ER 200 Problemset 3, Nick Clarke

1 Cogeneration

On the first field trip, some of your classmates visited UC Berkeley's 24 MW cogeneration plant that supplies electricity and steam to campus facilities. Cogeneration, also known as combined heat and power, is considered an energy efficient technology. Visit these websites to learn more about cogeneration: The Environmental Protection Agency's CHP Partnership: http://www.epa.gov/chp/ and the Pacific Region CHP Application Center: http://pacificchptap.org. [7 points]

1a

Thermodynamically, why is cogeneration more efficient than conventional generation methods?[3 points]

ANSWERS: Cogeneration takes advantage of the low-grade waste heat that under conventional generation methods is not able to be converted into W_out. Cogeneration adds an additional step to harvest this waste heat as part of W_in in the second stage, and uses this heat as part of additional W_out. Thus, less energy leaves the system as Q_out.

1b

Cogeneration is often discussed in the context of climate change mitigation and greenhouse gas reduction technology. Write one brief paragraph on why this is the case. [4 points]

ANSWERS: As is seen in the calculations of 2c below, the total heat energy that is turned into useful work, also known as thermal efficiency, is quite low. In this case, over half of the heat energy is lost. Cogeneration helps alleviate this by harvesting a portion of this waste heat energy that is unusable by the first stage, and gathers some additional useful work out of it. This allows us to get more work out of a fuel that is already going to be burned regardless. Furthermore, given that the second stage work is normally used in the same locality to the cogeneration plant, it may be even more efficient than the energy that would otherwise need to be used to perform the task. For example, if the cogeneration plant delivers steam condensate as its work in the second stage for use in heating a building, the thermal efficiency of creating the steam could be higher than the imported electricity the building may use to run HVAC units to heat the building.

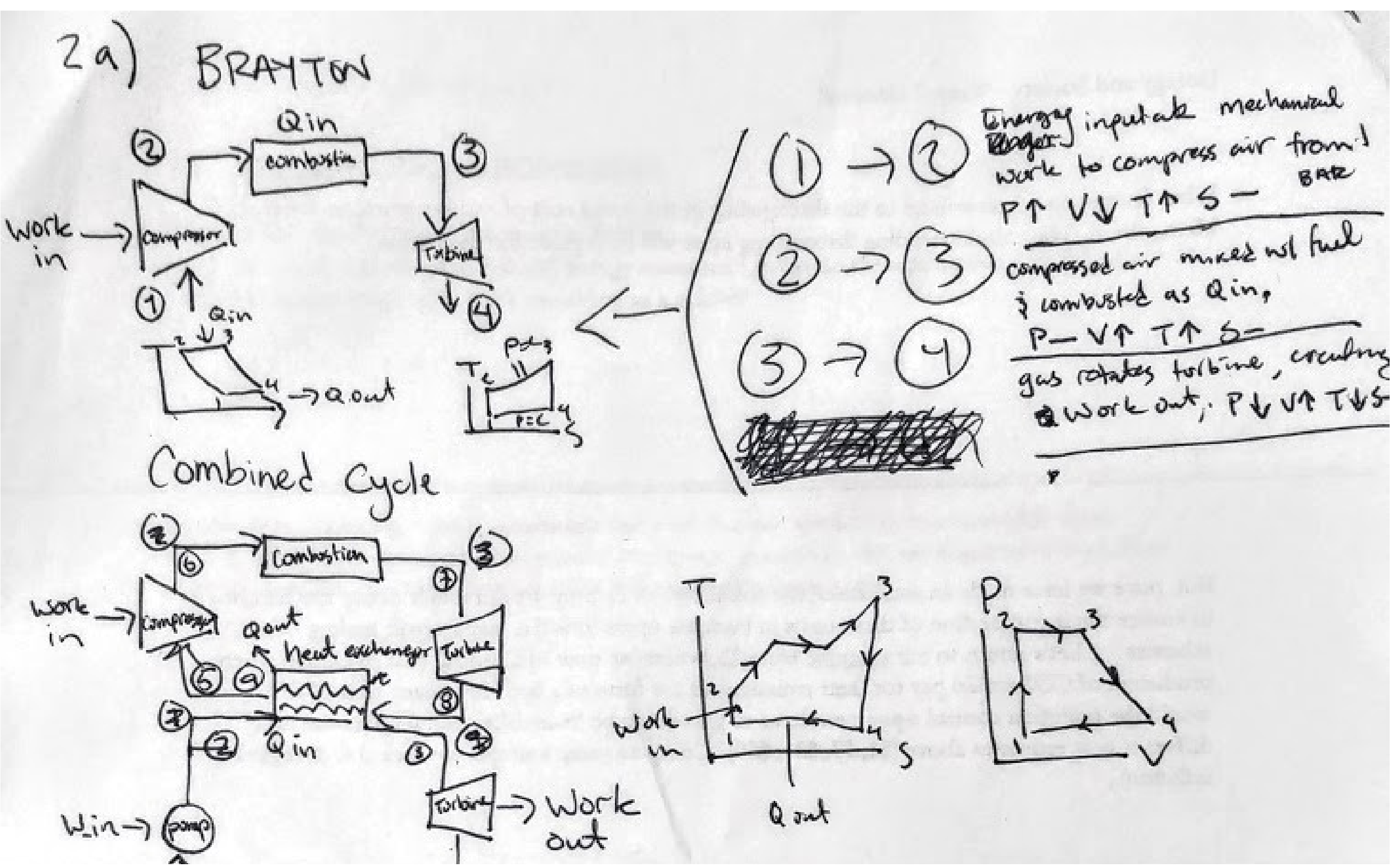
2 Thermodynamics of Energy Systems

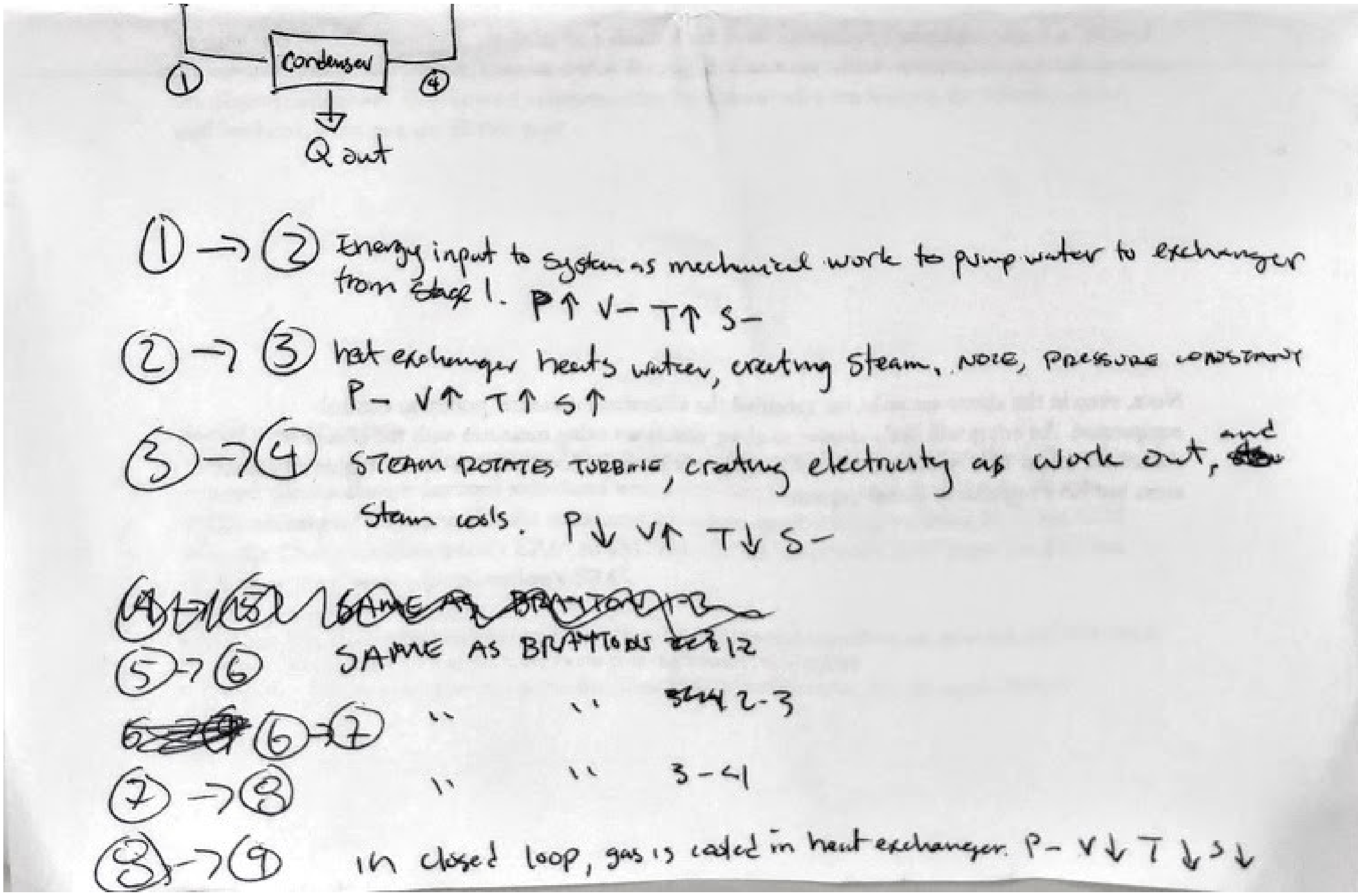
Combined Cycle Plants 2. Dynegy's Moss Landing Power Plant in Monterey, a natural gas fired plant, used to be the largest generation facility in the state of California with a total installed capacity of approximately 2,540 MW. Of the four generators in the facility, the two newer generators are still in operation, but the two older generators were retired in December 2016. The two newer generators (1,020 MW total) are combined cycle (using both the Brayton cycle for gas and Rankine cycle for steam), and the older two generators (760 MW each) used gas turbines only (the Brayton cycle). Combined cycles are another way to improve the overall efficiency of a power plant. The rate of energy added during the combustion of fuel when the generator is running at full capacity (not taking into account cycle efficiency) is 5,350 million Btu/hr per older generator. Combined cycle natural gas power plants in California have an average annual capacity factor of about 42.7%1. [29 points]

2a -

Draw 2 schematics showing the difference between the Brayton Cycle and Combined Cycle and label all components. In thermodynamic terms, briefly explain the function of each component, including what takes place in each component in terms of heat exchange, work, temperature and pressure

ANSWERS:





1 → 2 Energy input to system as mechanical work to pump water to exchanger from stage 1. P↑ V– T↑ S–

2 → 3 heat exchanger heats water, creating steam. NOTE, PRESSURE CONSTANT P– V↑ T↑ S↑

3 → 4 STEAM ROTATES TURBINE, creating electricity as work out, and steam cools. P↓ V↑ T↓ S–

~~4 → 5 SAME AS BRAYTON~~

5 → 6 SAME AS BRAYTONS 1-2

6 → 7 " " 2-3

7 → 8 " " 3-4

8 → 9 in closed loop, gas is cooled in heat exchanger. P– V↓ T↓ S↓

2b

Calculate the Carnot efficiency of a Brayton cycle system operating at the following temperatures. In one sentence, explain what Carnot efficiency represents. (Note: all temperatures given in degrees Celsius) [5 points]:

- *T1 = temps at exit of the exhaust heat exchanger and inlet of the compressor = 30ºC*
- *T2 = temp at exit of the compressor and inlet of the combustor = 390ºC*
- *T3 = temp at the exit of the combustor and the inlet of the turbine = 1085.ºC*
- *T4 = temp at the exit of the turbine and the inlet of the exhaust heat exchanger = 535ºC*

```
t_high = 1085
t_low = 30

def carnot(t_high, t_low):
    # convert to Kelvin
    high = t_high + 273
    low = t_low + 273
    return (high - low) / high

nc = carnot(t_high,t_low)
```

ANSWERS: Carnot Efficency = 0.78. Carnot efficency represents the maxiumum amount of energy that can be extracted from a heat engine in an ideal setting.

2c

Calculate the 1st law efficiency of the generator that uses the Brayton cycle. In one sentence, explain what first law efficiency represents. [4 points]

```
w_net_mw = 760
q_in_btu_hr = 5350e6

mw_to_btu = 1 / 3.41e6

def first_eff(w_net, q_in):
    return w_net / q_in

q_in_mw = q_in_btu_hr * mw_to_btu

n1 = first_eff(w_net_mw,q_in_mw)
```

ANSWERS: N1 efficency = 0.48. This is the "thermal" efficency, and is how efficiently a heat engine converts heat input into work output. I like to think of it as "realized" efficiency

2d

What is the second law efficiency of the generator that uses the Brayton cycle? In one sentence, explain what second law efficiency represents. [4 points]

```
def second_eff(n1, nc):
return n1/nc

second_eff(n1,nc)
```

ANSWERS: N2 efficency = 0.62. This is how close to the theoretical maximum, the carnot efficiency, you have achieved.

2e

Consider the newer combined cycle generators. Assume that the performance of the gas turbines in these generators is the same as the older generators which use only the Brayton cycle. If the thermal efficiency for the steam turbine system (the Rankine cycle) is 33%, calculate the overall efficiency for the combined cycle. [4 points]

```
e1 = first_eff(w_net_mw,q_in_mw) # 0.48
e2 = 0.33

def overall_eff(e1, e2):
    return e1 + (1 - e1) * e2

print(overall_eff(e1,e2))
```

ANSWERS: Overall efficiency = 0.65.

2f

As of 2018, what is the total energy output from the Moss Landing Power Plant in a typical year (in kWh)? [2 points]

```
mw_2018 = 1020
cap_factor = 0.427

kwh_2018 = (1020 * 8760) * 1000 * cap_factor
print(kwh_2018)
```

ANSWERS: 3.8E9 Kwh in 2018

The Environmental Impacts of the “Oil Transition”

[For ER200/PP284 Students Only] We will now look quantitatively at the CO2 implications of a transition to oil substitutes. We will use stylized equations to estimate roughly the impacts of this transition. (Hint: one easy way is to build simple models that are easily reconfigurable for different input values, e.g. in Excel.) [30 points]

ANSWERS: See spreadsheet, sheet "Problem 4" for anwswer to 4A - 4D. See Methods below:

4A

- Used 3,000 BBL (farrell, 2006) as Q for curve A.
- Curve A
  - Solved q = sigma Pm sqrt(2 pi) for PM (max production rate
  - Graphed Production (P) vs time (t) using t_2006 as t_m and years 2000-2025 for t
- Curve B
  - Increased curve A Pm by 10% for Curve B, since the question noted there is "less oil in curve a". We assumed this was total oil.
- Graphed P vs t using t_2017 as tm and 2000-2025 for t

4B

- Increased each P value by 2% per year starting after the peak year, y = Pm_tm(102)^t.
- plot these new y-values against from 2000-20025

4C

- (gap amount 2025) / (MJ/gbbl)(g-c/MJ) = g-c
- calculate for 50% tar sands, 25% synthfuels 25% oil shale, then add up

4D

- same process as C. Carbon inplicatoinare are 1/2 of that previous question, implying that vehicle efficiency alone can make a significant cut to emissions

4E

$$Q_{synthfuels} = (X_{conventional} * Q_{conventional}) - (X_{hybrid} * Q_{hybrid})$$

$$Q_{cars} = (X_{conventional} + X_{hybrid})$$

Solve for the System of Equations:

$$(3.1E9 * \frac{42_{gal}}{1_{barreloil}}) = (X_{conventional} * \frac{10,000_{miles}}{30_{mpg}}) - (X_{hybrid} * \frac{10,000_{miles}}{80_{mpg}})$$

$$130.2E9 = [(800E6 - X_h) * 333] - [X_h * 125]$$

$$130.2E9 = (2.6E11 - 333 * X_h) - (125 * X_h)$$

$$X_h = \frac{1.3E11}{458}$$

$$X_h = 2.8E8$$

Device	Power Load (watts)	Time Start	Time End	Total Time (hours)	Energy (kWh) [1]	Energy (Joules)	Power Rating Notes/Source
OnePlus 5	3	08:00:00	23:44:00	15:44:00	0.047	1.70E+05	Assuming rough estimate of 3 watt avg draw. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6881397
Dell XPS 15	25	11:00:00	13:15:00	2:15:00	0.056	2.03E+05	Draw under load from hardware review: https://www.kitguru.net/lifestyle/mobile/notebook/dominic-moass/dell-xps-13-9360-review/8/
Viewsonic Monitor	24	11:00:00	13:15:00	2:15:00	0.054	1.94E+05	Assumes "average load" from their specs. https://www.viewsonic.com/us/va2446m-led.html
Kettle	750	08:31:00	08:39:00	0:08:00	0.100	3.60E+05	Rated draw from label
Fridge (home)	76	00:00:00	23:59:00	23:59:00	1.823	6.56E+06	Rated draw from EnergyGuide http://manuals.frigidaire.com/prodinfo_pdf/energyguides/FFSS2315T_EG.PDF
Bathroom Lights	56	8:30:00	9:00:00	0:30:00	0.028	1.01E+05	Assumes 14 watts per bulb http://www.westinghouselighting.com/light-bulbs/cfl-bulbs/covered/14-watt-a-shape-cfl-light-bulb-3790100.aspx
fridge (erg)	60	10:50	14:02	3:12:00	0.192	6.91E+05	Assumes 463 kwh / year from similar model's EnergyGuide rating. https://i.sears.com/s/d/pdf/mp-tc/10099713/prod_17720492812
Microwave	1200	13:00	13:03	0:03:00	0.060	2.16E+05	Rated draw from back of microwave
Dell XPS 15	25	18:30	21:10	2:40:00	0.067	2.40E+05	see above
Viewsonic Monitor	24	18:30	21:10	2:40:00	0.064	2.30E+05	see above
Fluorescent lights (ERG)	224	18:45	21:10	2:25:00	0.541	1.95E+06	Assumes T8 sized tubes https://www.mge.com/saving-energy/business/tips-comm/t8.htm
				TOTALS:	**3**	**1E+07**	

Indirect Consumption

Source	Power Load (watts)	Conversion factor (if ne	Time Start	Time End	Total Time (hours	Energy (kWh) [2]	Energy (Joules)	Power Rating Notes/Source
Cycling	222	3	9:10	9:43	0:33:00	0.002	5.94E+03	3watts/kg, 74 kg: https://www.trainingpeaks.com/blog/power-profiling/
1 cup avocado	NA	234	NA	NA	NA	0.27195948	9.79E+05	234 per cup - https://ndb.nal.usda.gov/ndb/foods/show/09037?fgcd=&manu=&format=Full&count=&max=25&offset=&sort=default&order=asc&qlookup=09037&ds=&qt=&qp=&qa=&qn=&q=&ing=
3 cups chowder	NA	603	NA	NA	NA	2.10245598	7.57E+06	603 kcal per cup: https://ndb.nal.usda.gov/ndb/foods/show/45353601?man=&lfacet=&count=&max=25&qlookup=chili+soup&offset=&sort=default&format=Full&reportfmt=other&rptfrm=&ndbno=&nutrient1=&nutrient2=&nutrient3=&subset=&totCount=&measureby=&Q552411=3&Qv=1&Q552411=1&Qv=1
2.5 yogurt	NA	138	NA	NA	NA	0.4009659	1.44E+06	138 kcal per cup: https://ndb.nal.usda.gov/ndb/foods/show/01116?man=&lfacet=&count=&max=25&qlookup=yogurt&offset=&sort=default&format=Abridged&reportfmt=other&rptfrm=&ndbno=&nutrient1=&nutrient2=&nutrient3=&subset=&totCount=&measureby=&Qv=1&Q322683=1&Q322684=2.5&Q336826=0.5&Q322686=1&Qv=1&Q322683=1&Q322684=1&Q336826=0.5&Q322686=1
4 slices bread	NA	79	NA	NA	NA	0.36726152	1.32E+06	79 kcal per slice: https://ndb.nal.usda.gov/ndb/foods/show/18064?fgcd=&manu=&format=&count=&max=25&offset=&sort=default&order=asc&qlookup=bread&ds=&qt=&qp=&qa=&qn=&q=&ing=
					TOTALS:	**3.1**	**1E+07**	

[1] Column E uses the "Duration" format for calcuating time, in which 24 hours = 1, and then coverts that into a format legible as time.

As such, we need to multiply our answer by 24. Thus =B*E / (1000) * 24

[2] This is variable, depending on the source I am calculating:

For Column E uses the "Duration" format for calcuating time, in which 24 hours = 1, and then coverts that into a format legible as time.

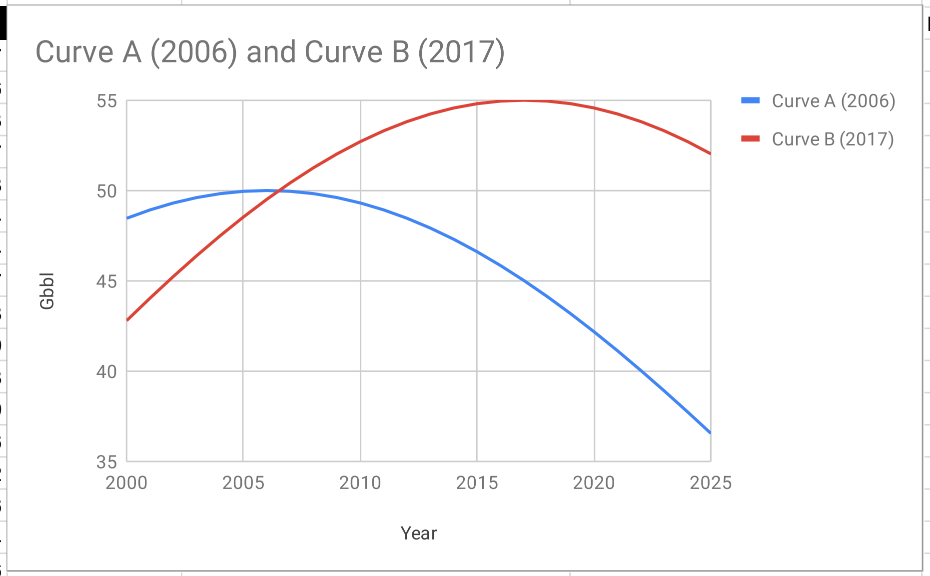
As such, we need to multiply our answer by 24. Thus =B*E / (1000) * 24

Collaborative work by Nick Clarke, Jess Carney, Nancy Freitas

4A

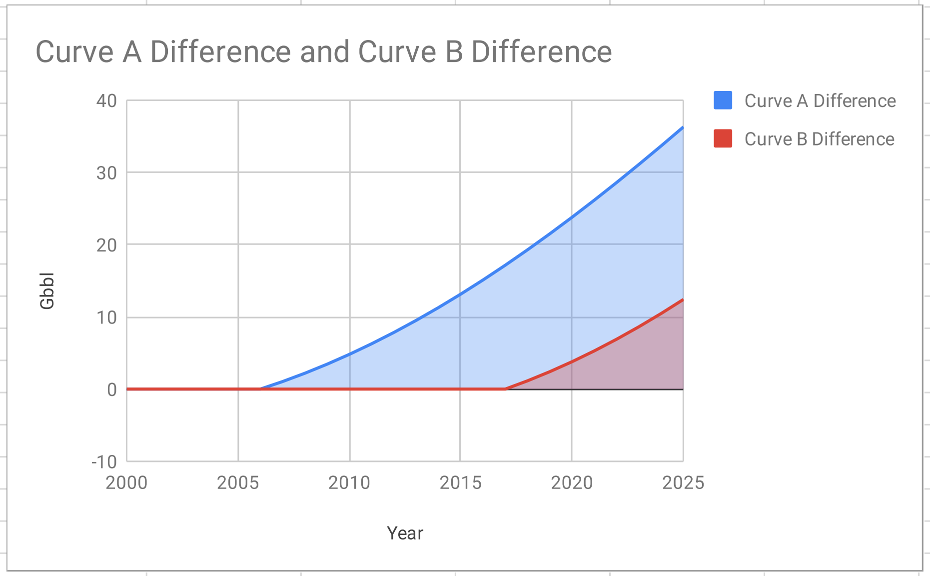
NOTES ON METHODS, ROLLOVER [1]

Year	Curve A (2006)	Curve B (2017)
2000	48.46166172	42.79687687
2001	48.9266196	44.04055716
2002	49.31035584	45.24176593
2003	49.61089691	46.3951207
2004	49.82668995	47.49534928
2005	49.95661605	48.53732964
2006	50	49.5161294
2007	49.95661605	50.42704457
2008	49.82668995	51.26563708
2009	49.61089691	52.02777079
2010	49.31035584	52.70964538
2011	48.9266196	53.3078279
2012	48.46166172	53.81928156
2013	47.91785943	54.24139142
2014	47.29797345	54.5719866
2015	46.60512462	54.80935894
2016	45.84276779	54.95227766
2017	45.01466309	55
2018	44.12484513	54.95227766
2019	43.17759025	54.80935894
2020	42.17738245	54.5719866
2021	41.12887812	54.24139142
2022	40.03687015	53.81928156
2023	38.9062517	53.3078279
2024	37.7419801	52.70964538
2025	36.54904107	52.02777079



4B

Year	Curve A (2006)	Curve A + 2% @ peak	Curve A Difference	Curve B (2017)	Curve B + 2% @ peak	Curve B Difference
2000	48.46166172	48.46166172	0	42.79687687	42.79687687	0
2001	48.9266196	48.9266196	0	44.04055716	44.04055716	0
2002	49.31035584	49.31035584	0	45.24176593	45.24176593	0
2003	49.61089691	49.61089691	0	46.3951207	46.3951207	0
2004	49.82668995	49.82668995	0	47.49534928	47.49534928	0
2005	49.95661605	49.95661605	0	48.53732964	48.53732964	0
2006	50	50	0	49.5161294	49.5161294	0
2007	49.95661605	51	1.043383945	50.42704457	50.42704457	0
2008	49.82668995	52.02	2.193310051	51.26563708	51.26563708	0
2009	49.61089691	53.0604	3.449503087	52.02777079	52.02777079	0
2010	49.31035584	54.121608	4.811252163	52.70964538	52.70964538	0
2011	48.9266196	55.20404016	6.277420556	53.3078279	53.3078279	0
2012	48.46166172	56.30812096	7.846459239	53.81928156	53.81928156	0
2013	47.91785943	57.43428338	9.51642395	54.24139142	54.24139142	0
2014	47.29797345	58.58296905	11.2849956	54.5719866	54.5719866	0
2015	46.60512462	59.75462843	13.14950381	54.80935894	54.80935894	0
2016	45.84276779	60.949721	15.10695321	54.95227766	54.95227766	0
2017	45.01466309	62.16871542	17.15405233	55	55	0
2018	44.12484513	63.41208973	19.2872446	54.95227766	56.1	1.14772234
2019	43.17759025	64.68033152	21.50274127	54.80935894	57.222	2.412641057
2020	42.17738245	65.97393815	23.7965557	54.5719866	58.36644	3.794453396
2021	41.12887812	67.29341692	26.1645388	54.24139142	59.5337688	5.292377379
2022	40.03687015	68.63928525	28.60241511	53.81928156	60.72444418	6.905162612
2023	38.9062517	70.01207096	31.10581926	53.3078279	61.93893306	8.631105163
2024	37.7419801	71.41231238	33.67033228	52.70964538	63.17771172	10.46806634
2025	36.54904107	72.84055863	36.29151755	52.02777079	64.44126596	12.41349517



4C

	High (g-C/MJ)	Low (g-C/MJ)	Avg (g-C/MJ)	g-C in 2025	Difference in Emissions by percentage
Conventional Oil			25	1.89E+26	0.00E+00
Tar Sands	35	29	32	2.42E+26	2.65E+25
Gas-to-Liquid	29	27	28	2.12E+26	5.68E+24
Oil Shale	70	30	50	3.79E+26	4.73E+25
				Total additional emissions	7.95E+25
Energy Content (J)	6.10E+09				

4D

	High (g-C/MJ)	Low (g-C/MJ)	Avg (g-C/MJ)	g-C in 2025	Difference in Emissions by percentage
Conventional Oil			25	1.89E+26	0.00E+00
Tar Sands	35	29	32	2.42E+26	2.65E+25
Gas-to-Liquid	29	27	28	0	0
Biofuel			22	1.67E+26	-5.68E+24
				Total additional emissions (g-C in 2025)	2.08E+25
Energy Content (J)	6.10E+09				

4E

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$$Q_{cars} = (X_{conventional} + X_{hybrid})$$

Solve for the System of Equations:

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$$130.2E9 = (2.6E11 - 333 * X_h) - (125 * X_h)$$

$$X_h = \frac{1.3E11}{458}$$

$$X_h = 2.8E8$$

Total Hybrids	2.80E+08

This seems ambitious, but doable at an appropriate time scale

[1] - Used 3,000 BBL (farrell, 2006) as Q for curve A.
4A
- Curve A
  - Solved q = sigma Pm sqrt(2 pi) for PM (max production rate
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4B
- Increased each P value by 2% per year starting after the peak year, y = Pm_tm(102)^t.
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4C (gap amount 2025) / (MJ/gbbl)(g-c/MJ) = g-c
 - calculate for 50% tar sands, 25% synthfuels 25% oil shale, then add up

4D same process as C. Carbon inplicatoinare are 1/2 of that previous question, implying that vehicle efficiency alone can make a significant cut to emissions