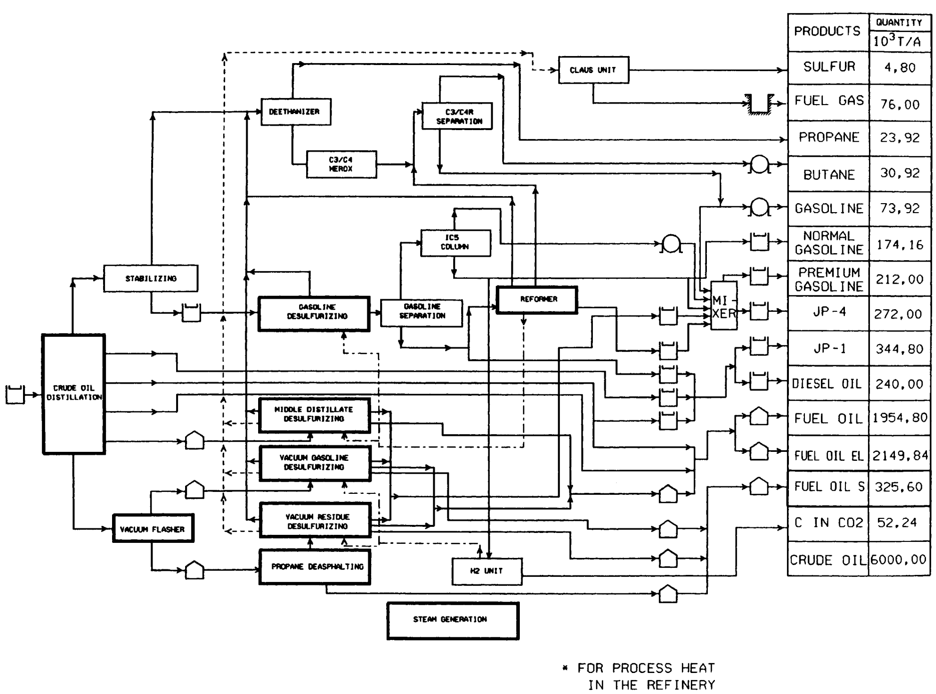
Process	**Heat [MW]**	**Temperature [˚C]**	**Pressure [MPa]**
Crude Oil Distillation	117	230 - 370	0.1
Vacuum Distillation	46	230 - 385	0.004
Propane Deasphalting	53	50 - 80	3.5
Vacuum Residue Distillation	20	340 - 385	10
Vacuum Gas Oil Desulphurisation	17	340 - 385	4
Middle Dist. Desulphurisation	15	340 - 385	2.5
Gasoline Desulphurisation	12	340 - 385	3
Gasoline Reformer	53	430 - 540	3
Hydrogen Generation	5	820 - 850	3
Effluent Water Cleaning	3	20 - 60	0.1
Steam Generation	112	20 - 500	2
Total Power Demand	**453**		

from [12]

Refinery Layout

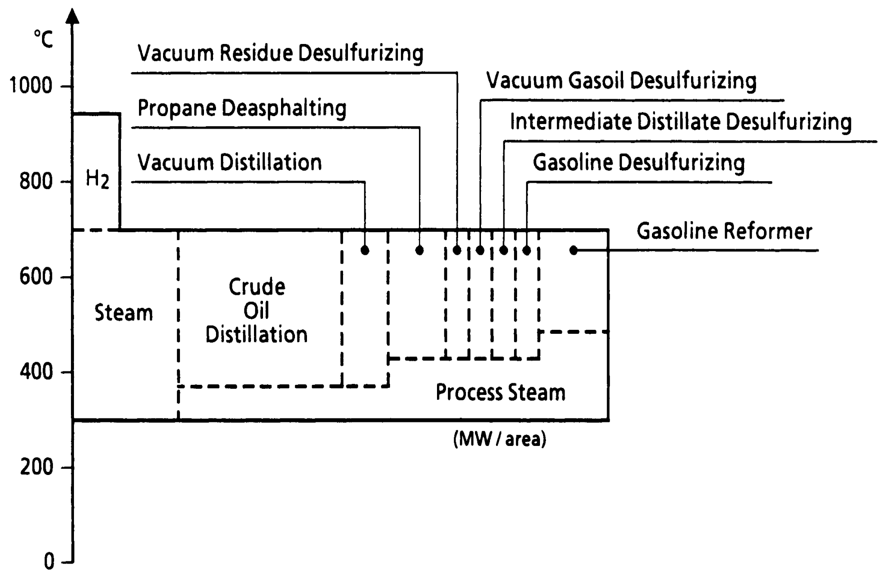


Refinery Flow Diagram

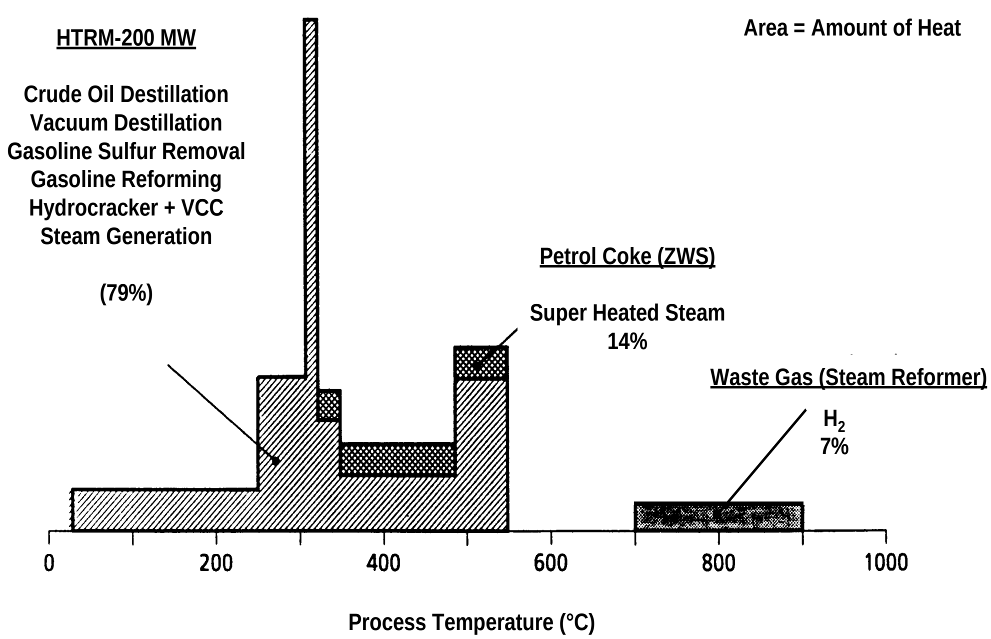


from [2]

Distribution of Process Heat Supply in a Refinery with the HTR-M

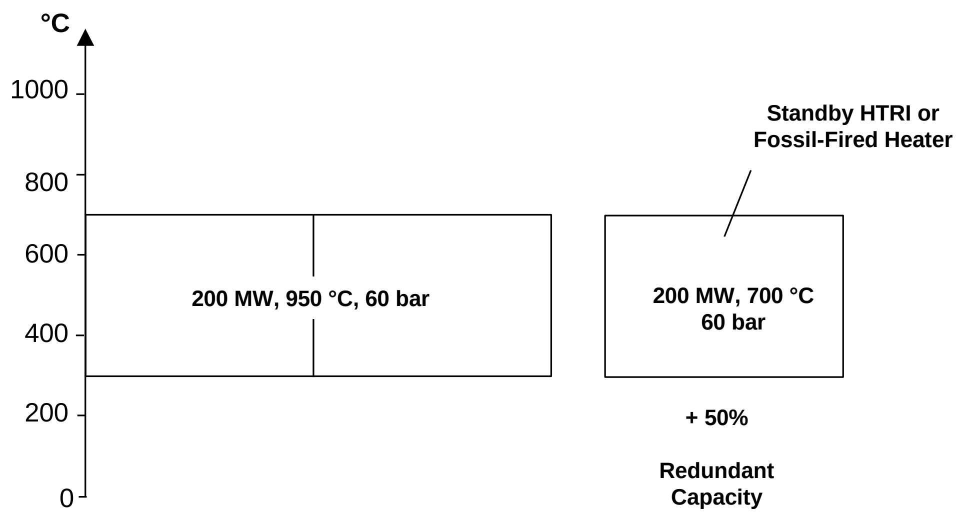


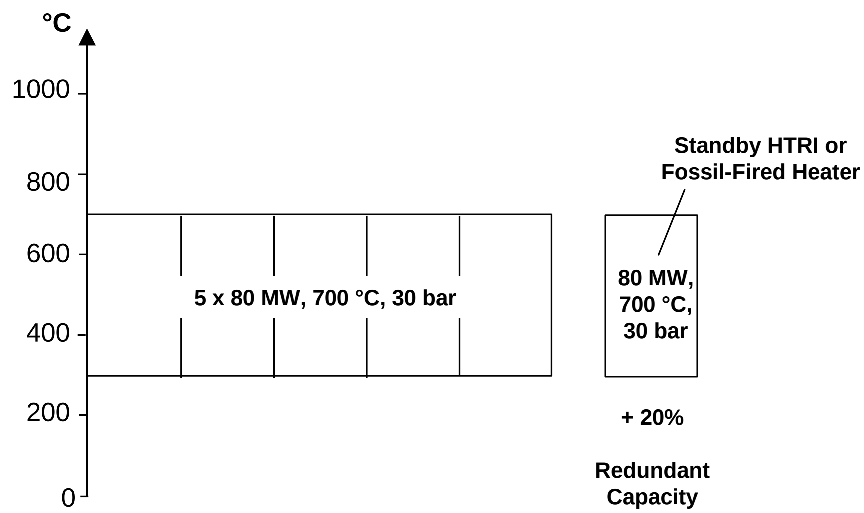
Heat Supply of Investigated Refinery



from [2]

Possible HTR-M Selections for a 400 MW(th) Refinery

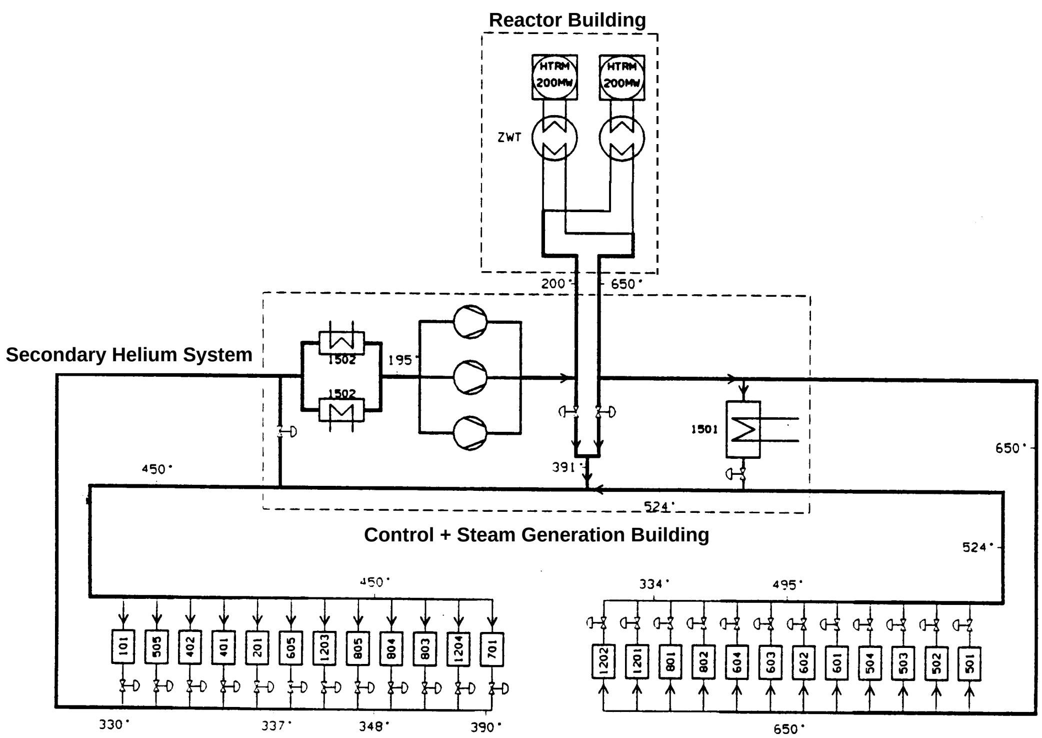




80 MW HTR-M specific less expensive as 200 MW HTR-M

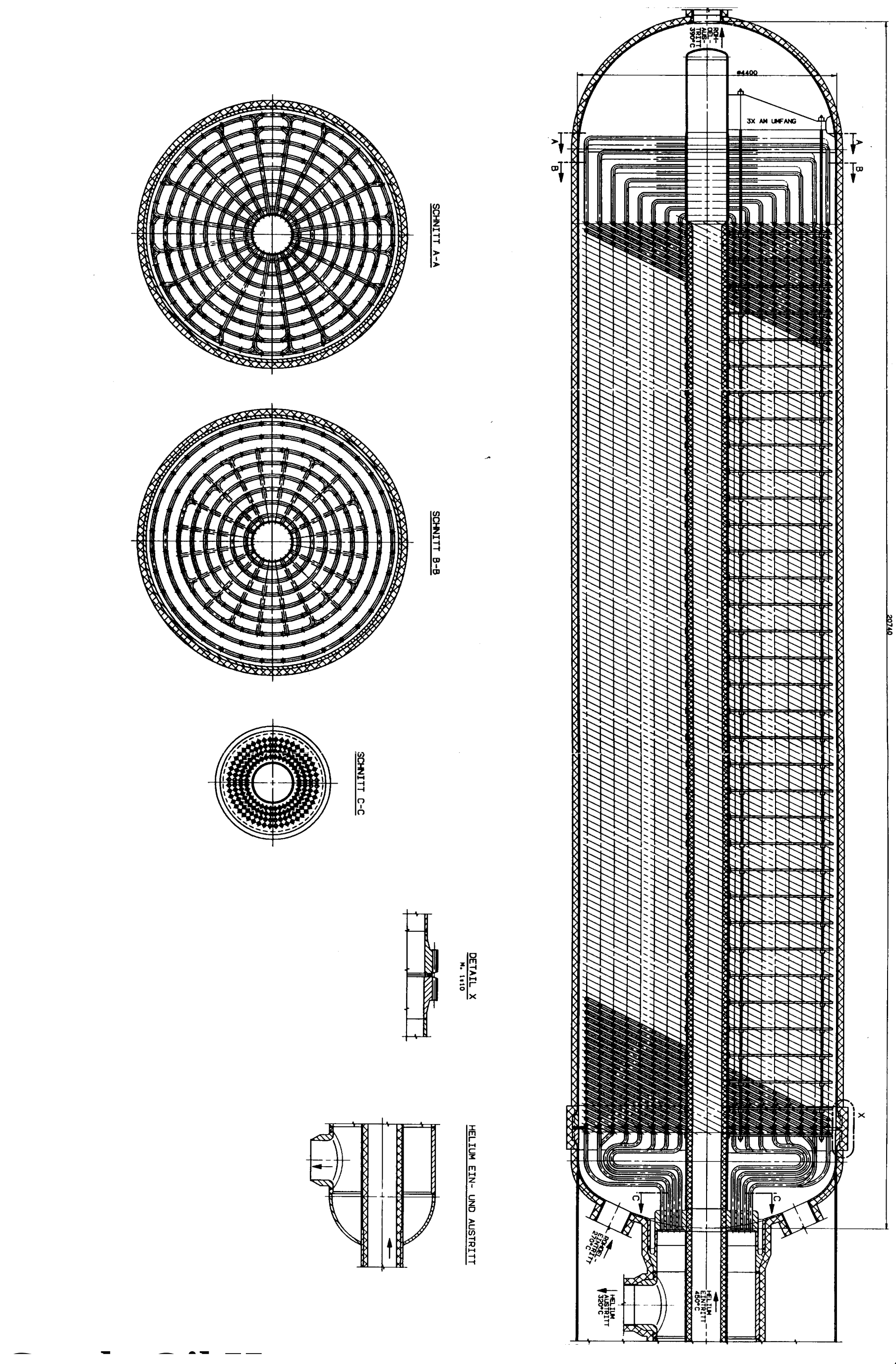
from [12]

Heat Transfer System: HTR-M Refinery



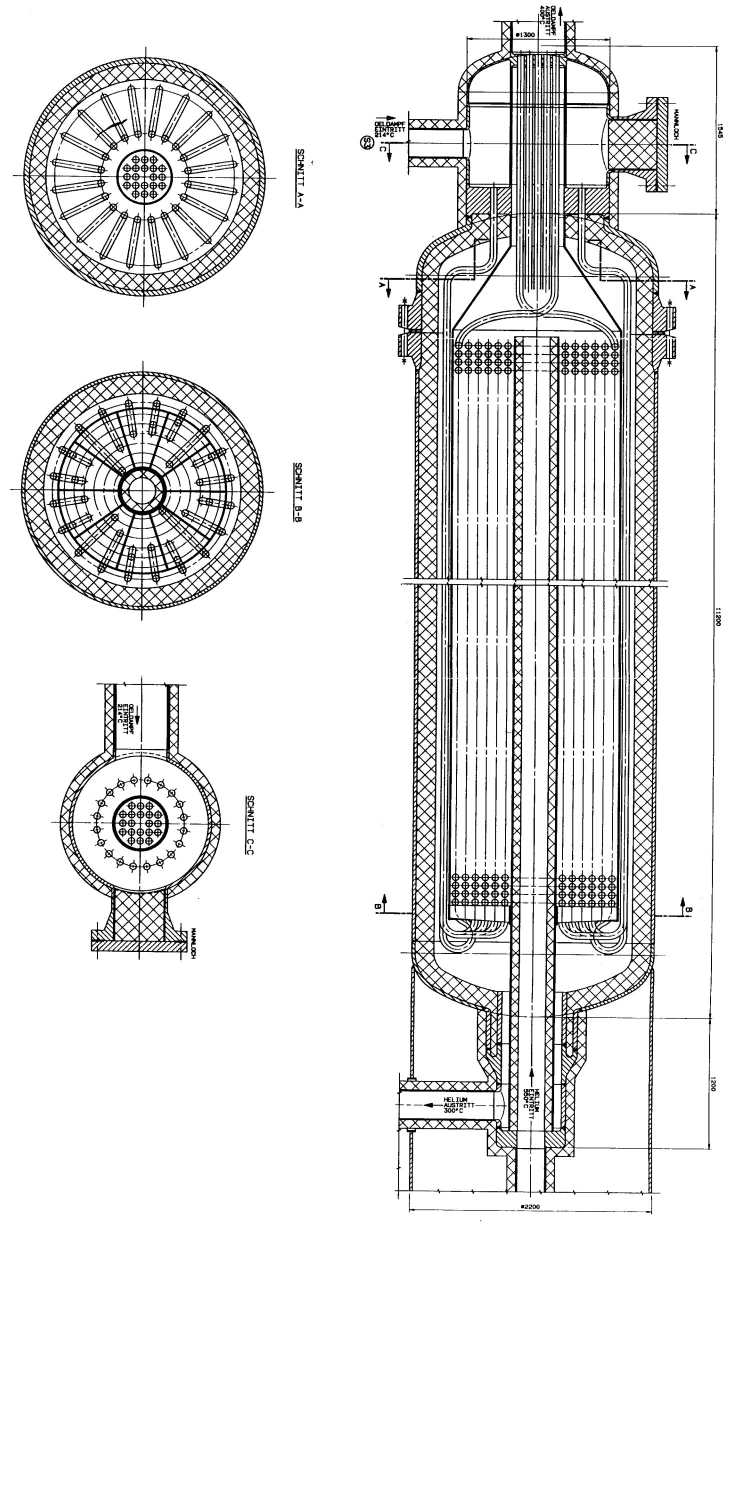
from [12]

Crude Oil Heater



from [12]

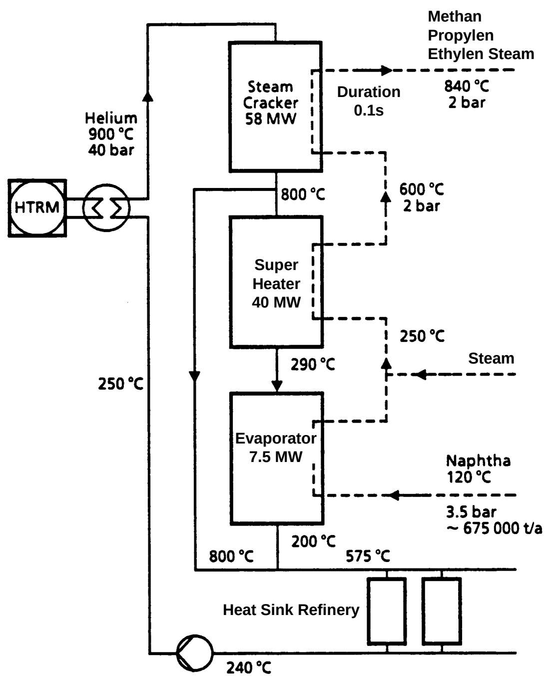
Oil Vapor Heater



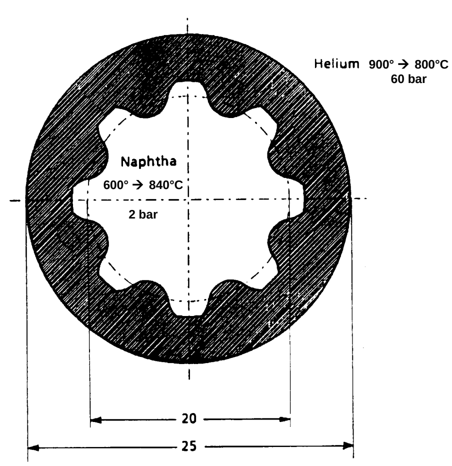
from [12]

5. PETROCHEMICAL APPLICATIONS

Concept Heat Transfer : Secondary Helium-Naphtha



Steam Cracker Tube Cross Section



from [12]

Typical Products and Heat Consumption of Refineries in Connection with Petrol Chemical Plants

Refinery

Crude Oil **10 000 000 TPY** ← **~ 1000 MW (550° - 350°C)**

↓

15% Naphtha

↓

Petrochem. Plant

1 500 000 TPY ← **~ 234 MW (900° - 200°C)**

↓

13 % Methan

↓

Steam Reforming **175 000 TPY** ← **~ 37.4 MW (950° - 300°C)**

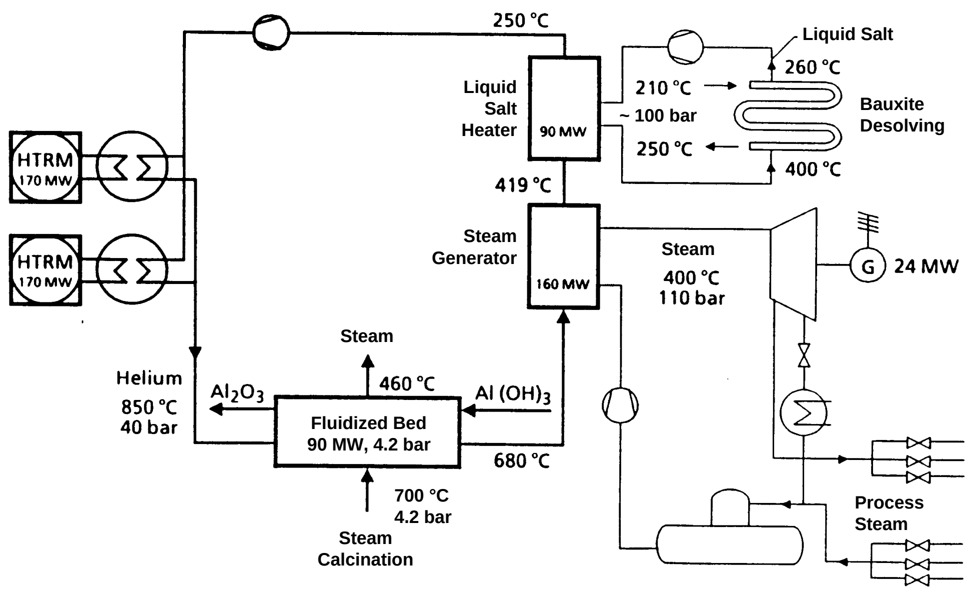
↓

Hydrogen	Ammonia	Methanol
87 750 TPY	72 200 TPY	213 000 TPY

from [12]

6. ALUMINUM PRODUCTION

Process Heat Supply at Aluminum Oxide Production

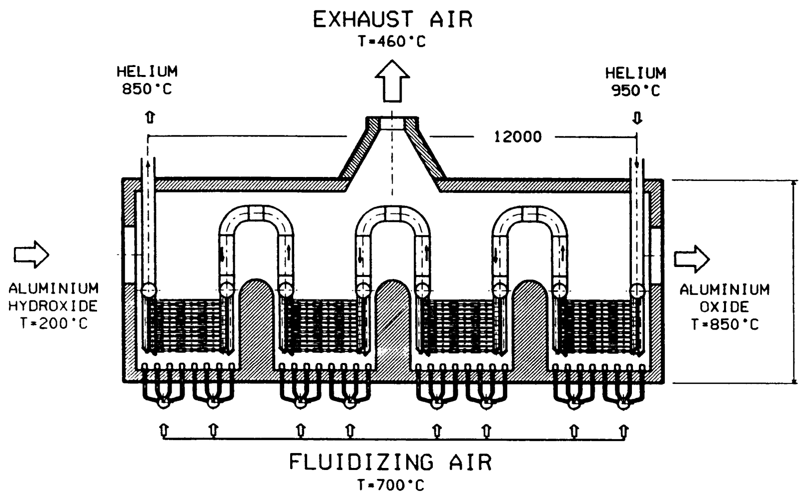


Main process Steps

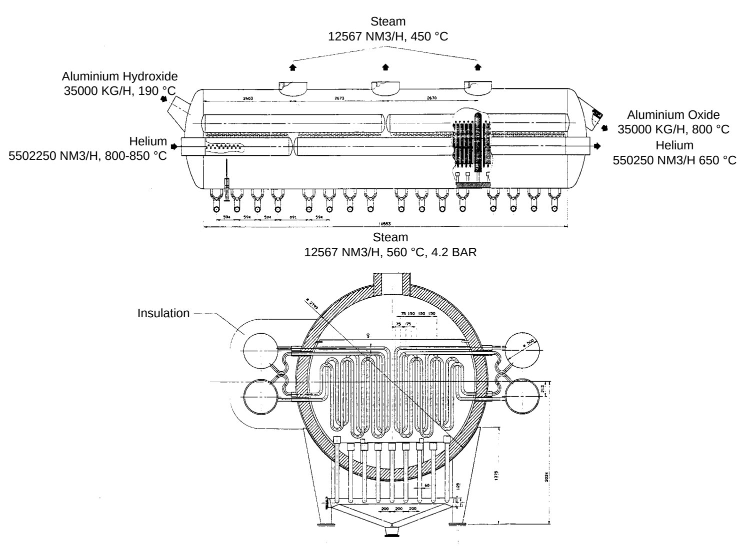
- Leaching Alumina Hydroxide out of Bauxite with Sodium Hydroxide (~ 10 MPa , 210 - 250° C).
- Separating the Alumina Hydroxide from the Sodium Hydroxide. (0.1 MPa , 70° C).
- Calcination of the Alumina Hydroxide to Alumina Oxide (~ 0.4 MPa, 200-850° C).

from [12]

Fluidized Bed Heater

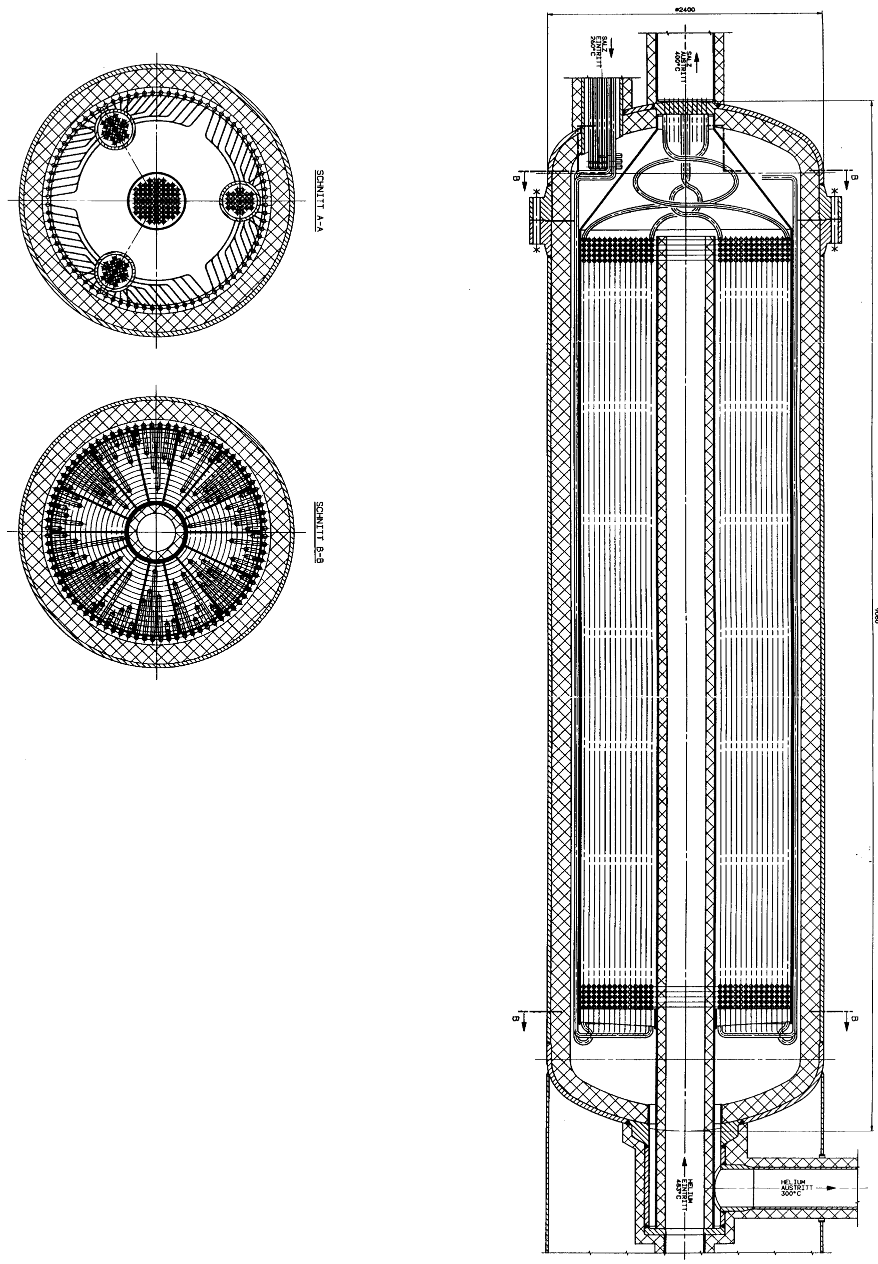


Fluidized Bed Aluminum Oxide Heater



from [12]

Liquid Salt Heater



from [12]

7. DESALINATION

Estimate of Water Availability (based mostly on 1990 data)

№	Region	Water supply for 1990					Water supply for 2025 (the 'business as usual' case from [19])				
		pop., mln	water use per cap, m^3	% beyond the limits: > 40% of AWR[1]	< 500 m^3/ca total	< 36 m^3/ca dom.	pop., mln	water use per cap, m^3	% beyond the limits: > 40% of AWR	< 500 m^3/ca total	< 36 m^3/ca dom.
1	North America (NAM)	281	1842	0%	0%	0%	374	1842	0%	0%	0%
2	Latin America and the Caribbean (LAM)	487	492	0%	67%	10%	793	471	0%	69%	22%
3	Sub-Saharan Africa (AFR)	489	142	8%	89%	91%	1231	143	6%	91%	93%
4	Middle East and North Africa (MEA)	279	1028	66%	30%	25%	585	895	90%	28%	16%
5	Western Europe (WEU)	434	593	2%	22%	3%	473	589	2%	22%	17%
6	Central and Eastern Europe (EEU)	124	640	0%	58%	4%	125	614	0%	61%	5%
7	Newly independent states of former Soviet Union (FSU)	292	925	23%	24%	0%	319	1056	30%	22%	0%
8	Centrally planned Asia and China (CPA)	1265	459	0%	98%	93%	1714	478	0%	98%	2%
9	South Asia (SAS)	1134	648	0%	11%	99%	1987	689	87%	12%	98%
10	Other Pacific Asia (PAS)	430	338	10%	57%	70%	658	335	9%	63%	62%
11	Pacific OECD (PAO)	144	755	0%	0%	0%	151	768	0%	0%	0%
	World total	5359	614	6%	50%	60%	8410	593	*30%*	*52%*	*46%*

[1] The shaded areas indicate cases with most likely water availability problems.
[2] AWR (Available Water Resources) = internal resources + inflow – outflow

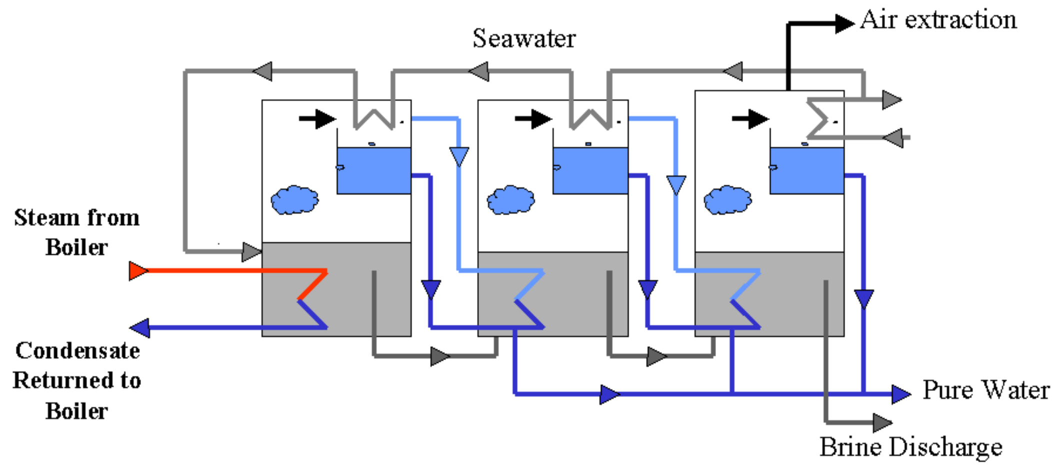
from [1]

Prospective Competitiveness of Nuclear Power Plants in Water desalination

Region	Case for nuclear	Nuclear / coal ratio		Nuclear / gas ratio	
		S_n scenario	S_f scenario	S_n scenario	S_f scenario
Desalination with RO (reverse osmosis), water production capacity 120000 m^3/day					
1 (Southern Europe)	best	0.73	0.87	0.68	0.85
	worst	0.88	1.02	0.80	0.99
2 (Red Sea, South-East Asia, North Africa)	best	0.75	0.89	0.72	0.89
	worst	0.91	1.05	0.85	1.04
3 (Arabian Sea)	best	0.73	0.89	0.72	0.89
	worst	0.91	1.06	0.85	1.04
Desalination with MED (multi-effect distillation), water production capacity 120000 m^3/day					
1 (Southern Europe)	best	0.63	0.82	0.58	0.80
	worst	0.90	1.05	0.82	1.00
2 (Red Sea, South-East Asia, North Africa)	best	0.70	0.87	0.67	0.86
	worst	0.95	1.09	0.89	1.06
3 (Arabian Sea)	best	0.70	0.87	0.68	0.86
	worst	0.97	1.11	0.91	1.07

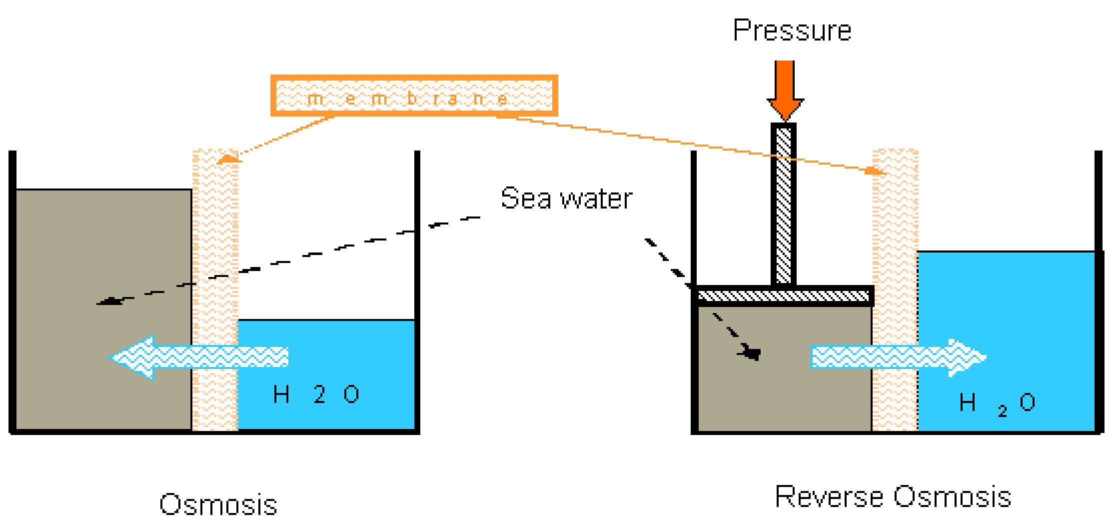
from [1]

Schematic of a MED System



from [7]

Osmosis and Reverse Osmosis Processes



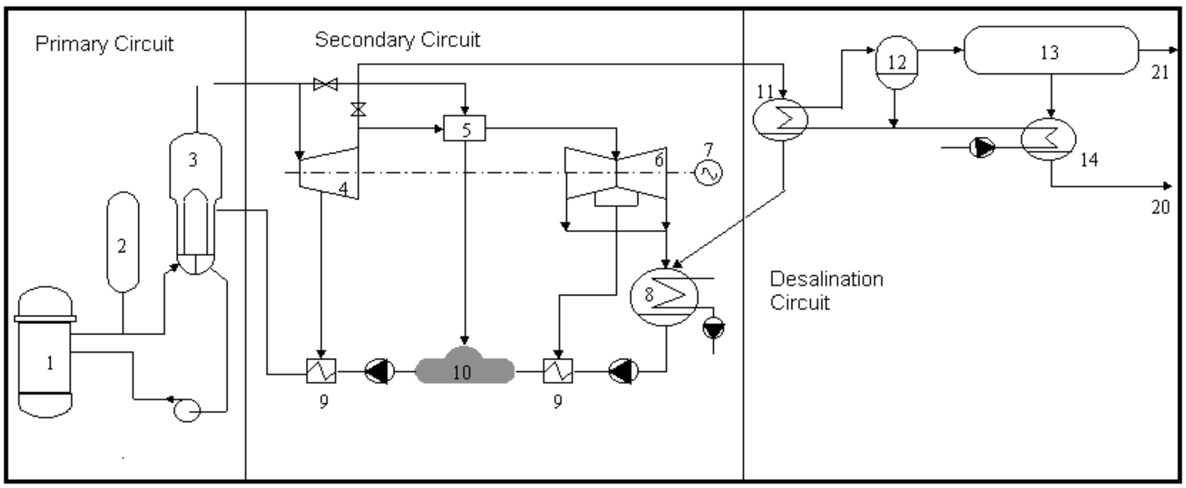
from [7]

Average Energy Consumption in Desalination Processes

Process	Specific Heat Consumption $kW_{th}.h/m^3$	Specific Electricity Consumption $kW_e.h/m^3$
MED	50	3*
MSF	100	3
RO	-	4.5

* Some electricity is required to run the pumps and other auxiliary systems in MED and MSF

Conventional Coupling of a Nuclear Reactor to a MED Plant



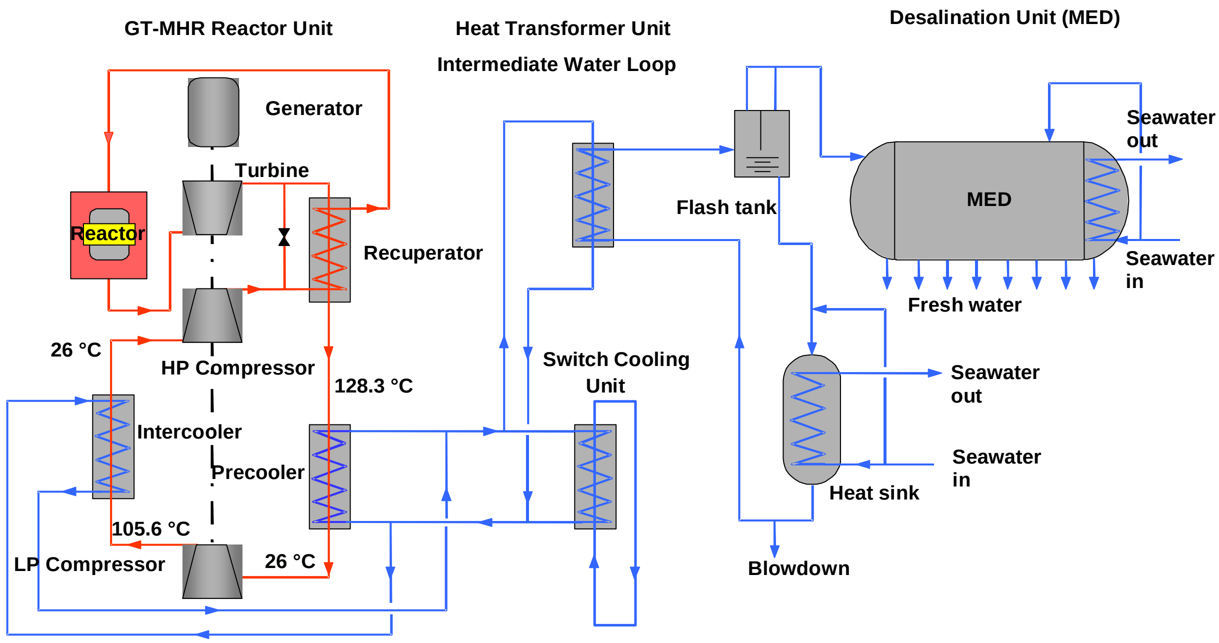
1: Reactor core, 2: Pressurizer; 3: Steam generator; 4: High pressure turbine; 5: Intermediate steam heater; 6: Low-pressure turbine, 7: Generator,8: Main condenser, 9: pre-heaters, 10: De-aerator; 11: Sea-water heater;12: Flash tank, 13: MED plant, 14: MED output condenser, 20: Fresh water out, 21: Brine out-fall

Water production in the conventional MED coupling to a PWR

Production Capacity (m^3/day)	Thermal Power Used (MWth)	Initial Vapour Flow Rate (kg/s)	Lost Shaft Power (MWe)
216 000	402	190	51
264 000	484	229	61
312 000	581	275	73
336 000	628	297	79
504 000	940	445	119

from [7]

Coupling of the GT-MHR to MED via a Flash Tank



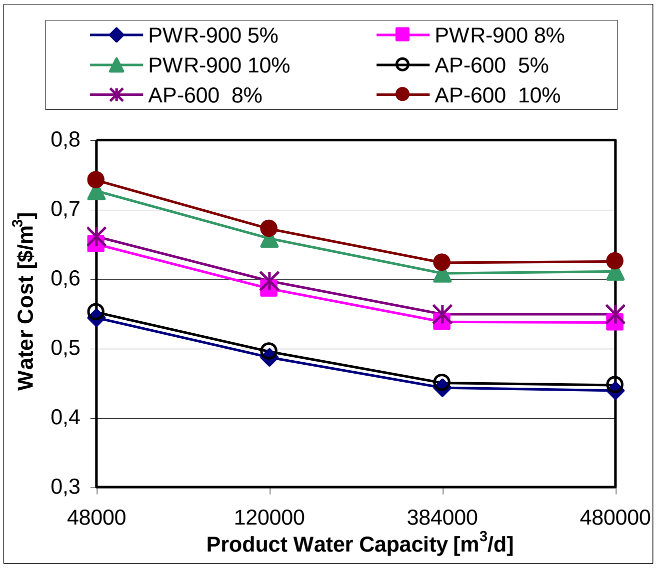
from [7]

GT-MHR Coupling with a Flash Tank

Coolant temperatures, high/low	°C	106/22	80/22
Coolant flow rate (60000 ppm)	kg/s	895.4	1313.9
Flash-tank temperature	°C	69.5	52
Steam produced	kg/s	57.1	61.6
Make-up flow rate	kg/s	180.2	194.7
Rejected flow rate	kg/s	123.1	133.0
Heat rejected in the heat sink	MW	155.7	145.81
Total heat rejected	MW	166.2	157.2
N° of MED effects	-	14	7
Distillate production.	m^3/day	61508	38306
GOR	-	12.48	7.19
H.P.	kJ/kg	210.37	360.75

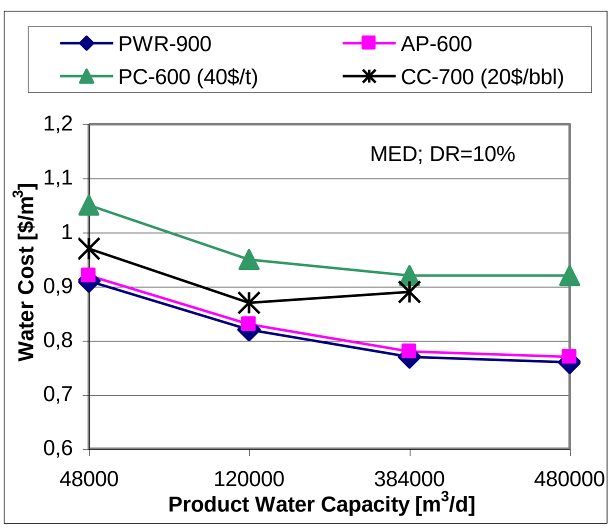
from [7]

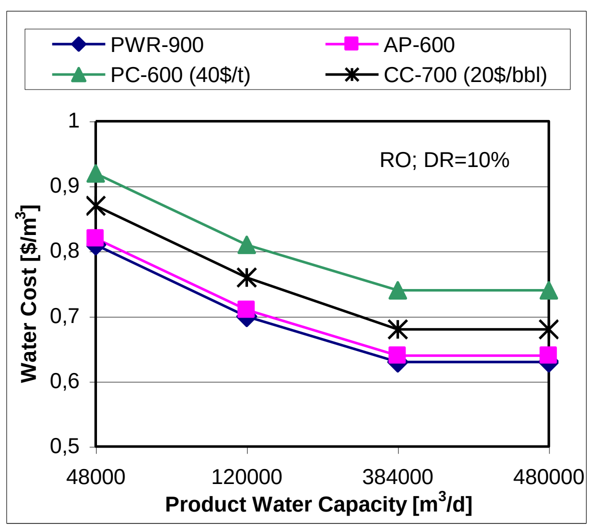
Desalination with ROph and Nuclear Power Plants for Different Discount Rates



from [7]

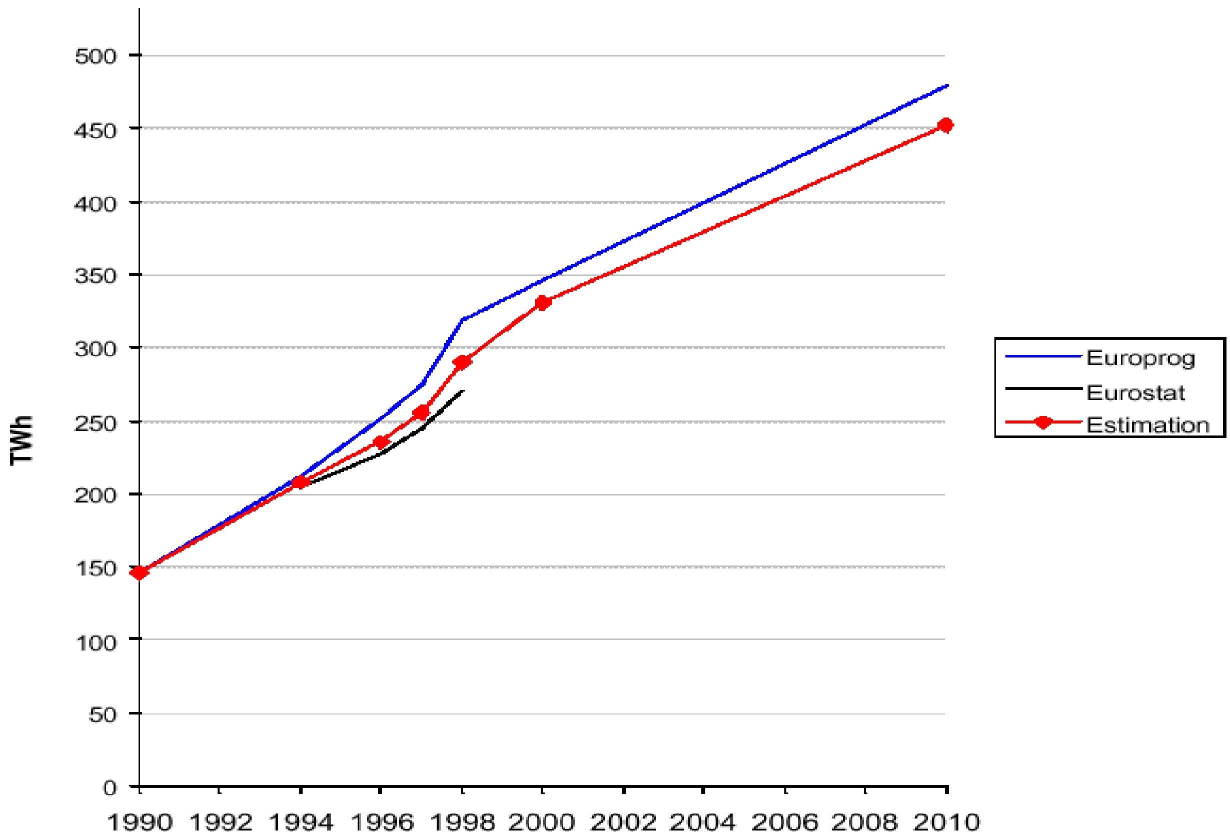
Comparison of Nuclear and Fossil Options for Desalination with MED and RO; Low Fossil Fuel Prices and Discount Rate=10%





from [7]

8. COMBINED HEAT AND POWER (CHP)



from [8]

Cogeneration in Europe

Total Maximum Electric Output Capacity [MW] (Continuous electric power considering that the CHP operates in the mode of maximum electric power)			
	1996	**2000**	**2010**
Austria	3232	4036	4998
Belgium	643	1135	1765
Germany	-	-	-
Denmark	8261	8621	8770
Finland	4270	5000	5700
France	2600	3600	6600
Greece	221	242	353
Ireland	-	-	-
Italy	7478	12021	16125
Luxembourg	32.7	61.3	422
Netherlands	7430	9848	9109
Portugal	777	895	-
Spain	2192	3573	4954
Sweden	3504	3650	3900
United Kingdom	3562	4700	7500
Total	**44192.7**	**52882.3**	**70196**

from [8]

Industry Steam Requirement

	Temperature [°C]	Pressure [MPa]	Flow [t/h]
Petrochemical Industry	150 - 850	60 15 - 20 3 - 10 (max) (demand)	~ 400 - 800
Wood and Pulp Factories	180 - 400	20 12 2 - 6 (max) (demand)	100 - 300
Textile Manufacture	150 - 300	10 - 12 2 - 5 (max) (demand)	30 - 60
Food Industry – Sugar	120 - 300	1.5 - 12	130 - 150
Food Industry – Milk	120 - 250	1.5 - 12	10 - 30
Food Industry – Drinks	120 - 200	1.5 - 10	10 - 30
Ceramics and Bricks	120 - 150 and < 600	High air flow requirements	(~120,000)
Automobile Industry	120 - 250	3 - 6	20 - 50
Tertiary Sector	120 - 200	1.5 - 3	10 - 100
Furniture Manufacture	120 - 300	3 - 6	25 - 30
Paper Manufacture	120 - 300	3 - 6	10 - 60
Desalination (med)	50 - 75	0.15 - 0.4	100

from [8]

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