HTR-TN
High Temperature Reactor Technology Network

Nuclear Power for the Production of Liquid Hydrocarbons

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0. Outline

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1. Hydrocarbons: Ideal Energy Carriers

	liquid hydrocarbons	hydrogen
1. Liquid between –40℃ and +80℃ even at high altitudes	✓	requires pressurization or cooling
2. Easy, inexpensive and energy efficient production, handling, storage, transport	✓	high pumping power, losses through leakage and permeation, special safety requirements
3. Limited needs for new infrastructure	✓	new infrastructure
4. Suitability for use in internal combustion engines	✓	✓
5. Suitability for use in fuel cells	✓ (methanol)	✓
6. Non-toxic	✓ (in handled quantities)	✓
7. High energy density per volume	✓	high energy density per mass but not per volume
8. Ability to be synthesized from hydrogen and CO_2 using heat and electricity	✓	✓

Criteria for ideal energy carriers [Bossel, 2003]

Fuel	Formula	molecular weight	density	**H_2-Density**	Energy per mass (HHV)	**Energy per volume**
		g/mole	kg/m³	**kgH_2/m^3**	MJ/kg	**GJ/m^3**
Methanol	CH_4O	32	792	**99**	22.7	**17.97**
Ethanol	C_2H_6O	46	789	**103**	29.7	**23.45**
Dimethlyether (DME)	C_2H_6O	46	666	**87**	31.7	**21.14**
Ethylmethylether	$C_4H_{10}O$	74	714	**96**	28.5	**20.34**
2-Methylpropane (Isobutane)	C_4H_{10}	58	557	**96**	49.4	**27.54**
2-Methylbutane (Isopentane)	C_5H_{12}	72	620	**103**	48.7	**30.17**
Ethylbenzol	C_8H_{10}	106	866	**82**	43.1	**37.30**
Methylcyclohexane (Toluol)	C_7H_{14}	112	769	**96**	34.9	**26.85**
Octane	C_8H_{18}	114	703	**111**	48.0	**33.73**
Ammonia	NH_3	17	770	**136**	22.5	**17.35**
Hydrogen (liquid or 800 bar)	H_2	2	70	**70**	141.9 120.1 (LHV)	**9.93**
Kerosene			817			**35.74**

Energy density per m³ of HC is 2-4 times greater than in liquid H_2

H_2 density in most HC greater than in liquid or compressed (800 bar) H_2

➔ Hydrocarbons are better H_2 carriers than H_2 itself

Well-to-Wheel

H_2 wastes 40% of LHV for compression, liquefaction, transport, leakage

➔HC fuel uses much less primary energy and produces less CO_2 than H_2

H_2 today mainly produced by SMR of natural gas (premium energy carrier)

➔ prefer use of NG directly instead of conversion to H_2 -
unless end user has a significantly higher efficiency with H_2 than with NG

H_2 has to compete with the energy source for its production (cost, energy)

➔ Certain experts (Bossel, Olah etc.) question economic and energetic attractiveness of a H_2 economy

2. How Can Nuclear Provide New Hydrocarbon Sources … and at the same time reduce CO_2 emissions?

Various HC can be synthesized depending on available carbon feedstock, chemical processes and desired end product.

All processes require:

- a carbon feedstock (coal, crude oil, natural gas, biomass or recycled CO_2)
- water (for the production of steam and H_2)
- (nuclear) process heat for the production of steam (and H_2 if thermochemical cycles are used for production)
- suitable catalysts
- (nuclear) electricity for process use (and for H_2 if produced by electrolysis)

Many of these processes could use the "Syngas Route"

a) From carbon feedstock and water:

$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$ $\Delta H° = +131.3$ kJ/mol (high temperature)

b) From carbon feedstock, oxygen and water:

$2\ C(s) + \frac{1}{2}\ O_2(g) + H_2O(g) \rightarrow 2\ CO + H_2$ "Shell entrained gasifier"

c) From carbon-dioxide and hydrogen:

$CO_2(g) + H_2(g) \rightarrow CO(g) + H_2O(g)$ $\Delta H° = +41.2$ kJ/mol

$2\ H_2O \rightarrow 2H_2 + O_2$ from electrolysis or thermochemical

Example: Methanol Synthesis

1. Syngas production

Coal is brought to high temperature through combustion and is then exposed to steam.

$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$ $\Delta H° = +131.3$ kJ/mol (high T)

2. H_2/CO adjustment

1 CO and 1 H_2 are coming from the syngas, the second required H_2 comes from the WGS:

$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$ $\Delta H° = -41.2$ kJ/mol

3. Hydrocarbon synthesis

$CO(g) + 2\ H_2(g) \rightarrow CH_3OH(l)$ $\Delta H° = -90.6$ kJ/mol, ≈250°C, 5-10 MPa, now with new catalysts down to RT

4. Overall reaction

$3C(s) + 4\ H_2O \rightarrow 2\ CH_3OH(l) + CO_2(g)$

CO_2 release from methanol synthesis could be reduced or eliminated by:

step 1: heating the coal with nuclear process heat instead of coal combustion;
step 1: producing the steam with nuclear heat;
step 2: using nuclear-produced H_2 instead of the WGS to reach H_2/CO = 2.

Example: Methanol from fossil CO_2 and nuclear H_2

Direct conversion of a CO_2/H_2 mixture to methanol. Acts as a CO_2 "sink".

$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$$

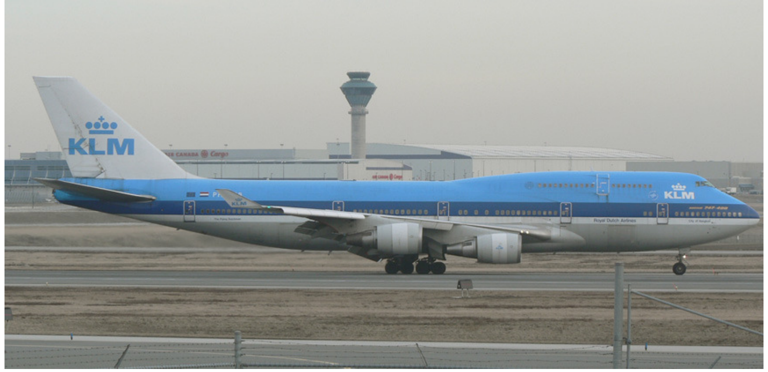
Various temperatures, pressures and catalysts are used:

- High pressure 30–35 MPa, 320–380 ℃, ZnO/Cr_2O_3 catalyst
- Medium pressure 10–15 MPa, 230–260 ℃, $CuO–ZnO–Cr_2O_3$ catalyst
- Low pressure 5–10 MPa, 240–260 ℃, $CuO–ZnO–Al_2O_3$ catalyst

This process can also be established in a reversed fuel cell.

- Production of HC consumes large amounts of water that needs to be available, desalinated where necessary, and purified.
- The use of nuclear power to produce syngas or syngas products from coal would save 1/3 of coal resources and would lead to an equivalent reduction in CO_2 emission.
- Nuclear power would enable coal-to-liquid processes without CO_2 rejection.
- Nuclear power can even act as a CO_2 sink and fully recycle CO_2 to liquid hydrocarbons.
- CO_2 from fossil fuel combustion can be employed as a valuable carbon feedstock.
- CO_2 recycling potentially makes CO_2 sequestration superfluous.

3. Example: Nuclear Power for Aviation Fuel



Classical coal-to-liquid processes are extremely dirty:

1. Similar amounts of coal and water are needed to produce similar amounts of ethanol and CO_2.

168 t coal + 176 t water → 150 t ethanol + 144 t CO_2 (+ 50.6 t ash)

2. The mass of waste (CO_2 and ash) together is almost a third more than the product (ethanol) itself.

Production of ethanol for a single 150 t fuel load/day would:

	Classic Coal Liquefaction	**Coal Liquefaction with CO_2 Recycling**	**CO_2 feedstock**
consume carbon	117.4 t ≈ 168 t raw coal	78.3 t ≈ 112 t raw coal	0
consume H_2	0	19.6 t	39.12 t
power equivalent for H_2 production (40% efficiency), LHV = 120 MJ/kg H_2	0	68.1 MWth	136.1 MWth
produce CO_2	143.5 t	0	(- 287 t)
produce ash	50.6 t	33.7 t	0
consume water (incl. for H_2 prod.)	176.1 t	176.1 t	176.1 t

Conclusions for an airport consuming the *mass equivalent* of 50 B747 fuel loads of ethanol per day (50×150 t/d):

- **Pure CTL:** CO_2 production (> 14,000 t/d) imposes CO_2 recycling with large quantities of H_2. CO_2 release equivalent to 2.43 GWe coal-fired power plant.
  Coal use corresponds to 50 × 168 t/d × 33.3 MJ/kg = 3.24 GWth,
  Ethanol production corresponds to 50 × 150 t/d × 26.74 MJ/kg = 2.32 GWth.
  ➔ Conversion efficiency: 2.32 GWth/3.24 GWth = 71.7%.
- **CTL with CO_2 recycling:** fuel production itself is CO_2 neutral, no sequestration required. CO_2 is used twice before emission. The liquefaction complex for this airport with CO_2 recycling would consume the water of a town of 63,000 (140 l/person-day).
  Coal used corresponds to 50 × 112 t/d × 33.3 MJ/kg = 2.16 GWth.
  Ethanol production corresponds to 50 × 150 t/d × 26.74 MJ/kg = 2.32 GWth.
  Nuclear power used 3.41 GWth (approx 6 HTRs of 600 MWth each) for H_2, for water cleaning, process steam, electricity
  ➔ Conversion efficiency: 2.32 GWth/(2.16 GWth + 3.41 GWth) = 41.7%.
- **CO_2 feedstock:** Power requirements for H_2 production double against coal liquefaction with CO_2 recycling. If centralized, a very large fossil-fired power plant (2.16 GWth or 972 MWe) would need to be in the neighborhood of the liquefaction plant in addition to a nuclear complex of 6.8 GWth. If decentralized smaller fossil plants could be twinned with nuclear reactors of approx. three times their thermal power.
  ➔Conversion efficiency: 2.32 GWth/6.8 GWth = 34%.

➔ Conflict between energy efficiency and CO_2 emission

4. Cost Considerations

US military study: CO_2 extraction from air with nuclear synfuel production for maritime transport and aircraft carrier-based fighter planes would lead to liquid hydrocarbon at < 3.67 $/gal.

These numbers are so positive that they require verification!

Factors for cost reduction:

- use of flue gas instead of ambient air
- thermochemical H_2 production with HTR technology instead of electrolysis from LWR electricity
- CO_2 credit

Cost in [US$/gal]	Coal-to-Liquid		CO_2 from fossil power plant		Atmospheric CO_2	
	LWR	HTR	LWR	HTR	LWR	HTR
Fuel cost without CO_2 credit (30 $/t)	2.36	2.06	**3.31**	2.75	3.67	N/A
Fuel cost with CO_2 credit (30 $/t)	1.61	1.32	3.02	2.46	N/A	N/A

Synthetic liquid hydrocarbon cost as a function on carbon feedstock and production method for a fixed charge rate of 5% [Locke Bogart, 2006]

Price for mechanical energy

	Synthetic kerosene*	**Diesel****	**Electricity*** (household)**
Price	3.31 $/gal = 0.665 €/l	1 €/l (at pump)	0.196 €/kWh
Energy density	9.93 kWh/l	10.1 kWh/l	
Conversion efficiency	30%	30%	85%
Price of mechanical energy w/o tax	0.223 €/kWh		
Price of mechanical energy w/ tax	**0.294 €/kWh (tax = 0.7 €/l)**	**0.33 €/kWh**	**0.231 €/kWh**

1 € = 1.315 US$

*: fossil CO_2, LWR H_2, no CO_2 credit

**: price quoted for December 2006 in the Netherlands

***: price quoted for January 2006 in the Netherlands

**Price for synthetic liquid hydrocarbons including tax comparable to fossil Diesel.
No tax loss for governments.**

5. Conclusions

- Huge potential for nuclear-produced syngas, methane or liquid hydrocarbons: chemical industry, trucks, aviation, ships. Massive deployment of NPP would require FBR and the Th-U fuel cycle.
- Policy choice is overdue between a synthetic hydrocarbon economy and a hydrogen economy. H_2 is still politically attractive due to its *apparent* cleanliness and simplicity, it is challenging technically, energetically and economically.
- Hydrocarbons appear as the more realistic option for short- and mid-term CO_2 reductions. Existing infrastructure for liquids and gas. But: Encourages fossil fuel burning (for CO_2 recovery) and continued use of low-efficiency combustion engines like for cars (20-30%) which could run more efficiently on cheaper (nuclear) electricity.
- Nuclear-assisted HC enable reducing CO_2 emissions and avoid technically risky and expensive CO_2 sequestration. The quoted economic assessment requires verification. It suggests that synthesis of liquid hydrocarbons from flue gas and nuclear hydrogen would lead to cost of mechanical energy that is more stable and very similar to what is paid today for mechanical energy from fossil fuel.
- There is a conflict between energy efficiency, CO_2 emission reduction and economy. The amount of a future CO_2 tax is decisive for finding the economic optimum.