Week 1 Energy workshop: 7.013 @ ESG, Spring 2009

In the introduction to Chapter 8 of your textbook, the authors point out:

"Powered by sunlight, green plants use the reactions of photosynthesis to convert simple chemicals in the environment - carbon dioxide and water – into carbohydrates. The emergence of photosynthesis was a key event in the evolution of life, integrating an external energy source – the energy of sunlight – into the living world. Photosynthesizing organisms using solar energy to make their own food provide an entry point to the biosphere for chemical energy. Most other organisms depend on photosynthesizers for the raw materials of metabolism, such as glucose, as well as for atmospheric oxygen."

In this problem, we will find out the efficiency of photosynthesis in terms of energy flow from producers through tertiary consumers. Then, this efficiency is compared to the efficiency of laboratory researched artificial photosynthesis, which is being researched as a possible source of H_2 for fuel cells.

To start, the sunlight has to arrive at the photosynthetic organisms (plants.) In one year, an average of 2.8×10^{24} J of energy from the sun arrives at the earth's surface.

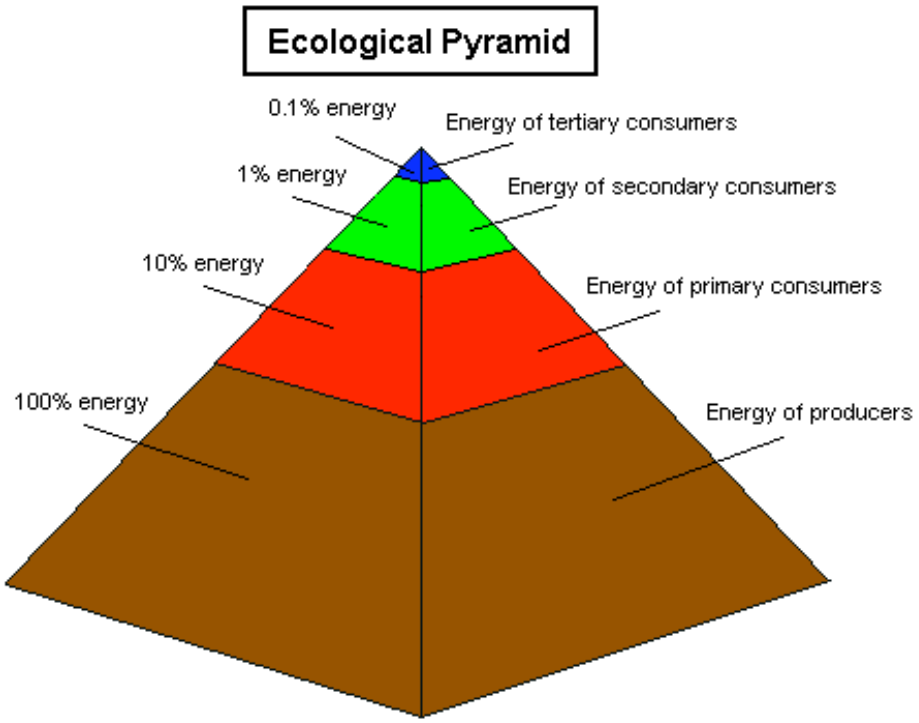
1) Assume that all photons coming from the sun have a wavelength of 590. nm, how many photons of sunlight make it to the Earth's surface in one year?

2) Since light must be absorbed for photosynthesis to begin, one might wonder if all the light from the sun is absorbed. This is not the case. Why not? Also what colors in the visible spectrum may be the most absorbed in most plants? Why?

3) According to the article you were given, most people associate the efficiency of photosynthesis with biomass and food production. This efficiency is around one percent. This number seems very low. However, the actual efficiency of photosynthesis is around 40-50%. Why is that?

4) Some studies show that only around 30 percent of the light from the sun is absorbed by plants. How many photons of sunlight are used in a year by plants to produce our food and biomass? Use the 590. nm assumption from above to alleviate confusion.

5) There is a model of energy flow from the primary producers (plants) → primary consumers → secondary consumers → tertiary consumers that states the energy transfer from one level to the next is about ten percent. This can be shown as an ecological pyramid shown below:



What is the overall efficiency of the sunlight becoming our food? That is, what percentage of sunlight that reaches the Earth is finally used by tertiary consumers?

Experiments show that one of the main steps in photosynthesis is the production of hydrogen atoms by Photosystem II. Very detailed info on Photosystem II can be found at http://www.bio.ic.ac.uk/research/barber/psIIimages/PSII.html. These hydrogen atoms combine with electrons to produce hydrogen gas. This hydrogen gas, in turn, can be used in fuel cells to produce energy.

6) What is the maximum efficiency of artificial photosynthesis (i.e. mimicking Photosystem II to produce hydrogen atoms)?

7) The actual estimated efficiency of artificial photosynthesis is around 15%. What factors limit the overall efficiency of these cells?

Solutions to week 1 workshop:

1) **Assume that all photons coming from the sun have a wavelength of 590. nm, how many photons of sunlight make it to the Earth's surface in one year?**
Answer:

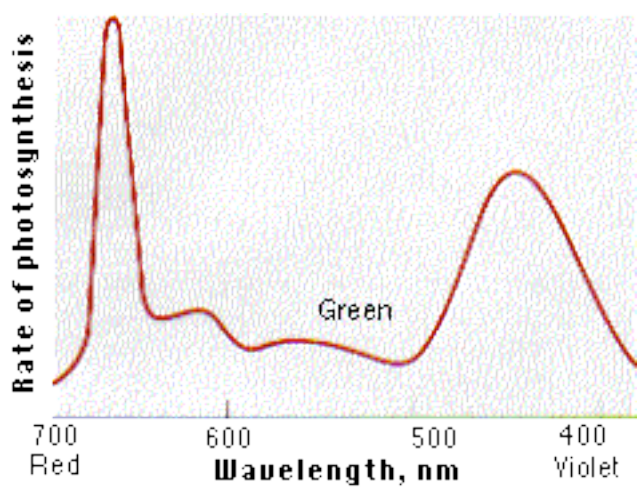
First, you have to calculate the energy of one photon at 590. Using $E=\frac{hc}{\lambda}$, this is a plug and chug:

$$E_{photon}=\frac{\left(6.626 \times 10^{-34} J \cdot s\right)\left(2.998 \times 10^{8} \, m/s\right)}{5.90 \times 10^{-7} m} = 3.37 \times 10^{-19} \, J/photon$$

Since you are given the energy of the sun arriving at the Earth's surface, solve for the number of photons:

$$\boxed{\#\ photons=\frac{E_{total}}{E_{photon}}=\frac{2.8 \cdot 10^{24} \, J/year}{3.37 \cdot 10^{-19} \, J/photon}=8.3 \times 10^{42} \, photons/year}$$

2) **Since light must be absorbed for photosynthesis to begin, one might wonder if all the light from the sun is absorbed. This is not the case. Why not? Also what colors in the visible spectrum may be the most absorbed in most plants? Why?**
Answer:
If all the light from the sun were to be absorbed by plants, every plant would act as a mini-black hole, taking in all the light and not reflecting anything. Most plants are green, so they absorb either red-orange or blue-violet light, reflecting green light. One can view the action spectrum of green plants/chlorophyll in photosynthesis to explain this further:



In an action spectrum, the maxima are at wavelengths of light most absorbed by green plants. The rate, or action, of photosynthesis is at its maximum in red-orange and bluish light.

3) **According to the article you were given, most people associate the efficiency of photosynthesis with biomass and food production. This efficiency is around one percent. This number seems very low. However, the actual efficiency of photosynthesis is around 40-50%. Why is that?**
Answer:
The actual efficiency of photosynthesis given is the efficiency of plants using light to create energy. The efficiency based on biomass/food production is only part of the 40-50% of the light energy efficiency. There are many dark reactions in photosynthesis where the energy

made with the help of light goes towards plant growth, reproduction, etc. So the key in production of useful energy for humans is to take advantage of the light reactions with high efficiency, avoiding the dark reactions that plants need to sustain life, but humans do not.

4) **Some studies show that only around 30 percent of the light from the sun is absorbed by plants. How many photons of sunlight are used in a year by plants to produce our food and biomass? Use the 590. nm assumption from above to alleviate confusion**.

Answer:

Here, we are going to solve for the number of photons that are used to produce a final product of biomass and food. Assuming one percent food and biomass production efficiency for photosynthesis, along with plants absorbing around 30 percent of sunlight, we find that 0.3% of the sunlight that reaches the earth's surface produces biomass and food, or 0.003 x $2.8 \cdot 10^{24}$ J = 8.4x10^{21} photons in one year.

5) **What is the overall efficiency of the sunlight becoming our food? That is, what percentage of sunlight that reaches the Earth is finally used by tertiary consumers?**

Answer:

Here, 100% energy corresponds to the 30 percent of sunlight that is used by the plants for photosynthesis. So, 1/1000 the energy absorbed by plants eventually makes it to the tertiary consumers, or around 0.03 percent efficiency. If we take into account the 40-50 percent efficiency of light photosynthesis, this number decreases to around 0.015%.

6) **What is the maximum efficiency of artificial photosynthesis (i.e. mimicking Photosystem II to produce hydrogen atoms)?**

Answer:

The maximum efficiency is dictated by the maximum efficiency of light photosynthesis in plants, or around 40-50%. The intent of artificial photosynthesis is to mimic as much as possible light photosynthesis in plants to produce hydrogen atoms and molecule for use in fuels. The large ruthenium and molybdenum-based complexes explained in the artificial photosynthesis articles are based on the molecules found in photosystem II that enable the hydrogen producing reactions to occur.

7) **The actual estimated efficiency of artificial photosynthesis is around 15%. What factors limit the overall efficiency of these cells?**

Answer:

The first, and most major, limitation currently is obtaining the technical know-how for setting up the new cells to work. Artificial photosynthetic cells have been found to be quite efficient, but not in a use-to-power-your home way. Another limitation is the molecule used for artificial photosynthesis. It is not an exact duplicate of the molecules/complexes involved in Photosystem II. The current systems are not yet ideal. The catalyst used to convert the hydrogen atoms and protons into hydrogen molecule has not yet been perfected. This leads to efficiency loss. Also, the actual hydrogen fuel cell itself limits efficiency because after the hydrogen is made, the process of the fuel cell is not 100% efficient.