Homework 2 Submission – CBE 9413 Intro to Sustainable Energy Systems

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Disclaimer: Gemini was used to develop pseudo-code for Q2. I have discussed the problems with Anu Deshmukh and Harsh Gandhi.

Problem 1

1. **Methodology**
   1.1. For each technology, we need to first estimate the energy equivalent amount of fuel (biofuel, electricity and synthetic fuel resp.) required to run 1 mile over a year.
   1.2. We will do backward calculation for each fuel type (see attached python code) to estimate land area required.
   1.3. For solar electricity generation, we will use code from HW1 to obtain GHI values at both sites.
   1.4. For DAC + H2 based synthetic fuel route, we will also add land area required for DAC plant into the calculation.
2. **Findings and key takeaways**
   2.1. BEVs are 4 times more fuel efficient than ICEVs. Since all three routes are powered by solar electricity, BEVs utilize the least amount of fuel land footprint to drive a mile.
   2.2. Land area required for Boston is higher than Phoenix due to the differences in solar GHI.
   2.3. Conversion of solar electricity into synthetic fuel is ~27% energy efficient. The takeaway here is that it is best to use synthetic fuels for heavy-duty mobility vehicles which are difficult to electrify.
   2.4. Biofuels have the highest land footprint among the three options. This can be attributed to low solar-to-energy efficiency of biomass growth.
   2.5. Long-term use of biofuels can, therefore, lead to substantial land use change and hence associated LUC emissions, which is one of the issues we discussed in the lecture.

Problem 2

1. **Task A**
   1.1. Logic used to build pseudo-code is described in the python code as well.
   1.2. We will follow a spoke and hub kind of model to estimate the land area required to meet biomass requirement for biofuel facility.
   1.3. We start with a pre-defined county (Hub) for each biofuel facility and then identify all adjacent counties (1st level) to this county.
   1.4. We can expand this analysis to nth level of adjacency (2nd level – counties adjacent to each county in 1st level) so that this expands like a circle.

1.5. Afterwards, we take each county starting from 1st level adjacency and calculate the sum of biomass collected (forestry, agricultural and waste) in that county along with land required to grow each type of biomass.

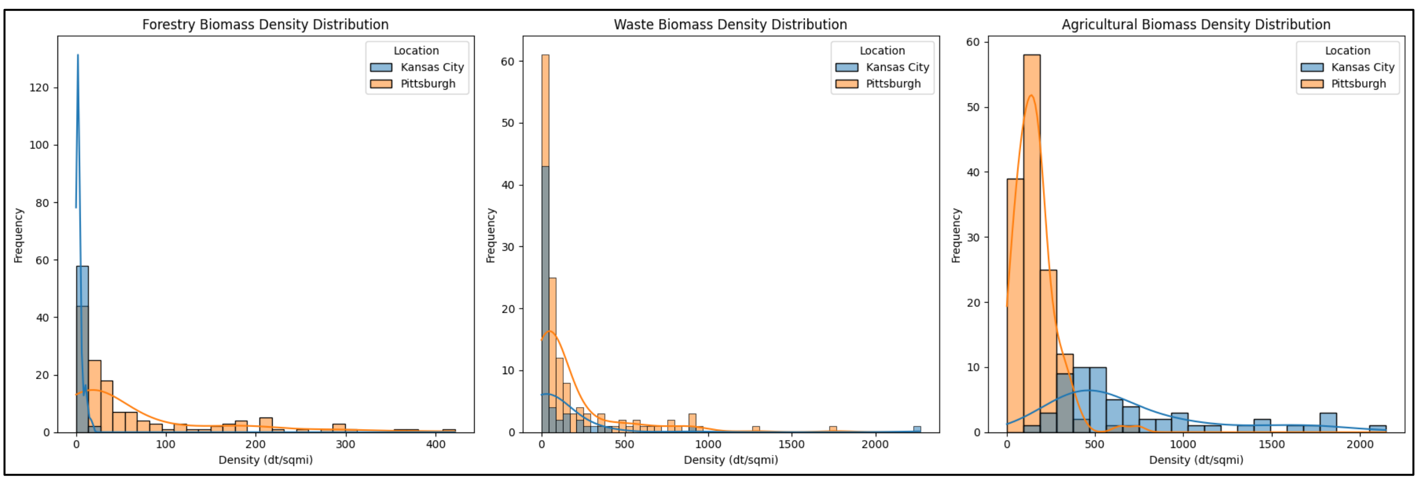
(This is not the most optimum way of identifying land required, an optimal way could be to sort counties by highest biomass yield and then use counties at nearest adjacency level with the right biomass type, but I was unable to develop this code.)

1.6. We keep adding the biomass collected and land area required till we reach the annual biomass requirement of each biofuel facility.

1.7. The results of the analysis of land area required in each biofuel facility are tabulated below:

SN	Biofuel facility scale	Kansas City, MO	Pittsburgh, PA
1	Biofuel facility location	Jakson County	Allegheny County
2	10,000 bpd	4500 sq miles	17370 sq miles
3	150,000 bpd	106,660 sq miles	235,740 sq miles

1.8. The analysis of biomass density distribution reveals that Kansas City has higher biomass density resulting in lower land footprint setting up same amount of biofuel facility.



Problem 3

1. **CO2 Recovery:**
   1.1. Using material balance (in terms of moles of CO2) on all output gaseous streams (4,5,6 and 8) over the control volume, we will estimate total CO2 feed to the process.
   1.2. Since 1.59 kmol/s of pure CO2 are captured in stream 6, we can estimate the CO2 recovery of the process to be ~**91%.**
2. **Part A:**
   2.1. For the minimum work requirement calculation, we will refer to the general case (involving reaction and separation) from the lecture sides.
   2.2. We have Feed streams: 1,2,3 and Output streams: 4,5,6,7,8,9. Using the provided material balance, we can estimate the minimum work required based on enthalpy and entropy change.
   2.3. The minimum work required turns out to be negative (-600 MW) indicating that the system generates **net heat output** (~**2.5 MWh/ton-CO2 captured**).
   2.4. This is somewhat counter-intuitive but can be explained as follows:
      2.4.1. There are two highly exothermic reactions: NG combustion and lime carbonation.
      2.4.2. Heat is also recovered from condensation of water vapor (stream 7).
      2.4.3. Only part of this heat is used for calcination, cryogenic separation (O2 feed and CO2 capture), this may lead to net heat output.
3. **Part B:**
   3.1. For the simplified process of carbon capture, let us use 1 kmol/s of captured CO2 from a flue gas stream containing 4% mol CO2 (same as Part A).
   3.2. The min. work required in this process is ~10 MW i.e., ~62 kWh/ton-CO2 captured (consistent with values derived in the lecture slides).
   3.3. In contrast to Part A, this process requires work input to capture CO2.
4. **Recommendation:**
   4.1. From a thermodynamic perspective, proposed process of CO2 capture from flue gas is an attractive choice – it is a net exporter of heat in addition to CO2 capture.
   4.2. However, the process required capital investment as well as mechanical work for pumping in other processes:
      4.2.1. Cryogenic distillation for O2 supply to calciner (this maintains higher CO2 concentration).
      4.2.2. Calciner
      4.2.3. Cryogenic and membrane separation for pure CO2 stream.
   4.3. Further due diligence will be required to judge the economics of process (cost of CO2 capture with the additional investment and heat export credit) vs conventional route or no CO2 capture to make an informed decision on investing in the startup.