

Decarbonizing Heat in Petroleum Refining Application

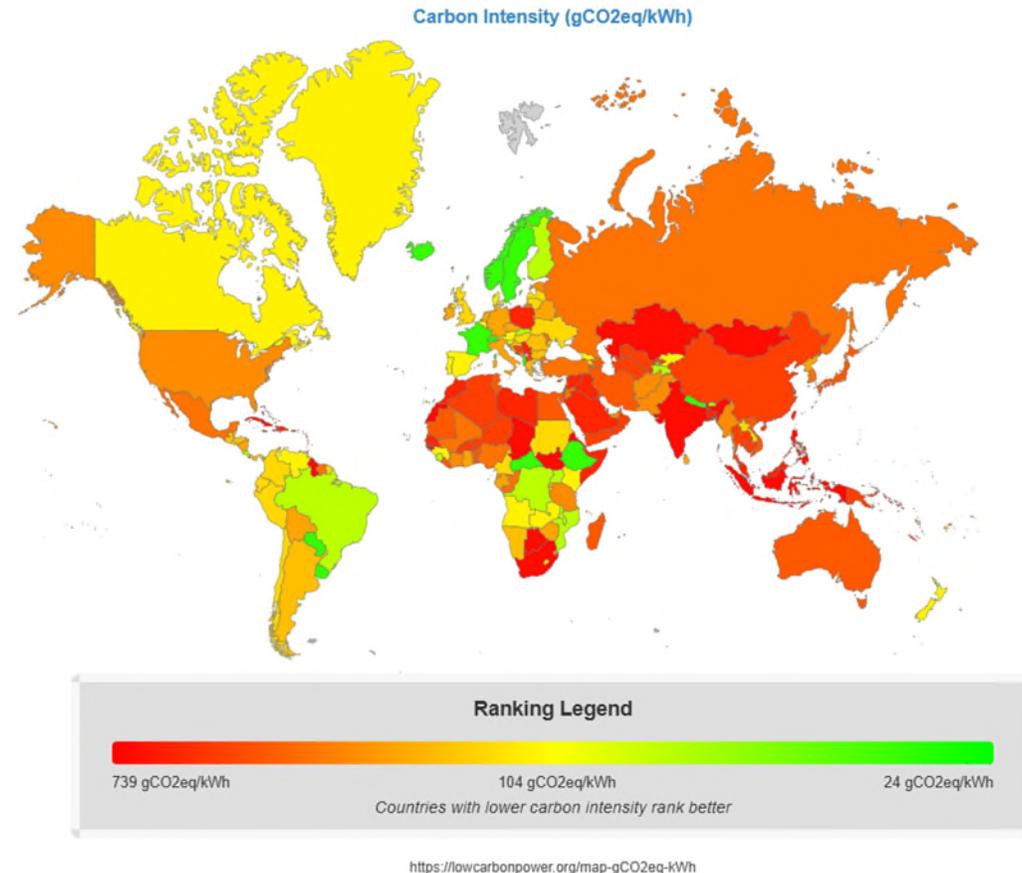
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Motivation for Decarbonization in Refining

- Is it more effective for the government to subsidize electric vehicles or to subsidize refinery heat pump projects?

	US Avg	UK	Canada	Norway
Electric Vehicle Analysis				
Daily Drive [mi/day]	29.9	29.9	29.9	29.9
ICE Fuel Economy [mpg]	22.8	22.8	22.8	22.8
Carbon Intensity of Gasoline [kg CO ₂ / gal gasoline]	8.89	8.89	8.89	8.89
Annual CO ₂ emission [ton CO ₂ / annum]	4.257	4.257	4.257	4.257
Electric Vehicle Efficiency [mi/kWh]	3.6	3.6	3.6	3.6
Carbon Intensity of Electrical Energy [kg CO ₂ /kWh]	0.393	0.217	0.185	0.017
Annual CO ₂ emission [ton CO ₂ / annum]	1.193	0.658	0.561	0.052
Avoidance per Electrical Vehicle [ton CO ₂ / annum]	3.064	3.599	3.696	4.205
Electrical Vehicle Subsidy [\$ / vehicle]	7500	7500	7500	7500
Cost of CO ₂ avoidance [\$ / CO ₂ per annum]	2448	2084	2029	1784
Refinery Thermal Application Analysis				
Refinery Thermal Application [MW _t]	10	10	10	10
Capacity Factor [%]	98%	98%	98%	98%
Furnace Efficiency [%]	85%	85%	85%	85%
Carbon Intensity of Fuel Gas [ton CO ₂ / MMBTU]	0.053	0.053	0.053	0.053
Annual CO ₂ emission [ton CO ₂ / annum]	18264	18264	18264	18264
Heat Pump COP	1.25	1.25	1.25	1.25
Carbon Intensity of Electrical Energy [kg CO ₂ /kWh]	0.393	0.217	0.185	0.017
Annual CO ₂ emission [ton CO ₂ / annum]	27019	14903	12706	1168
Avoidance on specified Application [ton CO ₂ / annum]	-8755	3361	5559	17096
Cost of a heatpump system [\$ / kWt]	400	400	400	400
Cost of CO ₂ avoidance [\$ / CO ₂ per annum]	-457	1190	720	234



For USA right now, switching to EVs is better....

...but in some countries YES and hopefully in the USA soon.

Major Energy Consumers in Petroleum Refining

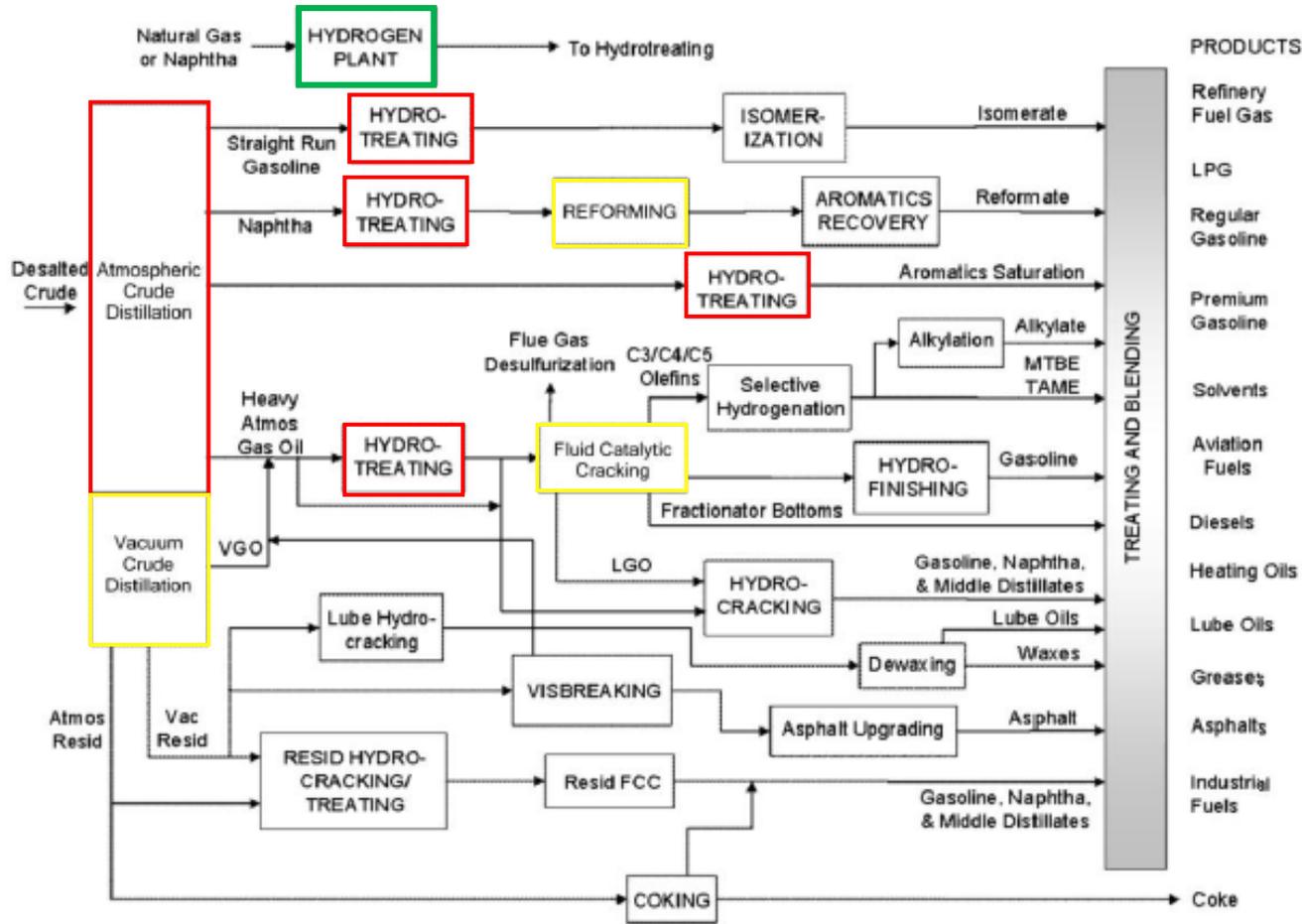


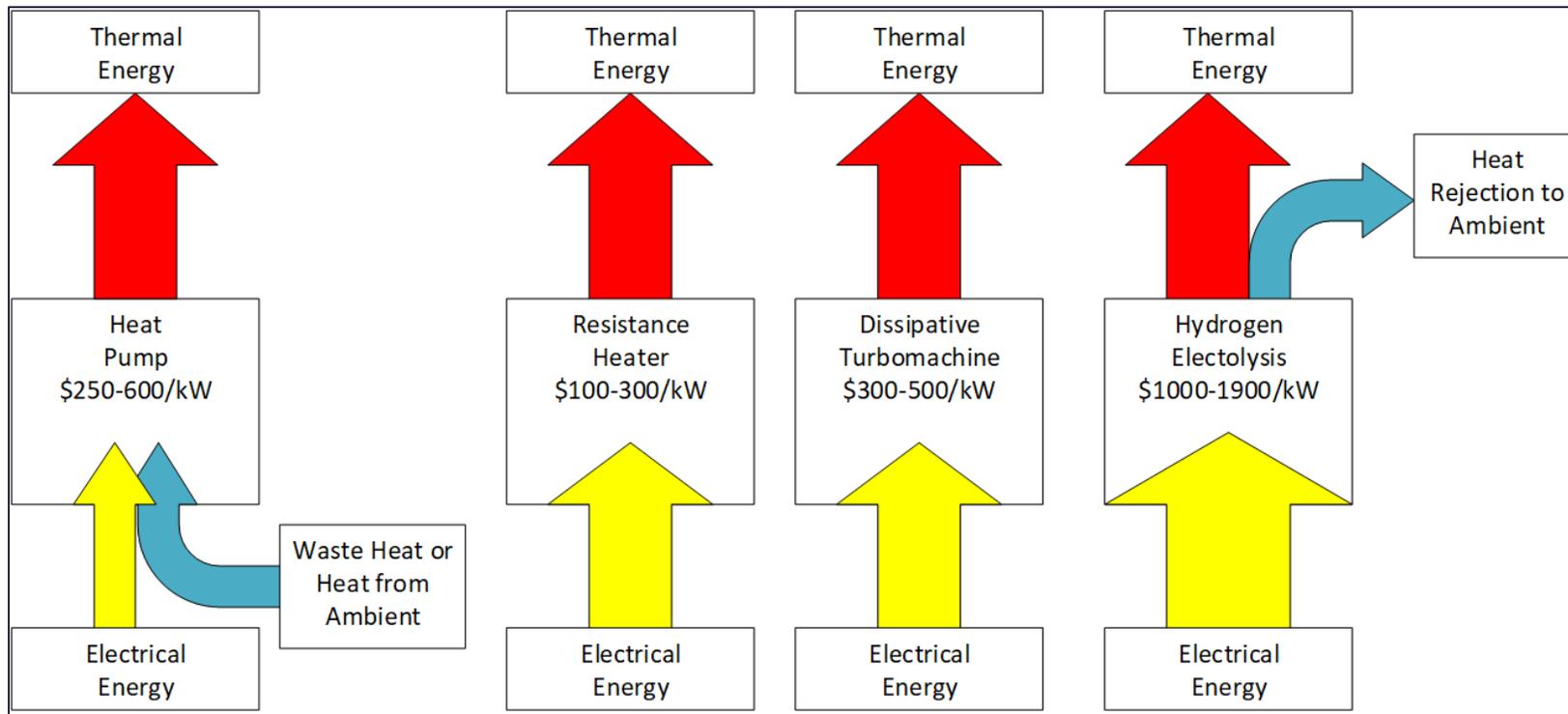
Table 4-2. Calculated U.S. Onsite Current Typical Energy Consumption for Processes Studied in 2010 with Calculated Primary Energy Consumption and Offsite Losses

Process	Energy Intensity (Btu/bbl)	Throughput or Production ¹ (million bbl/year)	Onsite CT Energy Consumption, Calculated (TBtu/year)	Offsite Losses, Calculated (TBtu/year) ²	Primary CT Energy Consumption, Calculated (TBtu/year)
Alkylation	246,700	365	90	11	101
Atmospheric Crude Distillation	109,100	5,540	604	72	676
Catalytic Hydrocracking	158,900	532	85	10	95
Catalytic Reforming	263,900	1,055	279	33	312
Coking/Visbreaking	147,700	770	114	14	127
Fluid Catalytic Cracking	182,800	1,827	334	40	374
Hydrotreating	80,800	4,829	390	46	437
Isomerization	216,000	203	44	5	49
Vacuum Crude Distillation	89,100	2,504	222	27	250
Total for Processes Studied			2,163	257	2,420

Current typical (CT)
¹ Values for alkylation and isomerization are production; all other process values are throughput
² Accounts for offsite electricity and steam generation and transmission losses. Offsite electrical losses are based on published grid efficiency. EIA Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from offsite sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Offsite steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011, [Steam Systems Best Practices](#)) and offsite steam transmission losses are estimated to be 10% (DOE 2007, [Technical Guidelines Voluntary Reporting of Greenhouse Gases](#) and EPA 2011, [ENERGY STAR Performance Ratings Methodology](#)).
 References for throughput or production data and energy intensity data are provided by process in Appendix A2. The other values are calculated as explained in the text.

Heat Pump Rationale

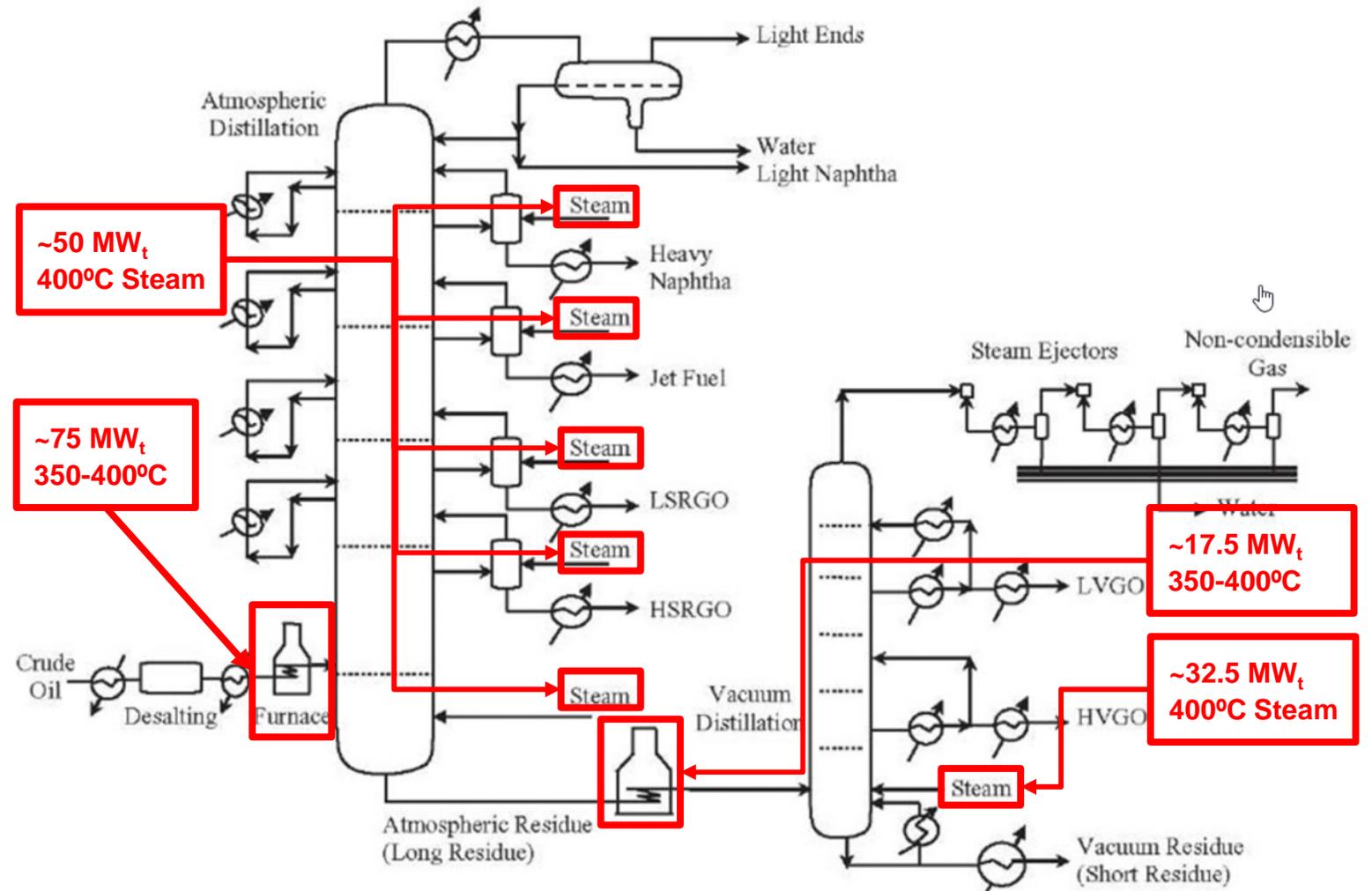
- To eliminate carbon emissions, electricity must be used to serve demands which are currently served by the combustion of fossil fuels.
- Of the various means to electrify thermal demands, heat pumps consume the least electricity for the amount of thermal energy they provide.



Crude and Vacuum Distillation Units

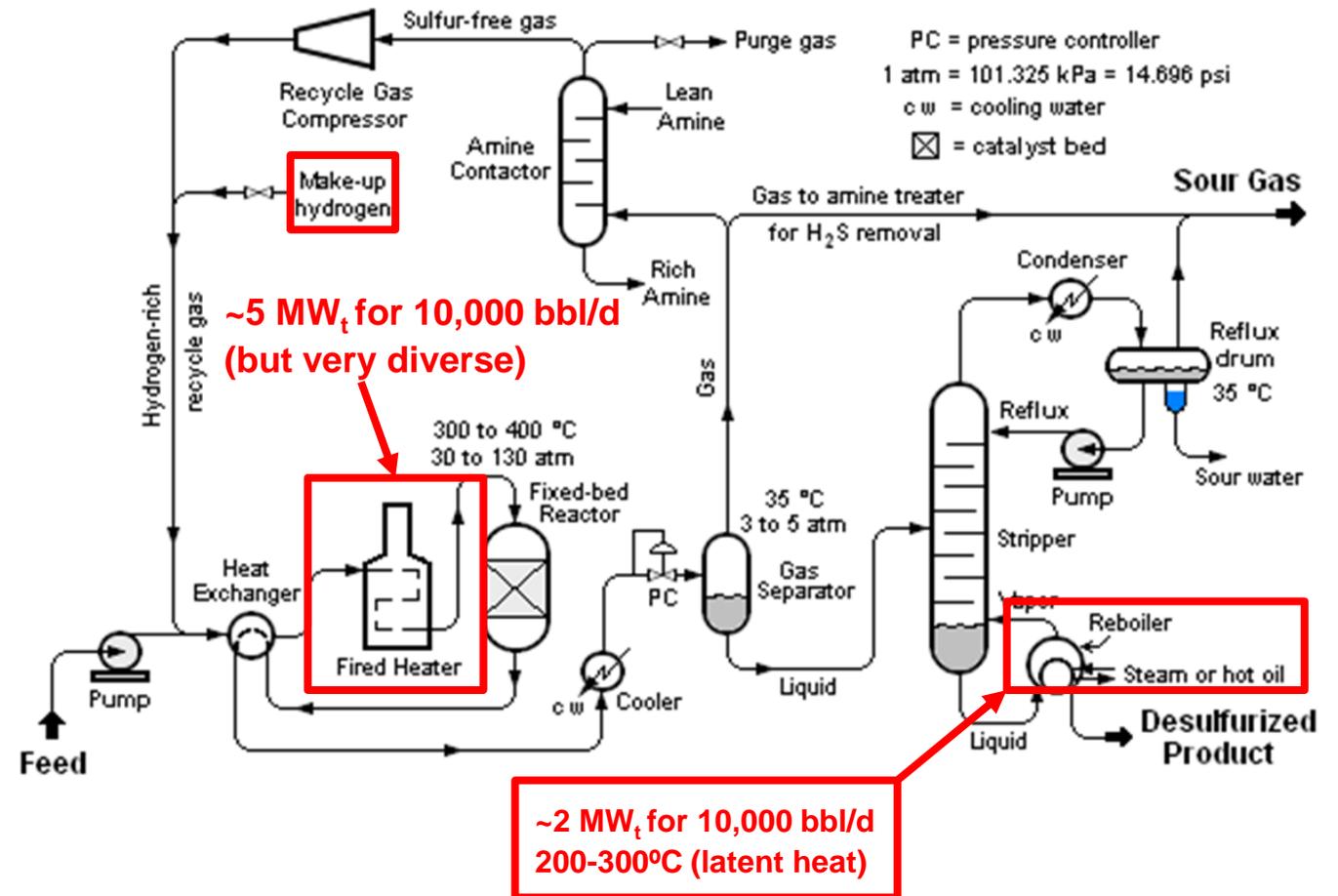
- Crude and vacuum distillation units divide crude oil into various boiling point range products which then go on for further processing / blending
- Main “non-process” opportunity for decarbonization is to replace gas-fired furnaces with heat pumps.
- Electrifying steam production is also possible but more difficult at higher temperature and also difficult to compete with cogeneration efficiency

100,000 bbl/d Refinery Example



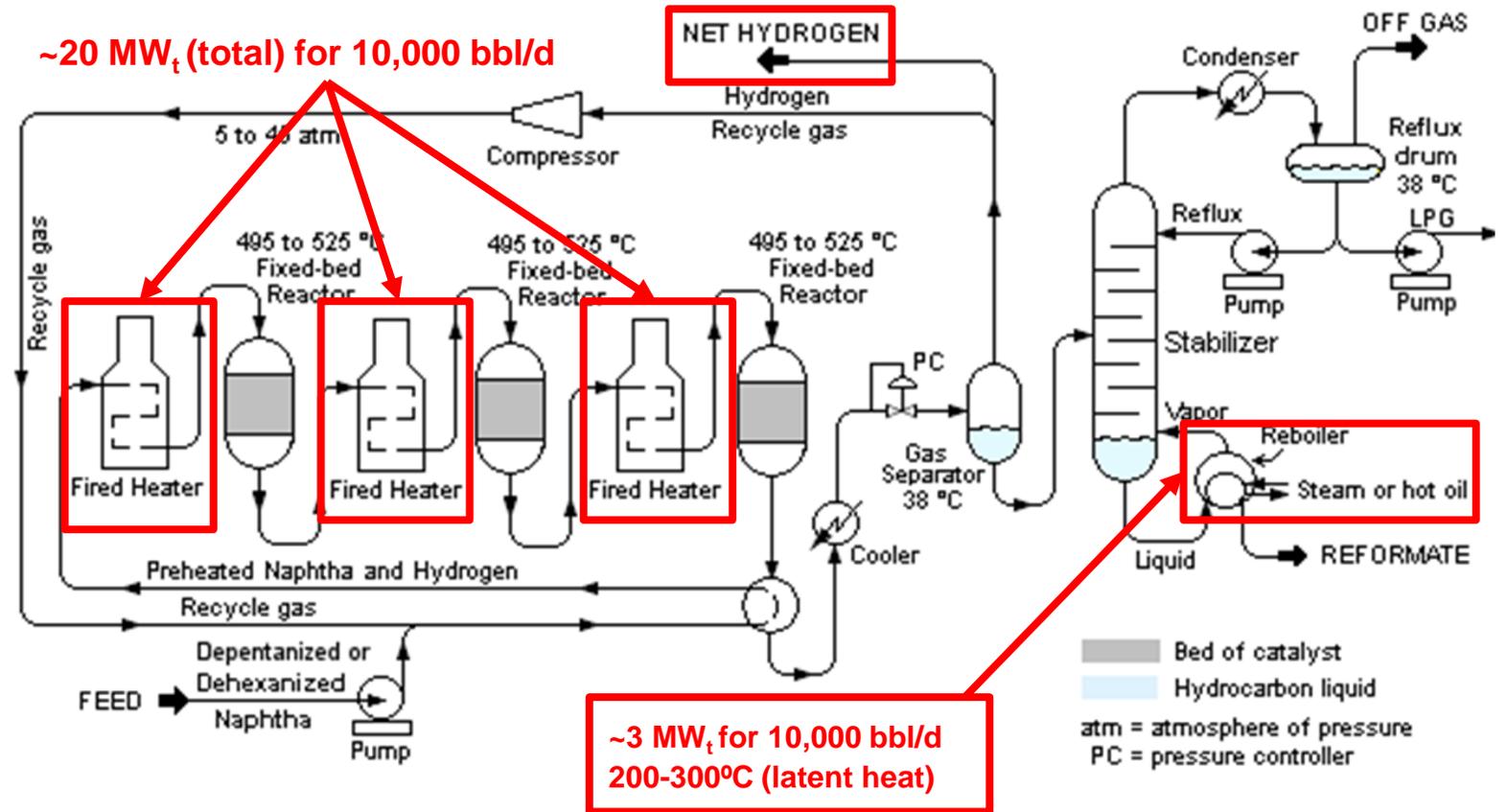
Hydrotreaters

- Hydrotreating removes sulfur and nitrogen compounds from liquid hydrocarbons
- Main “non-process” opportunity for decarbonization is to replace gas-fired furnace with heat pump
- Heat source for distillations might also be achieved by heat pumping
- Hydrotreating consumes hydrogen so green hydrogen also helps



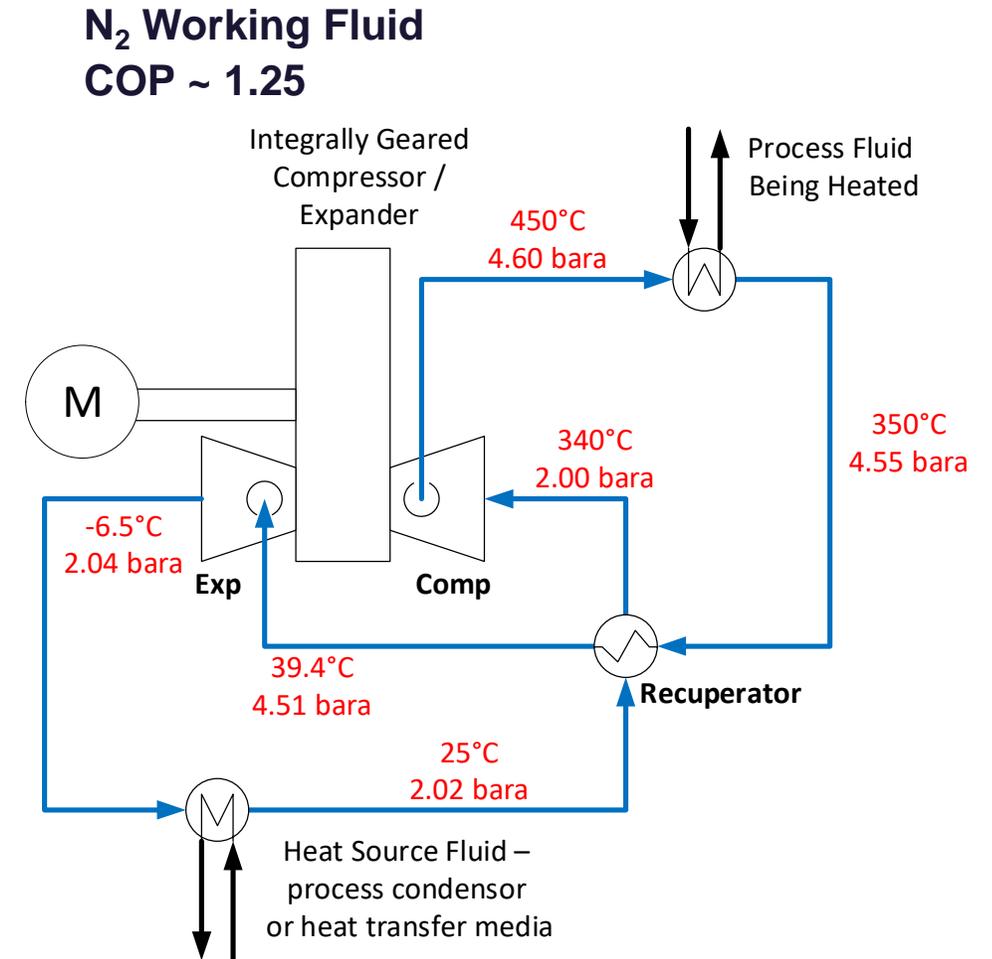
Reforming Example

- Reforming converts straight-chain hydrocarbon molecules into cyclic molecules which have higher octane rating.
- Main “non-process” opportunity for decarbonization is to replace gas-fired furnace(s) with heat pump
- Heat source for distillations might also be achieved by heat pumping
- This process produces hydrogen (not helped by green hydrogen).



Reverse Brayton Cycle Heat Pump

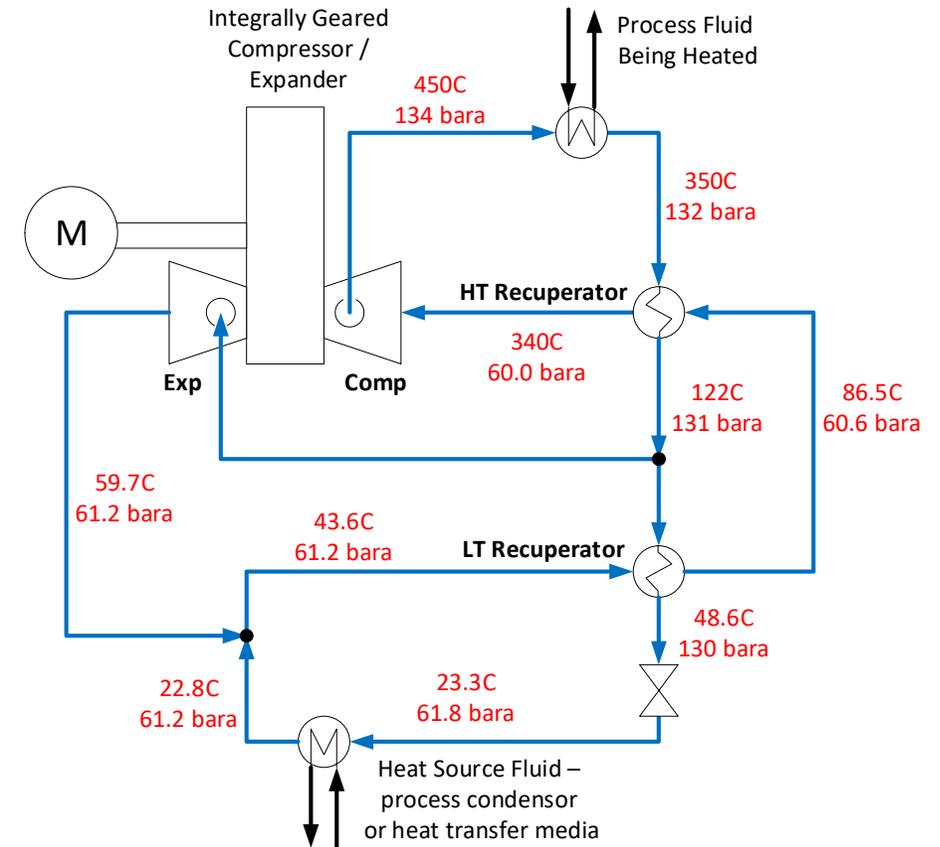
- To reach temperatures in the 300°C - 500°C range, schemes based on ideal gas are likely preferred.
- Ideal gas cycle requires an expander to absorb energy (i.e. to become a heat pump and not a dissipative turbomachine)
- A recuperator is required to concentrate the heat delivery at an elevated temperature range
- Cycle pressure level selection is arbitrary and could even be modulated to control output.
- There may be some synergy if a process has simultaneous need of or could derive some benefit from refrigeration.



Supercritical CO₂ Cycle Heat Pump

- Supercritical CO₂ cycle can also achieve target temperature range.
- However, a more complicated system given need to split recuperator and slightly lower COP due to temperature pinches in the heat exchangers
- On the positive side for CO₂, the heat input is boiling / latent heat at considered heat input temperature

CO₂ Working Fluid COP ~ 1.23

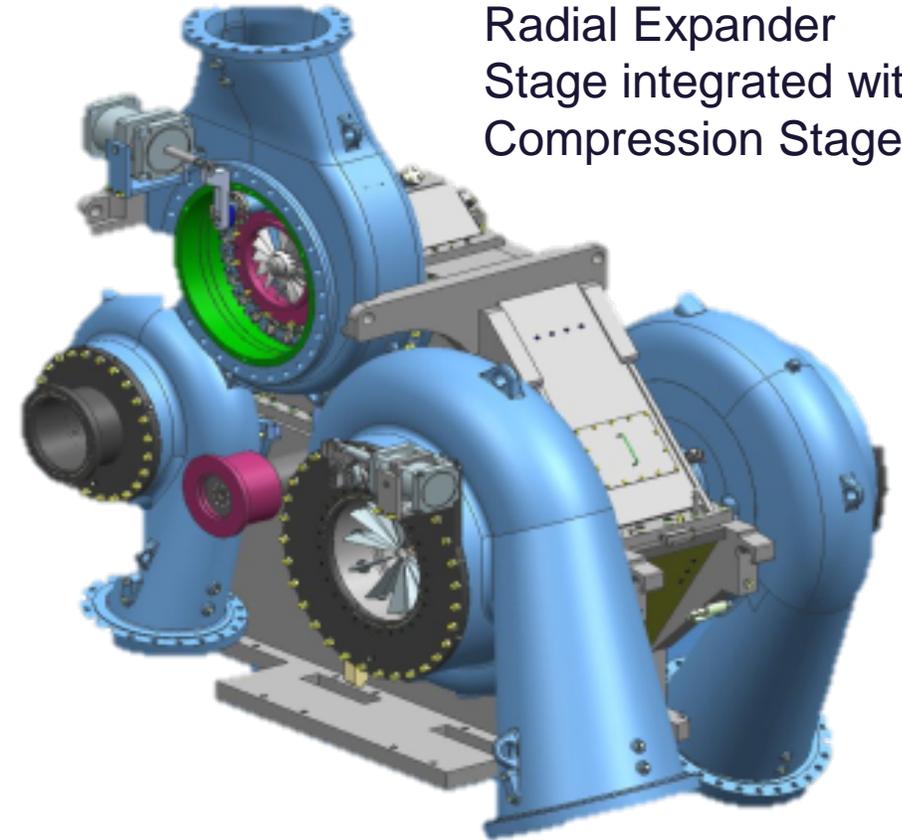


Integrally Geared Machinery Configuration



Radial Expander Stages applied using Integrally Geared Platform

Integrally Geared Compressor Train



Radial Expander Stage integrated with Compression Stages

Conclusions

- Heat pumps offer a compelling solution to electrify thermal energy applications in petroleum refining, thereby eliminating combustion of fossil fuels
 - Of the possible alternatives, heat pumps use the least amount of electricity per unit of thermal energy delivered.
- For temperature ranges most interesting in refining applications, solutions based on ideal gas working fluid are most interesting
 - Ideal gas heat pumps involve gas expansion, which results in a low temperature sensible heat duty for the heat source. This low-temperature heat absorption could provide low-level refrigeration as a co-product with the delivered heat.
- An integrally geared platform likely offers the best opportunity to create such heat pumps as applications are likely bespoke and it is relatively easy to customize compression and expansion stages to suit the application

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