Back-of-the-Envelope Calculations and Estimates for Scale and Impact

The W.E.B. DuBois library is one of the largest consumers of energy on the UMass campus, according to the Building Energy Explorer (BEE). As such, we will be calculating approximately how much energy would be required to heat and light the building while it is open. We will be stating several assumptions to simplify these calculations, as you will see below.

<u>Calculation 1: How much energy is required to heat the library while it is open?</u>

According to the BEE, the library consumed **12,537,649 KBtu** (thousands of British Thermal Units) in the form of steam energy in 2015. This translates to an approximate energy usage of over **13 trillion Joules (J) per year** in the form of steam. To understand the relative efficacy of the heating system in the library, we will be comparing these values to the ideal heat consumption of the library (using thermodynamic calculations). To make these ideal-scenario calculations, we will make the following assumptions:

- All (100%) of the steam energy consumed by the library is used directly for heating.
- We can treat the library approximately as one large volume rather than around 28 individual floors, so we assume that there is no insulation or significant concerns with the floors.
- While the basement is not the same shape as the other floors of the building, we will treat it as if it is the same shape as these floors, so we can approximate with a rectangular prism building with 28 stories.
- We can approximate calculations by assuming the temperature outdoors is an approximate 40° F.
    - This is meant to account for the fluctuation of the outdoor temperature, the wind, and any insulation from the exterior wall of the building (for the duration of when the building needs to be heated).
- We would like the interior of the building to remain at 72° F while it is in use.
- The steam energy consumption of the library is approximately the same for each day of the year.
    - With this assumption, we can approximate that the library uses approximately **36.2 billion J / day**.
- The library only needs to be heated for 16 hours a day.
    - The library's longest opening hours are 8 AM – 11 PM on weekdays, totaling to 15 hours. We add 1 hour to these calculations to account for the time that the building needs to be heated while staff open or close the building.

Using these assumptions, we can calculate the approximate ideal steam energy consumption of the library with two equations:

A. The energy required to heat up the building: $\boldsymbol{Q_c = mc\Delta T}$
    a. Q_c = energy required to change the temperature of the building (or rather, the air inside of the building) [J]

b. m = mass of the air in the building [kg]
c. c = specific heat of the air in the building [J / (kg * °C)
d. ΔT = Change in temperature of the air from the exterior temperature (40° F) to the desired interior temperature (72° F) [°C]

B. The energy required to maintain the building's internal temperature while it is open:

$$\boldsymbol{Q_m = \frac{kA(T_h - T_c)t}{d}}$$

a. Q_m = energy required to maintain the building's temperature (or rather, the temperature of the air inside the building) [J]
b. k = thermal conductivity of the building's exterior wall [W / (m * °C)]
c. A = surface area of the library's exterior surfaces (walls, ceiling, and floor) [m^2]
d. T_h = the temperature maintained in the building [°C]
e. T_c = the temperature of the air outside of the building [°C]
f. t = the time that the building's interior temperature is maintained (s)
g. d = the thickness of the building's exterior wall (m)

Using these two equations and our assumptions, we can calculate the ideal energy consumption of the library for heating. As such, our next step is plugging in our variables:

- $m \cong$ 24,800 kg
  - Library dimensions: height ≅ 90 m; width ≅ 15 m; length ≅ 15 m
  - Library volume (V) ≅ 90 m * 15 m * 15 m = 20250 m^3
  - Density of air (ρ) ≅ 1.225 kg/m^3
  - $m = V * \rho$
- $c \cong$ 1015 J / (kg * °C)
  - This is a constant based on the properties of the material (air, in this case).
- $\Delta T = T_h - T_c \cong$ 18 °C
  - Exterior temperature ≅ 40 °F ≅ 4.4 °C
  - Desired interior temperature ≅ 72 °F ≅ 22.2 °C
- $k \cong$ 0.84 W / (m * °C)
  - This is a constant based on the properties of the material (brick or glass, in this case).
- $A \cong$ 5850 m^2
  - Library dimensions: height (h) ≅ 90 m; width (w) ≅ 15 m; length (l) ≅ 15 m
  - A = (h * w) * 2 + (h * l) * 2 + (w * l) * 2
- $t \cong$ 16 hr ≅ 57600 s
- $d \cong$ 0.3 m
  - This assumes that the wall of the building is approximately 1 ft thick.

Using these variables and the equations stated above, we find:

- $Q_c \cong$ 0.45 billion J / day
- $Q_m \cong$ 16.7 billion J / day
- **Total Ideal Energy Consumption for Heat: $\boldsymbol{Q_T = Q_c + Q_m}$ ≅ 17.5 billion J / day**

Altogether we find that the library consumes over **2 times** as much energy as it would in the ideal condition. While the ideal condition does make assumptions, it is plausible that a notable portion of UMass' steam energy usage for the library goes to waste. What's more, by observing our qualitative heat map of the library's floors, we see that the heat is unevenly distributed across the building.

<u>Calculation 2: How much energy is required to light the library while it is in use?</u>

According to the BEE, the library consumed **15,861,719 KBtu** of energy in the form of electricity in 2015. This is equivalent to around **45.6 billion J / day** if we make a similar assumption in this case as we did in our heating calculations: that the library's electricity consumption can be approximated to be the same each day. However, unlike our heating calculations, we do not need to consider an "ideal" environment because the light calculations do not require complex math or physics. Rather, we can compare the power consumption of different kinds of light bulbs and we can make estimates for how many bulbs are across the building. Overall, our assumptions in this case are as follows:

- Around one-fifth (20%) of the electricity usage of the library goes to lighting.
    - This is meant to count for the variety of other uses for electricity in the building, including electrical outlets, the elevators, and the Procrastination Station (a café in the building).
    - This would result in around **9.12 billion J / day** being used for lighting in the library.
- For simple calculations, we will assume that the library has the equivalent of 3000 light bulbs throughout the building. This allows for 100 bulbs across 28 floors and an extra 200 for outliers and for good measure.
- All of the light bulbs in the building are rated for around 1400 lumens (this is a little bit brighter than the middle-range light bulb) so that they can effectively light spaces.

Note that this calculation leans on a certain variable: we only calculate the energy required to light the building *while it is in use* (around 15 hours for open hours and 1 hour for opening and closing the building). We intentionally calculate it this way because we know that UMass currently lights its library 24/7, and we want to see how much energy could be saved in one day by cutting out 8 hours of that operation.

Under these assumptions, we will be calculating the energy consumption of the library's lighting as if the library was *entirely lit* by 3 different light bulb types: incandescent, compact fluorescent (CFL), and light-emitting diode (LED). **We guess that the library primarily uses CFL bulbs based on its construction in 1972 and the popularization and cost of different light bulbs around that time period.** However, we are calculating with all three types to be thorough and to demonstrate the potential of upgrading the bulbs to LEDs (in an energy-based sense).

Incandescent Lights
The average incandescent light bulb of 1400 lumens consumes around 75 W [W = J / s]. As such, over 16 hours (57600 seconds), 3000 of these bulbs would consume around **12.9 billion J / day**. We should also note that incandescent bulbs are <u>the most inefficient of the three bulb types</u>, and we consider it <u>unlikely that the library primarily relies on these bulbs</u>. This means that with our guess of the library primarily using CFL bulbs, the library would likely use less energy than this for 16 hours of lighting.

Compact Fluorescent Lights (CFLs)
The average CFL of 1400 lumens consumes around 23 W. As such, over 16 hours, 3000 of these bulbs would consume around **3.97 billion J / day**. Considering that this is only around **43%** of the building's electricity consumption that we assume for lighting (and if they run for 2/3 of the time, we would guess that this calculation should be around 66.6% of reality), we can guess one or multiple the following:

- The library uses a mix of light bulb types, at least some of which consume more than 23 W of power.
- The light bulbs in the library are brighter than 1400 lumens on average, meaning that their power consumption is greater than 23 W.
- Less than 20% of the library's electricity goes to lighting, and we would need to reevaluate our estimates.

Regardless of our uncertainties, we observe that there can be significant energy-saving potential in lighting the library for 16 hours instead of 24 hours and maintaining a consistency in our light bulb power consumption. In fact, if we perform this same CFL calculation for 24 hours instead of 16 hours, these 3000 lights would only consume **5.96 billion J / day**.

Light-Emitting Diodes (LEDs)
The average LED of 1400 lumens consumes around 13 W. As such, over 16 hours, 3000 of these bulbs would consume around **2.25 billion J / day**. LEDs are the most efficient type of light bulb as of today, which explains why this calculation results in only about **25%** of the estimated electricity consumption for lighting in reality. Even if we make this calculation for 24 hours (in case the library has a need to be lit 24/7), we will find that these bulbs only consume around **3.37 billion J / day**, which is still only around **37%** of our estimated electricity consumption for lighting.

Even with the uncertainty of how much of the library's electricity consumption goes to lighting, we can see the potential to reduce energy usage in (a) reducing the time for which the library is lit and (b) changing the light bulbs in the building to be more efficient. If we find these sorts of changes to be feasible, they could potentially save billions of joules. And while that may sound like a random number, consider this: 4.2 billion J is the equivalent to the explosion from 1 ton (2000 lbs) of TNT.