Central Coast Climate Science Education

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Making quantitative estimates about Climate Change and Energy
An Example:
Waste heat from the Diablo Canyon Nuclear Plant and Global Warming
Dr. Ray Weymann, January 24, 2022, Atascadero, CA

Who is the intended audience for this post?: ***Everyone***
What are the objectives of this post?
To illustrate how complex problems can be broken down to simpler terms by quantitative estimates using arithmetic and logic. This can lead to an understanding of what things are important and what things are not.

TWO NOTES TO READERS ADDED MAY 5, 2022:

1) ***This essay was completed January 24th, as indicated above. Posting it was withheld while waiting for input which did not arrive and I forgot to go ahead and post it! My apologies***
2) ***This essay is in no way intended to take a position one way or the other on the still-controversial issue of closure of the DCPP nuclear plant. As noted above it is simply intended to illustrate the value of making quantitative estimates of factors where this is possible.***

A reader of these posts remarked that some of the recent ones were quite complicated. I plead guilty to this. At the same time, however, the fact is that we live in a complex world and some of the issues we face *are* complex. In some, but by no means not all, cases, better understanding of these issues is made easier by making even approximate *quantitative estimates* of various quantities. *This is often useful in separating out those things that may be important from those that are not.*

In the following material, I give an example of this by estimating two quantities:
First: The contribution of the "*waste heat*" (the concept of waste heat is explained below) from the Diablo Canyon nuclear plant to global warming as well as this same contribution from all the nuclear reactors worldwide.
Second: Heat put in the ocean by burning fossil fuels, can be "avoided" if energy from nuclear, wind, or solar energy is generated instead. This heat from the carbon dioxide which is avoided by using such sources is called *"avoided heat"*. In the case of DCPP over its years of operation, it displaced some fossil fuel combustion as a source of electricity. I also estimate this avoided heat and emission for the total of *all* nuclear power plants since they began generating electricity.

At the conclusion of these calculations, I give my opinion on what the real issue is as we plan for the future.

I have tried to provide explanations for each step along the way and a "road map" of where we are headed. So, I encourage all readers to give it a try, *even if you don't want to follow the arithmetic*. For those who only care about the "bottom line" for these two calculations, however, they are given in **red** at the end.

The basic components of the most common type of a nuclear power plant.

Since we are discussing nuclear energy, it is important to understand the basic components of the most common type of a nuclear power plant. including the two at Diablo Canyon.
Here is a diagram:

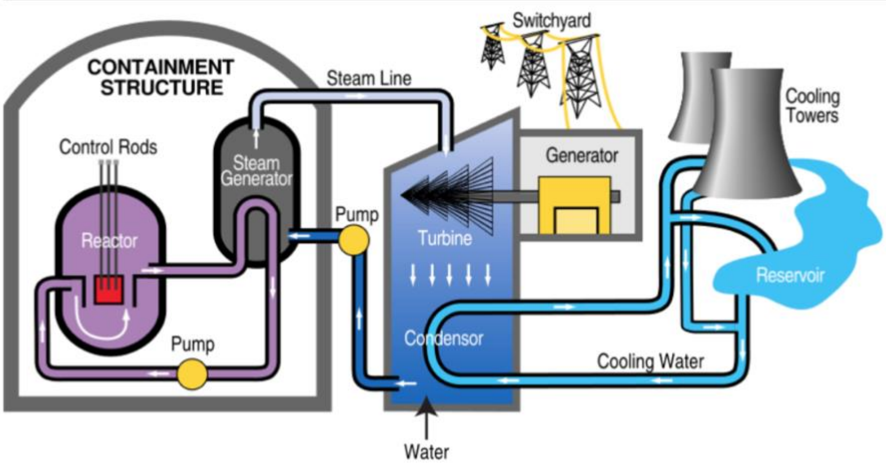

Figure 1. A schematic diagram of a typical Pressurized Water Reactor (PWR.) Note that the nuclear reactions and the radioactive material generated is confined to the 1st (purple colored) reactor system; radioactive water does not circulate through the 2nd and 3rd systems.

Nuclear power-generated electricity involves nothing more than a glorified steam engine, except that the circulating water surrounding the nuclear fuel is heated to high temperature and pressure by nuclear fission instead of burning gas or coal. The high pressure in the (purple) reactor system keeps the water from boiling even though it is much hotter than the ordinary boiling point. Thus, the name "Pressurized Water Reactor". This hot water gives up some of that heat to a second separate circulating system where high-pressure steam is produced in the grey region marked "steam generator." The stream then travels to the turbine and pushes against the blades of the turbine, spinning it, which in turn spins a generator to produce electricity. In the process, the temperature in this second circulating system drops, and the steam condenses to water, but is still somewhat warm. A third circulating system (in light blue) captures this "waste heat" contained in the warm water. In the case of the Diablo Canyon Power Plant (DCPP) using nuclear reactors, this cooling water is discharged into the ocean at a temperature of about 18 degrees ^{o}F, (or 10 degrees ^{o}C) above the ocean water temperature. Cooler ocean water is circulated back inside, where it cools and condenses the steam into water in the second circulating system, which in turn circulates back to where the steam is generated.

Discharge of "waste heat" into the ocean

In the figure shown, the cooling towers release the waste heat to the atmosphere or a nearby reservoir. But in the case of the Diablo Canyon plant, the waste heat is discharged into the ocean. In a recent Viewpoint in the San Luis Obispo Tribune[1], it was pointed out that this discharge of 'waste heat' will warm the ocean and thus contribute to global warming. This heat is called "waste heat" because unlike the much hotter steam that turned the turbines, this heat is no longer available to do useful work (like turning the turbines) and so is "wasted."

But it is always helpful in a situation like this to be as quantitative as possible in order to see how significant this is when compared to the other human-caused processes which have given rise to all the recent global warming, especially during the last few decades.

What is the main process causing global warming?

The main cause of recent global warming is the increasing amount of long-lived greenhouse gases, especially carbon dioxide, resulting from fossil fuel burning. This increased carbon dioxide intercepts and redirects downwards an increased amount of heat-transporting infrared radiation which is absorbed by the earth's surface, warming it. This has upset the Earth's energy balance which had been very stable over the last 8 thousand years—the period in which virtually all of the developments of the civilized world have occurred.

Where is most of this human-caused heating deposited?

Climate scientists have determined, by direct measurements, that about 90 percent of this energy has been absorbed by the ocean.

The first calculation we want to perform: Compare the contribution of the heat from the DCPP waste heat to that from the heat absorbed due to increased carbon dioxide emitted all over the world.

How does the warming associated with the DCPP discharged waste heat compare with the total energy recently deposited in the ocean, which is mostly the result of our fossil fuel burning?

A Digression; "Big numbers" and "Scientific Notation": Don't be afraid of this!

In the following calculations, some of the numbers we deal with are quite large. I have often heard people say that they find it difficult, even intimidating, to work with very large numbers. They are fine with dividing 25 by 5. But what about 2,500,000,000,000 (two trillion, 500 billion) divided by 500,000 (five hundred thousand.) This is very simple to do when numbers are represented in '*scientific notation*.' If you are not familiar with 'scientific notation' when doing arithmetic, please see **Appendix 1** where this is explained, and illustrated with a real example from the U.S. economy. It is not hard. Give it a try. Question to math teachers: According to the California Math framework, facility in doing arithmetic using scientific notation is taught in the 8^{th} grade. Is this happening?

End of digression

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[1] https://www.sanluisobispo.com/opinion/readers-opinion/article256624776.html

Step 1. Since we want to compare this waste heat with the main cause of wrming, we first ask how much energy has been deposited in the ocean over the last 10 years (say 2010 to 2020), due to our putting so much carbon dioxide in the atmosphere?

The following figure shows the growth of this deposited heat into the ocean since 1960.

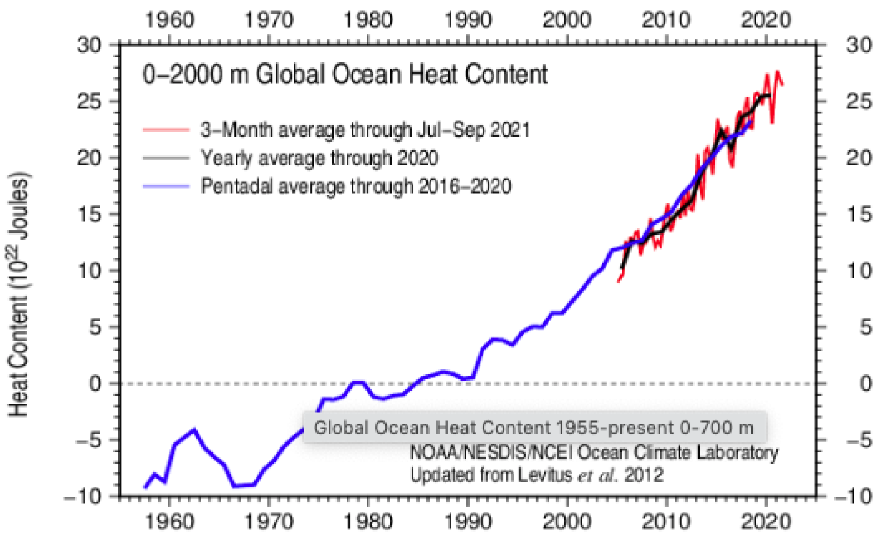

*Figure 2. The change in heat content in the ocean over the last 60 years. The "zero point" of the graph is arbitrary as we are only interested in the **change** with time, which is independent of the chosen zero point. The accuracy has improved substantially over these years but measurements prior to about 1990 are more uncertain.*

The carbon dioxide we put into the atmosphere has a long lifetime and accumulates. As one can see, the rate of heat deposition, primarily caused by this cumulative continual increase of carbon dioxide we have put into the atmosphere, has rapidly grown. Each tick mark on the y-axis represents 10^{22} Joules. (A joule is a unit of energy.) Reading the graph, between 2010 and 2020, the amount of heat deposited in the ocean amounted to about (25 – 15) = 10. $*10^{22}$ joules which is that same as 1.0$*10^{23}$ joules.

Thus, the *annual rate* of heat deposition is 1.0$*10^{23}$ divided by 10 years, or 1.0$*10^{22}$ joules per year.

(When a joule of energy is either consumed or produced every second that amounts to a *power rate* of one Watt. The number of Watts is defined to be the number of joules divided by the number of seconds over the time we are measuring. Since there are about 3.15$*10^{7}$ seconds in a year, it means we have been depositing energy into the ocean at the *rate* of 1.0$*10^{22}$ joules per year divided by 3.15$*10^{7}$ seconds per year, which gives 3.17$*10^{14}$ Watts. Another unit of energy—the one you see on your utility bill—is a kilowatt-hour (kWh) which is the power measured in kilowatts --kilo means one thousand-- times the number of hours.)

Step 2: The two starting facts concerning waste heat at DCPP.

To estimate the contribution from the waste heat discharged at DCPP to this annual total energy deposition of $1.0*10^{22}$ joules, we start with two facts*:* **One:** about $2.5*10^9$ *gallons* of water are discharged into the ocean *every day*, and **Two:** This discharge water is about 18 ^oF = 10 ^oC warmer than the ocean water drawn back in.

Step 3: We first find the total volume of the cooling water entering the ocean every year from DCPP, (because we want to compare this with the amount of energy put into the ocean every year by fossil fuel burning,) but we are given how much is discharged every day at DCPP.

Important point: Units: In doing this it is necessary to be consistent in using units: The metric system should be used. If we carelessly mix pounds and kilograms, or gallons and cubic meters, we are bound to run into trouble.

Consistent with using metric units, we first convert *gallons* into *cubic meters*. (A meter is a little longer than a yard.) An internet inquiry tells us there are $2.64*10^2$ gallons in every cubic meter, so to get the rate of discharge in cubic meters every day we divide $2.5*10^9$ gallons by $2.64*10^2$ gallons in a cubic meter to get $9.47*10^6$ cubic meters per day. Since there are 365 = $3.65*10^2$ days in a year we multiply $9.47*10^6$ by $3.65*10^2$ to get $3.46*10^9$ cubic meters per year.

Before describing the next step, we have to introduce the concept of '*specific heat.*'

Specific heat refers to the amount of energy that must be delivered to a definite amount of a given substance to increase its temperature by one degree centigrade.
The word 'specific' means for a specific (i.e. definite) weight of the substance. In the metric system that specific weight is the **kilogram.** Two kilograms would require twice the amount of heat energy. By the same token, raising one kilogram of the substance 4 degrees centigrade requires 4 times the energy specified by its specific heat.

Think of your microwave oven: It takes longer to heat a quart of water than a cup, and it takes longer to heat water from room temperature to a 'hot' temperature than to heat it to merely warm. The specific heat also varies with the particular substance. The same weight of pitted dates will heat by a given amount 4 times as quickly as the same weight of water.

The same concept holds if we want to know how much heat energy is transferred when a warm substance cools and transfers its heat to a cooler substance.

Step 4: Convert the volume of sea water (in cubic meters) annually discharged, to the weight of water annually discharged (in kilograms) since specific heat involves weight, not volume.

Weight is related to volume by multiplying the volume of a substance by its *density*. Density is the number of kilograms for every cubic meter. So, to get the number of *kilograms* discharged every year we have to multiply the volume of the discharged water by its density. Once again relying on the internet for basic physical data, we find that a cubic meter of ocean water weighs about $1.03*10^3$ kilograms , so multiplying the volume of $3.46*10^9$ cubic meters by the density ($1.03*10^3$ kilograms per cubic meter) we get $3.56*10^{12}$ **kilograms** of water being discharged every year.

Step 5: We use the concept of specific, the weight of water being discharged annually and the fact about how many degrees it is cooled when it mixes into the ocean.

Once again using the internet, we find that the specific heat of sea water is $3.85*10^3$ Joules for every kilogram and every degree of heat given up to the ocean. Since the discharged sea water is 10 degrees warmer than the ocean water, each kilogram adds (10 ºC) times the specific heat of $3.85*10^3$ which equals $3.85*10^4$ joules.

Step 6: Knowing how much waste heat energy each kilogram gives up, we multiply by the number of kilograms deposited every year to get the waste heat energy given up every year.

Since we found in step 4 that there are $3.56*10^{12}$ kilograms of water being discharged every year, if we multiply $3.85*10^4$ joules by $3.56*10^{12}$ kilograms we get the final answer of *$1.37*10^{17}$ joules.* This is to be compared with the total heating every year caused by fossil fuel burning, which we found was $1.0*10^{22}$ joules

Thus, the annual waste heat discharge from DCPP contributes a very small fraction ($1.37*10^{17} / 1.0*10^{22} = 1.37*10^{-5}$) or about 14 millionths, of the total annual increase of 10^{22} joules, which results mostly from the buildup of carbon dioxide.

Incidentally, dividing the amount of DCPP waste heat discharge in joules, $1.37*10^{17}$, by the number of seconds in a year, $3.15*10^7$ gives us the *rate* of heat discharge, since joules divided by seconds is the average number of Watts. Doing the arithmetic gives us $4.35*10^9$ Watts—*almost double the actual rate of about $2.2*10^9$ Watts in generated electricity at the DCPP.* This is characteristic of heat engines of this sort—their efficiency is not very high: they produce more waste heat than the heat which does useful work (i.e., spinning a generator.) Efficiencies of heat engines get higher when the input temperature of the 'working fluid' (in this case the hot steam) is very high. Improvements in reactor design take advantage of this fact and get the "working fluid" temperature as high as possible.

Step 7 What about all the other reactors in the world? What is their total contribution?

Of course, DCPP is not the only reactor discharging waste heat into the ocean, or rivers, or air. A total of $2.5*10^6$ GWh (1 gigaWatt-hour = 1 million kWh) was produced in 2020 by nuclear power worldwide,[2] which is about 140 times that produced by DCPP.

Thus, if this same ratio of waste heat to electrical energy as in DCPP applies to all the nuclear reactors the total nuclear waste heat contribution from all nuclear reactors is 140

[2] https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx

times $1.37*10^{17}$ or about $2*10^{19}$ joules, still only about 2 one thousandths of the total annual heating of **10^{22}.**

At the risk of annoying readers who have had the patience to go through this so far, I need to tell you that the concern about the waste heat from nuclear reactors is a bit of a red herring. The reason is that, if the same amount of energy had instead been generated by a coal plant, they too would have deposited about the same amount of waste heat. But in addition, of course, the coal plants would have also spewed out a tremendous amount of carbon dioxide, far more than the carbon dioxide produced over the entire lifetime of nuclear generators, from their construction, their operation and their decomissioning. This brings us to the second topic of "avoided emission."

The Second Calculation: The "avoided emission"

We are now going to calculate the "avoided heat" described above in the introductory comments. By using nuclear generation of electricity instead of coal-fueled or gas-fired energy generation, one has avoided nearly all of the production of carbon dioxide by either of these two processes which in turn will end up warming the ocean. For a given amount of energy, both coal- and gas-generated electricity produce far more carbon dioxide than that produced during the entire life cycle of nuclear plants. *Of course, the same general argument can be made about wind and solar, as discussed below.* But we here are focusing specifically on existing nuclear facilities.

Step 1: For a given amount of energy produced, how does the amount of carbon dioxide generated by coal compared to that generated by a nuclear reactor? (In reality, some energy would have been generated by natural gas as well as coal, but we will assume only coal.)

Elsewhere,[3] I presented a summary of 'life-cycle' estimates of the grams of CO_2 for every kWh of electricity generated by coal, natural gas, solar, wind and nuclear energy. The numbers were 980 grams of CO_2 for every kWh of coal generated electricity compared to 12 grams of CO_2 for every kWh of electricity generated by nuclear power, or a difference of 968 grams of CO_2 for every kWh. (Recall that a kWh is another unit of energy instead of Joules.)

Step 2: We calculate the total amount of kWh that DCPP has produced over its lifetime thus far

DCPP has a maximum power output of 2.2 billion watts. But it is not always producing this amount. It has averaged about 87% of this over its lifetime of about 36 years, so on average it has been generating power at the rate of 0.87 times 2 billion, or $1.74*10^9$ watts. This is the same as $1.74*10^6$ kilowatts, since there are 1000 watts in a kilowatt. There are 24*365 hours = $8.76*10^3$ hours in a year and it has been running for 36 or $3.6*10^1$ years, so it has been running for $3.6*10^1$ times $8.76*10^3 = 31.5*10^4$ or $3.15*10^5$ hours

Step 3: How many kWh of energy has DCPP generated over its life time.

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[3] http://www.centralcoastclimatescience.org/uploads/5/3/8/1/53812733/desert_tortoises_birds_and_nuclear_waste.pdf

Since kWh is the kilowatts time hours we finally $3.15*10^5$ hours times $1.74*10^6$ kWh = $5.48*10^{11}$ kWh, (since the energy measured in kWh is the number of kilowatts times the number hours.)

Step 4: How many grams of "avoided CO_2 emission" did this amount to if coal had been used instead of nuclear energy?
In step 1 we learned that using coal instead of nuclear energy produces about 968 grams more of carbon dioxide for every kWh of energy produced. In step 3 we found that DCPP has produced about $5.48*10^{11}$ kWh of energy. So, multiplying this by $9.68*10^2$ grams, results in about $5.3*10^{14}$ grams of avoided CO_2 (It would be about 60% of that for gas-generated electricity) from DCPP alone.)

Step 5: How much avoided emission has there been for all the nuclear-generated electricity that has ever been generated?

Worldwide, from the same source given in footnote 2, I estimate that the total electrical energy generated by nuclear reactors since they began producing energy amounts to about 170 times that from DCPP alone. It is difficult to know how much avoided CO_2 emission that amounts to, since we really do not know what would have replaced this power had nuclear energy never been discovered. Supposing it was all from coal, we again calculate, similarly as in the case of DCPP alone, that $1.70*10^2$ times $5.48*10^{11}$ = $9.3*10^{13}$ kWh. Thus, as in the calculation above $9.3*10^{13}$ times 968 grams of CO_2/kWh = ***$9.0*10^{16}$ grams** of CO_2 would have been avoided*.

Step 6: What are the consequences of that avoided emission in terms of "avoided heat deposition" in the land and (mostly the) ocean? (This step is more complicated, so if you want to, just skip to step 7)

Let's follow the consequences of the avoided emission a little further: We know from measurements that about half of the CO_2 produced by fossil fuel consumption ends up in the atmosphere. The other half is, thankfully, absorbed by the ocean and the biosphere. Thus, about half the "avoided emission" would have ended up in the atmosphere—about $9.0*10^{16}$ grams /2.0 = $4.5*10^{16}$ grams. This amount of CO_2 that was avoided would have made the greenhouse heating due to returned infrared radiation worse than what it already has become. *How much worse?*

To answer this question, we first have to ask how this $4.5*10^{16}$ grams of avoided emission would have changed the CO_2 "concentration". The reason we must take this step is that the amount of heating resulting from the CO_2 greenhouse effect depends upon its "concentration". I will put the actual calculation in **Appendix 2** and just give the results here after discussing what we mean by 'concentration':

Many people have heard that the increasing amount of CO_2 in the atmosphere has recently passed "400 ppm". The ppm stands for 'parts per million'. But what are these "parts?" The "parts" are just the number of CO_2 compared to the molecules composing most of our atmosphere. So, 400 ppm of carbon dioxide simply means that for every million molecules of air (80% of them are nitrogen molecules and 20 % are oxygen molecules) there are 400 molecules of carbon dioxide. In fact, the latest measurement of the CO_2 concentration is 417 ppm. What would the concentration now be if the $4.5*10^{16}$ grams of avoided CO_2 were actually put in the atmosphere? *The answer turns out to be about 6 more ppm, which would have meant that we would be at about 423 instead of the current actual value of 417*.

Step 7: The final calculation and result: How much additional heating has nuclear energy electricity generation avoided?

This avoided increase in CO_2 ppm can be estimated, and then translated into the additional energy input that would have gone into the ocean and land had the avoided emission actually occurred. This involves calculating yearly how the concentration of carbon dioxide in the atmosphere would have increased with the resulting increase in heating as additional outgoing infrared energy given off from the earth's surface is redirected downward. This is a more complex calculation so I will just quote the final result, but for those interested the details are given in **Appendix 3**.

The answer is that the avoided emission would have currently added about *XXX percent* more to the actual total resulting primarily from fossil fuel combustion and that about xx °C of heating were avoided.

However, we know that this avoided emission has, during the era of nuclear energy, been accompanied by three significant nuclear accidents. Opinions differ on whether the savings in heating and the corresponding small reduction in global warming was worth the negative effects of these incidents.

My conclusions and looking toward the future.

In my opinion, this entire discussion is not the most pertinent issue. As Lady MacBeth remarked, "What's done cannot be undone." Going forward, the question is not "coal or nuclear." The real issue is the urgency of quickly minimizing the use of coal and natural gas by replacing them with sources of energy, whether nuclear, wind or solar, all of which have much lower life-cycle emissions than coal or natural gas.

The question that needs detailed, thoughtful discussion, therefore, is the appropriate mix of these energy sources and the answer to that will depend on a host of factors as discussed in the reference given in footnote 2.

In making these calculations I also want to emphasize that I am not dismissing legitimate issues concerning nuclear energy, nor have I addressed any *environmental* impacts associated with the warm water discharge in the case of DCPP. This is a separate topic I have not attempted to address. Rather, I have gone through this exercise because I believe it helps to separate those issues which are not important from those which may be and will help to focus our attention on substantive issues.

I thank Walt Reil and Steve Kliewer for helpful suggestions , and especially Barbara Weymann for carefully going over a draft of this essay to make it as understandable as possible. As always, however, any errors are mine alone, as are the views expressed in this essay.

Appendix 1
Doing arithmetic using scientific notation

Use of scientific notation is universal in scientific work, as the name implies. But, as noted in the main body of this post, it finds application in today's economy, where I illustrated this with the following example: The national debt is currently estimated at 28 trillion dollars, or, written out with all the zeros, $28,000,000,000,000. There are about 120 million families in the United States today. What share of the national debt does each family bear if the debt is divided evenly? This is pretty clumsy to do by ordinary 'long division' but is very simple using scientific notation.

In scientific notation, the national debt can be written **$28.0*10^{12}$.** The red superscript number (12 in this example) is called the **exponent.** The meaning of the exponent 12 is that starting with the first number *after* the decimal point (the 0 in this case) you keep adding more zeros until you have added enough of them to be able to *move the decimal place 12 places to the right*: Thus: 28,000,000,000,000.0 Alternatively, we could write the same number as **$2.8*10^{13}$**, since in order to write this in "ordinary" notation, add enough zeros, starting with the first number after the decimal point (8) move the decimal point 13 places to the right. Similarly, the 120 million families in the United States, 120,000,000 is written $1.2*10^8$.

To ***divide*** two numbers using scientific notation you do the simple arithmetic using just the numbers before the exponents and then *subtract the bottom* exponent from the *top* exponent. So, in our example, to calculate $2.8*10^{13}/1.2*10^8$ we first divide 2.8 by 1.2, which is about 2.3. Then we subtract the exponent 8 from the exponent 13, getting 5. The answer, therefore, is $2.3*10^5$, or $230,000 for every family. To *multiply* two numbers, you again do the simple arithmetic using just the numbers before the exponent, and then *add* the two exponents. So had we wished to multiply $2.8*10^{13}$ times $1.2*10^5$ we multiply 2.8 times 1.2 = 3.36 which we will round up to 3.4. Then add the two exponents 13 and 5 to get 18, so the answer for this multiplication is $3.4*10^{18}$.

Sometimes we have to deal with exponents which are *negative* numbers. For example, the -5 in the number $6.0*10^{-5}$ tells us that we should add enough zeros to the *left* of the decimal point, and then move the decimal point 5 places to the left of where it started. So, this would result in 0.00006. Thus, for example, dividing $6*10^4$ by $3*10^9$ results in 6/3 = 2.0 and 4 -9 = -5 (negative 5) so the answer is $2.0*10^{-5}$.

Appendix 2

How would the *concentration* of CO_2 have changed if the additional amount of CO_2 that was 'avoided' were actually added to the atmosphere?

In the main text, we estimated that about $4.5*10^{16}$ grams of CO_2 were avoided by nuclear generation of electricity instead of from fossil fuels.

Since the "ppm" has to do with the number of molecules, if we know the mass of each CO_2 molecule and then divide the $4.5*10^{16}$ *grams* of CO_2 by the mass of each CO_2 *molecule*, we will know how many of these additional *molecules* of CO_2 would have ended up in the atmosphere.

The mass of the atoms which make up the various kinds of molecules are measured in 'atomic mass units' (AMU). The actual mass of an atomic mas unit is $1.66*10^{-24}$ grams. (If you are bothered by the minus sign in front of the 24 in the exponent, see **Appendix 1** on 'scientific notation.') The carbon atom has a mass of 12 of these units, and each of the two oxygen atoms in the CO_2 molecule has a mass of 16 of these units. So, the mass of a CO_2 molecule is $1.66*10^{-24}$ times (12 + 16 +16) = $7.30*10^{-23}$ grams. So to get the total number of CO_2 molecules we divide the $4.5*10^{16}$ grams by $7.30*10^{-23}$ grams per CO_2 molecule which gives ***$6.16*10^{38}$ CO_2 molecules***. *(Quite a few!)*

Next, we calculate how many *ordinary air molecules* there are in the atmosphere, since the meaning of "ppm of CO_2" is the number of CO_2 molecules for every million air molecules. We learn from the internet that the total mass of the atmosphere, whose makeup is largely 80% nitrogen molecules and 20% oxygen molecules, is $5.15*10^{21}$ grams.

The nitrogen *molecule* has two nitrogen *atoms*, each having a mass of 14 atomic mass units; thus, a mass of 2 time 14 = 28 AMUs. Similarly, the oxygen *molecule* has two oxygen *atoms*, each having a mass of 16 AM, thus 32 AMU. The *average* molecule of air therefore has a mass of (0.80*28 + 0.20*32) = 28.8 AMU. Multiplying 28.8 AMU by the mass of an AMU gives us *the mass of an average air molecule of $4.78*10^{-23}$ grams.* Finally, just as we did for the total number of avoided CO_2 molecules, we divide the mass of the atmosphere by the mass of an air molecule to get the number of air molecules in the atmosphere: $5.15*10^{21}/ 4.78*10^{-23}$ = ***$1.08*10^{44}$ air molecules.*** (21 minus a negative 23 is a positive 44.)

Now that we know the number of the supposed added CO_2 molecules and the total number of air molecules, we calculate the *ratio* of these avoided CO_2 molecules to air molecules. Then, knowing that ratio, we multiply this ratio by one million and this gives us the additional *concentration* of CO_2, measured in ppm, that would have been added if fossil fuels had been used instead of nuclear energy.

Here is the arithmetic: The ratio of these avoided CO_2 molecules to air molecules is $6.16*10^{38}$ / $1.08*10^{44}$ = $5.71*10^{-6}$. So, the concentration of CO_2 in "parts per million" would have been increased by $1.0*10^{6}$ times $3.07*10^{-6}$ = 5.71 (or about 6). In other words, the concentration would have been about 423 instead of at its actual current value of 417 ppm.

Appendix 3

There are some important features about the heating from the carbon dioxide that has been added to the atmosphere by human activities, now primarily from fossil fuel burning. Prior to these activities taking place on a large scale, (which commenced with the industrial revolution) the amount of carbon dioxide prior to this had been nearly constant for several thousand years. There was a balance between the continued release of CO2 into the atmosphere and its return to the land and ocean by natural processes—the “carbon cycle”.

These human activities have upset this balance, and one of the important aspects of this is that it will as long as we continue to do this, *the CO_2 concentration will continue to increase and even after fossil fuel burning stops the additional concentration, and the accompanying heating, will only slowly decrease over many decades or even centuries.*

Another feature of the additional heating from CO_2 is that it is not directly proportional to the amount added. Detailed calculations using high speed computers are required to accurately know this heating, and it is found that starting from the concentration at some given time, if that concentration is doubled, then the amount of additional heating is about 3.7 watts for every square meter of the earth’s surface. (And there are a lot of square meters!) You might suppose that then if, for example it were increased by 8 times instead of just two, that there would be 4 times as much. But in fact, there would be less than this. Since in fact the increase is approximately ‘log

An approximate expression for the additional heat directed downwards is given by the formula: Heat (in Watts) for every square meter = 5.35 times ln (C2/C1) where ln is the natural log, C2 is the concentration after an increase (423 in our case and C1 is the current actual concentration (17). This gives additional heating of $7.64*10^{-2}$ Watts per square meter. From the internet we find there are $5.1*10^{20}$ square meters, leading to an average heating rate of 3.9*1019 watts