Physics and Mathematics for Sustainable Energy: An Elementary Introduction

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Preface

This set of lecture notes is designed to accompany David MacKay's book, *Sustainable Energy—without the hot air* (SEWTHA). As soon as I got my hands on this book I immediately thought that I needed to teach a class based on it. I had in the back of my mind teaching a class on energy for quite some time, but when I found MacKay's book, I knew the time was right.

However, SEWTHA on its own isn't a textbook. I think students will need some more explanation of some of the physics and math than MacKay provides. And students will also need lots of practice in order to master the type of analysis that MacKay demonstrates in his book.

My aim in writing up these lecture notes is to complement SEWTHA so that it can be used as part of a course. This initial draft is still quite rough. Beware—I'm certain there will be typos and other blunders. But I hope it will nevertheless be useful.

I am developing these notes as I teach *Physics and Mathematics of Sustainable Energy* at College of the Atlantic during the Spring term of 2010. The current draft of these notes will be available on the course website. I expect to update the notes at least weekly. So be sure you have the most current version. If you catch errors, please let me know in class, or via email at `dave@hornacek.coa.edu`.

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These notes were produced exclusively with open-source, freely available software: the book was typeset using LaTeX; figures were produced with xfig and gnuplot; gnumeric was used for some data analysis; and all programming was done in `C++` using the `g++` compiler. All applications were run on various personal computers running the Ubuntu version of the Linux operating system. I am also grateful for resources such as google scholar, google books, the `citeulike.org` bibliography manager, and the often-maligned wikipedia. They all have been incredibly valuable and have saved me a great deal of time.

Contents

Introduction to Energy and Power

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This is a course about energy. So I guess we should start by saying what energy is. It turns out that this is somewhat subtle question. I think the best way to begin talking about energy is with a story. Initially it will seem that this story has nothing to do with energy. But once I tell the story I'll explain the connection.

I have to confess, this story is not original—Richard Feynman uses it to explain energy in his Lectures on Physics.

1.1 Jane's Blocks

1.2 Conservation of Energy

1.3 Kinetic Energy and the Joule

There are many different types of energy, just as there are many different places Jane can hide her blocks. Each type of energy has a different formula associated with it. The first type of energy we will consider is the energy associated with a moving object. This type of energy is called *kinetic energy*. The kinetic energy of an object with a mass m and a speed v is given by:

$$E_k = \frac{1}{2}mv^2 \ . \tag{1.1}$$

For example, a 2kg rock moving at 3 m/s has a kinetic energy of

$$E_k = \frac{1}{2}(2\text{kg})(3\text{m/s})^2 = 9\,\text{kgm}^2/\text{s}^2 \ . \tag{1.2}$$

Note what happens to the units. The units of energy are thus kilograms-meters-squared-per-second-squared. This is a mouthful, and perhaps not intuitive. Conveniently, this awkward unit has a name, so we don't have to use this long phrase. The unit is known as the *Joule* and abbreviated simply as J. I.e., one Joule is defined as:

$$1\text{Joule} = \text{kgm}^2/\text{s}^2 \ . \tag{1.3}$$

A Joule is a small amount of energy. One Joule is roughly the energy of a quart of water moving at one meter per second. If a filled quart container hit you at 1 m/s you would notice this but it would not do much damage. In contrast, if you left a typical toaster on for two minutes it would use 432,000,000 Joules.

Thus, while the Joule is the standard unit for energy, it is not convenient in most contexts we will be concerned with in this book. The Joule is far too small.

1.4 Power

Power is the rate of an energy flow. Before discussing power, though, let's think about flowing water, as this is easier to picture.

Finally, here is a collection of

- 1 Watt = 1 J/s
- On Mount Desert Island Maine, 1 kWh costs 17.2 cents.
- One kiloWatt-hour, abbreviated kWh, is the energy that results if one kW flows for one hour.
- kW is a unit of *power* and kWh is a unit of *energy*.
- 1 kWh = 3,600,00 J = 3.6 MJ.
- in the U.S., on average, one kWh of electricity production results in 613 grams of CO_2 being released into the atmosphere. The values for other countries can be found on page 335 of SEWTHA.

Exercises

(1.1) A 0.8 kg bird flies at 2 m/s. What is its kinetic energy?

(1.2) A 1 pound brick flies through a congressman's window at 12 miles per hour. What is the brick's kinetic energy? Express your answer in both J and kWh.

(1.3) Heating oil is pumped into a tank at the rate of 2 gallons/sec. How much oil flows into the tank in one minute? How much in one hour?

(1.4) The lights in my office draw 120 W. Suppose I leave them on for three hours a day for a month.

(a) How much energy does this use? Express your answer in both kWh and J.

(b) How much does this cost per month in Maine?

(1.5) Suppose you leave a 1000W toaster on for an entire year.

(a) How much energy does this use? Express your answer in both kWh and J.

(b) How much does this cost per month in Maine?

(1.6) What wattage light bulb uses 1 kWh in one day?

(1.7) In a typical day a typical person typically eats around 2500 calories of food[1]. These are dietary calories. Confusingly, 1 dietary equals 1000 "real" calories.

(a) How many Joules does a typical person consume in a day?

(b) What power is this? Express your answer in kW.

(c) Most of the food energy you consume ultimately gets converted to heat. Thus, we can view people as heaters—they convert chemical food energy into thermal energy. How many people would you need to have in a room to have a heating power roughly equivalent to one 1500 W space heater?

(1.8) Convert the following to kWh:

(a) 1 Joule

(b) 1,000,000 J.

(c) 7,500 J.

(1.9) Convert the following to Joules:

(a) 100 kWh

(b) 31 kWh

(c) 57,160 kWh

(1.10) Look up the cost of home electric power per kWh in another state in the U.S., and in a few another countries. (Try and find the price charged to individuals, not businesses or corporations, which usually pay a lower rate.) How does the cost of power compare to Mount Desert Island, Maine? Discuss briefly.

(1.11) Take a look at the greenhouse gas conversion factors on page 335 of SEWTHA. Note the enormous difference from country to country. The carbon intensity of electricity production in Denmark is ten times larger than France and Sweden. Why do you think this is? Discuss briefly.

[1] I believe this is the average for men in the U.S. I'm sure it's different in other counties and different for women and children.

Units and Estimation

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2.1 Scientific Notation

2.2 Engineering Notation and SI prefixes

2.3 Significant Digits

2.4 Estimation

Exercises

(2.1) Convert the following measurements into scientific notation and engineering notation.

(a) 4000 meters
(b) 0.00044 meters
(c) 80000000 kWh
(d) 15,000,000,000 Joules
(e) 3,600,000 Joules
(f) 55,000 meters

(2.2) Convert the following from scientific notation into engineering notation.

(a) 45 km
(b) 2 μm
(c) 314 GW
(d) 1.5 MJ
(e) 22.4 TW
(f)

Basics of Electricity and Electricity Generation

3

3.1 What is Electricity

3.2 Current, Voltage, Resistance

3.3 Generating Electricity

Exercises

(3.1) Convert the following measurements into scientific notation and engineering notation.

(a) 4000 meters
(b) 0.00044 meters
(c) 80000000 kWh
(d) 15,000,000,000 Joules
(e) 3,600,000 Joules
(f) 55,000 meters

Part I

Appendices