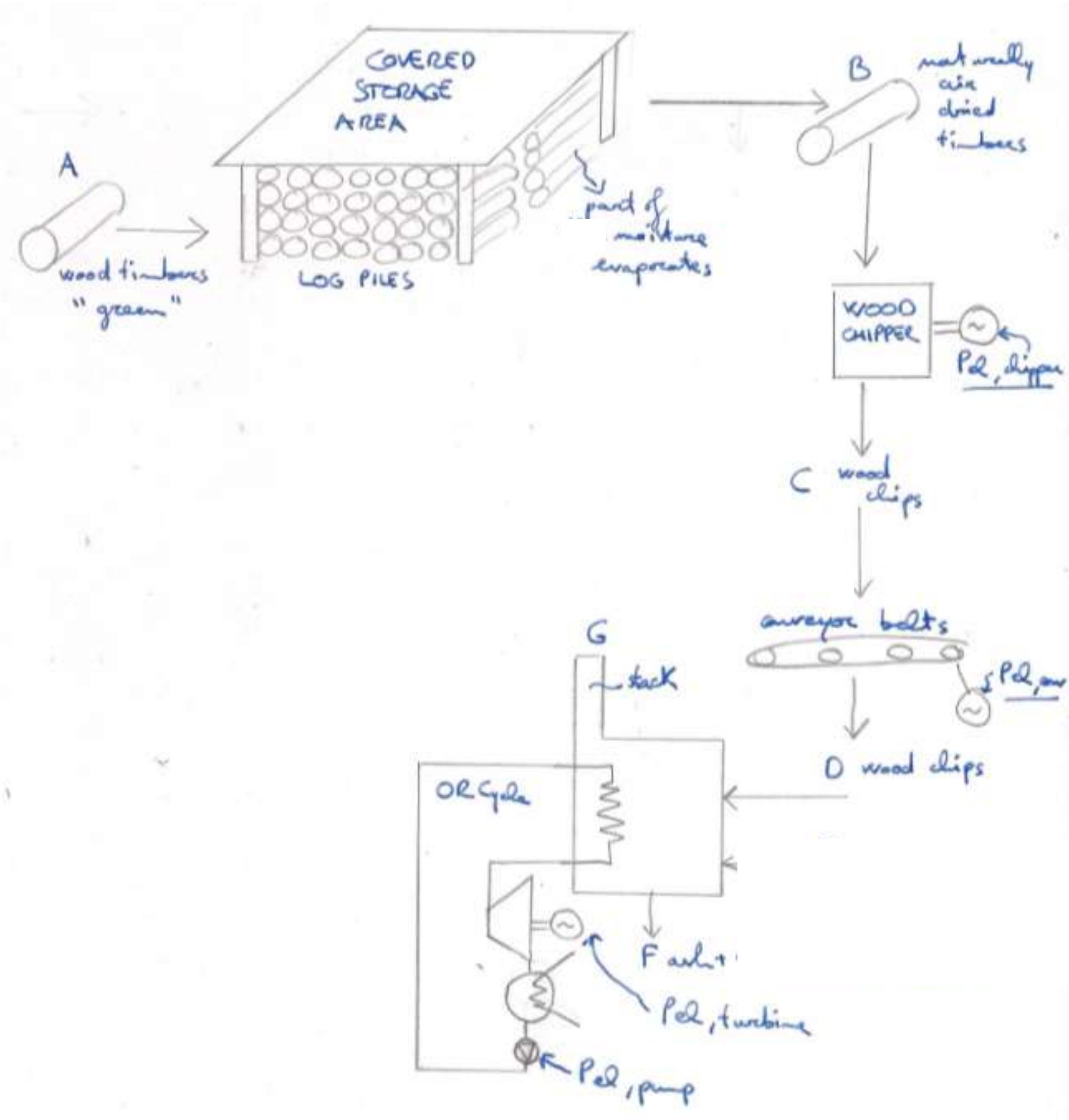
PRECEPT 2: FEEDSTOCK CHARACTERIZATION

Problem 2



Net electrical power:

$P_{el} = 1MW = (P_{el,T} - P_{el,P}) - P_{el,CO} - P_{el,CH}$

where:

- $P_{el,CO} = 45 \frac{kJ}{kg} \times \dot{m}_{fuel,C} \left(\frac{kg}{s}\right)$

  $\dot{m}_{fuel,C} = \dot{m}_{fuel,B}$ because the chipping doesn't change the wood composition or its moisture

- $P_{el,CH} = 170 \frac{kJ}{kg} \times \dot{m}_{fuel,B} \left(\frac{kg}{s}\right)$

- $P_{el,T} - P_{el,P} = \eta_{cycle}$ (electrical efficiency of the cycle) $\times Q_{in,cycle}$ (thermal load entering the ORC) $= \eta_{cycle} \times \eta_{boiler}$ (thermal efficiency of the boiler) $\times \dot{m}_{fuel,D} \times LHV_D$

$\eta_{cycle} = 25\%$

$\dot{m}_{fuel,D} = \dot{m}_{fuel,B}$ as seen before for section C

$LHV_D = LHV_B$

$LHV_B = DLHV_B \times (1 - M_B) - \Delta h\ eva\ (25°C) \times M_B$

where:

- $DLHV_B = 17769 \frac{kJ}{kg_{dry}}$
- $M_B = 35\%$
- $\Delta h\ eva = 2442.3 \frac{kJ}{kg_{water}}$

η_{boiler} must be evaluated → energy balance of the overall boiler:

$\dot{m}_{fuel,B} \times LHV_B = \dot{m}_{gas} \times c_{p,gas} \times (T_{stack} - 25) + Q_{in,cycle} + Q_{heat\ loss} + (\dot{m}_{ash} + \dot{m}_{unconverted\ carbon}) \times c_{p,ash} \times (T_{ash} - 25) + \dot{m}_{unconverted\ carbon} \times LHV_{carbon}$

Considering that D is equal to B, $\eta_{boiler} = \frac{Q_{in,cycle}}{\dot{m}_{fuel,B} \times LHV_B}$

$$\rightarrow \eta_{boiler} = 1 - \frac{\dot{m}_{gas} \times c_{p,gas} \times (T_{stack} - 25)}{\dot{m}_{fuel,B} \times LHV_B} - \frac{Q_{heat\ loss}}{\dot{m}_{fuel,B} \times LHV_B} - \frac{(\dot{m}_{ash} + \dot{m}_{unconverted\ carbon}) \times c_{p,ash} \times (T_{ash} - 25)}{\dot{m}_{fuel,B} \times LHV_B} + - \frac{\dot{m}_{unconverted\ carbon} \times LHV_{carbon}}{\dot{m}_{fuel,B} \times LHV_B}$$

- $\dot{m}_{gas} = \dot{m}_{air} + \dot{m}_{fuel,B} - \dot{m}_{ash} - \dot{m}_{unconverted\ carbon}$
  - $\dot{m}_{air} = \alpha^{ST} \times (1 + \varepsilon) \times \dot{m}_{fuel,B}$
    - $\varepsilon = 40\%$ (excess of air)
    - α^{ST} (stoichiometric air/fuel ratio) $= \beta_{O2}^{ST} \times \frac{1}{0.21} \times MW_{air} \times (1 - M_B)$
      - $\beta_{O2}^{ST} = 0.04183\ \frac{kmol_{O2}}{kg_{\ dry}}$ (for OAK combustion)
      - $MW_{air} = 28.95\ \frac{kg_{air}}{kmol_{air}}$
      - $M_B = 35\%$

  - $\dot{m}_{ash} = ASH \times (1 - M_B) \times \dot{m}_{fuel,B}$
    - $ASH = 0.11\%$

  - $\dot{m}_{unconverted\ carbon} = 0.03 \times \dot{m}_{carbon,\ B}$
    - 0.03 (unconverted carbon in the ash)
    - $\dot{m}_{carbon,\ B} = C \times (1 - M_B) \times \dot{m}_{fuel,\ B}$
      - $C = 48.8\%$

- $Q_{heat\ loss} = 0.008 \times \dot{m}_{fuel,B} \times LHV_B$
- $LHV_{carbon} = 32.8$ MJ/kg
- $T_{stack} = 130°C$
- $T_{ash} = 450°C$
- $c_{p,gas} = 1{,}11\ \frac{kJ}{kg\ K}$
- $c_{p,ash} = 7{,}5\ \frac{kJ}{kg\ K}$

$$\rightarrow \eta_{boiler} = 1 - \frac{[\alpha^{ST} \times (1+\varepsilon) + 1 - ASH \times (1-M_B) - 0.03 \times C \times (1-M_B)] \times c_{p,gas} \times (T_{stack} - 25)}{LHV_B} +$$
$$- 0.008 - \frac{[ASH \times (1-M_B) + 0.03 \times C \times (1-M_B)] \times c_{p,ash} \times (T_{ash} - 25)}{LHV_B} - \frac{0.03 \times C \times (1-M_B) \times LHV_{carbon}}{LHV_B}$$

With the efficiency of the boiler, $\dot{m}_{fuel,B}$ can be calculated:

$1000\ KW = \eta_{cycle} \times \eta_{boiler} \times \dot{m}_{fuel,B} \times LHV_B - (170+45) \times \dot{m}_{fuel,B}$

$$\rightarrow \dot{m}_{fuel,B} \left(\frac{kg}{s}\right) = \frac{1000\ KW}{\eta_{cycle} \times \eta_{boiler} \times LHV_B - 215\ kJ/kg}$$

To define the area for the storage, it is necessary to evaluate the time required by the drying process (Δt_{drying}). We have a model that gives the rate of drying as function of some parameters: the wood dimension, the relative humidity and the air temperature:

$$\frac{dM_{dry}}{dt} = - \frac{M_{dry} - M_{e,dry}}{\tau}$$

where:

- M_{dry} (dry basis moisture content) $M_{dry} = M / (1 - M)$
- $M_{e,dry}$ (equilibrium dry basis moisture content)
  The equilibrium moisture content measures the fraction of <u>bound water</u> that is into the feedstock even after an infinite time.
- $\tau = \frac{L^{1.52}}{0.0575 + 0.00142 \times P_{sat}(T)}$ (days)
  - P_{sat} (T) = 13.03 mmHg at 15°C
  - L = min (H/10, R) in inches (water diffuses 10 times faster along the longitudinal direction)

In our application:

$$M_{dry}(t_{end}) = M_{e,dry} + [M_{dry}(t_0) - M_{e,dry}] \times e^{-\frac{\Delta t_{drying}}{\tau}}$$

where:

- $M_{e,dry}$ can be defined with figure 1 (dry temperature 15°C; relative humidity 70%) → $M_{e,dry}$ = 13%
- $M_{dry}(t_0)$ (dry basis moisture content at the beginning) → $M_{dry}(t_0) = \frac{M_A}{1-M_A}$ = 0.5 / (1 – 0.5) = 1
- $M_{dry}(t_{end})$ (dry basis moisture content after the drying stage) → $M_{dry}(t_{end}) = \frac{M_B}{1-M_B}$ = 0.35 / (1 – 0.35) = 0.538

$$\rightarrow \frac{M_{dry}(t_{end}) - M_{e,dry}}{M_{dry}(t_0) - M_{e,dry}} = e^{-\frac{\Delta t_{drying}}{\tau}} \quad \rightarrow \Delta t_{drying} = - \tau \times \ln [\ldots]$$

To find the mass of wood in the covered storage area (m_{stored}), $\dot{m}_{fuel,A}$ must be calculated:

$\dot{m}_{dry\ fuel,A} = \dot{m}_{dry\ fuel,B}$ (only moisture is lost)

$\dot{m}_{fuel,A} \times (1 - M_A) = \dot{m}_{fuel,B} \times (1 - M_B)$

$m_{stored} = \dot{m}_{fuel,A} \times \Delta t_{drying}$

Finally it is possible to determine the storage area $S_{storage}$ (m^2):

$m_{stored} = \rho_{wood} \times S_{storage} \times h_{piles} \times (1 - \text{void fraction})$

where:

- $\rho_{wood} = 850\ kg/m^3$
- $h_{piles} = 5\ m$
- void fraction = 0.15

The size of the storage area is big. For this reason, covered storage area are not common in biomass plants. Green wood is usually directly burned or dried in dedicated drier: a device where wood is in contact with steam or air in order to increase the rate of drying.

If wood is directly chipped and burned (no covered storage area):

$\dot{m}_{fuel,B} = \dot{m}_{fuel,A}$

$M_A = M_B = 50\%$

$\eta_{boiler} \downarrow\ M\uparrow$

η_{boiler} (green) < η_{boiler} (dried)

As seen before:

$$\dot{m}_{fuel} = \frac{1000\ KW}{\eta_{cycle} \times \eta_{boiler} \times \text{LHV} - 215\ kJ/kg}$$

$\eta_{boiler} \downarrow\ \dot{m}_{fuel} \uparrow$

		demolition wood	oak (harvest conditions)	seasoned oak (after storage)	wood pellets	switch grass	straw	pig manure	MSW	plastic waste	RDF	coal Illinois #6
%, weight dry basis	C	49.10	48.80	48.80	47.10	47.80	47.50	35.00	30.80	81.10	40.90	64.60
	H	5.83	6.09	6.09	6.73	5.76	5.90	4.38	0.96	13.33	6.45	4.20
	O	44.10	45.00	45.00	45.81	35.10	40.80	21.30	21.50	0	34.00	13.70
	N	0.14	0	0	0.15	1.17	0.70	2.79	1.09	0.11	1.51	1.30
	S	0	0	0	0.01	0.10	0.15	0	0.78	0.01	0.43	2.90
	Cl	0	0	0	0	0	0.40	1.19	0.71	0.20	0.65	0.12
	ash	0.83	0.11	0.11	0.20	10.07	4.55	35.34	44.16	5.25	16.07	13.18
LHV, kJ/kg, dry basis		17813	17769	17769	18607	16767	17763	12829	11990	39182	18463	25200
Moisture content, %		10	50	15	8.5	15	8	66	35	14	20	2
Density (as received), kg/m^3		700	850	750	700	190	95	910	350	910	400	875

Table 1: Ultimate (elemental) analyses, LHV dry basis, moisture content (wet basis, i.e., moisture mass / total feedstock mass) and density of biomass and waste residues commonly used in energy systems.