Report on My Sabbatical Leave for the Year 2002-2003

Submitted to the Sabbatical and Leaves Committee
Mt. San Antonio College

by

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INTRODUC TION

My original intent was to do an educational sabbatical to study Renewable Energy. I had identified two Masters degree courses in England that seemed interesting and appropriate, and submitted my proposal to the Sabbatical and Leaves Committee. The problem was that the course units were "foreign" and I needed to demonstrate that they were equivalent to American course units. The usual way to do that is to have a transcript evaluated, but one can't have a transcript to evaluate without first having done the courses. The solution was to transform my "educational" sabbatical into a "project" sabbatical, where the main thrust of the project was to study Renewable Energy in the United Kingdom.

The difficulties in defining such a project (and the joys of doing one) are that you can't know quite what you are going to learn until you've completed the project. It turns out that besides learning about Renewable Energy I've also learned quite a bit about the English education system, English history and politics, English and European energy policy, emissions trading schemes, the economics of project investments, how Engineering differs from Physics, Third World development projects, and waste disposal. I've also had the opportunity to be reminded as to what higher education looks like from the student side of the desk. I've been exposed to a variety of teaching styles (some inspiring, some aggravating) and a very different assessment and testing scheme.

On the more personal side I got to be in a new and less stressful environment. I learned a tremendous amount about archaeology, Romano-British history, medieval weapons, the Crusades, castles and their evolution, siege engines, and the history of the English crown. I joined a local recorder group, attended weekly practices with "ordinary" people (although they were hardly ordinary) and got to perform at the 800th anniversary celebration of a local church and a manor house dating back to medieval times.

WHAT I DID

Back in May 2002 I flew to England for five days to evaluate two programs in Renewable Energy—one at Loughborough (in the Midlands) and the other at the University of Reading (about 25 miles west of London). On the basis of that visit I decided to enroll at the University of Reading. The official MSc. course title is "Renewable Energy and the Environment", which resides in the University's Engineering Department.

At the end of the summer I flew to England and stayed in University accommodations until I found a house to rent. I had a visit up to Edinburgh to visit friends and learn some Scottish history. Then I returned to Reading and I started my coursework

My first term's courses (Fall) were:
- Energy and the Environment
- Wind and Hydro Energy Systems (a double course)
- Biomass Energy Systems
- Solar Energy Systems
- Weekly visiting speakers

My second terms courses (Winter) were:
- Carbon Management
- Meteorology
- Sustainable Development
- Project Planning and Rural Energy Systems
- Advanced Solar Energy
- Advanced Biomass Energy
- Weekly visiting speakers

At the end of the winter term I sat for my exams, and then there was a course trip to Wales where we stayed at the Centre for Alternative Technology (CAT) and visited wind farms and small-scale (and not so small-scale) hydropower installations.

The rest of my time in England was spent in working on my MSc project (characterizing the energy flow in a particular anaerobic digestion scheme, and comparing the results with a self-built lab-scale anaerobic digester) and packing up to come back to the States.

Throughout the course and my stay in England I went to various conferences, museums, and renewable energy installations.

THE REPORT

It is difficult to summarize a year's studies in a single report. I have thousands of pages of notes from my courses; I've read hundreds of papers in preparation for assignments; done dozens of problems and written out dozens of responses to questions in preparation for exams; and spent hundreds of hours in lab or working on my research. I've also attended conferences and visited various sites.

For completeness' sake I have summarized the courses I've taken (objectives, lecture topics, and assessment methods). I have opted to include as appendices some of the many assignments I've done. For a group assignment I have included the parts that I wrote. I've also included a summary of my research project and results. I've included very short summaries of Renewable Energy sites I've visited.

I've intentionally chosen to leave out notes and worked problems from the exam preparation I've done, copies of course handouts and some of the papers I've written or lab practicals I've written up on the assumption that they would be of little-to-no interest to anyone but myself.

I'll conclude with an attempt to summarize the entire experience, and my hopes for where it is all going.

COURSEWORK

Energy and the Environment

Objectives

- Review some of the concerns associated with the sustainability of current energy use, in particular environmental concerns
- Evaluate possible alternatives, in particular in the electricity and transport sectors
- Emphasis the advantages and disadvantages of renewable energy, from an environmental point of view

Lecture topics

- Global Energy use and the environmental concerns
- Climate change and air pollution
- Electricity generation using fossil fuels
- Renewable energy: opportunities and environmental concerns
- Nuclear power. End use efficiency
- Fuels cells and their applications
- Cars and the environment
- Catalysts and automobile emissions

Assessment

- 25%--Briefing for a politician on global energy use
- 25%--Analysis of an article from Physics World: "Do we need nuclear power?"
- 50%--Individual report and presentation (I chose to write on Dye-Sensitized Photovoltaics)

Highlights:

- Examining global energy use statistics, developing an appreciation for how we get our electricity (55% from coal in the US), and how much energy is involved in transport
- Getting a sense of the disparities in energy use between the developed and the developing world
- Finding out just how hard it is to get good data on the costs and risks and benefits of nuclear energy
- Writing a paper and giving a presentation on a potentially revolutionary way of making photovoltaic cells (the ordinary window glass is the most expensive part of the whole module!)

Solar Energy

Course Objectives:

To provide:

- An understanding of the design and operation of solar energy systems
- Quantitative skills to assess the performance of solar energy systems
- An understanding of the social and environmental relevance of solar energy
- Competence at using PV-SYST, a photovoltaic systems design software package

(Solar Energy Systems, continued)

Lecture Topics (2 hours each):

- Applications of Solar Energy; Solar Radiation
- Solar Radiation
- PV cells and Modules
- Introduction to PV Systems
- Application and design of grid-connected PV systems
- Application and design of standalone PV systems
- Introduction to solar thermal, flat plate collectors
- Solar water heaters
- Solar thermal systems and applications

Assessment:

- 30%--Design a grid-connected solar roof for a 3x15 meter aviary at Beale Park (a local wildlife park), estimate the electrical output, and do an economic analysis of the project based on both the current United Kingdom government incentive scheme and the current German government incentive scheme.
- 70%--Final exam.

Highlights:

- Using a software package to predict outputs from various combinations of PV modules and inverters; designing and sizing the various components of a system
- Discovering how expensive solar energy systems really are, and how uneconomic they are except in very specific circumstances
- Learning the various clever ways that solar thermal collector manufacturers improve the efficiency of their systems

Biomass Energy Systems

Lecture Topics

- Biomass Resources
- Combustion of Biomass: Furnace and Stove Design
- Charcoal Manufacturing and Briquetting
- Anaerobic digestion—Digester design
- Energy from wastes
- Pyrolysis and Gasification
- Plant-derived Fuels—Alcohol and biodiesel

Assessment:

- 30%--Lab practical—Evaluating the Efficiency of an Ethiopian Stove
- 70%--Final Exam

Highlights:

- Learning how to convert wastes into useful energy
- Looking at the energy balance and economics of alcohol and biodiesel production

Wind and Hydro Energy Systems (a double course)

Lecture Topics

- Introduction to the physics of energy generation from wind and hydro power
- Aerodynamics of lift machines; Engineering description of wind and hydro machines (coefficients and dimensionless numbers used to describe their performance);
- Estimating output from a machine (wind distributions and flow duration curves);
- Central vs. Distributed electricity generation and distribution;
- Modern wind turbine generator technology
- Assimilating intermittent renewable sources
- Economic analysis of wind and hydro projects

Assessment:

- 30% (wind)—Characterizing Wind Turbine Performance
- 30% (hydro)—The Use of Induction Machines as Integrated and Stand-Alone Generators
- 70% (each course)—Final Exam

Highlights

- Application of Freshman and Sophomore level physics to a huge range of energy generation systems
- Understanding of how aggregation of intermittent energy sources can lead to a relatively dependable source of energy, and how flexible the grid is in absorbing intermittent generation

Sustainable Development

Objectives:

- To provide insight into the practice of Sustainable Development, with particular emphasis on the creation, application and interpretation of indicators as tools

Lecture Topics

- Meaning of Sustainable Development
- Environmental Quality
- Economic and poverty dimensions to sustainability
- Human Development
- Seeking Sustainability—Some examples
- Sustainable management of complex systems
- Sustainable agriculture and livelihoods and the Project Approach
- PRACTICAL: Fish Banks Game
- Institutional Sustainability
- Case Study—Nigeria

Assessment:

- 50%--paper (I chose to write on Integrated Biosystems for Sustainable Development)
- 50%--Final Exam

(Sustainable Development, continued)

Highlights:

- Fish Banks game, a group simulation exercise in which you (and everyone else) try to maximize your profit form a particular fishery. Points out the real-world difficulties in trying to regulate a common resource, and why such efforts usually fail until the resource is already at crisis point
- Seeing how traditional top-down project-based development tends to fail, and that successful develop tends to require a long-terms investment of time and money, and needs to reflect the self-perceived needs of the people being helped
- Researching integrated biosystems, and seeing how, in a well-integrated and well-managed system wastes from one part of the system (say, cow manure) provide energy and food for another part of the system (and anaerobic digester whose effluent feeds a duckweed pond) which cleans the wastes and provides food back into the system (duckweed gets used as cattle feed)

Meteorology

Objectives:

- To develop an understanding of the meteorological processes which are a potential energy resource or may be affected by human energy usage
- To provide a summary of meteorological parameters which are routinely measured and may be useful for energy assessment
- To investigate the methods of measurement of meteorological parameters with emphasis on the limitations of the instrumentation and error estimation

Assessment:

- 50%--two practicals—on analysis of variation of wind speed with height, and another of the distribution of wind speeds over time
- 50%--final exam

Highlights:

- Mostly interesting stuff. I'd never had a proper meteorology course before

Advanced Biomass

Lecture Topics:

- Modeling biogas plants
- Thermodynamic cycles
- Engines
- Combustion Theory

Assessment:

- 35%--Electricity from biomass—Description of a 15 Megawatt wood gasification plant where the gas produced would be used to generate electricity
- 30%--Engines lab—Comparison of engine operations on diesel and biodiesel
- 35%--Spreadsheet analysis of combustion of wood gas in an engine; design of a burner to use such gas from cooking

(Advanced Biomass, continued)

Highlights:

- Learning about Heat Transfer (a course I've never had, but now want to take)
- Using Physics 4B level thermodynamics to model engine operations
- Discovering how different the Physics and Engineering approaches to problem solving are.

Advanced Solar Energy Systems

Lecture Topics

- Heat-transfer modeling of a solar thermal collector
- Evaluation of solar resources
- Performance assessment of PV systems
- Performance and application of PV concentrators

Assessment:

- 35%--spreadsheet analysis of a solar thermal collector
- 30%--group lab report—analysis of the performance of a stand-alone battery-charging PV system
- 35%--Assessment of manufacturer's literature (advertising claims for solar PV and solar thermal collectors)

Highlights:

- Application of basic heat transfer to a "real" problem
- Critical analysis of manufacturer's advertising literature and claims

Carbon Management

Objectives:

- Examine the evidence for Global Warming; Examining the global carbon cycle
- understand the Kyoto protocol and the mechanisms embedded in it to reduce greenhouse gas emissions
- Develop a carbon management plan

Lecture Topics:

- Why manage Carbon? Overview of climate change
- Sources and sinks of greenhouse gasses
- Case studies of carbon management—examples, role of renewable energy and energy efficiency
- UK carbon emissions trading scheme
- Kyoto project based mechanisms: Joint Implementation (JI) and the Clean Development Mechanism (CDM)
- The Framework Convention on Climate Change and the history of the Kyoto protocol

Assessment

- 30%--Assignment on data-sourcing and analysis of greenhouse gas emissions data
- 30%--Group case study assignment and presentation
- 40%--Final Exam

(Carbon Management, continued)

Highlights:

- Deeper look at the problem of global warming
- Intellectual challenge of defining system boundaries and defining a "system" when looking at managing greenhouse gas emissions
- Looking at a particular company and seeing how government policy can "drive" corporate activities and decisions in a particular way
- Deep research into landfill operation

MY DISSERTATION/RESEARCH

Project Overview

Anaerobic digestion is a process whereby organic material is broken down, through the action of a mixed population of bacteria in the absence of oxygen, to produce a mixture of methane and carbon dioxide. This is a process that occurs naturally in lagoons and bogs and in the digestive systems of certain animals (such as cows).

Because the gas produced has the potential to be used as fuel, people have built anaerobic digesters in various forms to treat organic wastes and/or to capture the gas produced for use as fuel. Literally hundreds of digester designs exist. The details of the actual digester depend on numerous variables, including the type and volume of feedstock, the temperature at which the process is run, the amount of gas required, whether the ultimate purpose is for gas production or waste treatment, what level of technology is available, and of course, the amount of money available to be spent.

Biogas from anaerobic digestion is generally considered a renewable energy source, in that the fuel source is usually organic waste material. It is also generally considered "carbon-neutral" in that the carbon dioxide that is produced from the combustion of biogas for energy comes from carbon that was originally taken up from the atmosphere in the formation of the plant biomass that ultimately ended up in the wastes. Although on the national scale, anaerobic digestion of waste will not make a large dent in the overall national energy production, it does have the potential to generate significant energy locally where large supplies of waste organic material exist and the energy can be used locally.

This study attempts to look at one particular anaerobic digestion scheme, the Bioplex process, looking at one particular feedstock. It will look at the energy inputs and outputs for the process, and attempt to evaluate how "renewable" and "carbon-neutral" the process is. It will also compare the digester-scale gas production with lab-scale trials using the same feedstock.

How Bioplex fits into overall UK waste disposal scheme

The Bioplex process is one of many different ways of carrying out an anaerobic digestion scheme. Although the specifics of the process will be described in section 2.2, the general process involves the following steps:

- Organic waste (manure, catering wastes, food processing wastes, abattoir wastes, etc.) are loaded into an insulated trailer or tip
- The wastes are flooded with "liquor" containing bacteria that are acclimated to the particular conditions (in this case, 58°C)
- After three days, the liquor is drained into a digestion tank and the wastes are dumped onto a concrete pad and composted.
- The liquor is digested for approximately ten days and the biogas (approximately 60-70% methane) that is produced is used to co-fire a spark-ignition diesel engine connected to an electrical generator. The electricity (from the generator) and heat produced (from cooling the engine) are used to maintain the temperatures necessary to sustain the digestion, with any excess being used to operate other farm facilities (with the potential of selling the excess electricity to the grid).

Bioplex Limited markets the system as a means for farmers to make extra income by going into the waste treatment business. Because of recent changes to UK landfill legislation, the amount of organic waste that can go to landfill is being severely restricted, and the costs of sending this waste to landfill in increasing. Given this situation, a farmer who owns sufficient land and who has purchased the Bioplex system can charge tip fees slightly below those of the local landfill, process the waste so that it meets the government's regulations for disposal onto land, and then spread the wastes on his own farmland, thus improving his soil and saving money on fertilizer.

How Bioplex fits into the Renewable Energy picture

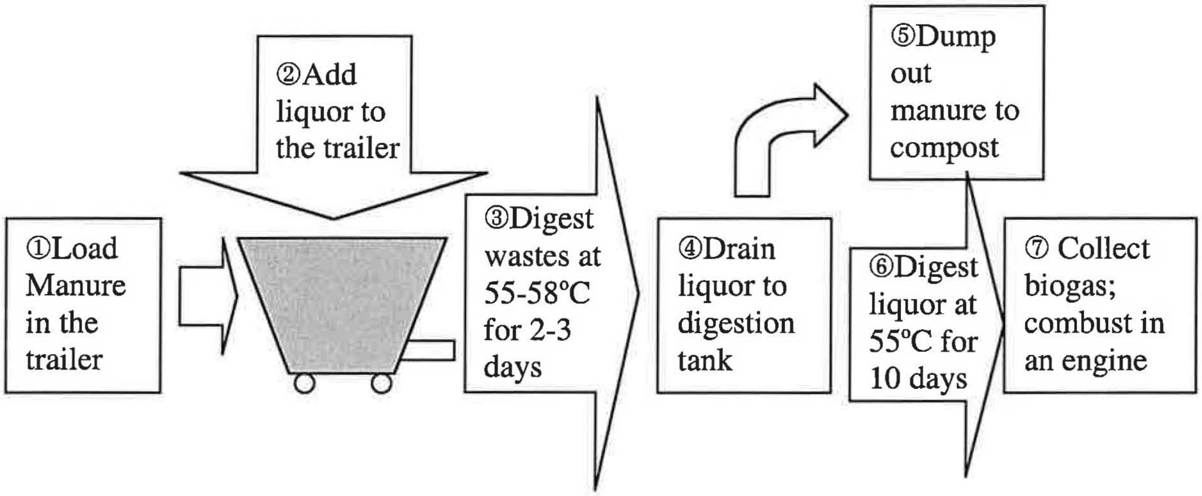
Since the Bioplex process produces methane, the process could be considered to provide renewable energy if the amount of energy in the biogas produces is more than what it takes to run the process.

Details of the Bioplex process

Anaerobic digestion proceeds via a complex set of interacting steps involving complex communities of micro-organisms, and there are numerous ways of modeling and classifying the various steps in the process. It is useful for this discussion to consider the anaerobic digestions process as taking place in two "stages". In the first stage (HYDROLYSIS) extracellular enzymes and extracellular non-biological processes combine to break down some of the complex organic polymers (carbohydrates, proteins, and fats) into simpler molecules (sugars, amino acids, and long-chain fatty acids). The second stage (DIGESTION) involves breakdown of the products of hydrolysis into shorter chain fatty acids (propionic, valeric, butyric acids), then to acetic acid, hydrogen, and carbon dioxide, and finally to methane.

The Bioplex process is a *two-stage* batch process which, in theory, serves to separate the hydrolysis stage of the process from the digestion stage, with each stage taking place in a different vessel. In practice the process involves:

- Loading a trailer halfway with manure or other feedstock
- Filling the trailer the rest of the way with "liquor"[1]
- Running the hydrolysis stage in the trailer for 3 days at 55°C
- Pumping the now-fortified liquor back to the liquor tank, where the digestion stage and biogas production takes place at 55°C for about 10 days, and dumping the remains of the feedstock somewhere for aerobic composting.



In short, the idea is to place the feed in the trailer and flood it with a bacteria-containing liquor that will hydrolyze and make soluble the carbohydrates, lipids, and proteins present in the feed. The assumption (to be tested!) is that after three days one has captured into the liquor much of the nutrients that will ultimately produce methane from the feed. Now one can drain the liquor into a digestion vessel (where the methane production will take place) and dump the remains of the feed onto a field where it can compost and ultimately fertilize the ground.

There are several perceived advantages to separating the process out in this way:

- Since you only hold onto the feed for three days, it is possible to process a relatively large volume of material over time without having a large facility.
- Since wastes have to be moved from where they are produced to where they will be disposed of anyway, the cost of the trailer is not an ADDITIONAL cost. If you site the digester close to the production site or the disposal site there is no additional cost for transporting the wastes. The only additional cost (on the trailer end of things) is in modifying the trailer for the addition and draining out of the liquor.

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[1] The liquor consists of a mixture of facultative and anaerobic bacteria from previous digestions that are acclimatized to working well at the thermophilic temperatures and with the feedstock that is being used.

- Because the feed never leaves the trailer, there is no expensive feed-handling equipment or pumps that are required, and no danger of straw or rocks plugging up or destroying the equipment.

The advantages of such a system can be best appreciated by comparing it will a more standard Continuously Stirred Reactor, usually run at mesophilic temperatures (around 35°C). Here the wastes are diluted by at least a factor of two, the retention time is typically around 15 days, and there are pumps for circulating the diluted slurry through the reactor. The reactor has to be much bigger to accommodate the extra fluids and the longer retention time, and the manure and straw have to be pre-processed before they can be added to the reactor. The wastes at the end of the process are wet and bulky and have to be pumped from the reactor to some trailer or truck for distribution or dewatering. Any straw or rocks in the feed can jam or break the pumps.

The obvious disadvantage of the Bioplex system is that you only get out from the feed those materials that can be hydrolyzed in a period of a couple of days. Any potential to produce gas from materials that take longer that this to break down (such as the cellulose in straw) is lost. Another disadvantage is that in order to perform the hydrolysis effectively in a relatively short period of time the process must be run at relatively high temperatures (55-60°C) so that some source of energy for heating the feed and liquor must be provided. Ideally the Bioplex system would produce enough methane to provide the necessary energy, resulting in a process that is self-sustaining from an energy point of view.

Experimental Work--Overview

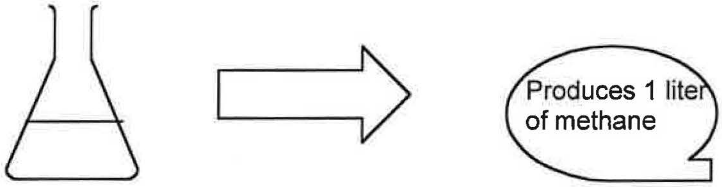
There are three parts to the experimental work:

- The first is perform an energy audit of the Bioplex process on the macroscopic scale (how much energy is required to run the process, and how much energy does is produce).
- The second is to characterize the process in terms of its efficiency in converting waste to biogas. Simply put, a given amount of manure has the potential to be transformed to a certain amount of biogas. Comparing how much gas the process produces compared to how much gas could be produced indicates the efficiency of the process.
- The third is to determine how well the results of small-scale lab digesters (using volumes of less than 5 liters) reflect the results from full-size digesters (with volumes of 10 m^3 or more).

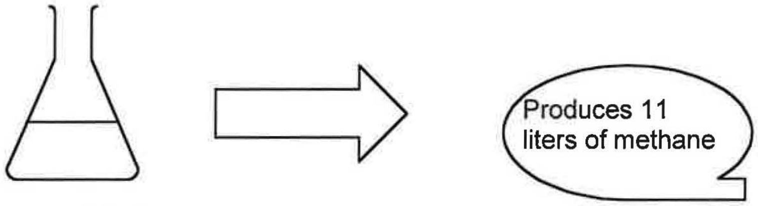
On the macroscopic scale, the amount of energy consumed to run the process can be determined by looking at the amount of diesel oil and biogas consumed over one process cycle. The amount of energy produced can be determined by looking at the amount of biogas produced over one process cycle.

The efficiency of the process can be determined experimentally by digesting a given amount of manure with some liquor and measuring the cumulative gas output and methane content of the gas, and comparing this to the difference in gas output between the original liquor and the enriched liquor. This can best be demonstrated by an example:

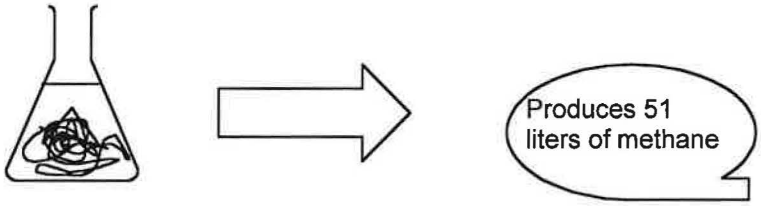
Suppose that:



1 liter of original liquor



1 liter of enriched
liquor (after the soak)



1 liter of original liquor
+ 1 kg of manure and straw

Then the process efficiency is:

$$\frac{11\,liters - 1\,liter}{51\,liters - 11\,liters} \times 100\% = 20\%$$

Finally, the "match" between lab-scale and full-scale digesters can be determined by measuring the gas output of the lab digester and scaling up the results.

Experimental Work

The actual experimental work consisted of:

- Loading the trailer with a know mass of feed (cow manure/straw or pig manure/straw) and flooding the trailer with a known amount of liquor, and running through the entire Bioplex process cycle, monitoring temperatures and energy use (diesel consumption and biogas production/consumption) along the way.
- Sampling the feed and liquor at various points of the process for analysis in the lab.

- Design and construction of a large (approximately 5' x 2' x2') insulated box with a circulating fan (which run all of the time) and a heater (which was connected to a temperature controller).
- Placement of the various samples (manure with liquor, liquor before the hydrolysis soak and liquor after the hydrolysis soak) into 5 1/2 liter bottles. The bottles were each stoppered with rubber bungs, and a hose through each rubber bung led out through a small hole in the side of the box, through a moisture trap and into a large Mylar party balloon. Thermocouples connected to a datalogger monitored the temperature of the samples within the box.
- Analysis of the biogas. A gas "sniffer" used in the natural gas industry was used to determine the methane content of the biogas in the balloons. The volume of gas produced was determined by sucking the gas from the balloon into a water-filled bottle from which the water was being siphoned. The volume of gas produced was equal to the volume of water siphoned out from the bottle.

I ran the farm-scale process through three cycles, once with cow manure and straw, and the other two times with pig manure and straw. In the lab I mirrored the farm process, digesting the liquor for a total of 10 days. A sample of cow manure and straw with the liquor was digested for 40 days to get a ballpark figure on how much gas could potentially be produced from the process.

Results

The gas production in the lab mirrored very nicely the results of the full-scale process as run on the farm. But it turns out that the process only produces between 2 and 5% of the energy needed to sustain the process. *That is, the same feed would have to produce between 20 and 50 times as much gas as it did in order for the process to be self-sustaining from an energy point of view.* The kinds of process changes that this would require (digesting the samples for longer times and improving the insulation on the trailer) would negate the advantages of the Bioplex process and make the process uneconomic, since the money is to be made by processing a large quantity of material. Increasing the trailer's and digester's retention times would require the purchase of many more trailers (a larger capital investment) or a reducing the volume of material digested (a much lower income from waste treatment). That the process is profitable now is due to the relatively low price of farm diesel in the UK.

A fuller analysis of the environmental friendliness or unfriendliness of the process would require looking into the energy consumption of alternative waste treatment regimes; taking into consideration the energy used to produce the fertilizers that this process replaces; and comparing the global-warming-potential of the methane that this process releases to the atmosphere with what would be released if the waste were put into landfill instead. Such an analysis would be interesting, but is outside the scope of my research project.

How this all relates to Mt. San Antonio College

One reason for choosing this particular research project was that I hoped it might apply to Mt. SAC. We have a farm with several dozen cows and some pigs. It was my understanding that the Agricultural District might be supportive of setting up a "model" anaerobic digestion system on campus. I was hoping that the Bioplex system might work out to be such a model system but it will not. Absent any requirements in California to treat manure at high temperatures before it can be spread on land there is no benefit to Mt SAC of using this particular system. There may be, however, some benefit to setting up SOME sort of anaerobic digester on the farm.

Field Trips/Visits

Scottish Museum (Edinburgh)—Exhibits of Science and Technology. Nice bits on clock design and steam engines.

Fibrowatt (Eye)—15 Megawatt power station that generates energy from the combustion of "chicken litter" (manure and feather-laden straw from chicken bedding). We toured the facilities and the control room. Highlights were seeing the management of the furnace, since we had just discussed furnace designs in class and how one manipulate the operation to a furnace to meet air quality regulations.

Wind Generator (Swaffam)—Ecotricity has a visitors' center which includes a 1.3 Megawatt wind turbine with a viewing platform located just below the generator nacelle, reached by climbing several flights of stairs located within the tower of the wind turbine. Very cool to see the surrounding countryside, watch these huge turbine blades (each 33 meters long) swing past, and to monitor electricity generation as it varies with the wind speed.

Royal Institution (London)—This is where Michael Faraday first attended public lectures given by Sir Humphrey Davy on electricity and magnetism. I toured the Faraday lab, and got to see the original coils and apparatus that Faraday built while doing his research, as well as to discover that he was involved in a lot more basic science (designing new varieties of glass, diamagnetic properties of gases) than just electricity. I later attended a public lecture in the same theatre that Faraday sat in over a century and a half ago.

Energy Expo (London)—Spoke with representatives of various manufactures of photovoltaic and solar thermal energy systems, saw examples of various microhydropower turbines, and people using ultrasound to speed up anaerobic digestion of municipal wastes

Greenfinch (Shropshire)—A small company that sells anaerobic digesters, that was running an experiment in digesting kitchen waste from a local community of about 170 households. It was a nice example of a continuously-fed mesophilic (medium temperature) digester. Toured the facilities and discussed the operation and monitoring of the digester, including the kinds of lab tests one does to analyze the feed and the "health" of the digester.

Dinorwig pumped storage plant (Llanberis, Wales). In the 1980's the British government converted an old slate mine site into a pumped storage site. They built a lake at the top of a mountain, dug out tunnels 3/4 mile into the mountain, and connect the set-up to a lake at the bottom of the mountain 400 meters below. During the day, when power is expensive, they run the water from the upper lake through some Francis turbines into the lower lake—300 m^3 or so per second, capable of generating 1800 Megawatts for 4 to 5 hours. At night when the grid has excess capacity and electricity is cheap they buy electricity to run the turbine backwards as pumps and pump the water back to the upper lake for the next day. The size of the system is amazing, and the fact that they can bring the whole system on line in about 12 seconds. It is all controlled by central grid control in Wokingham (a town just outside of Reading). It allows the grid to deal with sudden increases in consumption (such as what occurs during halftime during a soccer match when the whole country goes and plugs in their electric kettles for tea all at the same time). Awesome.

Cemmaes II wind farm (Wales)—A commercial venture of about 14 wind turbines. Awesome machines. Some discussion of the layout of the wind farm, the politics involved, the economics of operating a wind farm, and the conflict with some of the locals (in that they have to see the turbines but get no financial benefit from them.)

Centre for Alternative Technology (Near Machynlleth)—Originally set up to highlight various alternative technologies. Has evolved into a Renewable Energy Disneyland. Some nice displays, but the whole place has recently gotten a connection to the grid and so although they say they are getting energy from renewable sources they really are not.

Dulas Engineering (Machynlleth)—A small renewable energy consultancy in Northern Wales. Tour of their facilities, overview of some of their projects, and a visit to a micro-hydropower site in process of being installed, including some discussion of the engineering and economics of the system.

Ffestiniog pumped storage site (Ffestiniog)—Baby brother to Dinorwig, capable of producing about 300 MW for a few hours.

Moel Moelogan wind farm (Wales)—Set up as a co-op by three Welsh sheep farmers who had endured huge travails and expense to set up a wind farm of three 1.3 Megawatt machines. Each was about 75 meters in diameter with a hub height of 75 meters. Beautiful machines. They were passionate about the ability of wind farms to transform the economy of Wales and to guarantee a livelihood for their children. They hope to set up a second phase of the wind farm in which the local community has a 50% stake. Their ultimate success depends on perseverance, government grants and support, an understanding banker, and steady winds. They have since won an award from the Ashden Trust (a big deal) for their work.

National Railway Museum (York)—History of the development of the railways in Britain. It had a fascinating cut-away of a full-sized steam engine with the driving wheels and valves being run by an electric motor so that you could see the whole thing as an operating machine. Also an excellent talk by a steam engineer explaining all of the various bits of its operation.

Solar Century Ltd., (Waterloo, London) and *BedZED Centre* (Wallington, Surrey)—Solar Century is a consultancy focusing on the integration of PV into buildings. We had a presentation on their work, a tour of a demonstration roof array, and some time for questions. BedZED is a housing development built with recycled or locally-sourced materials. It is designed in an integrated fashion to minimize energy consumption. A wood-fired combined heat and power (CHP) plant provides most of the heat and electricity to the site, with additional electricity provided by a set of photovoltaic arrays.

REFLECTIONS ON THE ENGLISH EDUCATION SYSTEM

Students take a variety of courses until they reach the end of the equivalent of 11th grade, after which they take a set of exams called the GCSE's. If they choose to continue their education they specialize in three (or more) subjects for a year or two, after which they take their "A" levels (equivalent to the last year of high school and the first year of college). Then they do a three-year degree in a particular discipline, and take all of their courses within that discipline. For example, an Engineering student would take all of his math and physics from an Engineering instructor in the Engineering department, and would not take any courses except those related to engineering. So, once a student passes the age of about 16 he never takes anything that we would consider "breadth requirements" or "general education", nor would he experience any field from a point of view other than that of his own discipline. Contrast this with the situation here, where budding young engineers experience Chemistry as seen by chemists, Physics as seen by physicists, Mathematics as seen by mathematicians, and a whole raft of other subjects as seen by specialists in that particular discipline.

A second difference is the grading scale. 70% is considered an A, 60% a B, 50% a C, 40% a D, and less than 40%, a Fail. Outside of a technical field, it is virtually impossible to get above 80% on anything. 90% is what the instructor would give himself if he wrote a fantastic paper. Only God can get 100%. Whatever mark you do get on the paper is it. It is virtually unheard of for a student to question the marks he has received, and instructors are not expected to be able to justify why one paper is a 68% and another is only a 65%

A third difference is in the teaching strategy. In general, courses don't have a textbook. Although there may be a suggested reading list for a course, the students fully expect that the instructor will provide in lecture all of the material that is necessary for the students to know. This expectation is borne out in the final exams, which draw almost exclusively from information presented in lecture. Most instructors hand out detailed lecture notes for a course, upon which students might write comments or annotations. Instructors do not give quizzes, since virtually all of the formal assessment for the course is either based on a few papers or lab projects, or a final exam which one sits for in April or May even though the course may have finished in December.

Instructors may hand out various practice problems to do, but outside of assigned course papers there is no weekly homework set which is collected and marked. Lecturers cannot assume that students have done preparation before class, and don't have any way to "force" students to prepare.

Exams are taken at the end of the Spring ("Lent") term. They are generally similar to the exams given in previous years, all of which are provided by the department and are available from the University Web site. Combined with the grading scheme, this means that students are not held responsible for having mastered the material on an ongoing basis. It is possible for a student to do virtually no work between October and March and then cram for exams in April. Since a passing mark is 40% and the exams are very close to what was done in the past, this encourages students to do very little until a few weeks before exams, and then do the problems from the past exams over and over again until the answers are memorized.

The one exception to this approach that I saw was in a "Foundation" course in the Physics department, designed for students who did not do A levels in Physics (or who attempted the exam but did not pass) and who have decided that they want to do Physics anyway. The students had weekly quizzes and laboratories based on a set of packets that they were to work through, sort of at their own pace. During the Fall term I worked one hour a week in the program at a general study session where the students would come and work through questions they had from the packets or from their lab write-ups. Although the program was considered "innovative" by British standards and attempted to cover a lot of basic material, the execution was not very good. The packets were difficult to read and the explanations contained within were rather convoluted.

One "lesson" from all of this experience is that, in general, students will do just what they perceive is necessary to pass their courses, but not much more. Students much more familiar with the British system than I ignored all of the books and articles from the supplementary reading list unless they related directly to an assignment (a paper or lab write-up). Instructors <u>say</u> that all of this reading is important but don't follow up their words with any actions that would actually convince the students that the reading is important (such as testing on it*). This is not anything new to me*, but it is different to experience it from the student side of things. I found myself wondering why I was doing supplementary reading and searching out extra resources when the instructor wasn't going to test on it. It takes singular determination and interest to read extra material just because in enhances one's understanding, but it is unrealistic to expect students to do "extra" work just because the instructor suggests that they should.

Another lesson had to do with posing assignments. One instructor tried to make the assignments 'realistic" by tying them to a "real situation"—writing a informational briefing for a politician who was going to be making a speech on global energy usage, or designing a solar roof for an aviary at a local wildlife park. I became quite frustrated when I could not find out what the audience for the speech was going to be, or what the wildlife park's purpose was in installing the roof. Ultimately what was really wanted was answers to some questions about energy, and energy calculations for a roof, and it would have been better if that was made clear from the beginning.

EVALUATION—DID I ACCOMPLISH MY GOALS?

With rare exception most of what I studied in my Engineering coursework was a rather straightforward extension of the material we cover at Mt. SAC in the Physics 4 and Chemistry 1 sequence—basic mechanics (in the case of wind and hydro systems), basic electricity and magnetism (power generation technology), basic combustion and thermodynamics (engines and fermentation), basic heat flow (engines, solar thermal collectors, meteorology), and some basic solid state physics (photovoltaics). The pleasures were in seeing familiar ideas applied in new fields. Some of the lab projects I have done could be modified so that our students could do them.

One of the goals of my sabbatical leave was to become a resource of information about Renewable Energy for the Mt. SAC community. I think I've gained enough experience with the hardware and a lot of the engineering and policy questions one faces when dealing with renewable energy sources that I could be useful to Mt. SAC in that regard.

Another goal was to develop projects and activities related to renewable energy that our students could do. It turns out that much of the nuts and bolts of my research project is within the capacity of our students to carry out. Charlie Newman in Chemistry has said that the kinds of tests one carries out to monitor the progress of a anaerobic digester—Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Volatile Fatty Acids (VFA) and some others—are exactly the kinds of tests that students in the new Chemistry Technician program should be able to carry out. Elizabeth Meyer (in Biology) has indicated that she would be interested in mentoring students in research into anaerobic digestion. Larry Redinger has indicated that the farm might benefit from a manure treatment system, and that the state Agricultural District office (now located at Mt. SAC) might be interested in sponsoring the set-up of such a system. I see great potential for useful interdisciplinary research that our students could do.

I've discussed with Craig Webb (in Earth Sciences) the idea of setting up a campus wind survey. It's the kind of thing that GIS students could process the data from. In my ideal world it could lead to a wind turbine being set up on campus. I've also discussed with him the possibility of adding a solarimeter to the campus Weather Station so that we could collect local data on solar irradiation and possibly do research projects with students interested in photovoltaics. It would also give us reasonable data on how economic it would be to heat the Mt. SAC swimming pool using solar thermal collectors.

On a more basic scale it would be instructive to build a small anaerobic digester out of oil drums, fill it with manure at the beginning of the term, let it sit for two months, and then boil water for tea for my students from the gas produced. It's something that might make real for my Physical Science students the chemical processes that we discuss in class, and that elementary school students would think is fascinating.

I have communicated earlier to the Sabbatical and Leaves committee that although I had hoped to have curriculum and activities "ready-to-go" at the start of this school year, I was not going to be able to do this. Some of this is related to resource issues (access to materials, tools, and colleagues), but most of it is simply due to lack of time. The lab part of my research ran into the middle of July, after which I came back to

California with only a few weeks to move back into my house and get materials ready for the Fall. It is my plan to work on these projects over the course of this academic year.

My final goal was to establish a connection between Mt. SAC and the Center for Regenerative Studies at Cal Poly Pomona, where they teach a number of courses related to renewable energy. I have emailed with people at Cal Poly Pomona regarding their new Masters degree program in Regenerative Studies (their term for Renewable Energy). The program starts in Fall 2004, and I'm hoping to be involved in some of the planning and teaching of it. Ultimately I'd like to strengthen the connections between Mt. SAC and the Center for Regenerative Studies.

CONCLUSIONS

In my initial sabbatical proposal I stated that:

The studies I am proposing are about applying the basic ideas that I teach, and how engineers deal with the realities and limitations of real materials. . ..My courses could be richer and more applicable if they included examples from the alternative and renewable energy field. Examples could include engineering cost/benefit analyses; practical applications of thermal transfer and conductivity; control circuits; fluid flow in propeller design; momentum and energy considerations in turbine design; thermodynamic analyses of real engines and cooling systems; and how real generators and alternators are wired, controlled and integrated into the larger electrical grid system.

I would be able to serve the Mt. SAC community as an "in house" source of expertise in the field and to gain new, tangible information that I could use in my classes and share with others.

On a more personal level renewable energy has been one of my long-term passions. Beyond that, it will do me good to experience different models of teaching and learning and to be intimately reminded of what it is to be a student. It would give me a fresh perspective on the classroom environment and the conditions amenable to good learning.

Looking back on my sabbatical experience I can safely say that I've accomplished most of what I set out to do. I've studied the material I set out to. I had it confirmed that most of renewable energy technology is a rather straightforward application of the Physics and Chemistry we teach at Mt. SAC. I've gained experience with some of the hardware and a lot of the engineering and policy questions one faces when dealing with renewable energy sources. I feel like I've learned much that could be useful to the Mt. SAC community. I have come across many ideas and projects that I might integrate into my teaching at Mt. SAC.

As far as being able to draw conclusions goes there are two parts to my experience—the "education" side and the "renewable energy " side. On the education front I've experienced education from the other side of the desk. I've found the experience both exhilarating and sobering—exhilarating in that I was able to throw myself wholesale into my studies, and that I only had to worry about my own learning and not that of 200 other people. I had no committee meetings to attend, no college politics to be embroiled in, no lessons to plan, and no papers to grade. I could throw myself passionately into my work and still get enough sleep! The experience was sobering in that I realized (again) how much of the learning experience has to come from the student, and how for the most part students are not attending classes for the simple love of the subject.

I found that although lectures could be informative, I learned the most when I was working on a well-designed assignment or a well-designed lab that required me to critically analyze a problem. I found that having some bright colleagues made the course a lot more enjoyable. I found group projects (in which my grade depends upon someone else's performance) infuriating. I found that I learned the most from a straightforward, well-presented lecture, but that the lectures that I enjoyed most were the one's where I was forced to think for myself.

One thing that struck me was how much prior knowledge played a role in a student's success in the program. The three "top' students were myself (with close to 20 years experience teaching in the sciences) and two other students in their 30's who graduated from Cambridge with Honors Degrees and had been working engineers for 10-15 years. Other students without such a strong background struggled with the basic material, and had a very different course experience that we had. It is sobering to think that the best determinant of a student's success in my classes may be what he knew before he came in.

One surprise was in how much the field of renewable energy is as much about economics and social issues as it is about engineering and technology. Although the technology of renewable energy is fairly well established, most of the issues are about return on investment and whether people want to look at wind farms rather than "will the technology work?" Whereas in the States it is no big deal to take ten square miles of desert out in the middle of nowhere and set up a wind farm, there is no desert, and no "out in the middle of nowhere" in England. People are very attached to the landscape and there is nowhere that you can place a wind farm without it interrupting somebody's view of the landscape. Another issue has to do with deregulation of the electricity markets. With a lot of excess generating capacity available at the national level, it is difficult to make an economic argument for installing <u>more</u> electricity generation capacity when there are "perfectly functional" coal-burning plants around whose operators want to make a return on their initial capital investment. Many of the renewable energy plants that have come on line have done so with the encouragement of government subsidies, without which the projects would be uncompetitive.

One reason for the difficulties that renewable energy faces is that consumers do not directly pay the "true" cost of energy usage. Taxpayers pay for the effects of polluted air and congested highways, but not at the pump. The cost of maintaining a military presence sufficient to ensure the flow of oil does not show up in the price of gasoline. The cost of building a national nuclear wasted disposal site does not show up on our electric bills.

Another difficulty is that most renewable energy sources are intermittent—that is, they are not necessarily available when you need them. You can't turn up the wind because you have a particularly high demand. Renewable intermittent sources need some kind of back-up or storage that can be called upon when the wind isn't blowing or the sun isn't shining. The most "renewable" backup energy source presently available is a "pumped storage" system, where water is pumped up to a high reservoir when energy is cheap and plentiful, and then run through a turbine to a reservoir at a lower level during periods of high demand (I visited two such facilities in Wales).

Our present energy supply is cheap, available, and easy. Increases in demand can be met almost immediately (by firing up more gas-turbines, for example). Renewable energy sources in general do not have the kid of cheap storage that one gets with fossil fuels in the fuels themselves. With such a well-established infrastructure and distribution network it is extremely difficult to wean people away from fossil fuels to a renewable-based system. Although wind farms are presently competitive with fossil-fuel and nuclear based generation on a cost-per-kilowatt-hour basis, most other forms will become widespread only when government takes clear and decisive steps in that direction, or fossil fuels become so scarce that there are no other alternatives left to us.

The whole experience of my sabbatical is still relatively new and fresh. Although the immediate conclusions are evident, I suspect that there are deeper and subtler lessons that will emerge with time. I have come away with a much better understanding of renewable energy and how it fits into the total energy generation scheme; with many ideas about incorporating this understanding into my courses; and a better feel for what education looks like from the student side of the desk. It is my hope that all of this will conspire to deepen my understanding of energy and students and to enrich my teaching and their learning.

ASSIGNMENTS

CEMRE1: Briefing for a politician on global energy use

Background

For this assignment, regard yourself as a researcher for a politician who has to make a speech about global energy use. Your task is to provide clear, brief, factual information on a number of points, but not to write the speech!

Specifications and assessment

Make short written responses to the following points, each backed up with a graph or table. The responses should explain how you use data and the conclusions which you draw from it. At the end of each response you may want to add a few relevant (and referenced) comments which you think would be useful in developing the speech.

We suggest that you use the BP Statistical Review of World Energy 2002 (downloadable from www.bp.com) as the main data source, but check other sources as well.

1. "There has been a continuous, gradual increase in the use of commercial energy in all regions of the world over the past 10 years."
2. "Oil is the major source of energy in nearly all regions and countries."
3. "There should be no concern about the future supplies of fossil fuels because proved reserves and reserves/production ratios are higher than they were 10 years ago."
4. "Coal is a cheaper energy source than natural gas, both for direct use and for electricity generation. Coal would be cheaper even with a carbon tax of US$5 per tonne of CO_2."
5. "Current trends suggest that coal will remain cheaper than natural gas for the next ten years"

The report should have:

- An Abstract at the beginning which summarises the main points from each section (maximum 200 words)
- Responses to each of the points above (maximum 2 sides of A4 per response, including tables or graphs)
- References (see below on reference lists and use of references in the text)

The report will be assessed for how you use the data to make your responses, with emphasis on a clear, brief, informative presentation.

THE UNIVERSITY OF READING
SCHOOL OF CONSTRUCTION MANAGEMENT AND ENGINEERING

MSC/PGD IN RENEWABLE ENERGY AND THE ENVIRONMENT 2002-2003

ASSESSED COURSEWORK

Name: Phillip R. Wolf **Date submitted: 28 Oct 2002**

Title of assignment: Briefing for a Politician on Global Energy Use

Declaration of originality

I certify that this is my own work, and it has not previously been submitted for any assessed qualification. I certify that the use of material from other sources had been properly and fully acknowledged in the text. I understand that the normal consequences of cheating in any element of an examination, if proven and in the absence of mitigating circumstances, is that the Examiners' Meeting be directed to fail the candidate in the examination as a whole.

Signed: ....

For staff use:

Date received:

Date marked:

Mark (%): nb: A*>80%, A>70%, B>60%, C>50%, D>40%,
F<40%

Signed:

Comments:

Hey Boss:

Here are the background briefing notes you asked me to prepare for your upcoming Energy speech.

In terms of GLOBAL supply of oil and natural gas, the discovery of new economically exploitable reserves is outpacing global production, so it appears that the world is not in any immediate danger of running out of these two fuels. Unfortunately, over 2/3 of the world's supply of these two fuels lies in the Middle East and the former Soviet Union, and at the national level we are becoming increasingly dependent on imported oil and gas to maintain our national economy. This need to ensure steady imports of energy resources will undoubtably force us to make difficult national policy decisions that may run counter to our stated national mission of encouraging democracy in other nations. Coal (which we and much of the rest of the world have in abundance) will continue to make a large contribution to base national electricity generation. Because coal plants are not running anywhere near full capacity on average, much of the increases in base electrical generation could be borne by existing coal plants, but economics favors meeting peak electrical demands by use of high efficiency natural gas turbines.

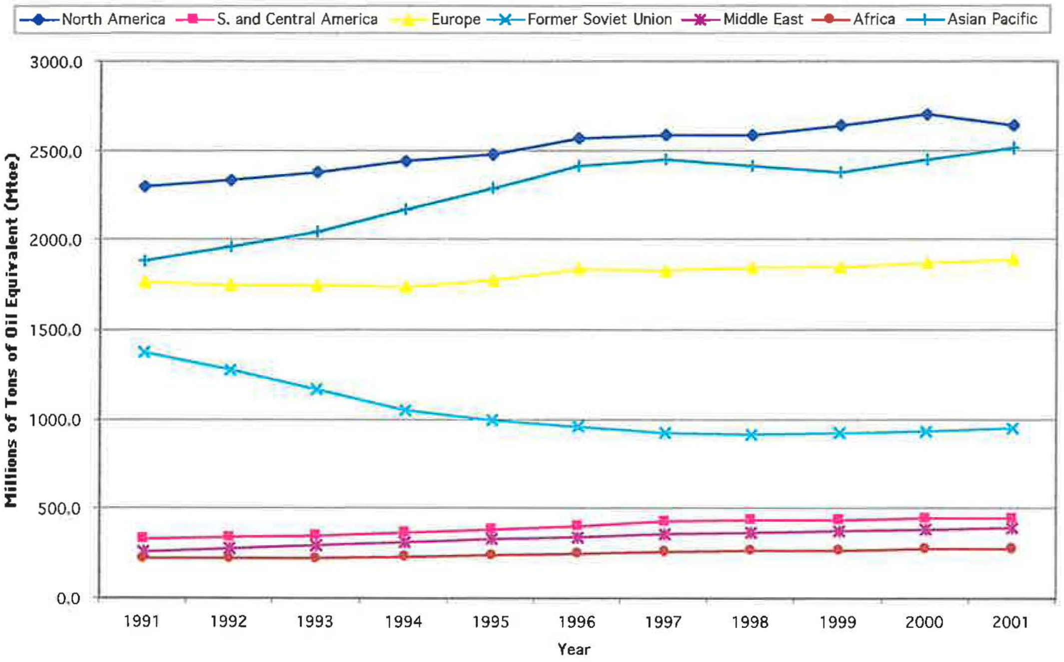
Good luck on the speech!

--Phil

"There has been a continuous, gradual increase in use of commercial energy in all regions of the world over the past ten years"

The graph below shows commercial energy consumption by region from 1991 to 2001.

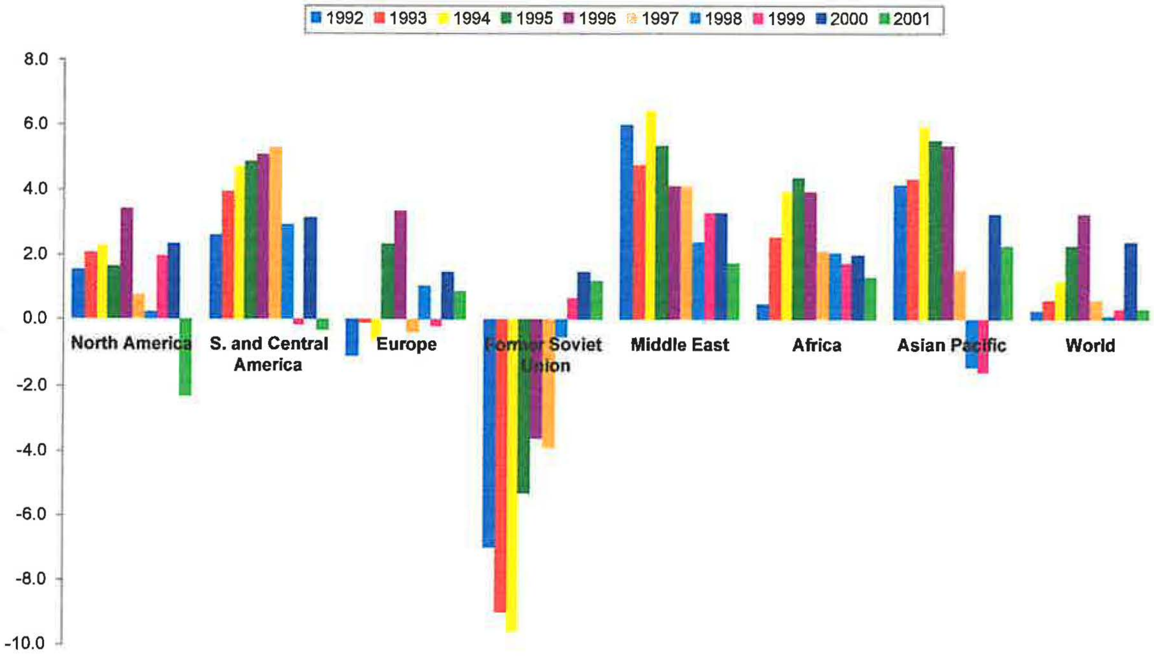
Consumption of Commercial Energy by Region, 1991-2001 (BP 2002)



Energy consumption has grown for all regions EXCEPT the former Soviet Union since 1991.

The chart below shows the year-to-year changes in each region relative to what it consumed the previous year.

Percent change in energy consumption for different regions of the world compared to the PREVIOUS year 1991-2001 (BP 2002)



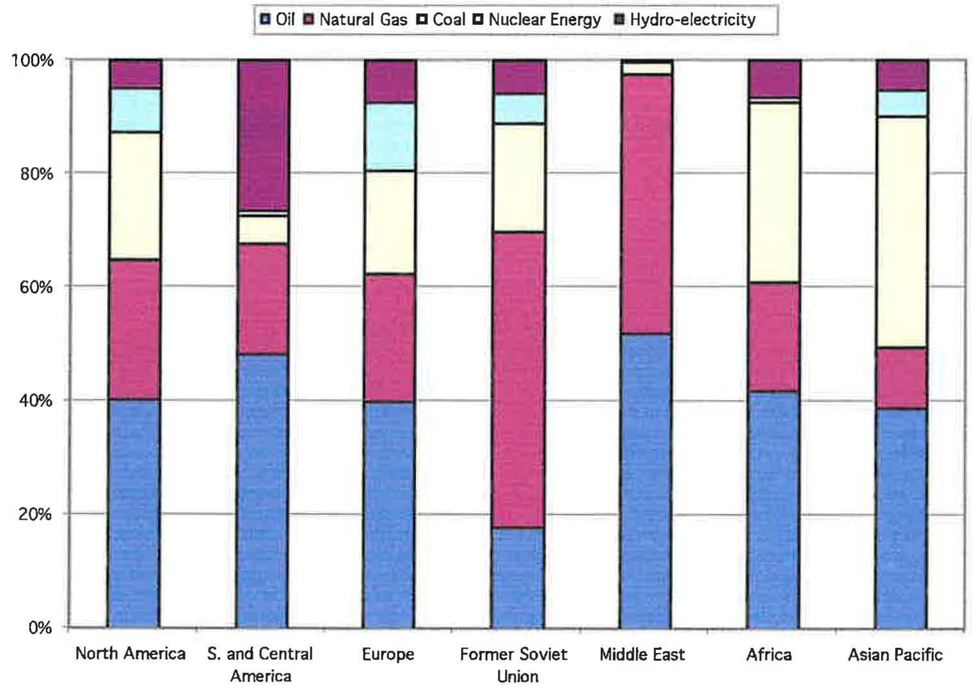
If we look at year to year percentage changes in energy it is evident that the overall worldwide increase masks regional and year-to-year volatility in energy consumption. For example, in 1998 and 1999 consumption in the Asian Pacific region dropped, which correlates well with the Asian Pacific financial crisis of the period. For North America consumption in 2001 was actually LOWER than that of 2000, correlating with a slowing economy and the immediate aftereffects of the September 11 bombing of the World Trade Center.

As an aside, consumption in Africa increased by 33% while that in North America increased by around 15%. In absolute terms a 10% decrease in energy consumption in North America (say by increasing energy efficiency) would consumption-wise balance out a doubling in the commercial energy use in Africa. If one is concerned about CO_2 emissions from the developing world, a relatively small reduction in CO_2 output in North America (primarily by the US) could more than make up for relatively large increases in CO_2 output in Africa.

Oil is the major source of energy in nearly all regions and countries.

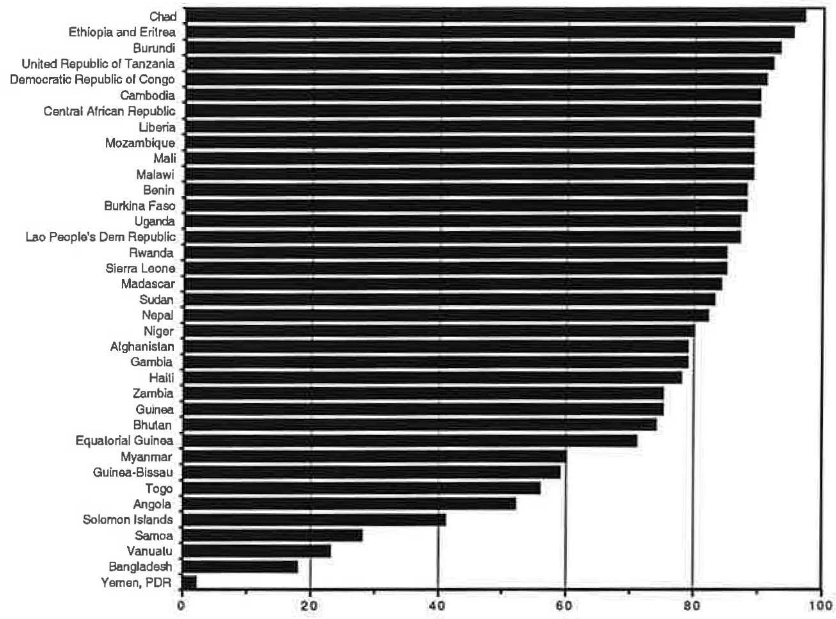
Below is a chart showing what percentage of the COMMERCIAL energy used in a region comes from what sources.

Contribution of Each Fuel to Commercial Energy Production by Region (Mtoe),2001 (BP 2002)



A more accurate statement would be that oil is _a_ major source of _commercial_ energy in all regions in the world, but with the exception of the Middle East (where it provides 52% of the commercial energy consumed), in _no_ region does oil provide the majority of energy used. In fact, in both the former Soviet Union and in the Asian Pacific regions coal accounts for a larger share of the total commercial energy produced than does oil.

What the above chart totally ignores is that in many developing countries biomass (wood, agricultural waste, etc.) provides a large portion of total energy use. This is shown on the cart below (data from UNCTAD, 2002).

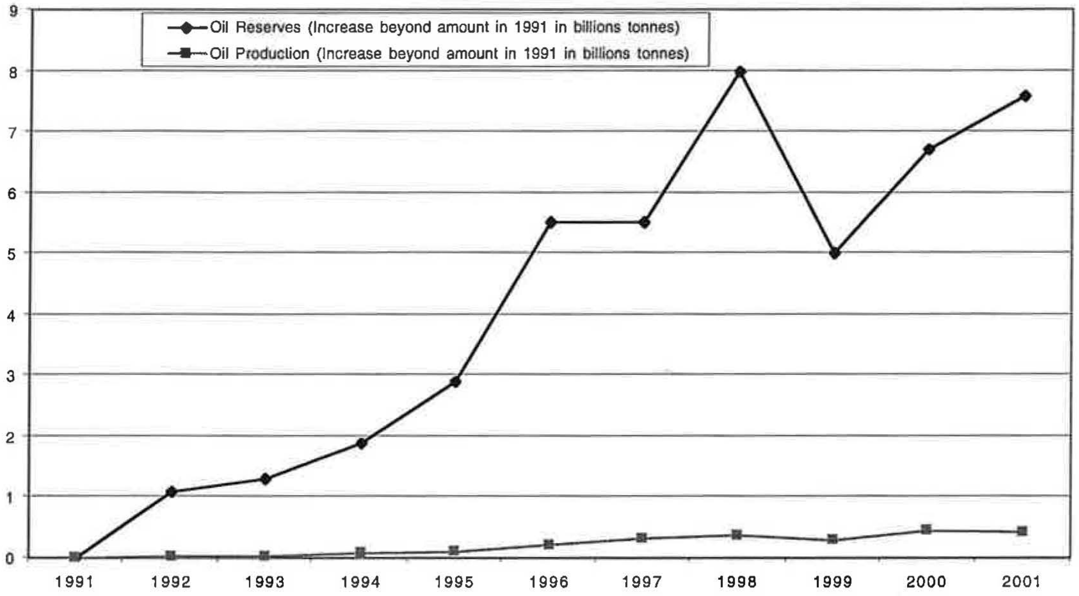

Percent of Total Energy consumption coming from Fuelwood, Charcoal, and Bagasse in 1998 (UNCTAD, 2002)

Where people have no connection to an electrical grid and no automobiles their primary uses of energy (mainly for cooking and heating) are in forms that are not traded on international markets and will NOT show up on any worldwide commercial energy statistics.

There should be no concern about the future supplies of fossil fuels because proved reserves and reserves/production ratios are higher than they were 10 years ago.

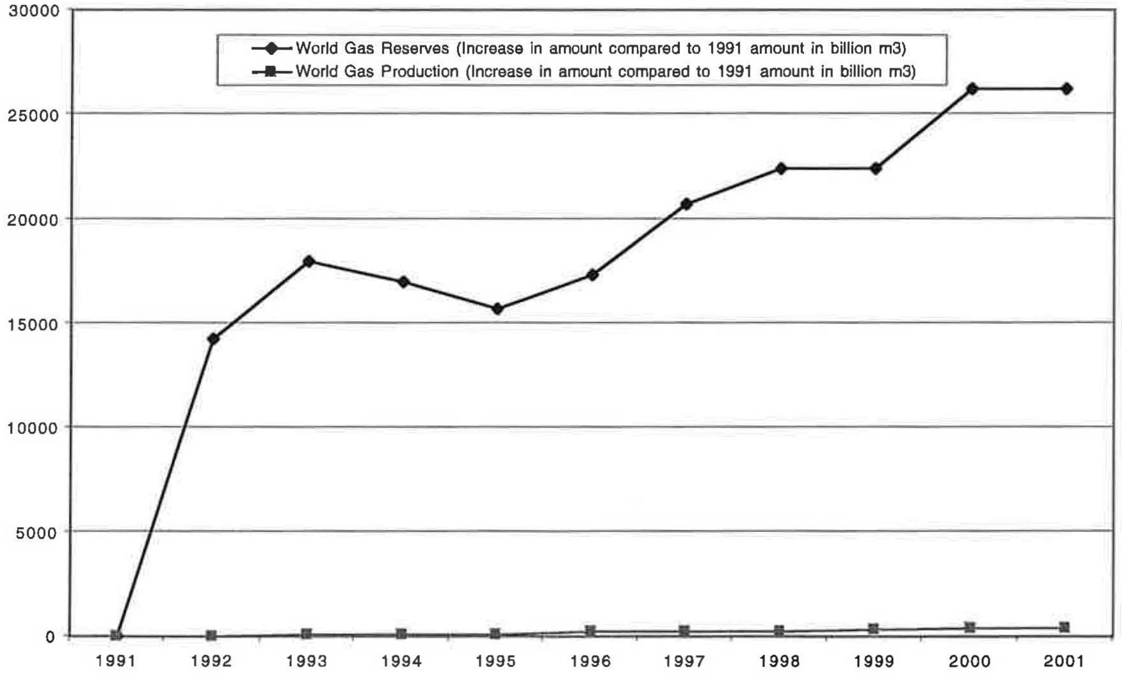
The graph below shows the changes in world reserves and production of oil since 1991 (BP, 1992-2002).

Change in World oil reserves and production (Billions of tonnes of oil) relative to 1991 amount (BP 1992-2002)

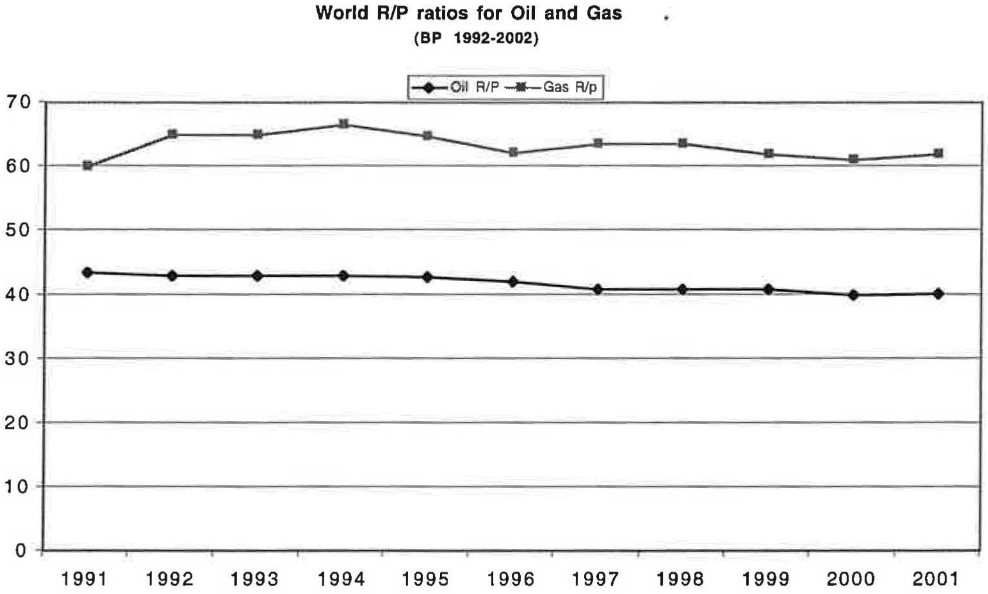


This next graph shows the change in world natural gas reserves and production compared to 1991 amounts (BP 1992-2002).

Change in World natural gas reserves and production (Billions of cubic meters) relative to 1991 amount (BP 1992-2002)



The next graph shows the world reserves-to-production ratios for oil and gas for the period 1991-2001 (BP 1992-2002)



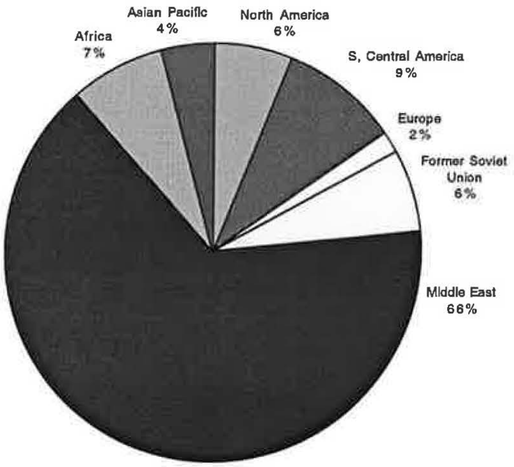
The definition of proved reserves is generally taken to be "those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoir under existing economic and operating conditions". (BP 2001) World proved reserves of oil have climbed by an average of 760 million tonnes of oil per year (an average increase of about 0,5% per year) while world production of oil has increased by an average of approximately 40 million tonnes per year (an average increase of approximately 1.1% per year). The fact that world reserves have increased in absolute terms DESPITE increases in oil extraction indicates that at present we are discovering more new economically exploitable oil resources in absolute terms each year than we are taking out of the ground. Since production is climbing at a greater rate *percentage-wise* than are the reserves, it makes sense that the reserves-to-production ratio has decreased.

The situation is similar for natural gas. In absolute terms reserves are growing faster than production is growing. Percentage-wise natural gas reserves have increased by 17% in the past ten years, production has increased by 21%, and the R-P ratio has stayed essentially unchanged.

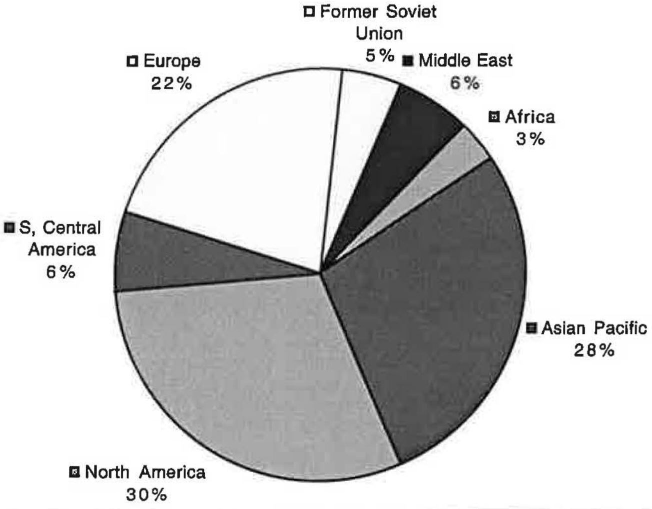
In 1966 the R/P ratio for oil was 31 (BP 1993), meaning that at that time, known reserves were sufficient to support comtemporary production until 1997. People could misuse the R/P ratio and state that "the world is going to run out of oil by 1997". The R/P ratio is more complicated than that. Such a simplistic view sees the reserves and production as fixed quantities. As is the case with oil, reserves have grown in an absolute sense faster than production, but production has grown in a relative sense faster than reserves, so we have more oil reserves than we had 35 years ago yet the R/P ratio has gone down. If prices of oil and gas rise or the technology of extracting oil and gas improves, resources which are not presently exploitable economically move into the "profitable to extract" zone, and reserves increase again even though no new oil has been discovered. If production decreases R/P ratios increase even if people have less oil to burn and are paying more for it.

The charts on the next page show the percentage of worldwide proved fossil fuel reserves per region and worldwide fossil fuel consumption per region (data from BP 2002).

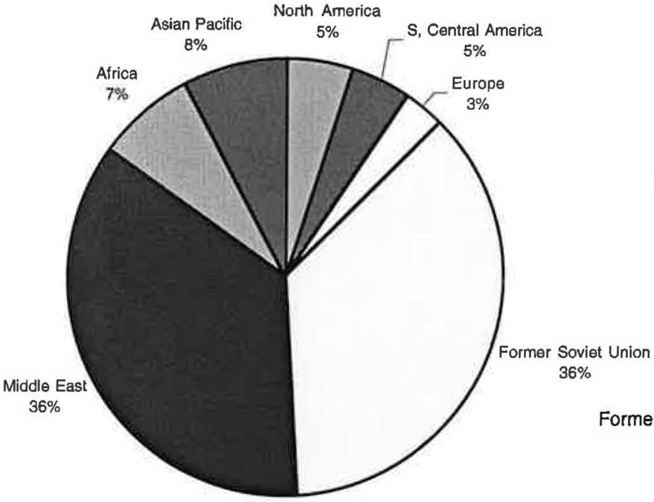
Proved Oil Reserves in 2001 as a percentage of the world total by region (BP 2002)



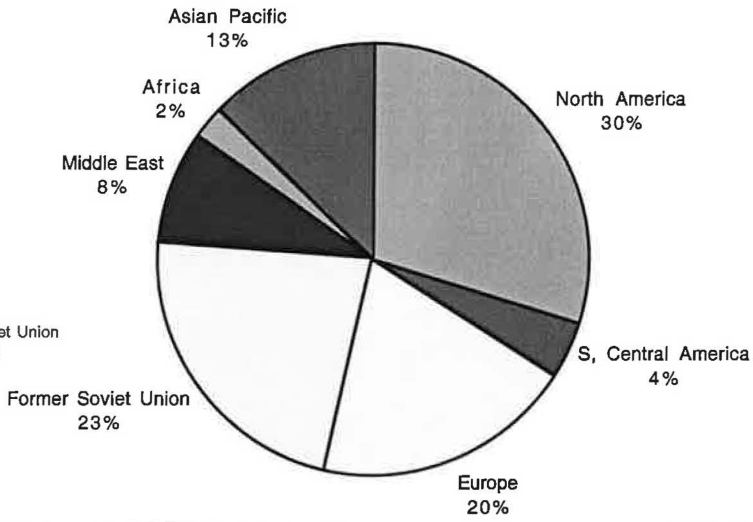
Oil Consumption in 2001 as a percentage of the world total by region (BP 2002)



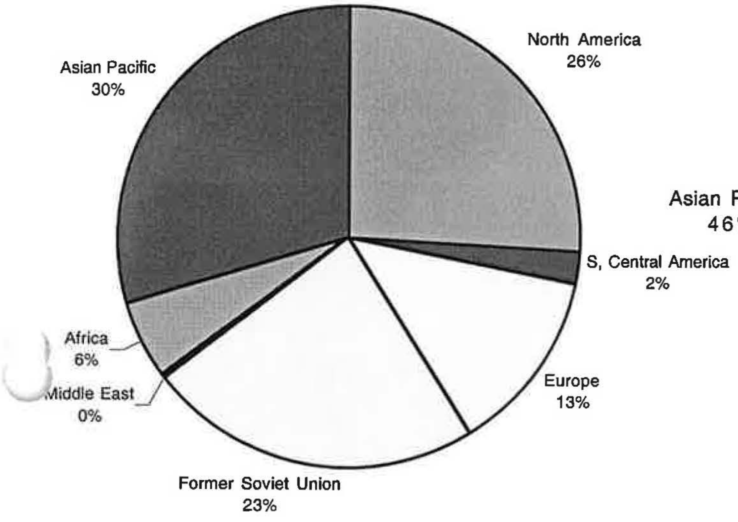
Proved Natural Gas Reserves in 2001 as a percentage of the world total by region (BP 2002)



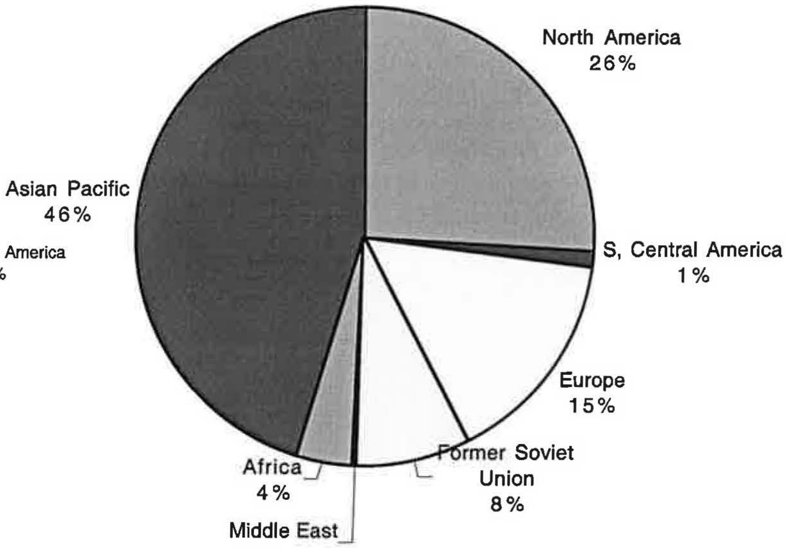
Natural Gas Consumption in 2001 as a percentage of the world total by region (BP 2002)



Proved Coal Reserves in 2001 as a percentage of world total by region (BP 2002)



Coal Consumption in 2001 as a percentage of the world total by region (BP 2002)



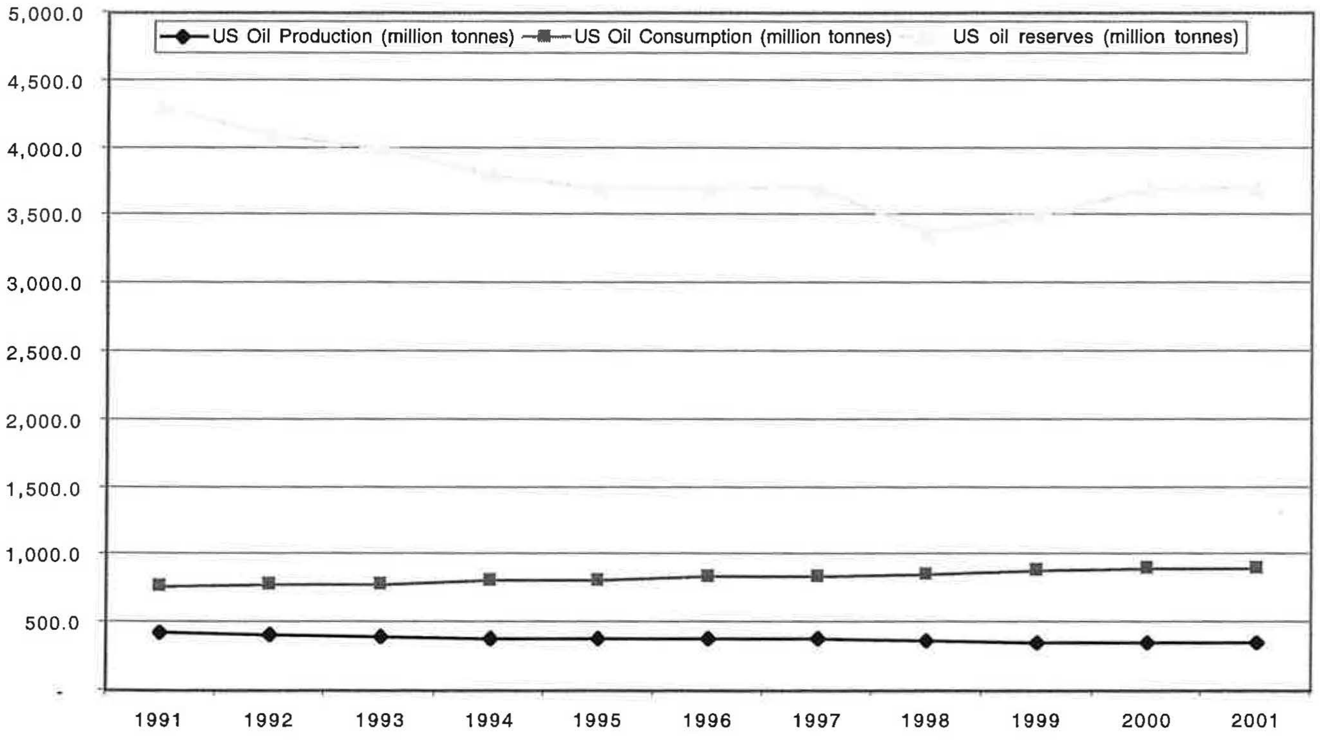
There are some very interesting patterns in these pie charts:

- OIL: the Middle East has almost two-thirds of the world oil reserves. Europe, North America and the Asian Pacific region together have 12% or the world oil reserves, but consume 70% of the world's oil.
- NATURAL GAS: The Middle East and the former Soviet Union control almost three-fourths of the world's natural gas reserves, Europe, North America, and the Asian Pacific region together control 16% of the world's natural gas reserves but account for 63% of the world's natural gas consumption.
- COAL: This is the ONE fossil fuel that Europe and North America consume more or less is proportion to their reserves. It is also the one fossil fuel for which each of these regions has over a150-year supply at present rates of fuel production (BP 2002).

If one looks at the global picture and assumes that oil-and-gas producing countries' and oil-and-gas consuming countries' interests will always coincide and that the two groups will always get along in harmony, there is no cause for concern about the huge disparities in terms of who has the oil and gas resources and who is consuming them.

If however you do not believe that the two groups' interests will always be aligned, the picture looks rather grim. Consider the situation for the United States (see chart below. Data from BP 1992-2002)

US Oil Production, Consumption, and Reserves of Oil (millions of tonnes), 1991-2001



US oil production has dropped by 17% in the last ten years. Its oil consumption has increased by 17% in the same period, and its oil reserves have decreased by 14%. It has gone from importing 44.8% of its oil in 1991 to 60.7% of its oil in 2001.

Since US oil production has percentage-wise dropped faster than its reserves, the US reserves-to-production ratio has actually INCREASED!

There are two big lessons to take from this:

- Again, an increasing R/P ratio is not necessarily good, and a decreasing R/P ratio is not necessarily bad. By itself the R/P ratio doesn't tell you much.
- Secondly, just because the world *as a whole* does not look like it will run out of oil or gas in the near future does NOT mean that *the individual countries* of the world can sit tidy and not worry about it.

The Middle East presently controls 65.3% of the world's oil reserves (BP 2002) and together with the former Soviet Union controls 72.3% of the world's proved gas reserves (BP 2002). Future gas or oil finds in, say, China may do great things for the world supply, but do nothing for the US energy security. To the extent that we maintain our dependence on nations whose political agenda does not always run in parallel with our own, we decrease our ability to make political decisions more in line with our political ideals and less influenced by the political realities of energy.

Coal is a cheaper energy source than natural gas, both for direct use and for electricity generation. Coal would be cheaper even with a carbon tax of US$5/tonne.

Current trends suggest that coal will remain cheaper than natural gas for the next ten years.

For 2001 we have the following data*:

	US Market Fuel cost♦	Fuel cost per $\text{kWh}_{\text{thermal}}$	Fuel cost per $\text{kWh}_{\text{electric}}$ ♉	Grams CO_2 produced per $\text{kWh}_{\text{electicity}}$
Coal	$27.68/tonne✝	0.402¢	1.20¢	1040
Coal with $5/tonne tax	$32.68/tonne	0.47¢	1.42¢	1040
Natural Gas	$4.07/million Btu	1.39¢	2.39¢	393

*The detailed calculations are carried out in the Appendix

♦(BP 2002 for US market)

✝Mix of 53.6% anthracite and bituminous coal, and 46.4% sub-bituminous coal and lignite (US production mix, 2001—BP 2002)

♉Assumes a 33.3% efficiency for the coal plant and 58% efficiency for the gas plant

Coal is a cheaper energy source than natural gas if the only factor one is considering is fuel costs. For the operation of EXISTING electricity or heating plants, coal is less expensive. A study at the Kennedy school of government at Harvard University (Harvard, 2000) looks at the actual costs of running coal and gas power plants. It says:

> "In 1996 the incremental cost of generating power from coal-fired plants . . . averaged around 1.6 cents per kWh, while the cost of building a new gas facility was approximately 3.1 cents. Given such a wide price differential, it is not surprising that consumers and producers alike are not anxious to switch to gas."

Installing new pollution control systems could raise the price of coal generated power to about 2.6¢/kWh (Harvard, 2000) but this would still make coal the cheaper fuel.

Almost 90% of the coal fired plants in the Midwest of the United States are over 25 years old (Harvard, 2000). Their initial capital costs have probably already been recovered by the utilities that own them. Thus, economics favors using existing coal plants over replacing them with new gas-fired plants.

The situation can look much different, however, if one is comparing the cost of installing NEW coal-fired generators with the cost of NEW gas-fired turbines in response to a steady increase in electrical demand. Due to economies of scale a typical coal fired plant has to produce about 1000 MW, while a typical gas turbine might produce100 MW. If you are anticipating a growth in electricity demand of 200 MW per year, that would mean either building one 1000 MW coal fired plant every five years or one 100 MW gas-fired plant every six months. When you build the coal plant you have very high initial capital costs (upon which you are paying interest) even though you are not earning money for selling 1000MW of electricity (since it will be five years until you are actually operating at full capacity). If instead you build a smaller gas-fired plant the initial capital costs are lower (even if the initial cost per installed kWh were higher) AND you are selling the full output of the gas plant right away. On top of that, there is a learning curve that tends to lower the cost for each subsequent gas-fired plant installation (ideas for this paragraph derived from MIT, 2001).

Beyond considering the costs of NEW plants, the present coal-fired plants do not operate at full capacity. In 1996 the coal plants in the Midwest were only operating at an average of 48.2% of capacity.

> "If further increases in demand were consistent throughout the day, most parts of the Midwest would not have to build new capacity for quite some time. They could simply increase the use of their existing coal fleet. However, increases in demands during peak load periods should increase the demand for peaking plants." (Harvard, 2000).

In other words, it doesn't make sense to build more large coal plants when they would require a huge initial capital investment and sit idle most of the time.

Finally, natural gas fired turbines can be set up in a relatively small area in a matter of a few months; the energy contents of the fuel is consistent (unlike the variations you experience with coal); and the pollution control equipment you need to manage natural gas plant emissions relative to coal plant emissions is miniscule (Vahdati, 2002).

Concerning a "carbon tax" the Harvard study

> "attempts to determine the percentage of existing coal capacity that will become less competitive than new gas-fired capacity at different carbon costs. It looks at several scenarios and projects that more than 60 percent of the region's coal capacity will be uneconomic compared to gas at a carbon penalty between $22 per ton and $142 per ton." (Harvard, 2000)

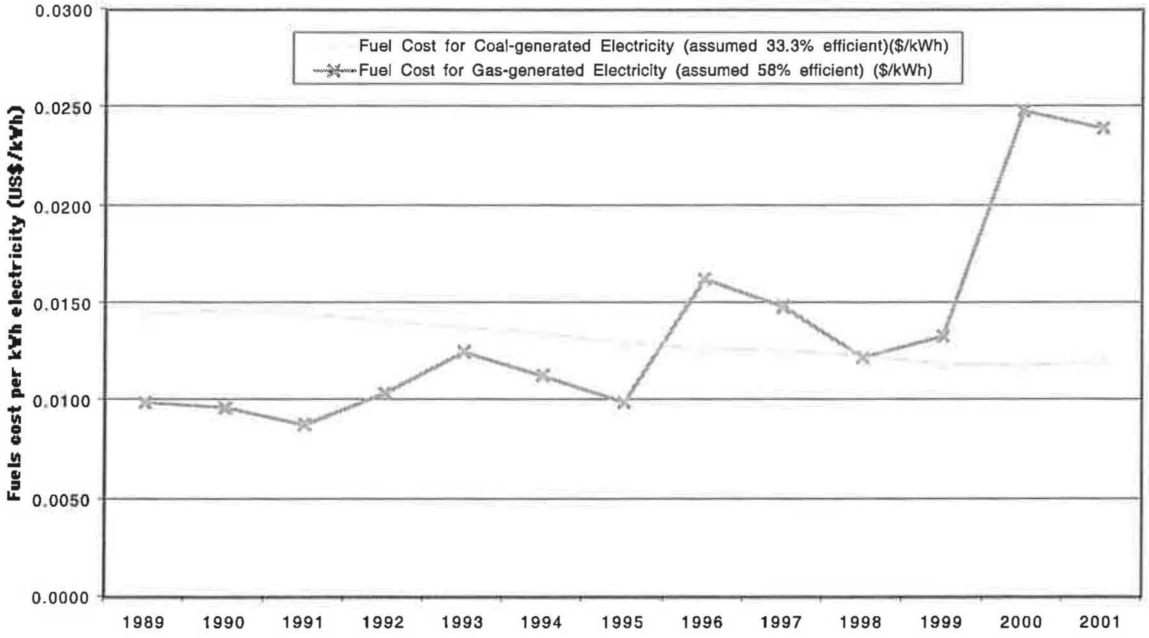
Certainly a carbon tax of $5 per ton will have very little effect on the economics of existing coal vs. new gas electricity generation capacity.

The lesson here seems to be:

- Coal-fired plants that are already built can be run cheaply, be made to run cleanly and still be economically competitive with natural gas.
- At present economies of scale it is cheaper to meet incrementally increasing energy requirements or peak energy demands by building smaller natural gas-fired plants as needed rather than building large coal-fired plants.
- If smaller coal-fired plants could be economically constructed at the same size and cost as present gas-fired turbines, and run economically as "peaking plants" in the same way that natural gas can be now, coal could be economically competitive with natural gas. The U.S. Department of Energy is presently running studies on the feasibility of building high efficiency (up to 60%) coal-fired gas turbines that work on the same principles as present gas turbines. (NETL, 2001)

Below is the cost of coal and natural gas for the US in US$ per generated kWh:

U.S. Fuel Cost for Coal and Natural Gas Produced Electricity (US$/kWh) (BP 2001)



It is rather clear that the trend for the US has been for coal prices to decrease, and for natural gas prices to increase. This trend will probably continue, at least for the US, in the US is a net coal exporter and has hundreds of years of coal reserves at present production levels (BP 2001) so coal will not be a "scarce" resource for the US. Since the US is a net importer of natural gas, as demand for natural gas increases worldwide prices for natural gas should be expected to continue rising.

You may want to make a distinction between "cost" and "price". The marke*t cost* of coal does not include cost of ameliorating the devastation wrought by strip mining or the effects of ash and radioactive materials released from even the cleanest coal-fired plants. Nor does it include the effects of the much larger amounts of CO_2 released by coal burning plants per kWh as compared to natural gas burning plants (Calculations for Coal vs. Natural Gas Cost, appendix). The real price of using coal is undoubtably higher than its market price.

APPENDIX--Calculations for Coal vs. Natural Gas Cost:

Assume:

- Coal burning ratio (Anthracite and bitumen)/(sub-bituminous coal + lignite) in US is the same as its production ratio
- Anthracite and bituminous coals gives approx. 13000 Btu/lb (Schobert 1987)
- Sub-bituminous and lignite coals give approx. 8000 Btu/lb (Schobert 1987)
- U.S. Anthracite and bituminous coal production in 2001 was 134 billion tonnes (BP 2002)
- U.S. Sub-bituminous and lignite coal production in 2001 was 116 billion tonnes (BP 2002)
- Average thermal energy output per tonne of coal is a weighted average of the two values: [(134 x 13000) + (116 x 8000)]/(134 + 116) = 10680 Btu/lb
- kWh_{th} per tonne of coal = (10680 Btu/lb) x (2200 lb/kWh) x (1 kWh/3412 Btu)
- = 6886 kWh_{th} /tonne coal
- 2001 US cost for coal = \$27.68/tonne x 1 tonne/6886 kWh_{th} = 0.402¢/ kWh_{th}.
- Fuel cost of coal generated electricity at 33.3% electrical efficiency (Schobert 1987)= (0.402¢/ kWh_{th}.)/0.333 = 1.20¢/ kWh_e.
- A \$5/tonne tax on coal would raise its cost by (5/27.68) x 100 = 18.1% so coal generated electricity would still cost only 1.18 x (1.20¢/ kWh_e) = 1.42¢/ kWh_e.
- A 600 MW coal fired power plant running at 41% efficiency would produce 4.44 million tonnes of CO_2 equivalent green house gases (GHG) per year (NREL, 2001). For a plant running at 33.3% efficiency, this would be the GHG output for a 600 MW x (33.3/41) = 487 MW power plant. To calculate the CO_2 equivalent output per kWh_e we'd do (4.44 x 10^6 tonnes CO_2/year)/ [(487 x 10^3 kW) x (365.25 x 24 hours/year)] = 1040 g CO_2/kWh_e.

- Natural Gas cost in the US for 2001 was \$4.07/10^6 Btu (BP 2001)
- 2001 US cost per kWh_{th} is (\$4.07/10^6 Btu) x (3412 Btu/kWh_{th}) = 1.389¢/kWh_{th}
- Fuel cost of Natural gas generated electricity at 58% thermal efficiency (Undrum et al, 2000) = (1.389¢/kWh_{th})/0.58 = 2.394¢/kWh_e
- Amount of CO_2 produced from a 58% efficient natural gas fired electrical generator is 393 grams CO_2/kWh_e. (Undrum et al, 2000)

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Vahdati, 2002

Conversation with Dr. Maria M. Vahdati, Professor of Engineering, University of Reading, Whiteknights, Reading, England. October 2002

CEMRE2: Do we need nuclear power?

Background

"Physics World", the magazine of the Institute of Physics, published an interesting article in June 2001, on whether or not the world needs nuclear power. (http://physicsweb.org/article/world/14/6/2/1) The article was written by two people, one for and one against nuclear power. They started with a statement of "common ground" and then presented arguments for and against. During the lectures, we will discuss which are the most critical issues raised in this article.

Specification and assessment

Your task is to make sense of the exchange by:

1. Making clear whether the critical issues are factual (ie. could in principle be verified), or a matter of personal opinion;
2. Cross-checking the factual issues with reference material and commenting: it is important that this is done quantitatively wherever possible;
3. Commenting on whether the writer has addressed or avoided the points made by the other writer;
4. Noting any additional points which you would have made on either side of the argument

The report should have:

- An Abstract at the beginning which summarises the main findings (maximum 200 words)
- Sections covering the four tasks above (maximum 8 sides of A4)
- Conclusions
- References

You will be assessed on how well you check the issues, on the supporting information which you find and how you use it.

Do we need nuclear power?

With rising fuel costs, concerns about global warming and the growing demand from the developing world for energy, the burning question is whether the world needs nuclear power. **Peter Hodgson**, a nuclear physicist, says yes. **Dennis Anderson**, an economist, says that we should first explore the possibilities of renewables and other forms of energy

Joint introduction


Peter Hodgson (left) and Dennis Anderson (right)

Our civilization and our standard of living depend on an adequate supply of energy. Without energy, we would not be able to heat our homes or cook our food. Long-distance travel and communication would become impossible, and our factories could no longer produce the goods that we need.

A century ago the world's energy came almost wholly from coal and "traditional" sources, such as wood, crop residues and animal dung. These are still major sources of energy, particularly in developing countries, where 2 billion people are without access to, or cannot afford, modern energy forms. Wood and dung are estimated to provide an amount of energy equivalent to 1 billion tonnes of oil each year; it is sobering to realize that this is 1.6 times more energy than is provided worldwide by nuclear power, and is about the same as the amount of energy provided by coal in Europe and the US combined (see table on page 17).

During the 20th century, the world's commercial output and population increased more rapidly than ever before, as did energy consumption, which rose more than tenfold, with a major shift towards oil and gas fuels, and to hydroelectricity and nuclear power. Most of the growth was in industrial nations, where the per capita consumption of commercial fuels is about 10 times that in the developing world.

Energy markets in the industrial countries are maturing, and may even peak and decline with continued improvements in energy efficiency. The last two centuries saw energy efficiency increase enormously – in motive power, electricity generation, lighting, in the use and conservation of heat, and in an array of other applications. There is no evidence that further gains will not be achieved in the future – for example through the use of fuel cells for transport, which could lead to a two- or threefold increase in fuel efficiency relative to that of the internal combustion engine, and through distributed sources of combined heat and power.

The situation is different in developing countries, where billions of people have hardly enough energy to survive, let alone enough to increase their living standards. If they are to achieve prosperity, their energy needs – which are doubling every 15 years – will have to be met. Moreover, their population will soon be 7–10 times greater than that of the industrial world, and (with the sad exception of several African countries) economic growth is much higher than it is for industrial nations.

If we assume that, after allowing for gains in energy efficiency, the developing world eventually uses only half of the energy per capita consumed by industrial nations today, then the world's energy consumption will still rise more than threefold. Developing nations will therefore need about 5×10^6 MW of new electricity-generating capacity in the coming decades, compared with the 1×10^6 MW they have today and the 2×10^6 MW in the industrial nations. (Electricity generation accounts for only about one-fifth of our final energy consumption – the rest mainly being for transport and heating.)

Our common ground in debating the question "Do we need nuclear power?" is therefore the fact that the world is likely to need yet more energy, despite the immense amount of energy consumed today. The environmental problems associated with energy production and use will also need to be addressed, including local and regional pollution, and the much-discussed problem of global warming.

Peter Hodgson and Dennis Anderson

YES

Finding ways of satisfying our energy needs is such an urgent problem that we must consider all possible sources, and evaluate them as objectively as possible, *writes Peter Hodgson*. In doing so, it is useful to apply the following criteria: capacity, cost, safety, reliability and environmental effects. No source can satisfy all our energy needs, and although there are several small-scale energy sources, such as solar panels for satellites, we must focus on the major sources.

Wood was a major energy source in ancient times, and is still extensively used in developing countries. It is, however, impractical as a major energy source in developed countries as it occupies much land and adds to atmospheric pollution. Oil, meanwhile, is fast running out and is needed by the petrochemical industry. It is wasteful to burn it, which also adds to pollution. The same applies to natural gas.

Hydropower is an important source of energy, particularly as it is renewable and does not pollute the atmosphere. However, it uses up valuable land and, in any case, the number of suitable rivers is limited. It is unlikely that hydropower will provide for more than about 8% of our energy needs. Tidal power is even more limited by geographical considerations.

The remaining sources – such as wind, solar and geothermal – account for only a few per cent of the global energy consumption. In addition, some of them are unreliable (wind and solar) or intermittent (tidal) and relatively costly. And although the energy in sunshine, wind, waves and tides is enough to satisfy our needs millions of times over, the difficulty is in harnessing these sources in a usable form. Despite continued efforts, wind and solar sources contribute less than 0.5% of our energy production (see table on page 17).

This leaves only coal as a major source of energy for at least a few centuries. However, a typical coal-fired power station emits some 11 million tonnes of carbon dioxide each year, as well as 1 million tonnes of ash, 500 000 tonnes of gypsum, 29 000 tonnes of nitrous oxide, 21 000 tonnes of sludge, 16 000 tonnes of sulphur dioxide, 1000 tonnes of dust and smaller amounts of other chemicals, such as calcium, potassium, titanium and arsenic. To produce 1 gigawatt-year of electricity requires about 3.5 million tonnes of coal – and this contains over

5 tonnes of uranium. Most of the by-products are caught by filters, but a few thousand tonnes of ash escape, carrying with it a corresponding fraction of the uranium. This accounts for the radioactivity emitted by coal-fired power stations. All the gaseous waste is poured into the air we breathe, and damages our health. To continue to rely on coal could lead to widespread environmental damage and unpredictable climate change.

Can nuclear provide the energy we need? It already generates about 20% of the world's electricity, including 50% in Western Europe and 80% in France. It is reliable, having high "load factors" – typically more than 90% – with nearly all of the remaining time spent on planned maintenance. Its long-term costs are similar to those of coal. It has little harmful effect on the environment and it is safer than all other sources, apart from natural gas.

Nuclear power only differs from other energy sources in that it emits nuclear radiations. The interior of a nuclear reactor is highly radioactive, and the spent fuel has to be removed periodically for reprocessing. However, the techniques for doing this are well developed and can be carried out safely. The relatively small volumes of highly radioactive residues (nuclear waste) are first stored above ground for several decades to allow the short-lived isotopes to decay, the rest being fused into a insoluble ceramic blocks, encased in stainless-steel containers and buried far below ground in a stable geological formation.

Nuclear reactors can also be improved. While current "thermal reactors" burn only uranium-235, which accounts for just 0.7% of natural uranium, so-called "fast reactors" can burn the remaining 99.3% of the uranium. One reason why fast reactors are not used is because they are more difficult to build, but they will become more economic as uranium becomes more expensive – and could eventually take over from thermal reactors.

Before then, other reactor designs may become available. A particularly promising line of research, which is being pioneered by the Nobel-prize winning physicist Carlo Rubbia and others, is into reactors that depend on spallation neutrons from a proton accelerator. The protons hit a target of a heavy metal, such as tungsten, producing a shower of neutrons that go into a sub-critical reactor assembly. This makes the reactor go critical, thereby generating power. Such reactors are easily controlled because the reaction stops as soon as the accelerator is switched off. The neutron fluxes are also so high that the radioactive wastes can be burnt inside the reactor. These are both highly desirable environmental features. "Pebble-bed" reactors are another promising development.

In the longer term, I have high hopes that fusion energy will ultimately become available. Intensive work is in progress on several possible designs for a fusion reactor. These reactors need deuterium, which is present in water in the proportion of about one part in five thousand. The energy available from fusion reactors is therefore practically limitless.

It is indeed fortunate that, just as other major energy sources are becoming exhausted or are recognized as seriously polluting, a new energy source – nuclear power – has become available to meet our needs.

It could cost the Earth – how can we meet our energy needs without damaging the environment?

Global primary-energy consumption

Energy source	1860	1900	1950	2000
Traditional (wood, dung, etc)	270	330	470	~1000
Coal	100	470	1300	2220
Oil		20	470	3400
Natural gas			170	2020
Hydro-electric		10	120	230
Nuclear power				630
Renewable (other than hydro)				~200
Total	**370**	**830**	**2530**	**~9700**

(In million tonnes of oil (toe) equivalent energy)

Sources. For 1860, 1900 and 1950: *Nuclear Energy in Industry* (1957 Crowther); figures converted from coal-equivalent to oil-equivalent energy by dividing by 1.5. For 2000: *Statistical Review of World Energy* (1999 BP Amoco), trended up to 2000; except traditional energy, from *Rural Energy and Development* (1996 World Bank). For primary energy, BP assumes that one tonne of oil produces 4000 kWh in a modern power station.

NO

I agree with the relevance of Hodgson's five criteria: capacity, cost, safety, reliability and the environment, *writes Dennis Anderson*. But I find he applies them unevenly toward the three main energy sources under discussion – fossil fuels, renewable energy and nuclear power – with a skew against both fossil fuels and renewable energy. Let me take fossil fuels first, since there is a moral in this for both nuclear power and renewable energy.

The United Nations "Atoms for Peace" conferences in 1955 and 1957, which set the stage for the expansion of the nuclear industry, were unambiguous about the need for nuclear power. The view was that fossil fuels would last for about 75 years and that, by the end of the 20th century, we would be faced with major energy crises unless we had nuclear power. The costs of fossil fuels would rise exponentially, while those of nuclear power would fall.

However, the opposite has happened. Fossil fuels have proven to be abundant and less expensive than nuclear power. Estimates of fossil-fuel reserves are enormous, especially of gas. "Commercially proven" reserves – those that companies have access to and declare in their assets – are a poor guide to actual reserves, which include unexplored resources and unconventional resources such as tar sands, shale oils and gas hydrates.

Estimates suggest that, at current extraction rates, we have over 200 years' supply of oil, 450 for natural gas and over 1500 for coal, the weighted average being nearly 700 years (see Rogner in further reading). Even this is an understatement, since it excludes natural-gas hydrates in the permafrost and under the ocean floors, and other sources that together are thought to amount to five times these values.

Moreover, the oil, gas and coal industries have made tremendous advances in exploration and production, and the electricity industry is steadily improving the thermal efficiency of fossil-fuel power stations. Estimates of reserves have increased more than tenfold, and costs have declined relative to those of nuclear power. Indeed, if nuclear power were to compete commercially with a natural-gas-fired power station, it would need a subsidy of more than £1bn per gigawatt.

It is, of course, easy to speak with the wisdom of hindsight, and to overlook the uncertainties and risks that the energy industry faced when nuclear-power programmes were being put in place. In the 1950s nuclear power held the promise of unlimited energy in an era when coal mining was an arduous, dangerous and unhealthy occupation for millions of workers (as it still is in China and India), when fuel shortages were common, and when coal burning in homes and industry was the source of intolerable levels of local pollution.

Nevertheless, nuclear power has been unable to compete in terms of cost with fossil fuels, and there is no commercial interest in it outside state-run electricity sectors. The subsidies for nuclear power over the past five decades have been colossal – about a hundred times the amount we have spent on developing renewable energy, for example – and further immense subsidies will be required to deal with the legacy of nuclear wastes and the decommissioning of power stations. Indeed, following the privatization of the electricity industry in the late 1980s, the UK introduced a Non Fossil Fuel Obligation (NFFO) to support nuclear power; it injected £8bn of subsidies into the industry *after* it had been sold off, while another

? £5bn is reportedly needed to deal with the decommissioning of the Dounreay nuclear facility. The NFFO, in contrast, injected just £750m (less than 10% of the funds) into renewable energy.

It is true that nuclear power makes a sizeable contribution to energy supplies in France and the UK, and that global production grew from near zero to the equivalent of 630 million tonnes of oil (toe) per year between 1960 and 2000. But the energy obtained from biomass – albeit unsustainably gathered over large areas – also increased by almost as much, in absolute terms, as that obtained from nuclear power. The contribution of fossil fuels rose by seven times this amount, notwithstanding the predictions that they would be nearly exhausted by the year 2000.

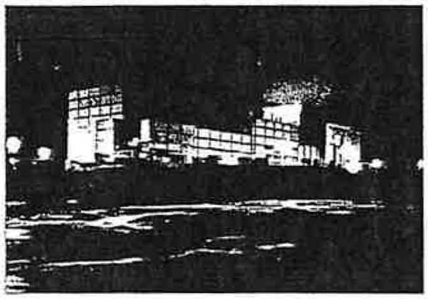
In terms of capacity and cost, it is thus difficult to make a good case for nuclear power. Fossil fuels are more than sufficient to meet the world's energy needs economically, not least in developing countries. Will environmental concerns change this? In response to successions of clean-air acts and environmental controls introduced in industrial nations, all sectors of the energy industry have made immense strides in reducing local and regional pollution per unit of energy consumption.

With the partial exception of nitrous oxides, the development of "clean" technologies and fuels is enabling pollution per unit of energy use to be reduced by several orders of magnitude. We have seen major reductions in local and regional pollution where these technologies and practices have been introduced: reductions of smog, lead in fuels and acid deposition in Europe and the US being striking examples. The associated costs have, moreover, proved to be small compared with the overall costs of energy use, and have sometimes been negative, with the "clean" practice being more efficient than the polluting practice it displaced. Further reductions are still possible, with hybrid vehicles and fuel cells holding considerable promise. Countries taking advantage of these technological developments have been able to use more energy with less pollution and have found themselves economically better off.

The fossil-fuel industry has thus responded remarkably well to local and regional pollution problems, and there is no reason why societies cannot enjoy the benefits of using these sources while striving to improve the local and regional environment. I shall tend to the global environment later.

YES

Anderson observes that fossil fuels have proven to be abundant and less expensive than nuclear power. It is not surprising that estimates of reserves differ, because surveys are inevitably incomplete. Furthermore, the quantities available depend on how much we are prepared to pay for extraction. Relative costs are difficult to estimate because nuclear costs depend on the lifetime of the reactor, which may be as long as 60 years. A small fraction of the output invested each year easily pays for decommissioning, and reactors are now designed to facilitate this process. The cost of nuclear power relative to fossil fuels would be very different if realistic estimates of the cost of pollution and climate change were also included. In the short term, fossil fuels may appear less expensive, but it is the long term that is more important.



Better by design – "fast" reactors like the one tested at Dounreay could make nuclear power cheaper

The Belgian government recently set up a commission to examine the options for electricity generation. Taking into account fuel costs, non-fuel costs (investment, operation and maintenance), external costs (air pollution, noise and greenhouse gases) as well as the cost of construction, grid connection and decommissioning, the commission estimated that it will cost BFr 2.34 to generate every kilowatt-hour of electricity from coal in 2010. The equivalent figures were 1.74 for gas, wind as 1.85 (seashore), 2.39 (offshore) and 3.26 (inland), but just 1.22–1.28 for nuclear power. In other words, nuclear power is not only more reliable, safer and less detrimental to the environment than the alternatives, but also substantially cheaper.

In his book *The Earth Under Threat*, Sir Ghillean Prance, former director of the Royal Botanical Gardens at Kew, describes in graphic detail the devastating effect on animal and plant life already attributable to climate change (see further reading). Many species, such as the golden toad in Costa Rica, have become extinct. This can be dismissed as anecdotal and lacking in statistical basis. Who cares about the golden toad? Well, I do, as I care about all threatened species.

Scientists on the UN's International Panel for Climate Change (IPCC) have amassed impressive evidence that climate change is real. Their work indicates that in the next 100 years average global temperatures will rise by several degrees and the sea level by 50–100 cm. There are, of course, many uncertainties, but it is prudent to take climate change seriously. Many of its potentially devastating effects are directly attributable to the carbon dioxide emitted when fossil fuels are burnt. Meanwhile, impurities in fossil fuels cause acid rain, which is already adversely affecting rivers, lakes and forests. While some countries are reducing the levels of pollution, this must be done world wide. It is therefore essential to eliminate fossil-fuel power stations.

As for wind and solar power, they contributed only 0.15% of the world's energy production in 2000 and disfigure large areas of land. They are also relatively expensive and five times as dangerous as nuclear power as measured by deaths from all causes during production. There is no hope that they can supply our energy needs. The only practical substitute for fossil fuels is nuclear power. In 1988 some 1.9×10^{12} kWh of electricity was generated by nuclear power stations. The same amount would be produced by burning 900 million tonnes of coal or 600 million tonnes of oil. In other words, the emission of 3000 million tonnes of carbon dioxide has been saved by using nuclear power, rather than coal. (While coal emits 850 tonnes of carbon dioxide per gigawatt hour, the figures for oil are 750, gas 500, nuclear 8, wind 7 and hydro 4.)

As countries switch to nuclear, their rate of carbon-dioxide emissions fall. Since 1970 France has halved its emissions, Japan (32% nuclear) has achieved a reduction of 20%, 2 while the US (20% nuclear) has reduced it by only 6%. The emission of noxious gases like sulphur dioxide is also dramatically reduced by going nuclear.

The UK government, meanwhile, wants its emissions of greenhouse gases to be 10% lower by 2010 than they were in 1990. A reduction of 6% had been achieved by 1995, which was due to nuclear-power output rising by 39% between 1990 and 1994. However, if no more nuclear power stations are built, the level of emissions will rise steeply. In subsequent years, as older nuclear power stations are decommissioned, the UK will find it impossible to reach its target.

Although many new gas-fired power stations, which emit only half as much carbon dioxide as coal-fired power stations, are currently being built, the problem is that they leak methane, which has a "global-warming potential" of about 60 times that of carbon dioxide. These two effects approximately balance out, which means that we can expect no reduction in global warming by switching from coal to gas. ? Even if this methane effect is neglected, then if gas increases to 43.5% of total production, while coal declines to 2.5%, we can expect carbon-dioxide emissions to fall by 10%. And if nuclear rises to 43.5% at the expense of coal there will be a 20% fall.

If we do not solve the world's energy problems now, then they will soon be solved for us. We are living in a special period in human history when oil, gas and coal are readily available. At present rates of consumption, the oil and gas will be gone in less than 100 years, and coal in about 200–300 years. Fossil-fuel burning will then cease and alternatives will have to be found. If we continue to burn fossil fuels, we not only pollute the Earth and initiate global warming, we also deprive future generations of these valuable materials, the bases of petrochemical industries. Would it not be better to solve these problems now – using nuclear power – instead of waiting until it is too late?

NO

I disagree with Hodgson that "the only practical substitute for fossil fuels is nuclear power". The alternative of renewable energy is abundant, as he points out, but its *practical* potential is also far greater than he suggests. It could, in theory, meet *all* of the world's energy demands. In practice, we will end up with a mix of energy supplies. Hydrogen production from coal-bed methane and natural gas is a promising option, for example (the CO_2 by-product being used for the enhanced recovery of oil or coal-bed methane on a non-net-carbon-emitting cycle). This is not merely my view: the IPCC, in all three of its assessment reports, has arrived at the same conclusion, as have many industrial and academic studies.

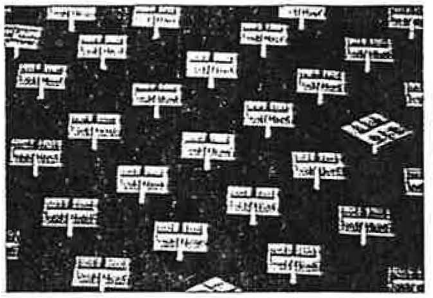
1. Renewables

First two myths about renewable energy need to be dispelled. One is that it is too dispersed to be of practical use without despoiling the landscape. Over vast areas of the developing world, the incident solar energy is 2000–2700 kWh per square metre of ground occupied per year. Solar-thermal power stations can convert more than 20% of this to electricity, and photovoltaics now on the market about 15% of it. This is more than two orders of magnitude higher than the energy produced by common crops and wood from an equivalent area of land. All of the world's future energy demands could, in theory, be met by solar devices occupying about:

- 1% of the land now used for crops and pasture; or
- the same area of land currently inundated by hydroelectric schemes, the electricity yield per unit area of solar technologies being 50–100 times that of an average hydro scheme.

A sizeable portion of energy supplies could also be produced by roof-top solar devices. Nor should we overlook resources such as biomass (which could enable vast areas of degraded land in developing countries to be restored), as well as offshore wind, geothermal energy and the energy in tidal streams and waves. Although I share Hodgson's concerns about the dangers of wind turbines despoiling the landscape, they are now being installed offshore. Multi-sourced systems based on wind, waves, tidal streams and solar power are also possible. Solar schemes are also architecturally attractive.

The second myth is that renewable energy (other than biomass) cannot be stored. A range of options is now being developed, including thermal, mechanical, thermochemical and electrochemical storage, as well as the production and storage of hydrogen for fuel cells or direct combustion for both stationary applications and transport. Even nuclear power needs to solve its "storage problem", both to service peak loads on electricity systems and to meet the immense energy needs of transport.



Practical challenge – solar devices could, in theory, meet all of the world's future energy demands

costs

Producing hydrogen from solar photovoltaics and wind power is estimated to cost between £0.05–0.10 per kilowatt hour, roughly 7–15 times the cost of natural gas. However, the costs could decline fivefold with economies of scale and as the manufacture of electrolysers develops (see Ogden in further reading). And although nuclear power has the economic advantage of using the capacity of electrolysers more fully, the long-term average costs of renewables are as low as – if not lower than – those of nuclear power. Renewable-energy–hydrogen systems are unlikely to cost more than nuclear–hydrogen systems – and possibly less.

The costs of renewable-energy technologies differ greatly with location. Solar technologies are more economical in the sun-drenched tropics, where seasonal variations in sun levels are lower than in other regions of the world and solar peaks match demand peaks much better. In fact, solar technologies are over five times cheaper per kilowatt-hour for most developing nations. What might look a distinctly unpromising technology to a pessimist on a rainy day in northern Europe is highly promising where 5 billion of the world's population live, and where energy demands are growing fastest.

There is already a rapidly growing market in the developing world for applications that use the Sun for water pumping, lighting and health clinics, and as a back-up for grid supplies and to supplement peak loads. Solar applications also avoid the capital expenditures on – and losses in – transmitting and distributing electricity, which account for about 50% of the costs of electricity supply in urban areas and over 75% in rural areas and towns. Fuel cells as decentralized sources of electricity generation – using hydrogen generated from renewable energy – would give rise to similar savings and, in colder climates, would be an efficient source of combined heat and power.

All of these renewable technologies are proven options and are fertile areas for R&D; the literature is notable for the range of advances that are being reported, not least in conversion efficiencies. They are still in an early phase of development, significant efforts having begun barely two decades ago. The technologies are modular and well suited for batch production. The lead times are just a few months, compared to 7–10 years for nuclear reactors and 3–5 years for fossil-fuel power stations. This is an important source of cost savings and allows the technologies to be developed quickly. They can also be decommissioned and the materials recycled relatively easily.

Such factors will not, of course, guarantee economic success, and it will be important to develop economically viable storage systems, including the fuel-cell–hydrogen option. But they do suggest that we have energy sources of immense promise if we are prepared to support them through wise policies.

It is hard to overstate the size of the task if we are to replace fossil fuels by renewable or nuclear energy to mitigate the effects of climate change. According to the IPCC and the World Energy Assessment – which was carried out last year by the UN Development Programme and the World Energy Council – global primary-energy demands will rise from about 400×10^{18} J today to $800–1600 \times 10^{18}$ J by the end of the 21st century, depending on assumptions about energy efficiency. This is equivalent to the output of 15–30 million MW of nuclear power.

Given the huge problems of decommissioning and waste disposal, the share of nuclear power in meeting future energy needs is bound to be limited. We cannot rely on nuclear power to solve the climate-change problem. We should therefore develop ways of using solar power – the one safe and abundant form of fusion energy that is already available to us in perpetuity. I appreciate how far developments in renewable energy and hydrogen-powered fuel cells have to go, the difficulties and risks of developing an industry from a small base, and the time it will take to switch from fossil fuels. But we must explore and develop these options.

YES

Meeting the world's energy needs is an urgent problem – and all practicable energy sources must be used to solve it. The exact mix in different regions will depend on many factors, particularly the indigenous fuels as well as local geography and economics. Developed countries must help developing nations to increase their energy supplies and curb existing wasteful habits. Continuing efforts must be made to reduce pollution and carbon-dioxide emissions. To make progress in discussions about energy production and the effects on the environment, it is essential to have numerical data. Without such information, it is impossible to know whether a proposed source or effect is important or negligible.

If we are to stabilize the emission of carbon dioxide by the middle of the 21st century, we need to replace 2000 fossil-fuel power stations in the next 40 years, equivalent to a rate of one per week. Can we find 500 km² each week to install 4000 windmills? Or perhaps we could cover 10 km² of desert each week with solar panels and keep them clean? Tidal power can produce large amounts of energy, but can we find a new Severn estuary and build a barrage costing £9bn every five weeks?

Nuclear power, however, is a well tried and reliable source, whereas the alternatives listed by Anderson are mainly hope for the future and have yet to prove themselves. At the height of new nuclear construction in the 1980s, an average of 23 new nuclear reactors were being built each year, with a peak of 43 in 1983. A construction rate of one per week is therefore practicable.

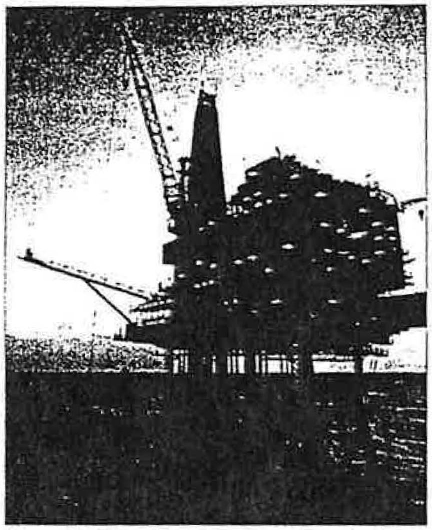
I hold no special brief for nuclear power. there were another way of providing our energy needs without destroying the Earth, I would support it. I am not, I must admit, happy about the dangers of nuclear radiation. I know that, in the hands of engineers at, say, Sizewell, nuclear power is extremely safe, but I can think of many places that would not inspire me with the same confidence. There is always the fallibility of human nature, and the danger that politics will domineer engineering prudence, although the same could be said of all modern technology. Strict controls and eternal vigilance are therefore the price we must pay for its benefits.

A careful and objective analysis will reveal the best energy policies to adopt. It is all too likely, however, that this will not coincide with public views. This puts governments in a dilemma; they can remain popular only by adopting policies that they know are not the best ones from an objective scientific viewpoint. Methods of tackling this serious and intractable problem will have to be discussed.

So do we need nuclear power? Obviously not, if all we care about is having enough energy for the next 100–200 years to continue our current wasteful lifestyles. But then we must pay the price in terms of pollution: sterile lakes and dying forests, climate change and the international tensions generated by the scramble for the last remaining oil. To avoid these consequences, such fuels must be replaced by non-polluting sources, and the only realistic possibility is nuclear power. If we care for the Earth, then, like it or lump it, we need nuclear power.

NO

I believe industrialized nations should adopt a modest carbon tax with the revenues being earmarked for R&D and tax incentives to commercialize the following technologies:


The end is nigh – despite advances in exploration and production, fossil fuels will eventually run out

- offshore renewable-energy resources;
- hydrogen systems and fuel cells;
- photovoltaics;
- advanced energy-storage systems, including hydrogen storage;
- geothermal energy; and
- improved energy efficiency, including small-scale systems that combine both heat and power.

Although industrial countries, including the UK, are already heading in these directions, their policies are minuscule in comparison with the effort they expended on nuclear power in the past.

Developing countries also need to initiate parallel programmes. Building on the work of the UN Framework Conventions on climate change and biodiversity, these programmes should – in addition to the above policies – include the development of advanced solar-thermal power stations and multi-purpose schemes for the sustainable production of biomass for energy use and the restoration of degraded lands and watersheds.

It is *precisely because* renewable energy still accounts for such a small share of output, coupled with its promise, that these programmes are justified from both an economic and an environmental perspective. When promising technologies are emerging, they need to be nurtured and researched more fully, to see what they will yield. Of all the arguments against renewable energy, the one that it still accounts for only a small fraction of output relative to nuclear power is the worst. Nuclear power generated little in the 1950s; but that did not stop governments subsidizing the industry to the tune of $0.5–1 trillion over the following 40 years. In the early phases of a technology, there is more to be discovered, more scope for progress, more scope for reducing costs through invention and innovation, and economies of scale are more marked. The costs of photovoltaic modules, for example, fell from $300 000 per kilowatt in the 1970s to $3000 per kilowatt by the late 1990s, and the scope for further reductions is far from exhausted.

The "learning curves" for renewable-energy technologies are steep, the unit costs falling by 15%–25% every time the cumulative volume of production doubles. There is every indication that fuel cells and hydrogen production will decline in cost at a similar rate, provided that we invest in their development. Indeed, over 5 GW of new renewable-energy capacity is already being installed each year, and markets are doubling every 3–4 years. If their share in energy production rose to 5%–10% of world energy supplies, their costs would decline by three- to fivefold. At worst, we would have an important source of energy supplies; at best a proven way of meeting the world's energy needs in perpetuity without carbon emissions, and a cheaper and abundant source of energy – most of all in developing nations.

As for nuclear power, it should be exempted from carbon taxes and climate-change levies. To put a carbon tax on non-carbon energy sources is illogical and inappropriate. The huge legacy of nuclear waste and the decommissioning of old nuclear plants must also be addressed by public policies. Beyond that, the nuclear industry is now surely mature enough to stand on its own feet. It does not merit further public financial support, which would be better used for other purposes. It should put the case for new plant to the financial markets, not to governments, and in doing so make the necessary provisions for meeting the costs of waste disposal and eventual decommissioning.

Further reading

P Hodgson 1999 *Nuclear Power, Energy and the Environment* (Imperial College Press, London)

T B Johansson *et al.* 1993 *Renewable Energy: Sources for Fuels and Electricity* (Island Press, Washington DC)

J Ogden 1999 Prospects for building a hydrogen energy infrastructure *Ann. Rev. Energy and the Environment* **24** 227

G Prance 1996 *The Earth Under Threat* (Wild Goose Publications, Glasgow)

H-H Rogner 1997 *Ann. Rev. Energy and the Environment* **22** 217

UN Development Programme and World Energy Council 2000 *World Energy Assessment: Energy and the Challenge of Sustainability* (UNDP, New York)

Peter Hodgson is a nuclear physicist at Oxford University and has been active in the field since 1948. He has written extensively on the influence of nuclear physics on society and served on the council of the Atomic Scientists Association, e-mail p.hodgson1@physics.oxford.ac.uk. **Dennis Anderson** is director of the Centre for Energy Policy and Technology, Imperial College, London, former chief economist to the Royal Dutch Shell Group and former economist and energy adviser to the World Bank, e-mail dennis.anderson@ic.ac.uk

An Analysis of Peter Hodgson and Dennis Anderson's Debate in the June 2001 edition of *Physics World*:

"DO WE NEED NUCLEAR POWER?"

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14 December, 2002

CONTENTS

INTRODUCTION:

The purpose of this paper is to evaluate the arguments Peter Hodgson and Dennis Anderson make in their in June, 2001 *Physics World* article entitled "*Do we need nuclear power?*" Peter Hodgson argues that nuclear power is necessary; Dennis Anderson argues that it is not. Both writers agree that the five appropriate criteria upon which to judge nuclear power are **capacity, cost, safety, reliability, and environmental effects.** It is upon these criteria that I will base my analysis of their arguments.

For each of the five criteria I have adopted the following approach:

- Summarising the arguments made FOR nuclear power.
- Analysis of the arguments made FOR nuclear power.
- Summarising the arguments made OPPOSING nuclear power.
- Analysis of the arguments made OPPOSING nuclear power.
- My two penny's worth—what has been left out, what may be true but misleading or irrelevant, and arguments that both sides might have made to better argue their respective cases.

I will summarise and draw conclusions at the end.

Where there are involved calculations I have simply stated the result in the analysis and left the full calculation for the Endnotes.

If in the summaries I am quoting directly from their arguments in the article, I will use *italics*. If I am paraphrasing their arguments I will use normal type.

CRITERION #1: CAPACITY

ARGUMENTS MADE IN FAVOR OF NUCLEAR POWER:

With the exception of nuclear power, all other sources for generating electricity are either fatally flawed or too hopelessly limited to provide electricity for the future. Wood is impractical, oil and natural gas are running out and need to be conserved for the chemical industry, hydropower has already dammed most of the usable rivers, and tidal power, wind, and solar are all intermittent and costly. Coal is abundant but produces unacceptable amounts of CO_2 and other pollutants.

By contrast, nuclear power already provides 20% of the world's electricity and 50% of Western Europe's electricity, has high load factors (typically over 90%), and is safe, cheap and reliable. New "fast" reactor designs can multiply by over 100 the amount of usable uranium.

In 1983 43 nuclear power plants were built. The industry has already shown that it can churn out power plants at a rate that would meet future electricity needs.

Using renewable energy sources would require finding 500 km^2 of land each week to install windmills, or require covering 10km^2 of desert each week with solar panels and then keeping the panels clean.

ANALYSIS OF THE ARGUMENTS MADE FOR NUCLEAR POWER:

The oil argument is a bit of a red herring, in that oil is rarely used to generate electricity.

Nuclear does run at high load factors, but the world-wide average availability was 83.4% in 2001[1] (not the 90% or more Peter Hodgson quoted as typical) and varies quite a bit from country to country (from a high of 94 percent for South Korea to a low of 51 percent for Brazil.) [2]

The spallation accelerator technology to breed nuclear fuel and burn nuclear wastes that he mentions in the article is, like fusion, nice in theory but not yet practicable. It is not something we should count on when deciding whether of not it makes sense to build more nuclear power plants.

Worldwide, nuclear energy did contribute about 20% to total electrical generation.[3] Western Europe produced 35% of its electricity from nuclear energy in 1998, not 50% the author claims.[3] Since nuclear power is not useful for meeting PEAK load demands (which are presently often met by natural-gas fired plants), he is really looking at replacing current coal-generated electricity (which also tends to be used to meet base demand) by nuclear generated electricity. By this criterion nuclear could replace up to 50% of US electrical generation[4] and up to 40% of world-wide electrical generation.[3]

Although using wind would require finding 500 km^2 of land each week to install windmills[EN1], this does not take most of that land out of use. The footprint of the wind turbine is quite small, and the land around each turbine can be used for agriculture or pasture. Alternatively, one can move the windmills offshore.

10 km^2 of desert needing to be covered each week in solar panels is too low by about a factor of about two. [EN2] If instead of desert you covered rooftops (where people are already living) this would require no NEW land being covered.

ARGUMENTS MADE OPPOSING NUCLEAR POWER:

Fossil fuels are still abundant and cheaper than nuclear power. Commercially proved reserves are a poor guide to what is really available, as they do not include tar sands, shale oils, and natural gas hydrates in the permafrost and on the ocean floors.

The energy obtained from biomass in the past 40 years has increased almost as much in absolute terms as that obtained from nuclear power.

All of the world's future energy demands could, in theory, be met by solar devices occupying about *1% of all the land presently assigned to crops and pasture or the same amount of land currently inundated by hydroelectric schemes. A sizeable portion of energy supplies could also be* *produced by roof-top solar collectors.* Ultimately, the answer is *multi-sourced systems based on wind, waves, tidal streams and solar power.*

By generating energy where it is needed rather than using central distribution of electricity, heavy transmission and distribution losses of 50% in urban areas and up to 75% in rural areas can be avoided.

ANALYSIS OF THE ARGUMENTS MADE OPPOSING NUCLEAR POWER:

There is about 200 years worth of coal still available.[5] Commercially available oil and gas do NOT have a 200 year lifetime.[5] As easily obtainable oil and gas become rarer and more expensive the argument that they are cheaper than nuclear power will probably not hold. Tar sands and oil shale contain large reserves of oil in theory, but the amount of energy it takes to extract that oil is very close to the amount of energy that you'd get out of that oil. If that energy for extraction has to come from oil or natural gas you end up generating five to ten times as much CO_2 as you would in processing the same amount of conventional oil.[6]

One percent of all of the land currently devoted to crops and pasture is about the right amount of land to cover to meet the world's future ELECTRICAL energy needs, but would be quite insufficient to meet the world's TOTAL future energy needs.[EN3] Taking land away from food production in developing countries at the same time as one expects rapid population growth in these countries defies logic. Covering vast amounts of pasture-land with solar cells presents the problem of developing the infrastructure to deliver the electricity to where it is needed. And since by definition it is rural land, one could expect to have the same electrical energy distribution losses in that the author claims that solar power will avoid. Roof-top solar, on the other hand, could cover a huge area at the point of use, and so his distribution and transmission losses COULD be avoided.

Mr. Anderson also gets his electrical distribution losses wrong. Typical distribution losses are less than 10%[7], not the 50-75% he quoted. The 50-75% figure might be attributable to power "theft" in developing countries rather than intrinsic inefficiencies in power distribution.[8]

The author himself admits that much of the growth in biomass comes from unsustainable harvesting practices. One can infer that growth in sustainably managed biomass harvesting will be offset (in a sane world) by a corresponding decrease in unsustainable forestry practices.

Invoking natural gas hydrates in the permafrost as a solution our energy problems is at best premature, as the technology to harvest and exploit them has not yet been developed.

MY TWO PENNY'S WORTH:

The pro-nuclear argument could have been made much stronger by emphasising the possible use of nuclear power to make electricity or hydrogen for clean transport. He might have emphasised the intermittent nature of renewables—even if you DO cover the desert in solar panels, you still need power at night.

The anti-nuclear argument could have been made more strongly by pointing to the successful utilisation of wind power in Denmark, or by not relying on out-of-the- mainstream estimates of current reserves. He could also have pointed out that developing countries might not have the engineering expertise or technical capacity to maintain the high technical standards to operate nuclear power plants. Neither will they likely have the infrastructure required to store, transport, and process the nuclear fuel and wastes safely. Nor will they likely have the economic resources to make the initial large capital investment in a nuclear plant.

CRITERION #2: COST

ARGUMENTS MADE IN FAVOR OF NUCLEAR POWER:

The long-term costs of nuclear are similar to coal and the amount of radioactive wastes nuclear energy produces are relatively small. A Belgian government study shows that nuclear power is substantially cheaper than any other form of power generation, even taking into account external costs including decommissioning the reactors.

ANALYSIS OF THE ARGUMENTS MADE FOR NUCLEAR POWER:

An OECD study concludes that

> "Well-run nuclear plants have operating costs similar to, or lower than, those of competing plants. . . new nuclear power plants face challenging competitive conditions. Fossil-fuelled plants are expected to have a lower total cost of electricity than nuclear plants in most countries under the energy market conditions and fuel prices that have prevailed in recent years. . . While governments have played a pivotal role in securing the economic viability of nuclear power in the past, today the technology is mature. Private investors and commercial generators must bear most of the financial risks of new nuclear plants. Nuclear power must increasingly face the future on its economic merits and economic drawbacks as judged by the electricity markets."[9]

This can be taken to mean that reactors already existing can be run economically, but that the economics of NEW reactors depend very much on the cost of capital and of the market prices of competing fuels. A nuclear power plant is a very expensive and long-term investment, whose ultimate profitability depends on volatile market conditions over a long period of time.[EN4]

The Belgian study quoted takes a statistical approach, and assumes that the risk of a nuclear accident is one Chernobyl-type accident spread out over 442 nuclear reactors operating over an average of 20 years each. They estimate the of external costs of nuclear power, which includes decommissioning, waste disposal, and the possibility of a nuclear accident, to total roughly 0.02 Eurocents/kWh[10] out of a total nuclear electricity generation price of 3.05-3.20 Eurocents/kWh.[11] The Belgian study itself says:

> *It is important to indicate that the figures mentioned are theoretical statistical values intended to permit comparison of the safety risks among various methods [of energy generation]. They must not be considered outside of this context and should not be construed to be realistic estimations of the actual safety risks.*[EN5]
> --(text italicised in the original document; translation my own)

The Belgian study's estimate of the TOTAL external costs of nuclear power is lower than the US Nuclear Regulatory Commission's estimates of the cost to just DECOMMISSION a nuclear reactor. The NRC estimates that the cost of decommissioning a nuclear plant is about $300-450 million[12] while others contend that the price may be as much as ten times higher.[13] Assuming a cost of $1 billion dollars to decommission a 1000 MW plant after 20 years of operation the total decommissioning cost comes out to 0.83¢ per generated kWh.[EN6] Even if you assume a reactor lifetime of 40 years and the minimum NRC decommissioning cost you still come up with 0.12¢ per kWh (still over 5 times larger than the Belgian study estimates for ALL external costs). Thus the Belgian study must have seriously underestimated the external costs of nuclear power.

ARGUMENTS MADE OPPOSING NUCLEAR POWER:

Nuclear power is more expensive than fossil fuels. To compete with existing gas-fired plants would require a government subsidy of £1 billion per installed gigawatt. In its 40 year history governments has subsidised the nuclear industry to the tune of 0.5-1 trillion dollars.

The learning curves for renewable energy are such that the price per unit falls 15-25% every time production doubles. With markets doubling every 3-4 years, the price for renewables could drop three to five-fold. If governments subsidised renewables to the same extent that they have subsidised nuclear power, we would see substantial improvements in technology and decreases in costs.

Producing hydrogen from solar PV and wind should cost between £0.05 and 0.10 per kWh, and should drop fivefold with economies of scale.

ANALYSIS OF THE ARGUMENTS MADE OPPOSING NUCLEAR POWER:

As stated above, whether NEW nuclear plants can be run economically depends on the cost of fossil fuels and of capital.

Existing renewables have initial capital prices at least as expensive as nuclear fuels. Assuming a 35% "capacity factor" for wind[14] it would take a 2.5 MW wind turbine to replace 1 MW of nuclear generation capacity. At a present cost of approximately $1/W for wind[14] this works out to $2500 per kW (25% more than nuclear)[15]. In the UK solar could be 30 times as expensive as nuclear energy.[EN7] Renewable energy has benefited from some of the same kinds of subsidies that the nuclear industry benefited from in its infancy (albeit not at the same levels). There are government–funded R&D labs that benefit the renewables industry. There were tax credits for investing in wind farms in California in the 1980's, and several governments have generous rebate plans and tax incentives for roof-top installation of solar PV.

Hydrogen presently costs at least £0.36 per potential kWh of electrical energy[EN8], at least 350% more than what Mr. Anderson claimed. Using solar energy to produce hydrogen would make it even more expensive

MY TWO PENNY'S WORTH:

Nuclear energy has had huge subsidies in the past and continues to be subsidised to this day. "According to official figures, OECD governments poured $159 billion in today's money into nuclear research between 1974 and1998." [16] It is hard to get solid data on the real costs of nuclear energy. The people with the actual information (the nuclear industry and the governments) do not have a vested interest in the public knowing exactly how much nuclear energy, waste disposal, and transport costs. The institutions against the use of nuclear power are not always completely honest with their figures either (In one article, the cost of decommissioning a nuclear reactor was given as $3 billion. Only later do you discover that they are talking about 2020 dollars, not present dollars).

Be that as it may, the real question in the article is whether we should build NEW nuclear power plants. The real economic debate should be: "Given today's situation and energy market, does it make sense to build new nuclear plants?" The author against nuclear power could have made a much stronger point by looking at the present subsidies for nuclear power or quantifying the disposal costs; that plants usually need costly (upwards of $200 million) refurbishment before their 40-year life cycle is complete;[9] that the nuclear industry in the US is only responsible for $9.54 billion in damages[17] in the case of a serious nuclear accident even though the cost of such an accident could exceed $150 billion[18]; and that the industry "cost of nuclear energy" estimate assumes that the government is responsible for paying for the eventual storage and security of nuclear wastes.[19] He might also have wondered "aloud" why so many nuclear power plants are being shut down before their design lifetime has expired if nuclear power is economical.

The argument for nuclear power could have pointed out that the government's role in covering the costs of a nuclear disaster is the same as the role it takes in flood and fire disasters,[17] and that the cost of a nuclear accident may be much less than that of the world-wide damages caused by global warming from CO_2 emissions. He might also have pointed out that the embodied energy costs of solar PV mean that the energy required to produce solar panels is at least 1/5 of their lifetime energy output. It may require the entire output of the worlds' present complement of nuclear power stations to build the solar panels that will eventually replace them!

Finally, he might have argued that in discussing the cost of nuclear power, people tend to include the real cost (hotly debated!) of nuclear waste disposal and decommissioning power plants because the process is so evident. With fossil fuels the waste disposal is "free" in the sense that the wastes just go up the stack and into the atmosphere, and the externalities of fossil fuel generation are NOT generally included in the perceived cost of the energy so derived. Assessing a carbon tax on fossil fuel-derived energy would "level" the field for nuclear and fossil fuel electricity generation and might shift the economics in favour of nuclear energy depending on the cost of fossil fuels and the magnitude of the tax.

CRITERION #3: SAFETY

ARGUMENTS MADE IN FAVOR OF NUCLEAR POWER:

Nuclear energy produces none of the ash, noxious gases, CO_2, or radioactive emissions that characterise coal-fired plants. Techniques for refuelling nuclear power plants are well established and safe, and the relatively small volumes of highly radioactive nuclear wastes can be safely processed, encased, and buried in stable geological formations. New research reactor designs under development are extremely safe and may be able to "burn" the nuclear wastes, reducing their effective half-lives to only 300 years or less.[19]

In the hands of capable engineers a nuclear power plant is extremely safe, but I can think of many places that would not inspire me with the same confidence. There is always the fallibility of human nature, and the danger that politics will domineer engineering prudence. . . Strict controls and eternal vigilance are therefore the price we must pay for it benefits.

ANALYSIS OF THE ARGUMENTS MADE FOR NUCLEAR POWER:

With the exception of Chernobyl, there has been no major nuclear accident with a large release of radioactivity in the past 30 years.[19] There is serious disagreements as to whether the present storage schemes are safe and lots of questions where to put the wastes. These new research reactors may be great, but no one has one working yet. It is not as yet a solution that we can depend upon.

Beyond that are those issues raised by the PRO argument. A large coal power plant in the hands of an idiot or maniac can explode and kill thousands of people, but it will not leave a huge swath of land uninhabitable for hundreds or thousands of years. The present situation in Iraq suggests that it is not always possible to exert strict controls.

ARGUMENTS MADE OPPOSING TO NUCLEAR POWER:

Given the huge problems of decommissioning and waste disposal, the share of nuclear power in meeting future energy needs is bound to be limited.

ANALYSIS OF THE ARGUMENTS MADE OPPOSING NUCLEAR POWER: Dennis Anderson simply makes a statement rather that any substantive argument. If he wants to convince people that nuclear energy is a huge safety risk, he could talk about potential shipping accidents, terrorist attacks on nuclear shipping or power plants, diversion of plutonium to make bombs, the lack of qualified technical personnel to run nuclear plants in developing countries, the dangers of nuclear wastes leaking into groundwater, logistics of providing security for nuclear wastes for the next 100,000 years, radioactive wastes getting into the food chain . . .

MY TWO PENNY'S WORTH:

The only major nuclear accident to kill people in the past 20 or 30 years was from a poorly designed reactor that was being run incompetently. I'm willing to believe that modern engineers can design a power plant that will not melt down. I'm less certain that Third World countries are technically competent to safely run such a reactor, or will have the political fortitude to shut down a malfunctioning reactor if it forms a large fraction of their total electrical generation capacity. I'm even less certain that it makes sense to substantially increase our nuclear generation capacity until we have figured out how to safely inactivate or store the wastes for as long as is necessary.

Beyond that, nuclear power plants produce plutonium, which can be separated from the nuclear fuels at the end of two years and processed into a bomb. A government that seems "friendly' at one point (think Iran in 1977) might be not-so-friendly at another point (think Iran in 1980). Even if the nuclear waste could be stored safely forever, there is nothing stopping a government from diverting plutonium into making bombs (as India did with plutonium from their reactors in 1974).[21] Nuclear proliferation poses a huge public safety risk even if the plants themselves were totally safe and the storage issues were completely resolved.

Although a typical fission bomb is difficult to produce, terrorists can produce low-tech "dirty bombs" from TNT and radioactive materials (such as cobalt-60) that are commonly used in medicine and industry.[22]

CRITERION #4: RELIABILITY

ARGUMENTS MADE IN FAVOR OF NUCLEAR POWER:
Nuclear energy has high "load factors"—typically more than 90%---with nearly all of the remaining time spent on planned maintenance. People have over 40 years experience running nuclear power plants.

ANALYSIS OF THE ARGUMENTS MADE FOR NUCLEAR POWER: Availability factors of nuclear power plants typically lie closer to 83%[1] rather than 90%. Many have undergone unscheduled shutdowns for unanticipated maintenance.

ARGUMENTS MADE OPPOSING NUCLEAR POWER:
No argument made on the reliability of nuclear power plants.

MY TWO PENNY'S WORTH:
Nuclear power as a whole is fairly reliable, if one means by that that the plants run the majority of the time and churn out energy as they are designed to. Similar to the safety argument, they are high-tech machines requiring an in depth understanding of the underlying engineering to be run safely. One could reasonably argue that industrialised countries can do this. One could ask what a developing country is supposed to do for electricity when they shut down a nuclear power plant for scheduled (or unscheduled) maintenance, or if they fail to maintain their plant.

CRITERION #5: ENVIRONMENTAL EFFECTS

ARGUMENTS MADE IN FAVOR OF NUCLEAR POWER:
Again, nuclear energy produces none of the ash, noxious gases, CO_2, or radioactive emissions that characterise coal-fired plants. It is economically competitive, especially if you take the nasty effects of fossil fuels burning into account.. Using nuclear energy would help preserve endangered species by averting the global warming and acid-rain fossil fuels produce.

In 1988 the electricity produced by nuclear energy would have required the burning of 900 million tonnes of coal.

The use of nuclear energy has prevent the emission of 3000 million tonnes of CO_2. (coal emits 850 tonnes of carbon dioxide per gigawatt hour, oil 700 tonnes, and gas 500 tonnes).

As countries switch to nuclear, their rate of carbon-dioxide emissions falls. Since 1970 France has halved its emissions, Japan (32% nuclear) has achieved a reduction of 20%, while the US (20% nuclear) has reduced it by only 6%). The emission of noxious gases like sulphur dioxide is also dramatically reduced by going nuclear. Between 1990 and 1995 the UK lowered their emissions by 6%, which was due to nuclear-powered output rising 39% between 1990 and 1994.

Increasing the use of natural gas would mean increases in leakage of methane, which has a global warming potential 60 times worse than that of CO_2. Even if one ignores the leakage of methane, replacing coal-burning plants with nuclear plants will reduce CO_2 emissions by twice as much as replacing coal with natural gas would.

The environmental effects of covering vast tracts of land with wind turbines or solar panels or covering the coasts with tidal barrages are much worse than the relatively benign effects of building one relatively compact nuclear power plant every week.

ANALYSIS OF THE ARGUMENTS MADE FOR NUCLEAR POWER:

It is true that, under ordinary circumstances, there are no nasty stack emissions from nuclear power plants and that the radioactivity released from uranium in coal ash is more than what is normally released on the periphery of a nuclear plant. The use of nuclear power would avoid the global warming and acid rain contribution that accompanies fossil fuel use for electricity generation.

Using nuclear power in 1998 did indeed avoid burning 900 million tonnes of coal.[EN9]

Peter Hodgson's numbers for CO_2 production from coal (850 tonnes of CO_2 per GWh of electricity produced) are reasonable if one assumes that one is burning the highest quality coal. For lower quality coal, the CO_2 production would be even higher than he assumes. In addition, his numbers for coal consumption avoided by the use of nuclear power since 1988 are too low (1600 million tonnes rather than the 900 million tonnes he quotes).[EN10] Similarly, his statement that 3000 million tonnes of CO_2 was avoid by using nuclear power is two times too high if he is talking about 1988 production, and much too low if he is talking about cumulative CO_2 since 1988.

His statement that methane has about 60 times the global warming potential (GWP) of CO_2 is correct if one is talking about GWP on a per molecule basis. On a per kilogram basis (how GWP is usually reported) methane has 21 times carbon dioxide's global warming potential.[23]

He is "spot on" when he states that replacing coal with methane would lower global CO_2 emissions by 10%, and that replacing coal with nuclear power would lower global CO_2 emissions by 20%.[EN11] His is NOT correct when he states that the amount of global warming caused by methane leaking out of pipes would balance out the CO_2 emission savings from switching from coal to methane. Pipeline leaks from new pipes are only 0.1% of the gas they carry.[24] In addition, since coal mining releases natural gas that is trapped in with the coal,[24] less natural gas would be liberated from coal beds if less coal was being mined, and this might balance out any new leakage from increased gas usage. Of course, switching to nuclear would avoid this extra methane release as well.

He is totally wrong on CO_2 emissions decreasing in countries using nuclear power. In France, Japan, and the U.S. CO_2 emissions increased between 1991 and 2000.[EN12] In the UK emissions did drop from 1990-1995 at the same time as nuclear power generation increased. On the other hand, from 1995-2000 UK CO_2 emissions decreased again, even as nuclear energy production in the UK was decreasing.[EN12] Correlation does not imply causation. If what the author meant was "As a country increases its nuclear generation capacity, its CO_2 emissions related to electricity production go down" he should have made that clear.

One could argue about whether a nuclear power plant and its accompanying mining, transport, waste storage areas and the effects of thermal pollution from the plants are preferable to having lots of windmills and PV and altering shoreline habitats.

ARGUMENTS MADE OPPOSING NUCLEAR POWER:

The development of "clean" technologies and fuels is enabling pollution per unit of energy use to be reduced by several orders of magnitude. We have seen major reduction in local and regional pollution where these technologies and practices have been introduced: reductions of smog, lead in fuels and acid deposition in Europe and the US being striking examples. . . Countries taking advantage of these technological developments have been able to use more energy with less pollution and have found themselves economically better off.

ANALYSIS OF THE ARGUMENTS MADE OPPOSING NUCLEAR POWER:

Clean technologies have reduced NOx, SOx, and other nasty emissions from combustion. Improving efficiencies have reduced CO_2 emissions per unit of energy produced. Unfortunately, technologies that reduce emissions and improve efficiency often require larger initial capital investment. If developing countries are to enjoy the benefits of these technologies, then industrialised nation will have to subsidise their implementation.

Ultimately all fossil fuels, no matter how efficient, still produce CO_2, and even gains in efficiency will be wiped out by increases in consumption.

MY TWO PENNY'S WORTH:

Electricity is only 20% of the world's primary energy usage. The argument favouring nuclear energy could have mentioned transforming vehicular transport by providing clean electricity for electric vehicles or hydrogen for hydrogen-fuelled vehicles. Waste heat from nuclear plants could be used for industrial processes, for desalinisation of sea-water, to sterilise sewage, or many other uses that require high temperature heat.

The argument against nuclear energy could have pointed out the potential environmental costs of nuclear proliferation. Dennis Anderson could have made a bigger point about the illogic of continuing to produce nuclear wastes without having figured out what to do with them, the environmental dangers of nuclear proliferation, or the ultimate environmental costs to future generations if we don't solve the waste problem ourselves.

CONCLUSIONS

Neither Peter Hodgson (pro-nuclear) nor Dennis Anderson (anti-nuclear) wins this debate. Hodgson generally gets his numbers right, although he bases his economic estimates on a study whose numbers are questionable. He dismisses any serious role that renewable energy sources might play in the future. Anderson quotes exceedingly optimistic estimates of fossil fuel reserves, and doesn't get down to specifics when criticising the costs of nuclear energy. He does argue strongly for the development of renewables. And to a certain extent both depend on unproven technology—clean fast breeder reactors for Hodgson, renewable-energy hydrogen systems for Anderson—to argue that their route is the one to follow. It may have been inappropriate in the particular forum of *Physics World* to reference and footnote each source and calculation that they made. But as a result, one is left with two conflicting arguments based upon "facts" whose veracity is hard to validate.

Modern well-designed nuclear power plants operated by competent and engineers can run safely and generate huge amounts of power reliably. They have the potential to allow stabilisation of CO_2 levels in the atmosphere and to reduce levels of other pollutants as well. These environmental benefits have to be weighed against the environmental costs of nuclear waste disposal. Peter Hodgson's assurances that the amount of nuclear wastes is small and that they can be safely stored are not the same thing as a plan that points out where the wastes are going to go and how they are going to be safely kept there.

That the nuclear energy industry has enjoyed huge financial subsidies in the past is beyond question, but it is also history. The real question is whether or not nuclear power is an economical and environmentally sound way of producing energy for the future. Unfortunately, there is no general consensus on what the actual cost of nuclear energy is. In an ideal world a judgement of the economic merits of building new nuclear capacity would be based on an informed and reasoned evaluation of the facts. That the facts are NOT transparently available does a disservice to both those who favour nuclear power and those who oppose it, and leaves both sides arguing about what is true rather than what we should do next.

All of my reading indicates that once the plant is paid for, the energy generation costs are low and the real costs that remain are for decommissioning, waste storage, and insurance against a major nuclear accident. Nuclear energy does have some environmental benefit, and shutting down nuclear plants that have already been paid for does not make sense economically or environmentally. Even if you wanted to cover every roof with solar panels and every field with windmills, the energy to make those solar panels and windmills has to come from somewhere. There is a certain irony in that the energy needed to produce the means to save the planet will require either burning fossil fuels and generating millions of tonnes of CO_2 or generating nuclear waste we have not yet figured out how to dispose of.

To my way of thinking the biggest environmental threat posed by nuclear power is that of nuclear proliferation. Any nuclear power plant produces plutonium and any country with plutonium and determination can, given time, build a nuclear bomb.

What I can conclude from this debate is:

1. Carbon dioxide emissions must be reduced. Renewables may be the ultimate solution to the problem, but that solution is going to take at least 20 to 30 years to be fully implemented. Nuclear power may be able to serve as the "bridge" technology between the predominantly fossil-fuelled economy of today and a renewably-powered future. As such, shutting down existing nuclear reactors that are running to specifications does not make sense.
2. A carbon tax needs to be universally implemented to reflect the true economic and environmental costs of fossil-fuels. The proceeds from this tax should go to subsidising renewables, and to research on nuclear reactors that "burn" nuclear waste. Success of such a reactor would

revolutionise the world's nuclear waste disposal problems and totally change the nuclear equation. Failure of such a reactor would force nuclear proponents to confront the realities of long-terms waste disposal issues.

3. Reprocessing of nuclear fuel and the operation of nuclear power plants should be an internationally supervised process. It would help prevent countries from diverting plutonium away from power production and into bombs.
4. A society that depends on nuclear power must have high levels of technical skills, a strong professional ethos, and a well-developed technical infrastructure. It requires a stable government that can supervise a technical undertaking over a period of decades. As such nuclear power is a technology that is presently inappropriate for much of the developing world. If the developed world wants to reduce greenhouse gas emissions from the developing world it is going to have to give the developing world the technology it needs to generate electricity renewably and to burn fossil-fuels cleanly and efficiently.
5. Although there was little discussion of it in the article, efficiency measures may help postpone some of the need for new generating capacity until we either have the nuclear problem solved or have enough renewables installed that additional nuclear energy is no longer necessary.

Peter Hodgson states:

> *If we continue to burn fossil fuels, we not only pollute the Earth and initiate global warming, we also deprive future generations of these valuable materials, the bases of petrochemical industries. Would it not be better to solve these problems now--using nuclear power--instead of waiting until it is too late?*

Nuclear power may not be the way to go, but without a doubt, it is better to solve the world's energy and greenhouse gas problems now. Investing heavily in renewables now is one sure way to reduce dependence on fossil fuels and global warming, regardless of how the nuclear debate turns out.

It is impossible to judge nuclear energy on its merits while people disagree upon the facts. Even in this article the "debate" sometimes reduces to statements that "nuclear power is safe" or "nuclear power is too expensive". Ultimately, there can be no settlement of the nuclear issue until the true economic and environmental costs of nuclear power have been laid bare and until the nuclear waste disposal problem is solved.

END NOTES

[EN1] Adding of 500 MW per week of nuclear electrical capacity is equivalent to adding about 1250MW per week of wind turbines, since the availability of wind turbines is only 35%[25] (compared to around 80% for nuclear power). This would require 500 2.5 MW wind turbines, each with blades approximately 100 m in diameter. Since wind turbines are usually spaced 10 blade diameters apart, that works out to 1 km^2 per wind turbine, or 500 km^2 of occupied space.

[EN2] Using Dennis Anderson's number of 2000 kWh/m^2/year:
2000 kWh/m^2/year x (3.6 x 10^6 J/kWh) x(1 year/3.16 x 10^7 sec) = 228 W/m^2 average.
With a conversion efficiency of 15% that gives 34 W/m^2. To get 500 MW of electricity would require (500 x 10^6 watts)/(34 W/m^2) = 14.7 x 10^6 m^2 or about 15 km^2 of solar panels. If you include space to get around the panels and service and clean them, and to keep them out of each other's shadow (unless they were flat) you would probably need closer to 20 km^2 of land per week.

[EN3]The world has 1.35 billion hectares of arable land, and 3.35 billion hectares of pasture land.[26]
1.35 + 3.35 = 4.70 billion hectares = 4.7 x 10^{11} m^2
Present electrical energy consumption is 15 x 10^{12} kWh/year.[3] Assuming (conservatively) that energy demand triples in the next 40 years, that makes 45 x 10^{12} kWh/year.
Assuming Dennis Anderson's number of 2000 kWh/m^2/year, a 15% conversion efficiency, and assuming that only about 3/4 of the land dedicated to solar power would be occupied by panels (with some space for maintenance) would require
(45 x 10^{12} kWh/year)/(2000 kWh/m^2/year x 0.15 x 0.75) = 600 x 10^9 m^2 of land
6 x 10^{11} m^2 is 60 million hectares, or 1.2% of all arable and pasture land. Assuming his higher solar irradiance number of 2700 kWh/m^2/year gives closer to 1% .

Since electricity is perhaps 1/5 of total world energy demand, it would actually require closer to 6% of all arable and pasture-land to meet all of the world's future energy needs.

[EN4] "Today's capital investment to construct a nuclear power plant is typically some 60% of generation costs, with fuel costs at 20% and operation and maintenance (O&M) costs the remaining 20%. Capital requirements to construct a fossil fuel plant can be significantly lower, with fuel the major generation cost component at some 50% for coal and as high as 70% for natural gas".[27] An article in the Economist quoted "Nuclear Power in the OECD". International Energy Agency, 2001, as saying that the initial capital construction costs were $2,000 per kW for nuclear, against about $1,200 per kW for coal and just $500 per kW for a combined-cycle gas plant. [15]

"A 1997 European electricity industry study compared electricity costs from nuclear, coal and gas for base-load plant commissioned in 2005. At a 5% discount rate nuclear (in France and Spain) at 3.46 cents/kWh (US), was cheaper than all but the lowest-priced gas scenario. However at a 10% discount rate nuclear, at 5.07 c/kWh, was more expensive than all but the high-priced gas scenario. (ECU to US$ @ June '97 rates)"[28]

[EN5]The Belgian report states:

Il est important de signaler que les chiffres mentionnes sont des valeurs statistiques theoriques destinees pernettre la compariaison des risques sanitaires entre les differentes filieres. Ils ne doivent donc pas etre retirees de ce contexte et ne peuvent pas etre consideres comme des estimations des risques sanitaires dans la realite.[29]

Which I translate as

It is important to indicate that the figures mentioned are theoretical statistical values intended to permit comparison of the safety risks among various methods [of energy generation]. They must not be considered outside of this context and should not be construed to be realistic estimations of the actual safety risks.

[EN6] 1000 MW at 70% capacity for 20 years =
10^6 kW x 0.7 x 8760 hr/year x 20 years = 1.23 x 10^{11} kWh
$1 billion = 1 x 10^9 \$ = 1 x 10^{11}¢, which works out to 0.83¢ per kWh.

[EN7] PV-SYST, a program used extensively in the solar industry, estimates that the cost for a 5 kW peak roof was about $45,000, for about 5200 kWh/year. Assuming that a nuclear power plant is available 80% of the time, the photovoltaics produce an equivalent average of (5200kWh/year)/(0.8 x 8760 hrs/year) or 742 watts from a nuclear plant. $45000/0.740 kW = $60,000/kW equivalent output.

[EN8] "Fuel cells require hydrogen that is 99.999 percent pure, which today costs about $15 to $22 per kilogram. . . The equipment for a retail fuelling station to produce just 60 kilograms of pure hydrogen—enough to refuel 12 cars—today costs about $450,000.[30] The energy content of Hydrogen is 52,000 Btu/lb (or 120.7 kilojoules per gram)[31]
120.7 kJ/g x 1000g/kg = 120.7 x 10^3 kJ/kg
15\$/kg/(120.7 x 10^3 kJ/kg) = 124.3e-6\$/kj x 3600 kJ/kWh = $0.447/kWh=£0.29/kWh.
Assuming an energy conversion efficiency of 80% (hydrogen to water in a fuel cell) gives a present cost of £0.36/kWh for hydrogen.

[EN9] Assuming a coal calorific value of 11000 Btu/lb[32] that gives
(11000 Btu/lb) x (2200 lb/tonne) x (1 Btu/3413 kWh) = 7093 kWh_{th}/tonne of coal
If your coal burning plant was 30% efficient in 1988 that gives
(7093 kWh_{th}/tonne of coal) x (0.3 $\text{kWh}_e/\text{kWh}_{th}$)= 2128 kWh_e/tonne of coal
So,
(1.9x10^{12} kWh_e in 1988)/(2128 kWh_e/tonne of coal) = 893 million tonnes of coal, which is exactly what he said.

[EN10] A 600 MW coal fired power plant running at 41% efficiency would produce 4.44 million tonnes of CO_2 equivalent green house gases (GHG) per year (NREL, 2001).[33] For a plant running at 30% efficiency, this would be the GHG output for a 600 MW x (30/41) = 439 MW power plant. To calculate the CO_2 equivalent output per kWhe we'd do (4.44 x 10^6 tonnes CO_2/year)/ [(439 x 10^3 kW) x (365.25 x 24 hours/year)] = 1154 g CO_2/kWhe or about 1100 tonnes of CO_2-equivalent GHG per GWh. Since most of those emissions are CO_2, his number of 850 tonnes of CO_2 per GWh is quite reasonable.

If 1988 electricity produced from nuclear energy was 1.9 x 10^{12} kWh then the amount of CO_2 that would have been produced if coal had been used instead is
(1.9 x 10^{12} kWhe)*(0.850 x 10^{-3} tonnes CO_2 from coal/kWh_e) = 1.6 x 10^9 tonnes CO_2 or 1600 million tonnes CO_2 avoided in 1988.

[EN11] In 2000 World electrical consumption was 15.4 x103 TWh,[34] or 15.4 x 1012 kWh

- Coal provided 39.1% of this[34] or 6.02 x 10^{12} kWhe for 5.12 x 10^{12} kg CO_2 produced (assuming his number of 850 tonnes CO_2 per Gwh from coal is correct) Gas provided 17.4% of this[34] or 2.68 x 10^{12} kWhe for 1.05 x 10^9 kg CO_2 produced (assuming 393 g CO_2/kWhe from a 58% efficient CCGT)
- Reducing coal to 2.5% of the total electricity and replacing it with gas would mean replacing (0.391-0.025) x 15.4 x 10^{12} kWh = 5.64 x 10^{12} kWh of electricity generated from coal. This would decrease CO_2 from coal by
  5.64 x 10^{12} kWh x 0.850 kg CO_2/kWhe =4.79 x 10^{12}kg CO_2,
  but would increase CO_2 from natural gas by
  5.64 x 10^{12} kWh x 0.393 kg CO_2/kWhe[35]) = 2.22 x 10^{12} kg CO_2, for a net decrease of 2.57 x 10^{12} kg CO_2.
- World production of CO_2 from fossil fuel burning was 23.6 x 10^{12} kg[36]
  Therefore:
  - replacing all but 2.5% of coal burning with natural gas would reduce atmospheric CO_2 emissions by 2.57/23.6 = 11%
  - Replacing that amount of coal with nuclear power would reduce atmospheric CO_2 emissions by 5.12/23.6 = 21.6%
- THIS ASSUMES THAT ALL OF THE ANTHROGENIC CO_2 COMES FROM FOSSIL FUEL BURNING!

New gas pipelines have leakage rates of 0.1%, while older pipes can have leakage rates of 2-5%.[24]

- 0.1% of 5.64 x 10^{12} kWhe x (1 kWth/0.58 kWhe) x (1 toe /11.7 x 10^3 kWth) x (1.23 toe/ 1tonne gas) = 1.022 x 10^6 tonnes methane leakage x 21 GWP methane/GWP CO_2)
  = 21.5 x 10^6 tonnes of CO_2 equivalent leaked each year
- (21.5 x 10^9 kg of CO_2 equivalent from)/ (net decrease of 2.57 x 10^{12} kg CO_2 from switching from coal to gas) = 0.8%
- Assuming the worst leakage rates of 5% would give (5/0.1)*0.8 = 40% which means that almost half of the decrease in global warming potential from the lower CO_2 emissions from burning gas would be wiped out by methane leakage.
- Since new gas usage would involve installing new pipes rather than leaky ones, the proper figure is closer to 1%.

[EN12] The following data are taken from World CO_2 Emissions from the Consumption and Flaring of Fossil Fuels, 1991-2000[36]

	CO2 emission from fossil fuels (million tonnes C equivalent)		
	1991	**1995**	**2000**
France	107.8	100.7	109.44
Japan	280	298	314
United Kingdom	166.3	152.6	147.8
United States	1343	1653	1832

Of these four countries only the UK experienced a decrease in CO2 emissions, and that was by 8%. That the reason for the decrease was an increase in nuclear power generation is only speculation at best, in that between 1995 and 2000 the UK's nuclear energy consumption actually decreased, but their CO_2 production decreased as well.

UK Electricity production (in million tonnes of oil equivalent[5]		
1991	1995	2000
16.0	20.1	19.e

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Dye-Sensitised Photovoltaics

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CONTENTS:

Introduction:

Dye-sensitised photovoltaics offer the promise of providing solar power at the same efficiency as current thin-film silicon devices but at a fraction of the cost. Like conventional silicon cells, they absorb sunlight and convert it into electricity. But the details of how the process actually proceeds are quite different. I propose in this paper to

- review briefly how silicon photovoltaics work
- draw parallels between conventional and dye-sensitised photovoltaics
- consider some of the challenges remaining for the commercialisation of dye-sensitised cells, and
- suggest where future developments lie.

I've also included as an appendix a "primer" on the fundamental principles underlying the absorption of light by matter to help clarify the operation of both silicon and dye sensitised photovoltaic cells.

Electricity Production in a Silicon Photovoltaic Cell

To make a silicon photovoltaic cell we form a junction from two pieces of silicon, each "doped" with a different kind of impurity atom.

When the two pieces are put together, electrons the n-type silicon migrate to the p-type of silicon and establish an electric field across the junction.

Now, when a photon strikes the silicon the liberated electron can be physically swept away from the "hole", travel through an external circuit, and rejoin the hole at the other end of the circuit. Thus we have a continuous way of converting light energy to electrical energy that can be delivered to an external load.

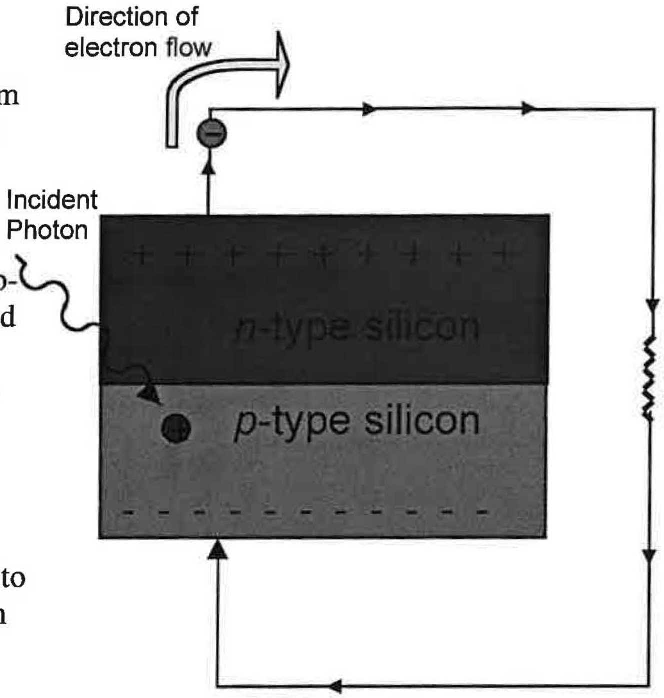


FIGURE 1. Operation of an ordinary silicon photovoltaic cell. A *pn*-junction has an electric field across it. When a photon excites an electron into silicon's conduction band the electric field sweeps the electron away from the hole so that the

In essence there are five basic steps to the operation of a silicon photovoltaic cell:

- A sufficiently energetic photon is absorbed by an electron
- The electron is promoted into the conduction band of silicon semiconductor
- The energetic electron is swept away from the "hole" it leaves behind
- The electron "dumps" its energy into an external load
- The electron recombines with the hole, ready to begin the cycle again.

The production of silicon photovoltaics is a mature field, but the manufacturing process is both expensive and energy-intensive. People have searched for alternative methods of producing electricity from light. Dye sensitisation is one method that has promise to avoid both the expense and embodied energy of silicon photovoltaics.

Electricity Production in a Dye Sensitised Photovoltaic Cell

Dye sensitisation has roots in photography, when it was first used in 1873 to sensitise silver halide particles[1]. The first observation of using dyes to inject excited electrons into the conduction band of a semiconductor was in the 1960's, but it wasn't until 1988 that Michael Grätzel put together a cell using nanoporous titanium dioxide with a ruthenium-based dye[2].

In order to make a dye sensitised photovoltaic cell:

- A transparent glass conducting support has spread across it a thin (10 μm) film made up of Titanium Dioxide (TiO_2) particles 10-30 nm in diameter.
- Adsorbed onto these TiO_2 particles is a monolayer of dye particles.
- The pores of the TiO_2 are filled with a liquid electrolyte containing a mixture of I^- and I^{3-} ions.
- A thin film of conductor/catalyst (typically platinum) is deposited on another piece of conducting glass to form a transparent counter electrode.

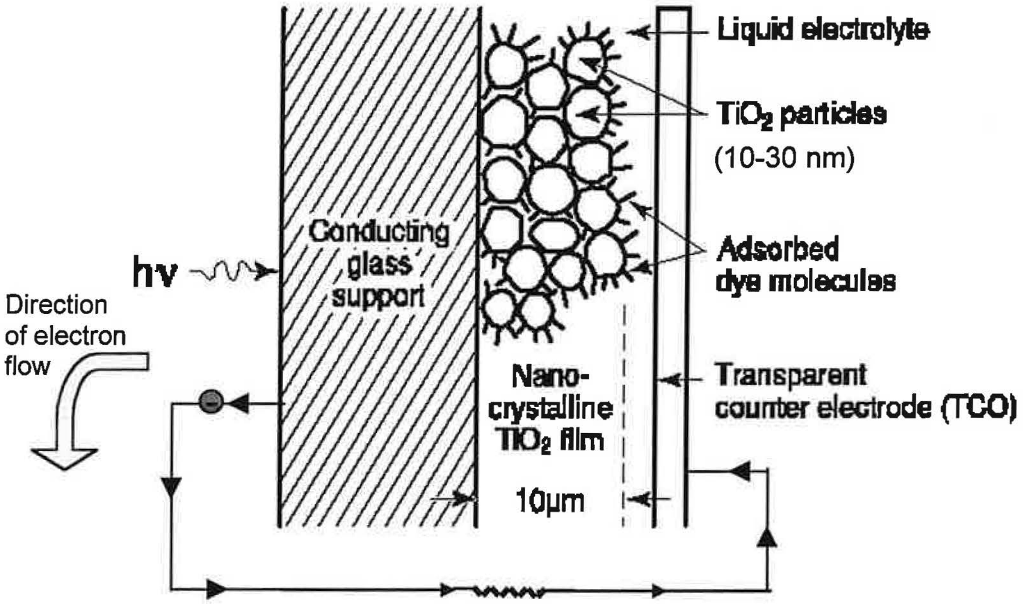


Figure 2. Schematic representation of a Dye Sensitised photovoltaic cell[3]

The electrical operation of the cell is shown below:

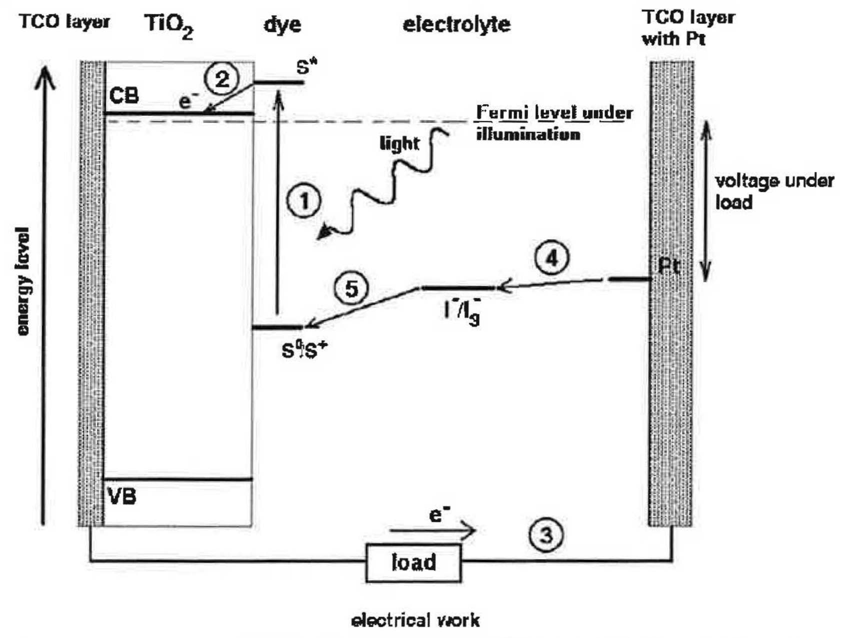


Figure 3. Energy level diagram for a Dye Sensitised photovoltaic cell.[4]

As shown in the figure 3, the steps are:

- Light passes through the glass surface and is absorbed by the dye, exciting a dye electron to a higher molecular orbital within the dye.
- The electron is then injected into the conduction band of the TiO_2, where it travels from particle to particle until it reaches the Transparent Conducting Oxide (TCO) layer on the glass.
- From there it travels around the circuit, through the load and to the TCO platinum covered counter-electrode.
- At the counter-electrode electrons reduce I^{3-} ions to I^-. The I^- ions diffuse across the cell and are oxidised by the dye, which regenerates the I^{3-} ions and neutral dye molecules and brings the system back to its starting configuration.

The reactions are detailed below

Figure 4. Summary of the chemical reactions occurring in a dye-sensitised photovoltaic cell. S stands for a dye molecule and hv represents a photon of incoming light.[5]

<u>Anode:</u> $S + h\nu \rightarrow S^*$ *Absorption*

$S^* \rightarrow S^+ + e^-(TiO_2)$ *Electron injection*

$2S^+ + 3I^- \rightarrow 2S + I_3^-$ *Regeneration*[10]

<u>Cathode:</u> $I_3^- + 2e^-(Pt) \rightarrow 3I^-$

<u>Cell:</u> $e^-(Pt) + h\nu \rightarrow e^-(TiO_2)$

Elements in the Operation of a Dye-Sensitised Photovoltaic Cell

<u>Absorption of the photon</u>

In ordinary photovoltaics the electron promoted into the semiconductor's conduction band comes from the valence band of the semiconductor. This requires that the semiconductor have a small band gap so that most of the incident photons can be absorbed.

By contrast, in a dye-sensitised cell you use a semiconductor with a LARGE band gap. The normal semiconductor used, titanium dioxide, has a band gap of 3.1 eV and an absorption edge in the near ultraviolet so that it is <u>transparent</u> to photons of visible light. The absorption of photon is accomplished by the <u>dye</u>; the electron is excited within the dye molecule, and THEN injected into the conduction band of the semiconductor.

The Dye

The choice of dye is critical to the success of a dye-sensitised cell. Ideally one would like a dye that:

- Adsorbs as a uniform monolayer to the semiconductor
- Is stable through the billions of electronic transitions you expect it to experience over the 20-year lifetime of a photovoltaic cell
- Is stable throughout the temperatures and pressures encountered in the manufacturing process.
- Remains stable over the entire expected temperature range of operation of your photovoltaic cell
- Is efficient in absorbing photons throughout the entire visible part of the spectrum and into the near infrared part as well
- Has its lowest excited energy level sufficiently high above that of the semiconductor's conduction band to ensure efficient injection into the conduction band, but not so high above that the energy is wasted, nor so low that the "driving force" for injection is small.

The choice of dyes has evolved over the roughly ten-year-history of dye sensitised cells. The original dyes were based on porphorin-like structures as found in chlorophyll. Present dyes are based on ruthenium complexes, as shown below:

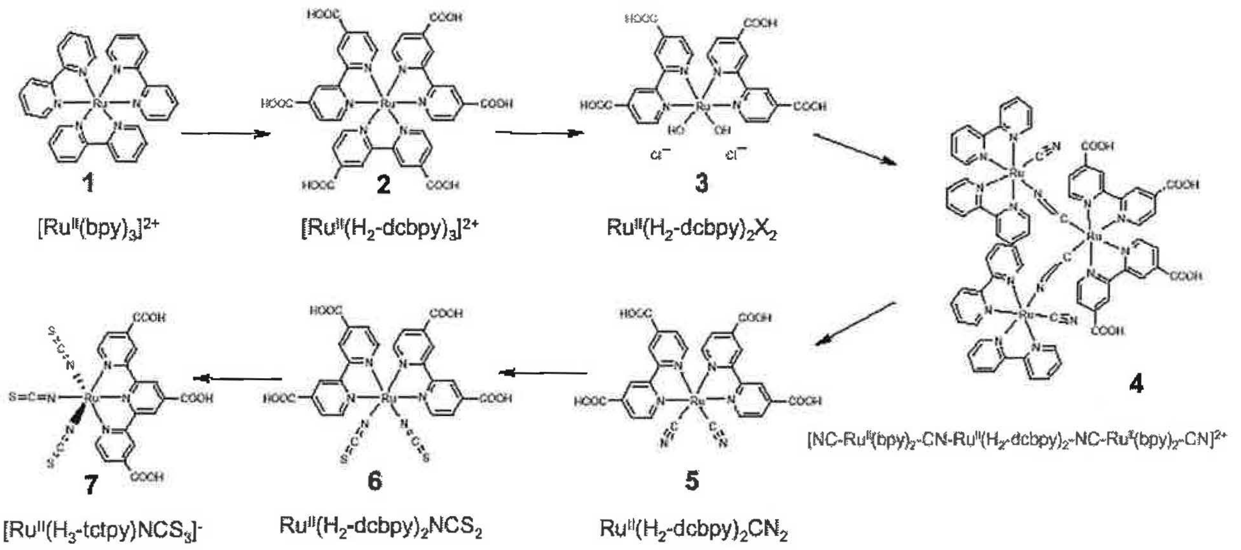
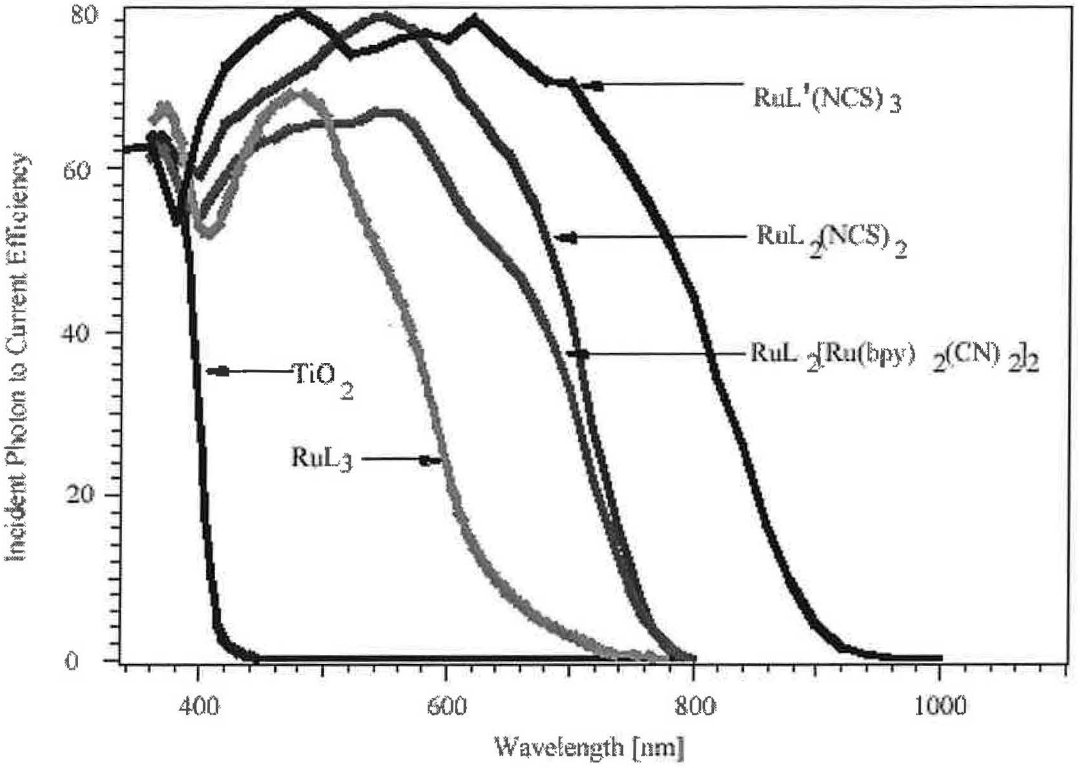


Figure 5: Evolution in the development of dyes used in dye-sensitised photovoltaics[6]

Each modification of the dye molecule has improved the absorption characteristics of the dyes. The present preferred dye (#7 above) can absorb photons throughout the visible range and up to about 920 nm. (Refer to figure 6). Such cells have been fabricated in the lab and produce electrical power with an efficiency of up to 10.4%[4].



L = 4,4'-COOH-2,2'-bipyridine; L' = 4,4',4"-COOH-2,2':6',2"-terpyridine

Figure 6. Absorption spectra of the various dyes that have been used for dye sensitised photovoltaic cells.[7]

Fabrication of the semiconductor

For conventional photovoltaics the semiconductor is either grown in crystals of incredible purity or laid down from the vapour phase as thin films. These are expensive and energy intensive processes,

In contrast, most dye sensitised cells use extremely small particles of titanium dioxide (10-30 nm). These are cheap, commercially available, and non-toxic (they are used in health-care products)[4]. They are usually spread out or "screen printed" as part of an extremely thin colloidal paste (approximately 10 µm thick) onto a piece of glass that has previously had deposited upon it a fluorine-doped tin oxide layer (usually written as SnO_2:F, and called a TCO for Transparent Conducting Oxide).

The glass is then sintered at 450°C which drives away the suspending medium leaving only the TiO_2 particles behind.

An electron micrograph of the TiO_2 layer after sintering is shown below:

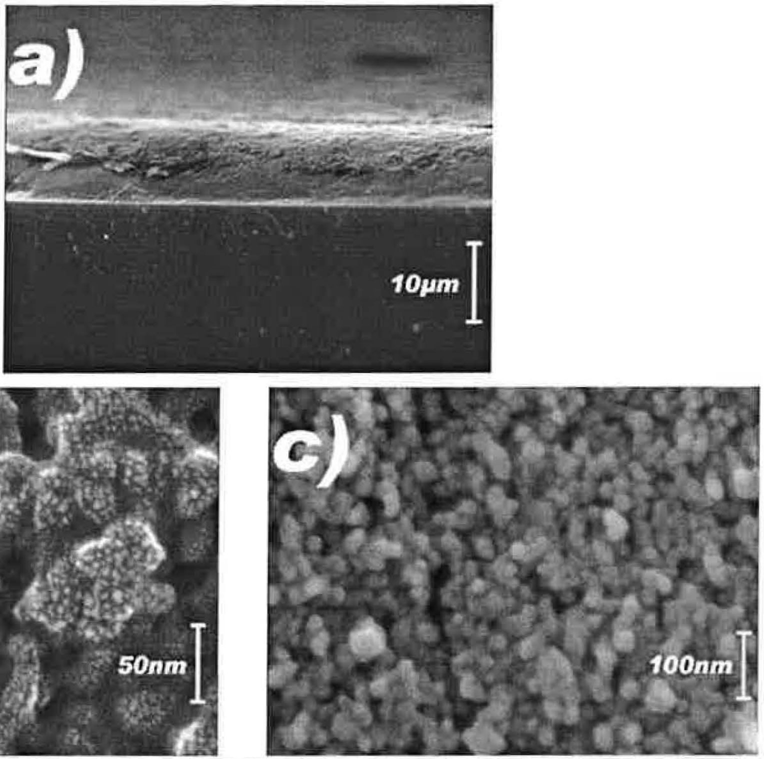


Figure 7.[8] . *IFESEM images of TiO_2 coated glass slides. a) side view, 30ekV, iridium coated, b) top view, 15keV, iridium coated, c) top view, 2.0keV, uncoated.*

The outstanding feature of this TiO_2 layer is that the particles form a single electrically interconnected mass of semiconductor with a total surface area thousands of times greater than that of the glass upon which it is spread[4]. This is important because

- A single layer of dye can only absorb about 1% of the incident light[9], and
- A dye molecule must be directly attached to the TiO_2 surface in order to inject an excited electron into the TiO_2's conduction band[1].

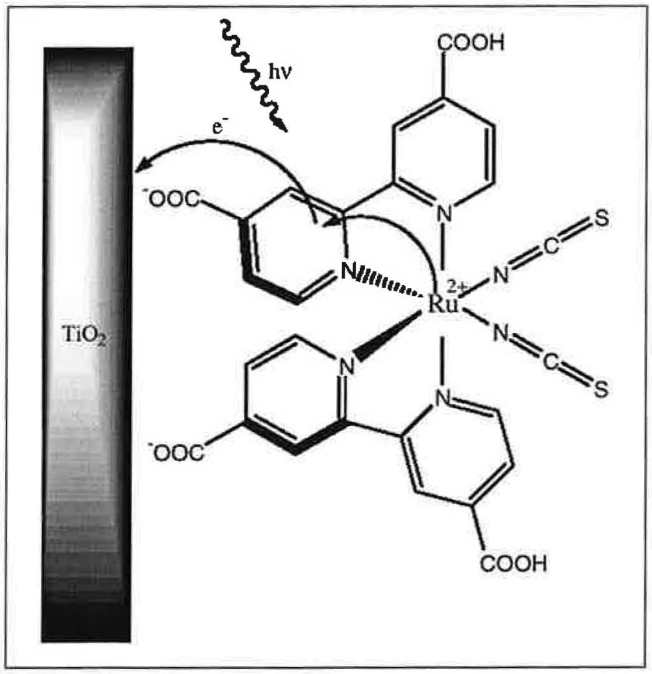


Figure 8. Adsorption of the Ruthenium-based "black dye" to the TiO_2 surface.[1]

The nanoporous structure of the TiO_2 layer allows many opportunities for an incident photon to be captured by a dye molecule, and a large surface area for those dye molecules to attach.

The Counter Electrode

After travelling through the circuit the electrons return to the dye cell through another transparent counter electrode consisting of another piece of glass with a conducting oxide coating and a thin (60 nm thick[3]) layer of platinum deposited onto it by an electron beam apparatus.

The Redox Shuttle

In a conventional semiconductors the excited electron can be thought of as travelling through the external circuit and eventually filling the original hole it left behind. In a dye sensitised cell, once an electron has been removed from the dye and injected in the semiconductor, there needs to be a way to neutralise the now positively-charged dye molecule left behind.

Referring back to figure 2 we can see that the dye molecules are on the opposite side of the cell from where the electrons return to the cell. Because of this the cell designers include a "redox shuttle" which carries the returning electrons back across the cell to the dye molecules. Although many others shuttles have been tried, the standard redox shuttle involves the I^-/I_3^- pair of ions which can travel in a liquid electrolyte. An I_3^- ion can pick up two electrons at the cell anode to give 3 I^- ions:

$$I_3^- + 2e^- \rightarrow 3I^-$$

These I- ions can travel across the cell through the electrolyte to the dye molecules and deliver the electrons back to the dye, regenerating the dye and the I_3^- ions:

$$3I^- + 2Dye^+ \rightarrow 2Dye + I_3^-$$

This last step completes the cycle.

Engineering and Design Challenges for Dye Sensitised Cells

Although simple dye-sensitised cells with efficiencies of around 0.5-1% can be routinely prepared by high school students[10], the commercial success of dye sensitised cells depends on optimisation of a huge number of variables. I will mention some of them below:

Dyes:

The "black dye" (see figure 8) has the broadest spectral absorption of all dyes tried so far. From figure 6 one can observe the gradual evolution of the dye as various chemical moieties and appended functional groups are tried out. Over 900 dyes have synthesized and tested specifically for dye cell applications, but very few have performed satisfactorily[6].

The dyes have several carboxylic acid groups. Using the salts of the dyes rather than the dyes themselves increases their solubility[4].

Semiconductors:
Although titanium dioxide is the preferred semiconductor to date, it can have a different crystal structure("rutile" or "anatase") depending on the conditions under which it is prepared[5]. Optimisation can include trying different proportions of the various crystal structure or mixes of TiO_2 with other metal oxides.

The sintering process/Backing Materials
The present production process requires sintering of the TiO_2 paste at high temperatures (450-500ºC). The only transparent conducting oxide (TCO) electrode that can withstand these temperatures is fluorine-doped SnO_2 on a glass surface.

One American company claims to have developed a "cold sintering" process which works at 150ºC[11]. This would allow using different TCOs, such as Indium Tin Oxide (In_2O_3:Sn), and deposition onto plastic films rather than onto glass.

Another process uses a spray deposition technique to deposit a mixture of a titanium compound and an aluminium compound onto the conduction glass surface. Upon heating to 500ºC the aluminium compound sublimes and leaves behind a porous TiO_2 film, although the crystals left behind are on the order of 100 nm across rather than the usual 10-30 nm[12].

Electrolyte/Solvent/Redox shuttle/Cell Sealing
The solvent of choice for dye sensitised cells has been acetonitrile or proprionitrile. Although these seem to have ideal properties as far as dissolving the dye and I^-/I_3^- pair are concerned, their boiling point is low enough that the stability and sealing of the cells can become a concern at temperatures above 65ºC[4]. One way of addressing this concern is to encapsulate the electrolyte in a gel rather than using a liquid. Another approach is to employ solid-state hetero-junction devices that still contain solid semiconductors and use a dye to inject energetic electrons into the titanium dioxide, but employ an organic p-type semiconductor[7] or use a conventional p-type semiconductor[13] (such as CuI) to transport holes. None of these cells has yet approached the efficiency of a "standard" liquid-electrolyte dye sensitised cell[12, 13,14].

The standard way of producing I^-/I_3^- pairs has been to use an iodide salt and iodine in solution. Many Iodide salts have been tried: LiI, NaI, KI, NH_4I, $(CH_3)_4NI$, $(C_2H_5)_4NI$ and $(C_4H_9)_4NI$. It has been observed that the largest photocurrents are obtained with the smallest cation. But researchers have noticed that the addition of small amount of an iodide salt with a small cation to a solution that is overwhelmingly made up of a large-cation iodide salt can cause a hundred-fold increase in the current production of a cell.[8]

Experiments have also been done with other redox shuttles rather than the I^-/I_3^- pair. This particular pair has two major deficiencies:

- I_3^- absorbs strongly in the wavelength region below 500 nm, and
- The redox potential of the I_3^- ion is about 0.5 V more negative than that of the ground state of the dye. Since the typical open circuit voltage of a dye sensitised cell is also around 0.5 volts the efficiency of the cell could be close to doubled if there was a better match between the energy levels of the redox shuttle and the dye[8].

But other redox shuttles that were tried (Br^-/Br_3^-. thiocyanate, ferrocene) that theoretically had better thermodynamic energy matches failed to produce anywhere near the same currents and the I^-/I_3^- pair does[8].

Counterelectrode

Typically the counterelectrode is made up of a thin layer of platinum (~60 nm) deposited onto a conducting glass surface. Researches have had some success with instead depositing onto the glass a porous carbon counter-electrode as a catalyst layer. This carbon electrode is made from a mixture of carbon black, graphite powder and nanocrystalline TiO_2 particles and has been claimed to be as catalytically active as the platinum layer.[15]

Other miscellaneous details

The making of dye-sensitised photovoltaic cells is still involves much art as well as science. Various washing steps with various solutions or solvents, or small amounts of additives in just the right percentages can have a large effect on the overall efficiency and lifetime of a cell.

Advantages of Dye-Sensitised Photovoltaics Over Silicon PV

There are several advantages of dye-sensitised cells over ordinary silicon photovoltaics[16]:

- They have a low production cost
- There is no need for highly skilled labour for assembly
- A relatively low capital investment is required to build a production plant
- The materials are relatively inexpensive
- The panels have a very low embodied energy (32 kWh/m^2 vs., over 1000 kWh/m^2 for crystalline silicon PV[17])
- The production methods are not environmentally unfriendly, and
- They have an efficiency equivalent to present thin-film silicon devices.

In addition, unlike silicon photovoltaics, the performance of dye cells improves as the temperature increases, and their power output is less sensitive to the angle of the incoming light than it is for silicon photovoltaics:

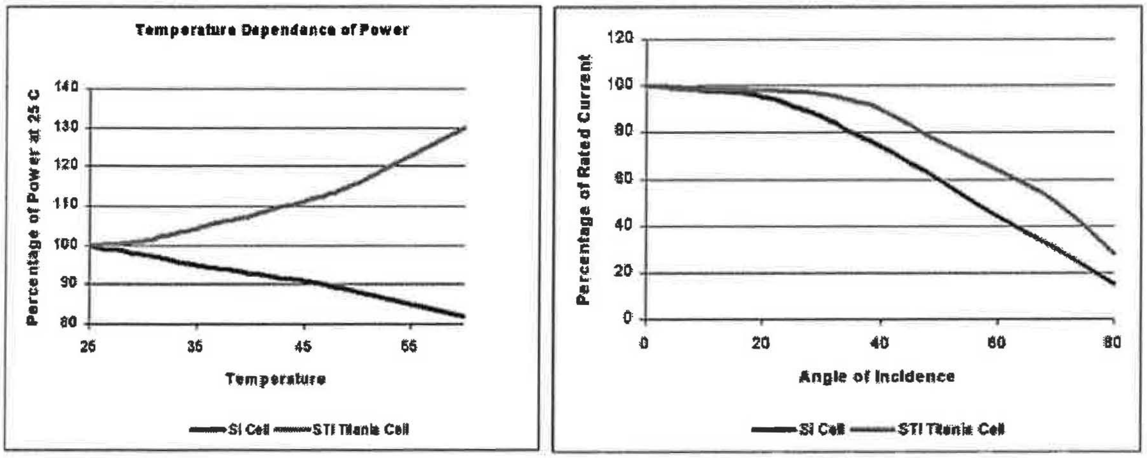


Figure 9. Comparing the relative effects of temperature and angle of incident light on the power output or dye-sensitised and silicon photovoltaic cells[16]

The Future of Dye-Sensitised Photovoltaics

I will mention three companies that are moving toward commercial production of dye-sensitised photovoltaic cells:

- *Sustainable Technologies of Australia* is about to produce dye-sensitised photovoltaic panels that can be manufactured cheaply and used as building elements in place of ordinary glass windows[16].
- *Konarka Technologies Inc.* in the US plans to produce small DSPV cells constructed on a plastic substrate for use in wireless electronic devices by early 2004[11].
- *Hydrogen Solar Production Company Ltd.* is developing a "Tandem Cell™" that combines two photovoltaic cells—a wide band gap tungsten trioxide (WO_3) semiconductor photovoltaic cell that absorbs in the 300-500 nm range on top of a conventional dye-sensitised cell that absorbs in the 400 –900 nm range—and connects these two cells in series to produce a more efficient, higher voltage cell than either would be on its own. They hope to use their Tandem Cell to produce hydrogen directly from water using solar energy.[18]

Current research aims at improving the stability and absorption spectrum of the dyes, finding alternative redox shuttles, finding low-temperature production techniques that allow the use of plastic rather than glass backing plates, optimising the many variables in construction of the cells, moving from "batch" to a continuous mode of cell production and to using gels or solids to replace the present liquid electrolyte.
Recent technical developments have led to cells that should have a stable working lifetime of 20 years under ordinary solar conditions.

Dye sensitised photovoltaic cells are becoming a mature technology.
Michael Grätzel, inventor of the dye sensitised cell notes that

> *" further improvements in efficiency are not likely to be the consequence of any radical breakthrough, but rather of careful incremental evolution, addressing each component of the cell, dye, substrate, semiconductor, electrolyte and catalysis of counter-electrode* [4]*."*

Dye sensitised photovoltaics hold great promise for the present and could be the photovoltaic cell of choice for many future applications.

APPENDIX: Interaction of light with matter—a primer

Light absorption by atoms

Suppose that a photon of light strikes an electron in an atom.

If the energy of the photon "matches" the energy gap between energy levels within the atom, the photon is absorbed and the electron will be excited to a higher energy level. If the atom is an isolated one (such as in a gas) the electron can de-excite and emit a photon with the same energy as the one it absorbed.

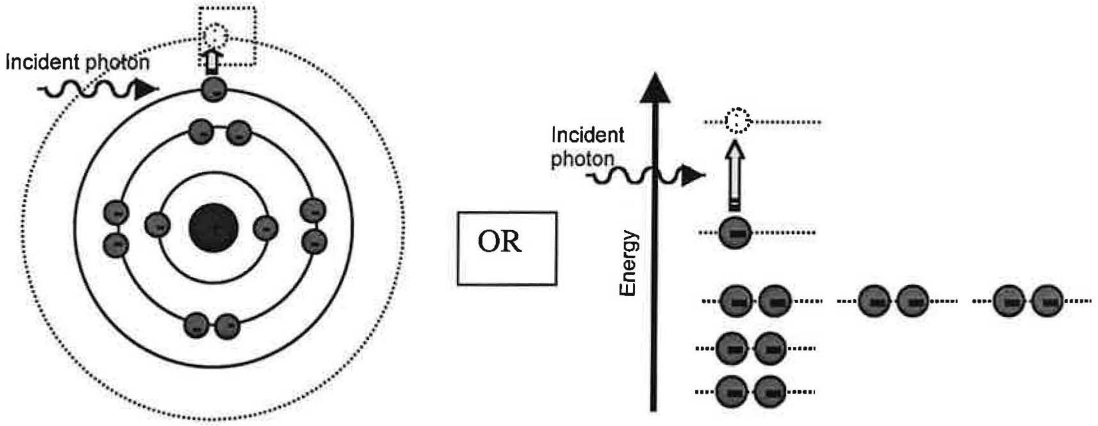


FIGURE A1. An outer electron in an atom is excited to a higher energy level by absorption of a photon.

Light absorption by molecules

When atoms join to form a molecule only their outer (valence) electrons participate in forming bonds. The atoms' outer energy levels split and "interfere" to make new molecular energy levels (molecular orbitals). An electron in an occupied "bonding" molecular orbital can absorb a photon and be excited to an anti-bonding molecular orbital. When the electron de-excites the energy can be re-emitted as a photon or transferred to vibrational or rotational energy within the molecule.

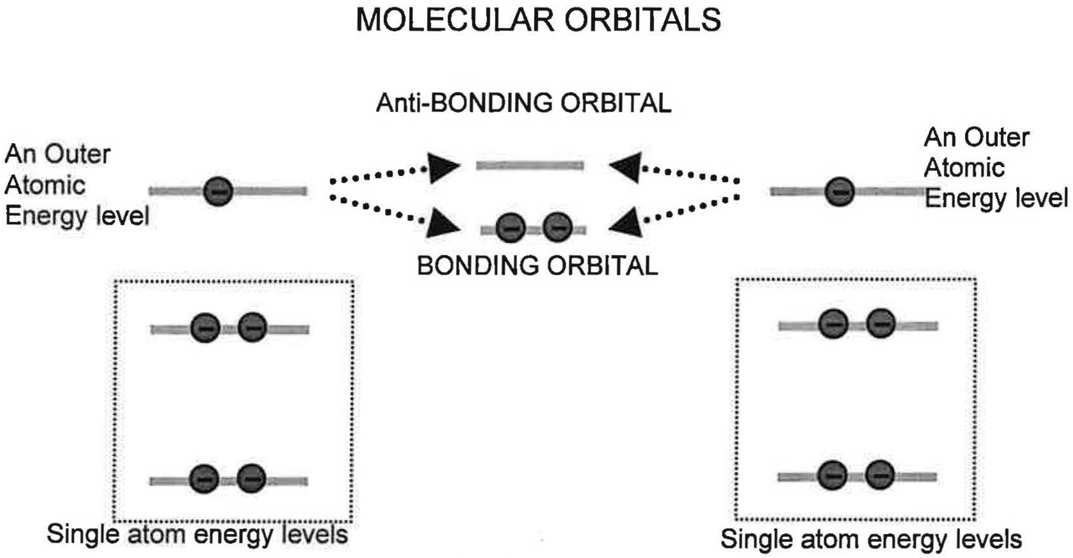


FIGURE A2. When atoms bond to form a molecule their outermost energy levels combine to form shared molecular energy levels (molecular orbitals).

Light Absorption by Solids

When billions of atoms combine to form a solid, the outermost energy levels split to form billions of shared energy levels that are so closely spaced energy-wise that they form two continuous bands of energy levels. Depending on the number of outer electrons each atom had and the spacing between the energy levels the resulting solid will have one of three possible electrical configurations:

- a CONDUCTOR, in which electrons at the top of the occupied band of energy levels (the valence band) have enough thermal energy to move into the vacant band of energy levels (the conduction band) and travel freely throughout the solid;
- an INSULATOR, in which electrons at the top of the occupied band will never have enough thermal energy to moving into the vacant band of energy levels (the conduction band) and thus are bound tightly within the solid; or
- a SEMICONDUCTOR, in which a very small fraction of the electrons at the top of the occupied band of energy levels (the valence band) have enough thermal energy to move into the vacant band of energy levels (the conduction band). Thus a semiconductor will yield very small currents when an electric field is applied to across it.

Insulators and semiconductors will only absorb light whose photons have enough energy to excite an electron across the band gap. For insulators, the required photon energy is far above the visible region of the spectrum, whereas for insulators it can range from the upper infrared region to the upper end of the visible spectrum.

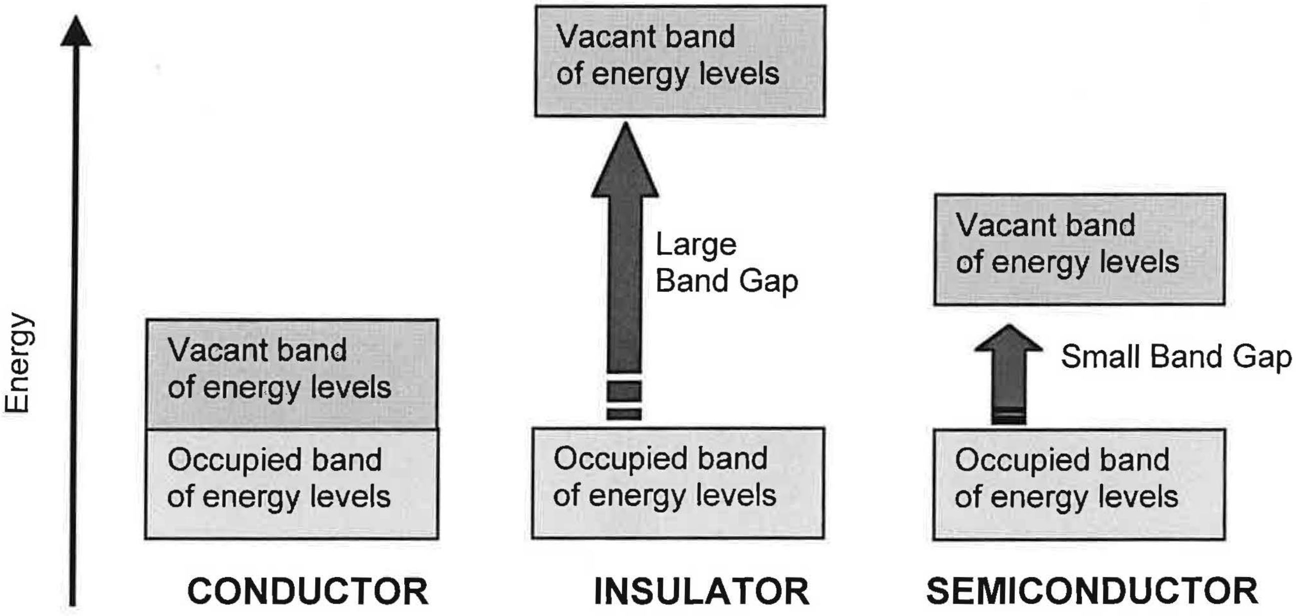


FIGURE 3. When atoms bond to form solids their outermost energy levels combine to form bands of shared energy levels. The number of shared electrons and the energy spacing of the bands (the BAND GAP) determines the electrical properties of the resulting solid

Light Absorption by Silicon

Band gaps and photon energies are usually measured in units of "electron volts". Since the band gap in silicon is about 1.1 eV (electron volts) and a photon of visible light has between 1.8 to 3.1 electron volts a photon of visible light (or even infrared light) has more than enough energy to promote an electron into the conduction band of silicon.

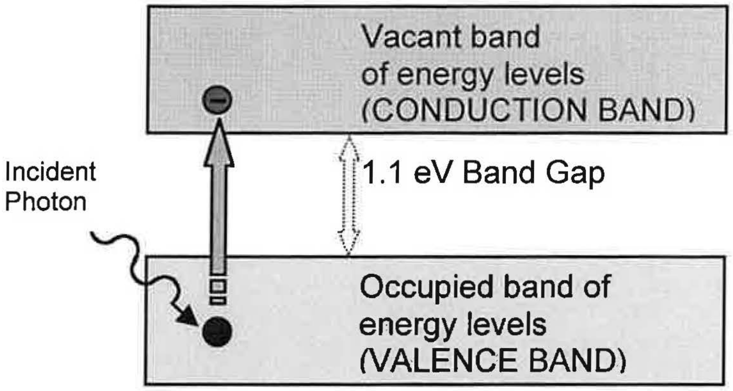


FIGURE A4. When an electron in the valence band of silicon absorbs a photon it is excited to the conduction band, leaving behind a positively charged "hole" in the valence band.

Since in the absence of any external applied electric field, the "freed" electron will stay put and eventually recombine with hole.

Using silicon to make photovoltaic cells

(This bit is repeated near the beginning of the paper)

To make a silicon photovoltaic cell we form a junction from two pieces of silicon, each "doped" with a different kind of impurity atom.

When the two pieces are put together, electrons the n-type silicon migrate to the p-type of silicon and establish an electric field across the junction.

Now, when a photon strikes the silicon the liberated electron can be physically swept away from the "hole", travel through an external circuit, and rejoin the hole at the other end of the circuit. Thus we have a way of converting light energy to electrical energy that can be delivered to an external load.

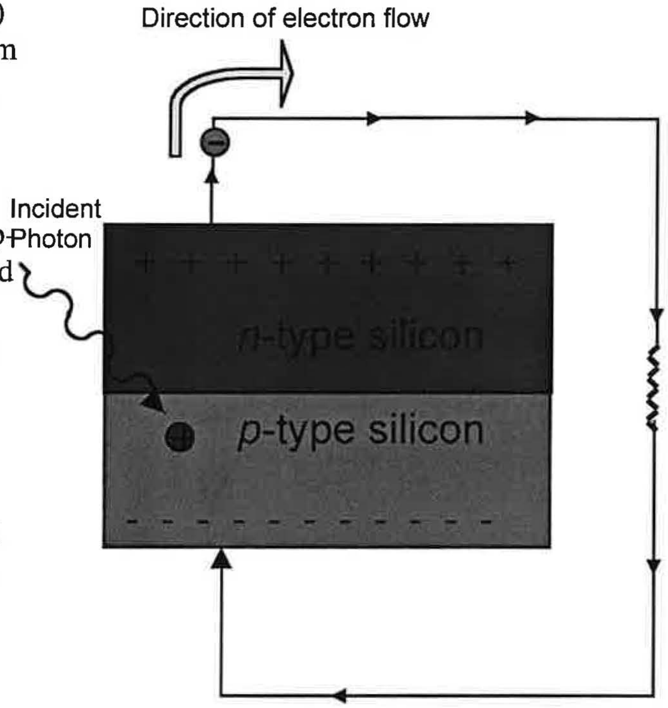


FIGURE A5. A *pn*-junction has an electric field across it. When a photon excites an electron into silicon's conduction band the electric field sweeps the electron away from the hole so that the electron can deliver energy to an external load.

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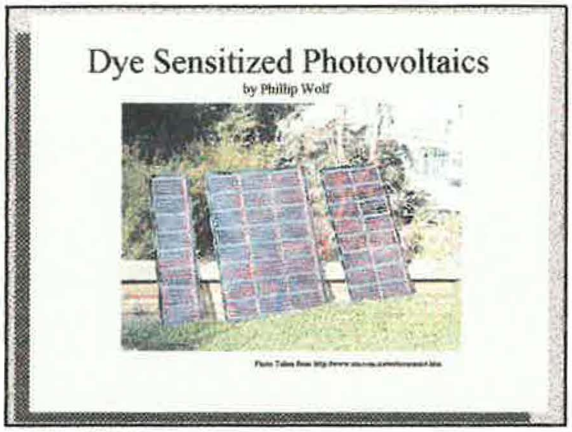
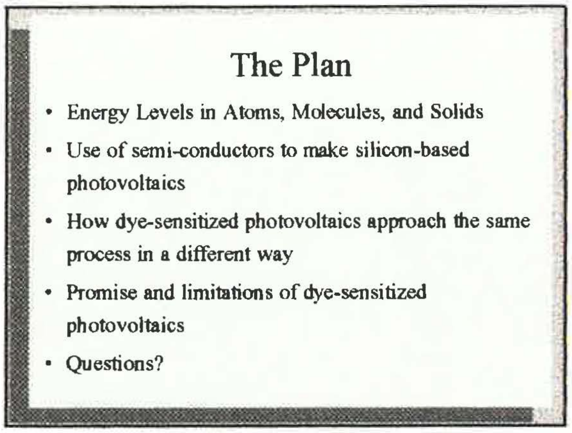


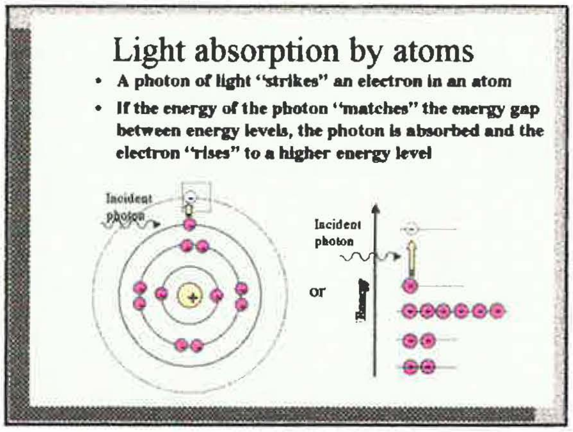
Dye Sensitized Photovoltaics

by Phillip Wolf



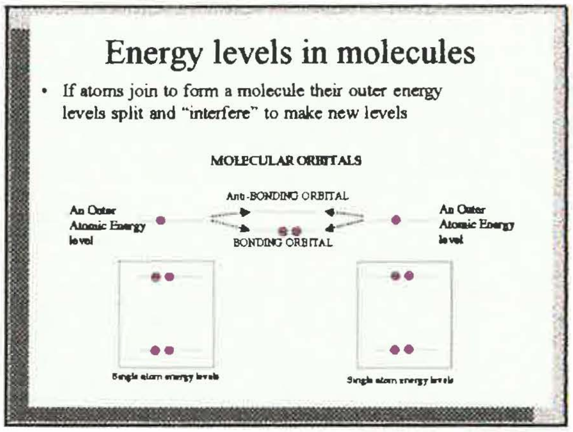
The Plan

- Energy Levels in Atoms, Molecules, and Solids
- Use of semi-conductors to make silicon-based photovoltaics
- How dye-sensitized photovoltaics approach the same process in a different way
- Promise and limitations of dye-sensitized photovoltaics
- Questions?



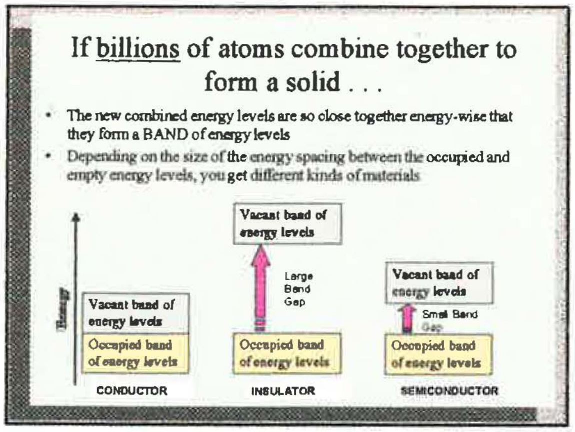
Light absorption by atoms

- **A photon of light "strikes" an electron in an atom**
- **If the energy of the photon "matches" the energy gap between energy levels, the photon is absorbed and the electron "rises" to a higher energy level**



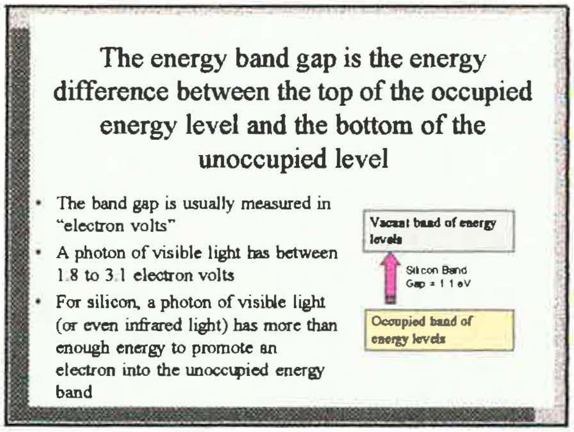
Energy levels in molecules

- If atoms join to form a molecule their outer energy levels split and "interfere" to make new levels



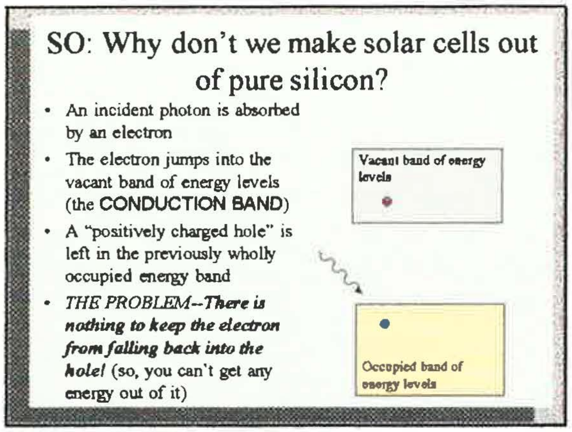
If billions of atoms combine together to form a solid . . .

- The new combined energy levels are so close together energy-wise that they form a BAND of energy levels
- Depending on the size of the energy spacing between the occupied and empty energy levels, you get different kinds of materials



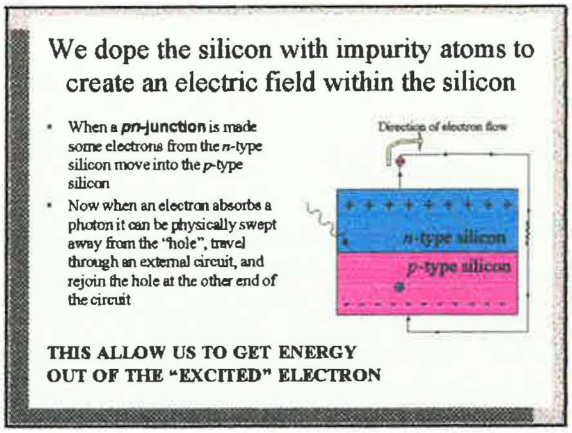
The energy band gap is the energy difference between the top of the occupied energy level and the bottom of the unoccupied level

- The band gap is usually measured in "electron volts"
- A photon of visible light has between 1.8 to 3.1 electron volts
- For silicon, a photon of visible light (or even infrared light) has more than enough energy to promote an electron into the unoccupied energy band



SO: Why don't we make solar cells out of pure silicon?

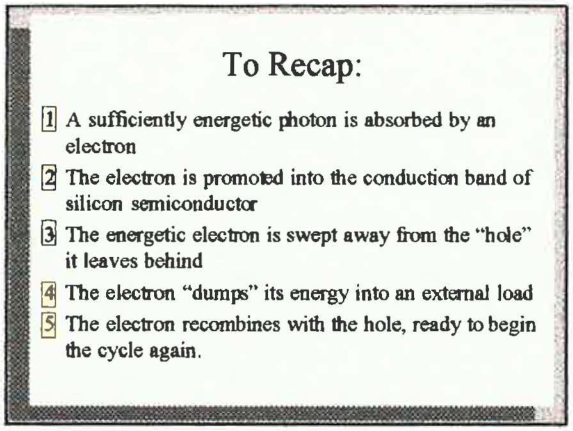
- An incident photon is absorbed by an electron
- The electron jumps into the vacant band of energy levels (the **CONDUCTION BAND**)
- A "positively charged hole" is left in the previously wholly occupied energy band
- *THE PROBLEM--**There is nothing to keep the electron from falling back into the hole!*** (so, you can't get any energy out of it)



We dope the silicon with impurity atoms to create an electric field within the silicon

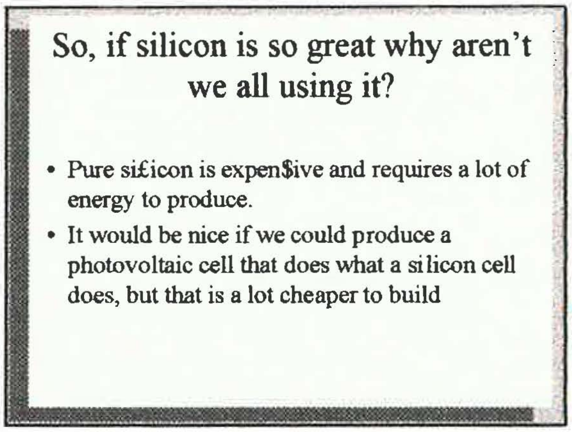
- When a ***pn*-junction** is made some electrons from the *n*-type silicon move into the *p*-type silicon
- Now when an electron absorbs a photon it can be physically swept away from the "hole", travel through an external circuit, and rejoin the hole at the other end of the circuit

THIS ALLOW US TO GET ENERGY OUT OF THE "EXCITED" ELECTRON



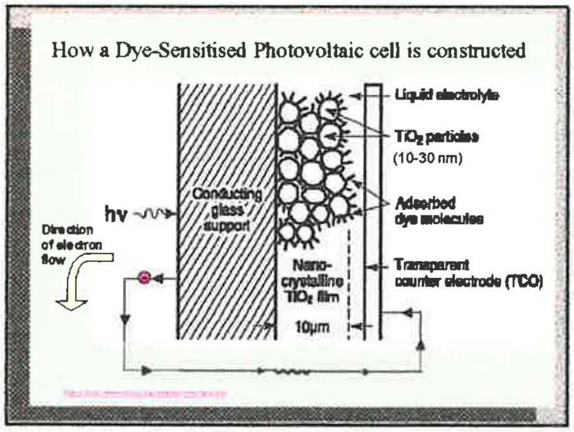
To Recap:

1. A sufficiently energetic photon is absorbed by an electron
2. The electron is promoted into the conduction band of silicon semiconductor
3. The energetic electron is swept away from the "hole" it leaves behind
4. The electron "dumps" its energy into an external load
5. The electron recombines with the hole, ready to begin the cycle again.

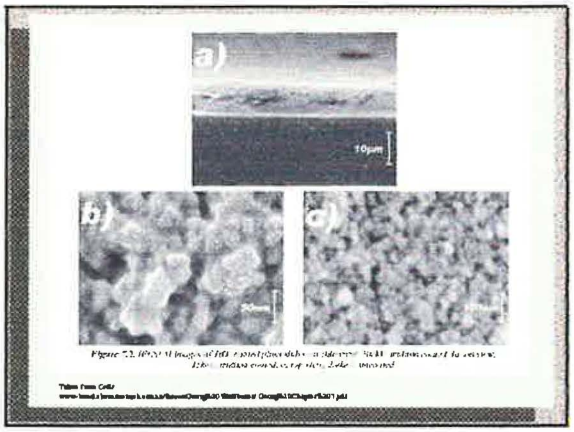


So, if silicon is so great why aren't we all using it?

- Pure si£icon is expen$ive and requires a lot of energy to produce.
- It would be nice if we could produce a photovoltaic cell that does what a silicon cell does, but that is a lot cheaper to build



How a Dye-Sensitised Photovoltaic cell is constructed



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Taken from Cells

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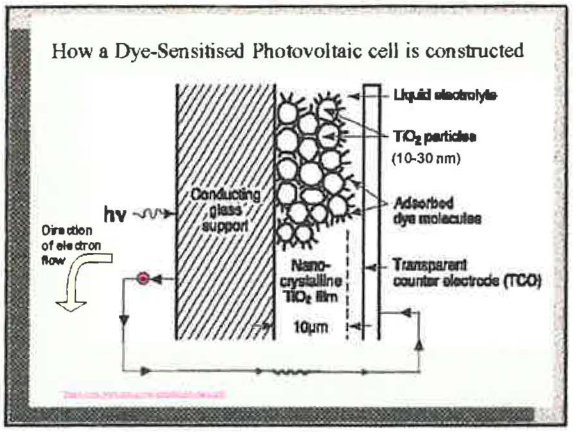
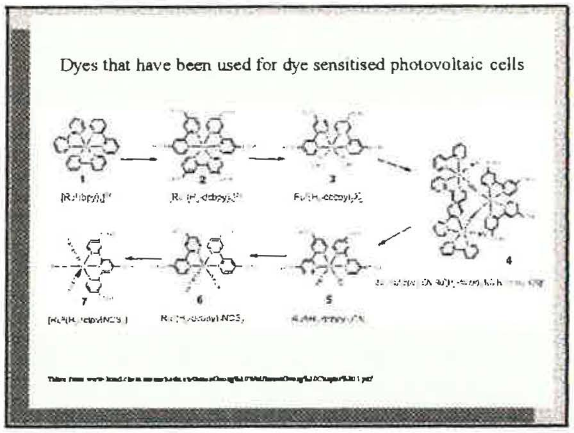
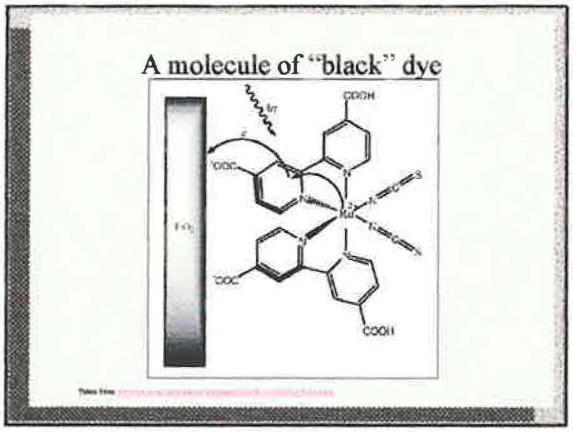


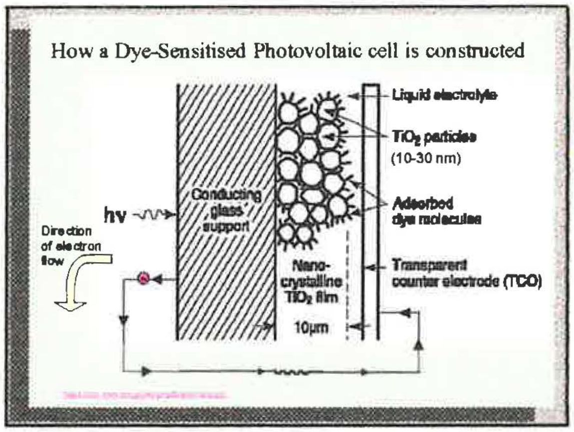
How a Dye-Sensitised Photovoltaic cell is constructed



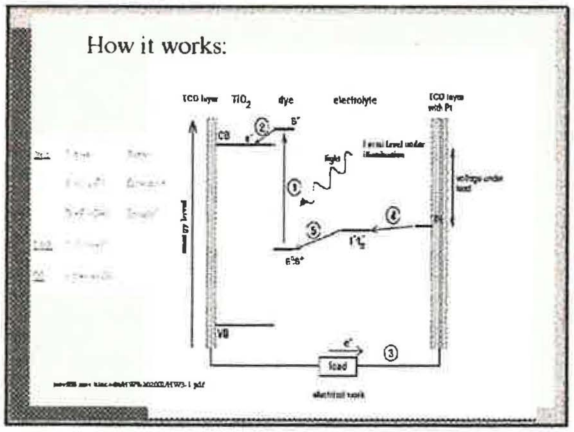
Dyes that have been used for dye sensitised photovoltaic cells



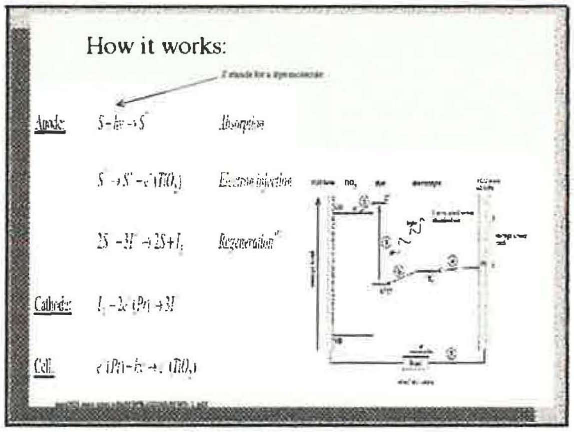
A molecule of "black" dye



How a Dye-Sensitised Photovoltaic cell is constructed



How it works:



How it works:

S stands for a dye molecule

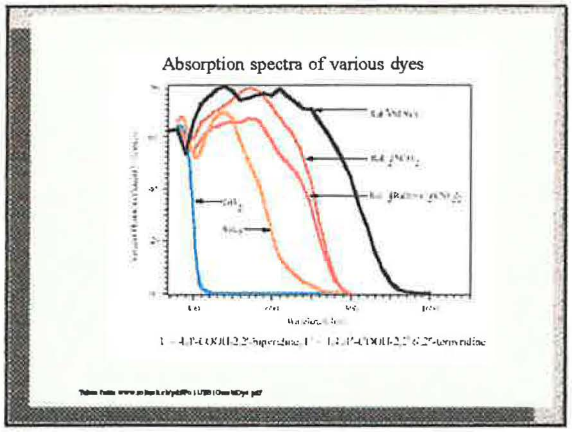
Anode: $S + h\nu \rightarrow S^*$ *Absorption*

$S^* \rightarrow S^+ + e^-(TiO_2)$ *Electron injection*

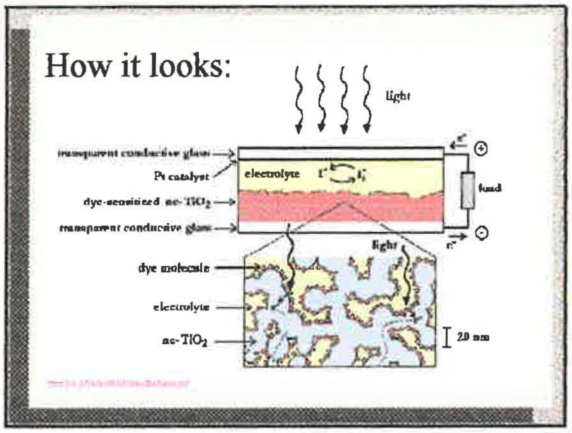
$2S^+ + 3I^- \rightarrow 2S + I_3^-$ *Regeneration*

Cathode: $I_3^- + 2e^-(Pt) \rightarrow 3I^-$

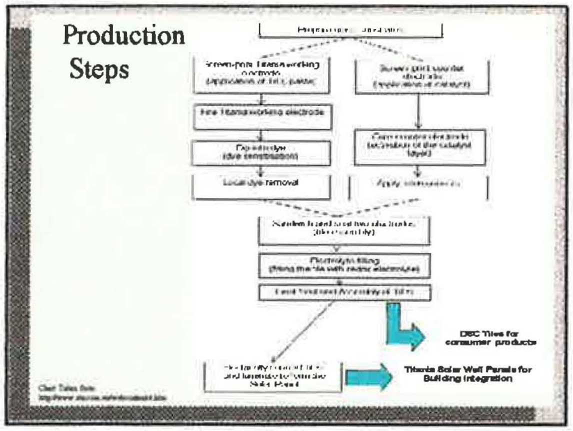
Cell: $e^-(Pt) + h\nu \rightarrow e^-(TiO_2)$



Absorption spectra of various dyes



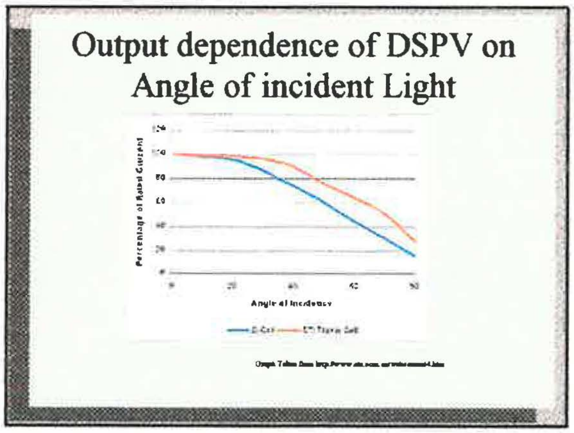
How it looks:



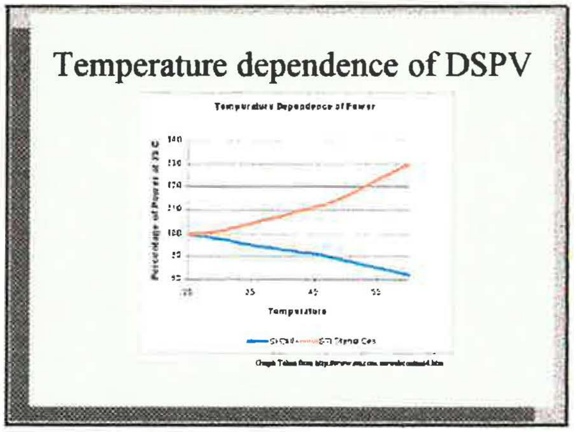
Production Steps

What makes these cells special?

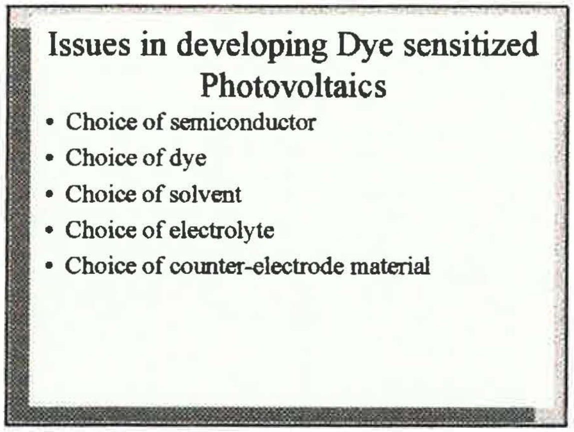
- They have a low production cost
- There is no need for highly skilled labour for assembly
- A relatively low capital investment is required to build a production plant
- The materials are relatively inexpensive
- The panels have a very low embodied energy (32 kWh/m^2 vs. over 1000 kWh/m^2 for crystalline silicon PV)
- The production methods are not environmentally unfriendly,
- They have an efficiency equivalent to present thin-film silicon devices.



Output dependence of DSPV on Angle of incident Light



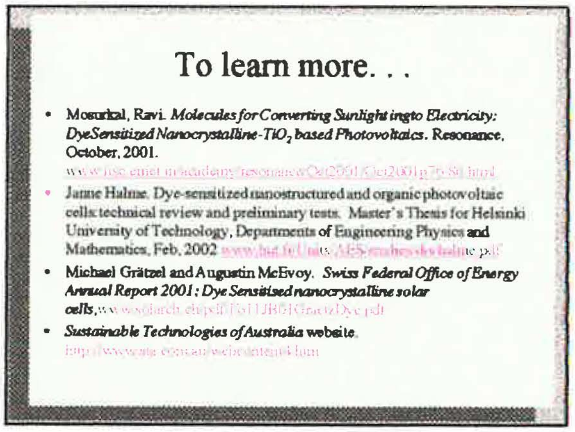
Temperature dependence of DSPV



Issues in developing Dye sensitized Photovoltaics

- Choice of semiconductor
- Choice of dye
- Choice of solvent
- Choice of electrolyte
- Choice of counter-electrode material

	Standard technology	New directions of development
Substrate	Glass	[illegible]
TCO	[illegible]	[illegible]
Counter-electrode catalyst	[illegible]	[illegible]
Electrolyte	[illegible]	[illegible]
Dye	[illegible]	[illegible]
Nanoparticle electrode	[illegible]	[illegible]
Electrical contacts	[illegible]	[illegible]
Sealing	[illegible]	[illegible]
Cell and module processing	[illegible]	[illegible]



To learn more. . .

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- Janne Halme. Dye-sensitized nanostructured and organic photovoltaic cells: technical review and preliminary tests. Master's Thesis for Helsinki University of Technology, Departments of Engineering Physics and Mathematics, Feb, 2002 www.hut.fi/Units/AES/studies/dis/halme.pdf
- Michael Grätzel and Augustin McEvoy. *Swiss Federal Office of Energy Annual Report 2001: Dye Sensitised nanocrystalline solar cells*, www.solarch.ch/pdf/[illegible]GraetzDye.pdf
- *Sustainable Technologies of Australia* website. http://www.sta.com.au/webcontent4.htm

THE UNIVERSITY OF READING
SCHOOL OF CONSTRUCTION MANAGEMENT AND ENGINEERING

MSC/PGD IN RENEWABLE ENERGY AND THE ENVIRONMENT 2002-2003

LABORATORY REPORT

Name: **Phillip Wolf** **Date submitted: 4 December, 2002**

Title of experiment: **Solar Roof for Beale Park**

Declaration of originality

In doing this laboratory work, I acknowledge that the measurements were done as a practical group, and that the results written in this report were those measured and calculated by the group on the day of the laboratory. I declare that the calculations, analysis and conclusions in the report are my own, although they may have taken into account discussions by the whole group on the results that we obtained. I understand that the normal consequence of cheating in any element of an examination, if proven and in the absence of mitigating circumstances, is that the Examiners' Meeting be directed to fail the candidate in the examination as a whole.

Signed: Phillip Wolf

For staff use:

Date received: 4/12/02

Date marked: 18 Jan 03

Mark (%): 85% nb: A*>80%, A>70%, B>60%, C>50%, D>40%, F<40%

Signed:

Comments: Excellent

4 December, 2002

Dear Sir or Madam:

Attached please find preliminary proposals for a solar roof for a proposed aviary. The specifications were that the aviary should

- Have a large flight cage area consistent in design with those you already have at the park.
- Have attached to the flight cage area a 3m x 15 m building roofed with solar panels.
- Serve as a public education tool and demonstrate your commitment to renewable energy.

What has been left unspecified is

- Power generation goals (maximum power output per £, maximum power output period, largest visual impact per square meter?)
- Budget and priorities (i.e., how the solar roof fits in with the other financial demands in the park).

As such I have proposed four alternate possibilities—two possible roof slopes, with two alternate technologies for each roof.

In the economic analysis of the project I have included the effects of

- The current British government plan which may pay up to 50-65% of the cost of a solar roof and the associated electronics and installation, depending on the roof's size and technology choices, and
- The current German government plan.

I hope that these scenarios prove helpful in assisting you in your decision about the roof. *I cannot overemphasise that the prices quoted are estimates rather than firm figures.* The actual price will depend on the technology you choose, the market price and availability at the time, and the availability of government financial incentives. It probably would be wise from the outset to involve your development expert in identifying and targeting potential donors and establishing possible naming opportunities.

In keeping with your request that this report be brief I have made a conscious effort to present only results while leaving detailed calculations and graphs to a minimum. Of course, I would be only too happy to make these available upon request
Please let me know if I can be of any further service.

Kind Regards,

Phillip R. Wolf (p.r.wolf@reading.ac.uk)
MSc student, Renewable Energy and the Environment
University of Reading, School of Construction Management and Engineering

Proposals for a Grid-Connected Solar Roof for an Aviary at Beale Park

Prepared by

Phillip Wolf
MSc programme, Renewable Energy and the Environment
University of Reading
School of Construction Management and Engineering

4 December, 2002

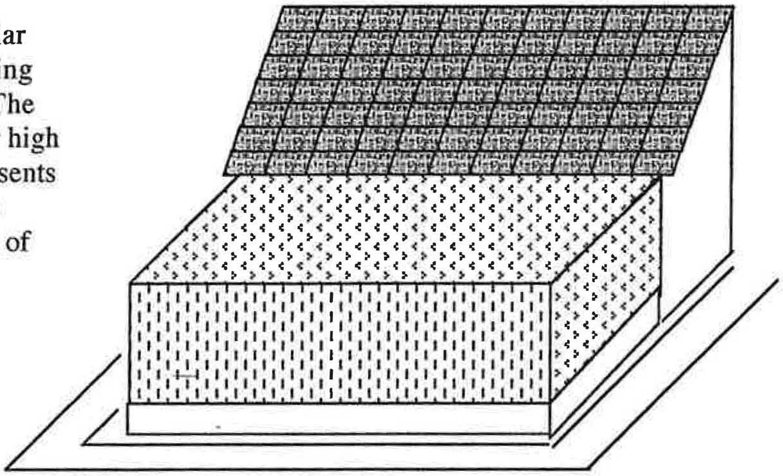
CONTENTS

GENERAL LAYOUT OF THE BUILDING

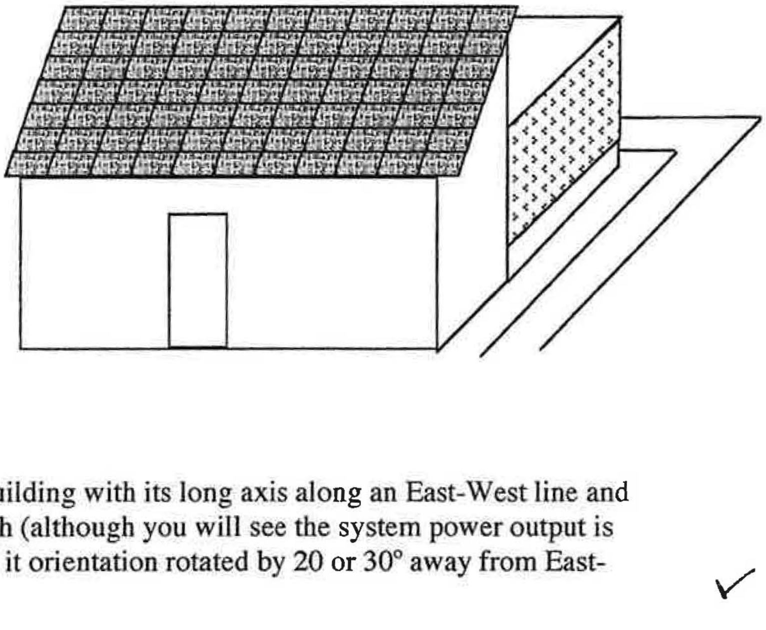
Consistent with the other flight cages in the park, my proposed design includes a small brick wall about 1/2 meter tall along the periphery of the cages, with the cages themselves about 3 meters tall and coming out 4 meters from the solid part of the building.

From where the cages abut the building I have come up with two different designs.

In the first design the solar roof faces a visitor viewing the birds in the aviary. The peak of the roof is rather high (about 7 meters) and presents a strong visual impact to visitors standing in front of the aviary.



In the second design the solar roof is on the opposite side of the building from where a visitor would stand to view the birds. The peak of the roof is closer to the ground (so the building does not have to be built quite so tall) but the solar panels are only evident to a visitor standing *behind* the aviary.



In both cases I have oriented the building with its long axis along an East-West line and the roof of the building facing south (although you will see the system power output is not particularly sensitive to having it orientation rotated by 20 or 30° away from East-West).

✓

TERMS AND DEFINITIONS

Photovoltaic (PV) Cell or Solar Cell: a "piece" of PV that produces an electrical current and voltage when light hits it.

PV Module or Solar Panel: a series of solar cells connected into a single manufactured unit to produce higher currents and voltages than an individual solar cell can produce, and to give mechanical stability to the system.

String of Modules connected in series: Modules connected to add their voltages together

Strings of modules connected in parallel: Strings of modules connected together to add their current and power output together

PV Array: The assemblage of PV modules connected together (as on a roof) to form a larger power-producing unit.

Inverter: a device that takes the PV array's direct current ("battery-like") electrical output (which can vary depending on the amount of light hitting it) and converts it to 230 Volt 50 Hertz alternating current (what you normally get out of the wall socket). The device has electronics to maximise the power output of the PV modules even as the light intensity and temperatures change. This is absolutely necessary for a grid-connected PV system as is being proposed.

Watt-peak rating: Power the solar module would put produce if it were facing the sun at noon on a sunny clear day in June in, say, Greece. Because this is not Greece and it is not always noon and the sky is not always clear, the effective intensity of the sunlight on the solar panel might be only $^1/_{20}$ of the "watt-peak rating" and you may get only $^1/_{20}$ of the power from the panel. So, a 110 Watt-peak solar panel will very rarely produce 110 Watts in the UK.

Monocrystalline PV: Photovoltaic panels where the individual solar cells are each sliced from a single crystal of silicon. These generally provide the most power output of any PV type but also are the most expensive.

Amorphous thin-film PV: Photovoltaic panels where the individual solar cells are deposited as successive thin layers of silicon atoms. This is a less costly process than making monocrystalline PV, but the resulting cells are correspondingly less efficient. The PV SYST program (describe more on the next page) assigns essentially the same price per watt for both types of PV.

useful for
your clients

SYSTEM DESIGN

There is a computer program called PV SYST that assists in choosing and matching components for a PV installation.

1. **Roof slope and building orientation:** PV SYST determined that *the roof orientation for maximum power output per square meter of surface is 30°*, tilted facing south, with the building oriented along an east-west line. The roof does NOT strictly have to be oriented like this. Below are the power penalties you pay relative to the optimum power output per square meter if you choose some other orientation for the roof or building:

South-facing roof slope	Power reduction from optimum level	Building rotation away from East - West axis	Approximate Power Reduction from optimum level
0° (horizontal roof)	-10 %	0	0 %
5°	-7.2 %	10 °	-0.2 %
10°	-4.8 %	20 °	-0.9 %
15°	-2.9 %	30 °	-2%
20°	-1.4 %	40 °	-3.5%
25°	-0.5 %	50 °	-5.4%
30° (Maximum power output per m²)	**0 %**	60 °	-7.4 %
35°	-0.1 %		
40°	-0.6 %		
45°	-1.7 %		
50°	-3.2 %		
55°	-5.2 %		
60°	-7.7 %		
70 °	-13. 9%		
80 °	-21. 9%		
90°	-30.8 %		

It is useful to note that output is not particularly sensitive to deviations from the "optimum" orientation. Two of the proposed scenarios involve a roofs tilted at 55° rather than 30°, which gives a 5.2% reduction in power per square meter of roof, but about 50% more roof area.

That the output is not particularly sensitive to roof orientation has to do with the diffuse nature of sunlight in the UK. Because of England's frequently moisture-laden skies, much of the sunlight that reaches the PV is scattered by clouds in all directions before reaching the ground, so the actual amount of sunlight hitting the PV is close to being the same over quite a range of angles.

It is possible to optimise the angle of the PV modules to maximise output for a particular time of year. For instance, one can produce a bit more power in the winter by making the roof angle steeper (so that the incoming sunlight is hitting the PV more "head-on") but that slight increase in production in winter is more than wiped out by corresponding decreases in efficiency in the summer (when the sun is higher in the sky and you are generating more power). ✓

again, this effect would be larger if the fraction of diffuse was smaller

Since this is a grid-connected system it is probably best to optimise the total annual output (which is what the above table is calculate for). ✓

2. **Estimating the electrical output in kWh for monocrystalline and amorphous PV**: Since the floor area to be covered is 3m x 1 5m, the roof (being built at an angle with the horizontal) will be LARGER than 45 m². As the roof gets steeper you can cover it with a larger area of PV,
I have estimated the output using a roof sloped at 30° and at 55° for monocrystalline and amorphous PV. The monocrystalline PV using incoming solar energy more efficiently, but it is correspondingly more expensive.

Roof angle	Approximate Roof Area	Approximate Active Area*	Type of PV	Estimated Annual Output
30°	52 m²	48 m²	Monocrystalline	5200 kWh
			Amorphous	2240 kWh
55°	82 m²	77 m²	Monocrystalline	7400 kWh
			Amorphous	3700 kWh

*The active area is that part of the PV module actual covered with photovoltaic material and able to intercept sunlight ✓

3. **How well the PV system will match electricity demand at the park:** Your largest electricity demand occurs in the winter, when the sunlight is the least intense, and the output from the roof would be the smallest. Your smallest electricity demand is in the summer, when the roof's electrical output would be the greatest.

   Below is a table based on the electricity bills you have provided, comparing your average daily use with the output from the LARGEST of the four proposed roofs.

Season	Average Daily Electricity Use	Average System Daily System Output for the LARGEST system
November to January	95 kWh/day	8 kWh/day
February - April	72 kWh/day	20 kWh/day
May-July	54 kWh/day	30 kWh/day
August-October	66 kWh/day (estimated)	24 kWh/day

Would there be problems with supplying too much ~~electric~~ of the demand from PV.?

SYSTEMS SUMMARY (Explanatory notes are on the next two pages):

Notes		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
	Roof slope	30°	55°	30°	55°
	Building orientation	East-west, south-facing roof	East-west, south-facing roof	East-west, south-facing roof	East-west, south-facing roof
1	Module type	Monocrystalline	Monocrystalline	Amorphous	Amorphous
	Specific Module	Siemens Solar M110	Siemens Solar M110	Unisolar SSR-60	Unisolar SSR-120
2	"Watt-peak" rating of each panel	110 Watts	110 Watts	60 Watts	120 Watts
	Individual Panel dimensions	1.321 x 0.660m^2	1.321 x 0.660m^2	2.896 x 0.406 m^2	5.479 x 0.4064 m^2
	Number of Panels in a "string" or series	11	11	15	9
	Number of "strings	5	8	3	4
	Total # solar panels	55	88	45	36
3	Roof Watt peak rating	5.8 kilowatts	9.2 kilowatts	2.7 kilowatts	4.3 kilowatts
4	Inverter type	Fronius IG60 EI (4.6 kW,150-400 V)	Sunmaster QA 500 (3.5 kW, 100-380 V)	Solarmax 2000 (1.8 kW, 90-450 V)	Sitop Solar Master (1.5 kW, 175-550 V)
	Number of Inverters	1	2	1	2
5	Projected Yearly Power output	5200 kWh	7400 kWh	2240kWh	3700kWh
6	Estimated cost of the PV (including wiring, inverters, supports, etc)	£28200-36700	£44800-58200	£17800-23100	£29300-38100
7	Foregone cost of roofing (52 m^2 at £100 m^2)	£5200	£5200	£5200	£5200
8	Estimated UK Gov't contribution to the cost of the PV	£18300-23800	£29100-37800	£8900-11500	£14600-19000
9	REAL additional cost borne by the TRUST to install the PV	£4700-7700	£10500-15200	£3700-6400	£9500-13900
10	Annual Value of Renewable Obligation Credits (@ £30/MWh)	£170	£220	£70	£110
11	Annual savings on Electric Bills (@ 6.5 p/kWh)	£340	£480	£145	£240
	Annual Savings by installing PV (#10+#11 above)	£510	£700	£215	£350
12	Payback time for PV system	~9-15 years	~15-22 years	~17-30 years	~27-40 years

p. cannot get ROCS unless you sell to the grid [illegible] the price determined by the contract with purchaser, but probably ~2p/kWh.

NOTES for System Summary Table

1. *Module type*: Monocrystalline PV gives the highest output per unit area relative to amorphous or "thin film" PV. It is also correspondingly more expensive. Scenarios 3 and 4 give you the option of having visual impact of the PV without the larger initial price tag.

2. *Watt-peak Rating, panel dimensions, Number of panels in a string, number of strings of modules, total number of solar panels*: I chose modules of reasonable size and power that could be combined to "fit" the proposed roof. These particular numbers were chosen to cover the roof and to optimise the choice of inverter (see next)

3. *Roof Watt-peak rating*: How much power the roof would produce at noon on a sunny summer day in Greece. Although you will virtually never get that output from the roof in the UK, the UK government's support scheme for PV is based on the Watt-peak rating of the roof.

4. *Inverter type and number*: An inverter is most efficient when it is operating in the top 80% or so of its rated power range. So, although a string of eleven 110 watt-peak panels could in theory produce 1.21 kilowatts in Greece, that will virtually never happen in the UK. The watt rating of the inverter needs to be a bit "undersized" so that even on a cloudy day in the UK you are still in the efficient range of the inverter. The amount of power you lose from not being able to take advantage of those few extremely sunny British days is much less than what you would lose if you chose a larger inverter. ✓

   The second factor that goes into choosing an inverter is the voltage range in which it operates. It must include both the highest possible voltages your PV modules might produce, as well as the lower values that the PV will produce on a more typical cloudy day.

   The number of inverters was selected to make the power and voltage work out right. ✓

   nb. highest are open circuit & cld. lowest are max power and hot.

5. *Projected yearly power production*: PV SYST takes the hourly solar incident power values for London for the entire year 1991 and uses them to estimate the annual output of the particular array of PV modules given the choice of inverters. ✓

6. *Cost of the PV system*: PV SYST **estimates** the cost of a system (including inverters, wiring, installation, etc.) based on general costs of PV. When you specify a particular system it **estimates** the system costs using a different set of general values and comes up with different numbers! I have included a 30% range in price to anticipate real costs more reasonably.

   5000 ~

NOTES for System Summary Table (continued)

7. *Foregone cost of roofing*: Since you would have had to put SOMETHING on the roof anyway, the best way to look at the cost of installing PV is to ask*: How much ADDITONAL money is the PV costing over and above the price of installing a conventional roof?* I am assuming here that the normal roof would have been sloped at 30°, consistent with the roof angle on most of the other similar buildings in the park. I am assuming that roofing (and the associated structure) would be about 3.5 m x 15 m and cost £100/m^2 and would therefore cost about £5200. The additional cost of adding PV is the price of the PV minus the £5200 you would have had to spend for a roof anyway.

8. *Estimated UK Gov't contribution to the cost of the PV*: There is a UK government scheme that reimburses individuals and charities part of the cost of installing grid-connected PV. The funding covers the cost of the modules, inverters, installation, connection, and warranty but not unrelated building works. You must submit your application BEFORE you start the work, and complete it within 6 months of getting the plans approved.

   As of this date the reimbursement rate is 50% of the cost for installations of less than 5-kilowatt peak (the 3rd and 4th scenarios I proposed). The grant approval is fairly automatic. The government will issue you a Grant Offer Letter before you begin the work but will not actually give you any funds until the work is complete. ✓

   The government scheme will fund up to 65% of the cost for installations of between 5 and 10 kilowatt peak (the 1st and 2nd scenarios I proposed). Here you can receive up to 70% of the government contribution as a grant <u>before</u> the actual work begins, and the balance after the work is completed and inspected. This grant is ✓ awarded through a competitive selection process.

   The actual reimbursement comes out of a fixed pool of funds (£20 million) for the 2002-2003 year. It is my interpretation that if the number of applications is very large the reimbursement may be less than 50% (or none if the funds run out for this year).

   The details of the grants are given at www.est.co.uk/solar/. ✓

9. *Real cost of the PV to the Trust*: This assumes that you include the foregone cost of roofing AND receive the maximum UK government contribution ✓

10. *Annual Value of Renewable Obligation Credits*: Renewable Obligation Credits (ROCs) are a government incentive to electricity suppliers to encourage them to buy electricity generated from renewable resources. The current market price of ROCs is around £30 per1000 kWh, which you can receive from your electricity supplier

11. *Annual savings on Electric Bills*: This is calculated assuming that the PV produces the estimated annual output, and that you are paying 6.5 pence/kWh. ✓

12. *Payback time for PV system*: This is calculated by taking the "real cost" of the system and dividing by the annual savings and revenue from the electricity generation and the ROCs. **This is an admittedly simple model for calculating payback time.** If you take into account the cost paying interest on a loan, the PV system may NEVER pay back the initial financial costs.

indeed

Economic Summary under the German Government Support System

Under the Germans support system

- you would get a ten-year 1.9% interest loan with no payments for the first two years, and
- The government guarantees that you can sell the electricity you produce for €0.5 (£0.33) per kWh the first year, with the amount per kWh decreasing by 5% per year. They guarantee this price for 20 years.

The table below summarises the economic results under the German program, looking at the low and high estimates for the initial system cost:

	Scenario 1 (30° slope, monocrystalline PV)		Scenario 2 (55° slope, monocrystalline PV)		Scenario 3 (30° slope, amorphous PV)		Scenario 4 (55° slope, amorphous PV)	
System Cost Estimate	LOW EST. £28200	HIGH EST. £36700	LOW EST. £44800	HIGH EST. £58200	LOW EST. £17800	HIGH EST. £23100	LOW EST. £29300	HIGH EST. £38100
Total payments you'd make over 10 years	£32000	£41000	£51000	£60000	£20000	£26000	£31000	£43000
Total money you'd receive for your electricity over 20 years*	£22000	£22000	£31000	£31000	£9500	£9500	£16000	£16000
Amount you'd be "in the hole" after twenty years	£10000	£19000	£20000	£29000	£10500	£16500	£15000	£25000

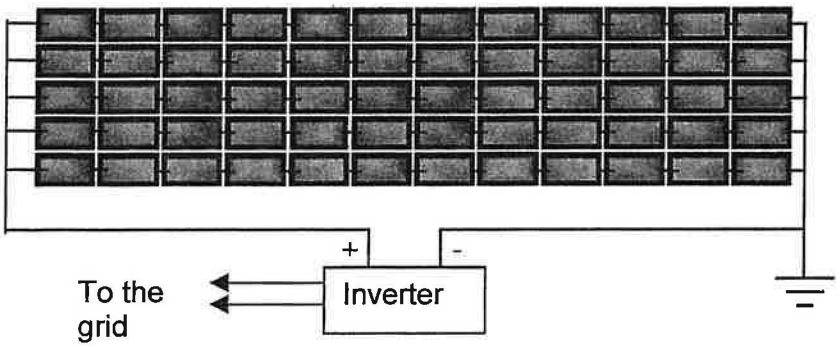
I got £[illegible]230 for 8 payments on £28200 – agree in principle though

* This assumes that you are receiving the guaranteed minimum price for the electricity you produce. It is quite possible that at the latter end of the 20-year period the price of electricity would be higher than this minimum, and you'd receive more than what I have estimated here.

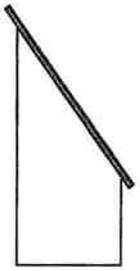
yes

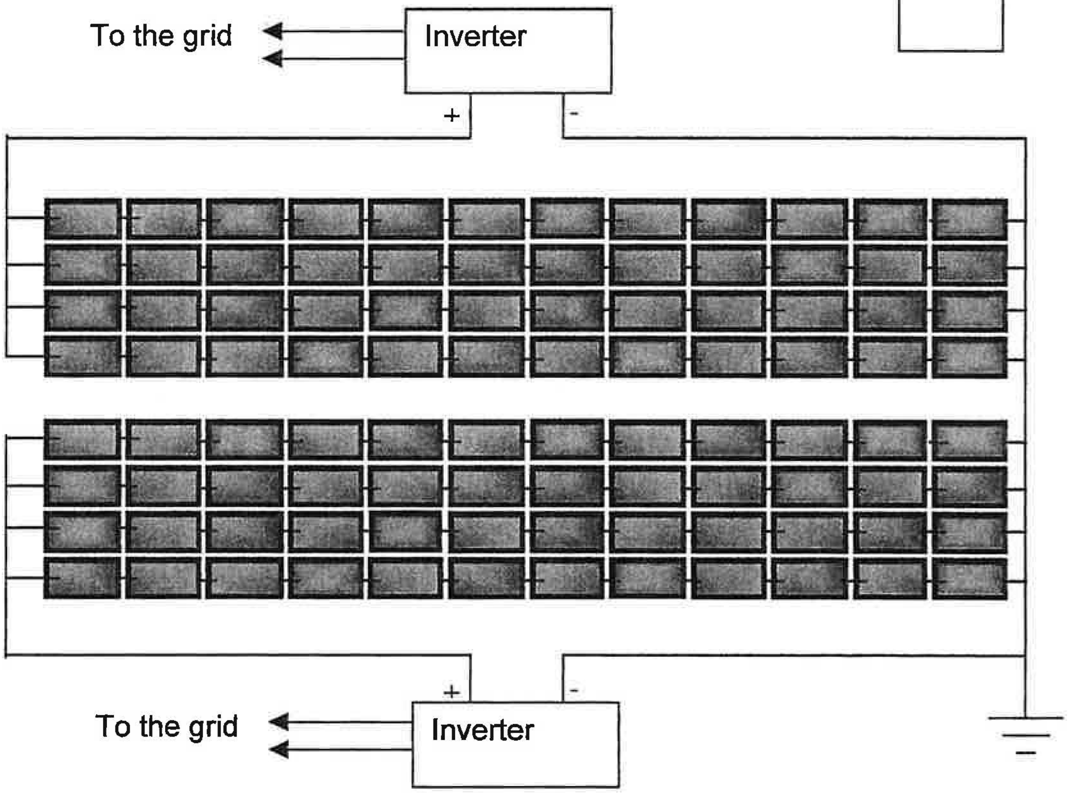
Module and Roof Dimensions; Electrical Layout

Scenario 1: 30° slope, monocrystalline PV. Each module 1.326 m x 0.66 m.
Total roof dimensions approximately 15 m x 3.5 m

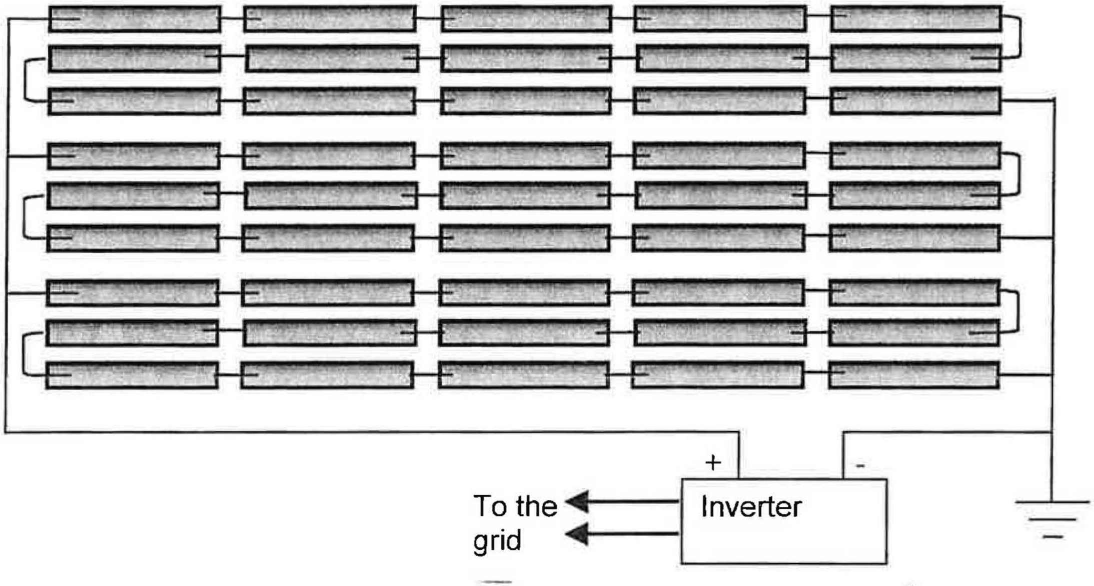


Scenario 2: 55° slope, monocrystalline PV.
Each module 1.326 m x 0.66 m.
Total roof dimensions approximately 15 m x 5.6 m

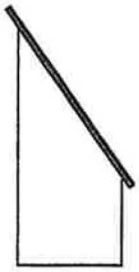


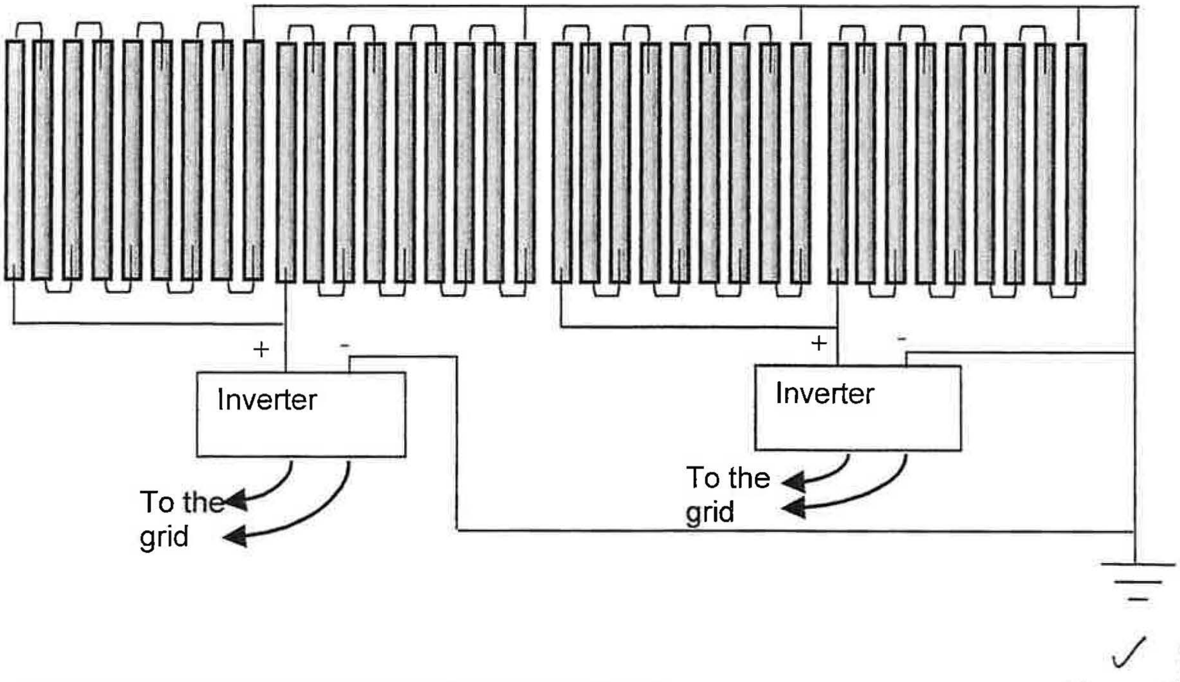


Scenario 3: 30° slope, amorphous thin-film PV.
Each module 2.896 m x 0.406 m.
Total roof dimensions approximately 15 m x 4 m
(panels cover almost the entire width of the roof)



Scenario 4: 55° slope, amorphous thin-film PV.
Each module 5.48 m x 0.41 m
Total roof dimensions approximately 16 m x 5.6 m



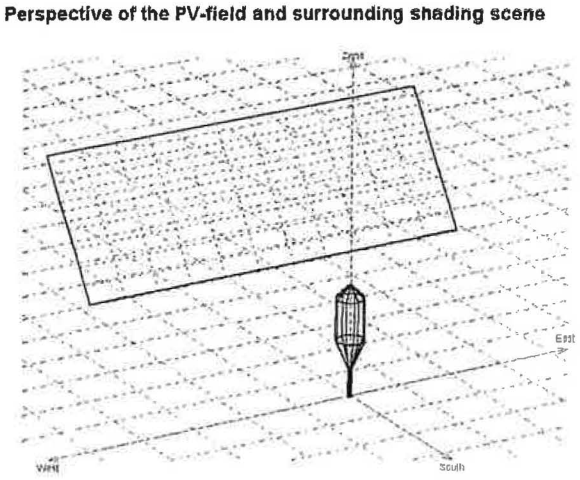


✓

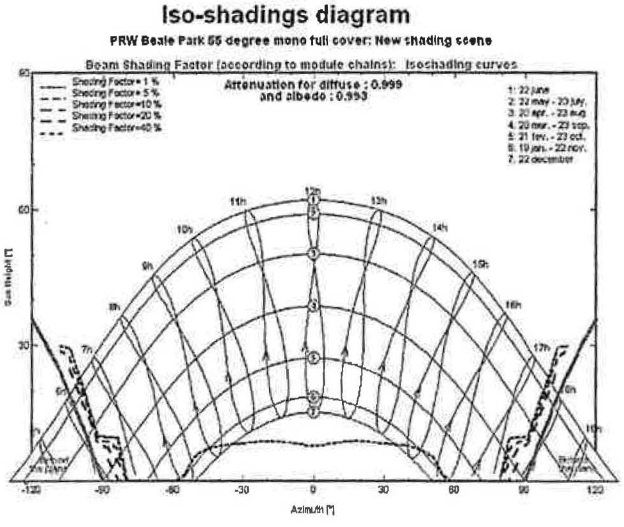
nb. useful but not essential to have a neat geometrical layout. Shading might influence choice of vertical or horizontal

Effect of a shading object on array electrical output

I looked at the effect a 4 meter tall tree located 5 meter from the array would have on the total electrical output of the solar roof over the year. PV SYST has a modeling tool that lets one do such analyses.



The iso-shadings diagram at right shows at what times of year and what times of day the solar roof would be shaded. It turns out that the tree would only shade a very small part of the roof, and then only in the early morning and late afternoon in winter when the amount of sunlight striking the roof is very little anyway. ✓



The total effect of the shading in this particular simulation was to reduce the annual output of the PV array by 7 kWh over the entire year, or by about 0.1% of the total annual output. ✓

yes - just have to make sure that it does not grow.

REFERENCES:

For information on the British government PV Scheme

The Major Photovoltaic Demonstration Programme: Guidance Notes and Scheme Conditions for Small Scale Photovoltaic Grant Applications. Department of Trade and Industry. The Guide and Forms can be download from the web at www.est.co.uk/solar/

The Major Photovoltaic Demonstration Programme: Guidance Notes and Scheme Conditions for Medium and Large Scale Photovoltaic Grant Applications. Department of Trade and Industry. The Guide and Forms can be download from the web at www.est.co.uk/solar/

For information on the German government PV Scheme

Sensational German Renewable Energy Law and its Innovative Tariff Principles. A speech delivered to EUROSUN 2000 conference in Copenhagen, Denmark on 20th June 2000 by Preben Maegaard, Folkecenter for Renewable Energy, Denmark and EUROSOLAR.
www.folkecenter.dk/en/articles/ EUROSUN2000-speech-PM.pdf

ALL SIMULATIONS WERE RUN USING PV-SYST version 3.2 ✓

BIOMASS MODULE—STOVE PRACTICAL

Phillip Wolf
MSc course in Renewable Energy and the Environment, 2002-2003

Lab partners: Nikos Katsouvas, Julian Elsworth, Seyhan Turan

TABLE OF CONTENTS

Biomass Practical--Ethiopian Stove

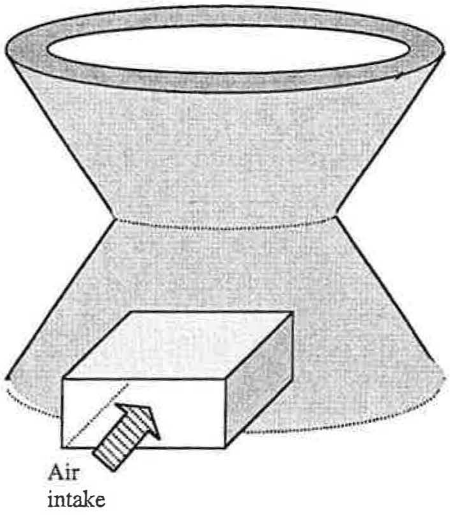
The purposes of the practical are:

⇨ to determine the efficiency of an Ethiopian charcoal-fueled stove in a simulated rice cooking exercise. We define efficiency in terms of how much of the total calorific value of the charcoal burned goes into raising the temperature of some water from roughly 20°C to its boiling point.

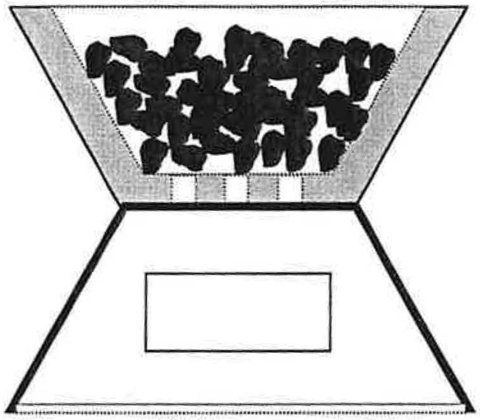
⇨ To calculate the heat balance for the stove. That is, to determine where the heat from the burning charcoal goes.

⇨ To determine the primary mode of heat transfer (convection or radiation) from the charcoal to the pot on the stove

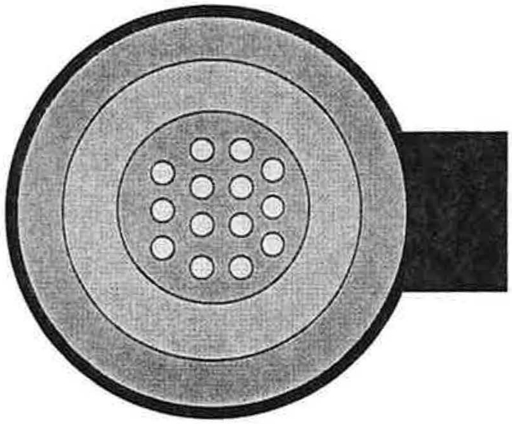
⇨ To suggest possible improvements to the design of the stove.



ETHIOPIAN STOVE: The stove is made of two truncated metal black-painted cones welded together as shown. The upper "cone" has a ceramic lining about 3.5 cm thick onto which the charcoal is placed. A cooking pot is suspended directly above the stove.



Side view of the Ethiopian stove showing charcoal placement, primary air intake, and holes in the bottom of the ceramic lining to allow entrance of the primary air.



Top view of the Ethiopian Stove

General approach

Our model is that in order to cook rice, water has to be brought to a boil quickly and then kept at a boil. We are simulating this by putting about 2 kg of cold water into a pot and allowing a total of 30 minutes for the water to be brought to a boil and for simmering.

We monitor the stove's performance by using several sensors connected to an Apple IIe computer. The computer records data from the sensors every minute.

The computer records the following measurements:

CHANNEL 1	Ambient air Temperature (°C)
CHANNEL 2	Outside Stove Wall Temperature (°C)
CHANNEL 3	Inside Stove Wall Temperature (°C)
CHANNEL 4	Stove Bed Temperature (°C)
CHANNEL 5	Air temperature directly under the pot (°C)
CHANNEL 6	Temperature of the water in the pot (°C)
CHANNEL 7	Temperature of the pot lid (°C)
CHANNEL 8	Intake air temperature (°C)
CHANNEL 11	Weight of the Charcoal + Stove + platform (kg)

Procedure:

We measured the various dimensions of the stove, pot, and lid (see the next page for details).
We weighed the pot and lid and then added approximately 2 kg of water to the pot.
We weighed out approximately 400 grams of wood-derived charcoal into the stove, and ignited the charcoal with a lit paraffin charcoal starter.
We suspended the pot such that the pot bottom was 1.5 cm above the top of the stove.
We had the computer commence making measurements.

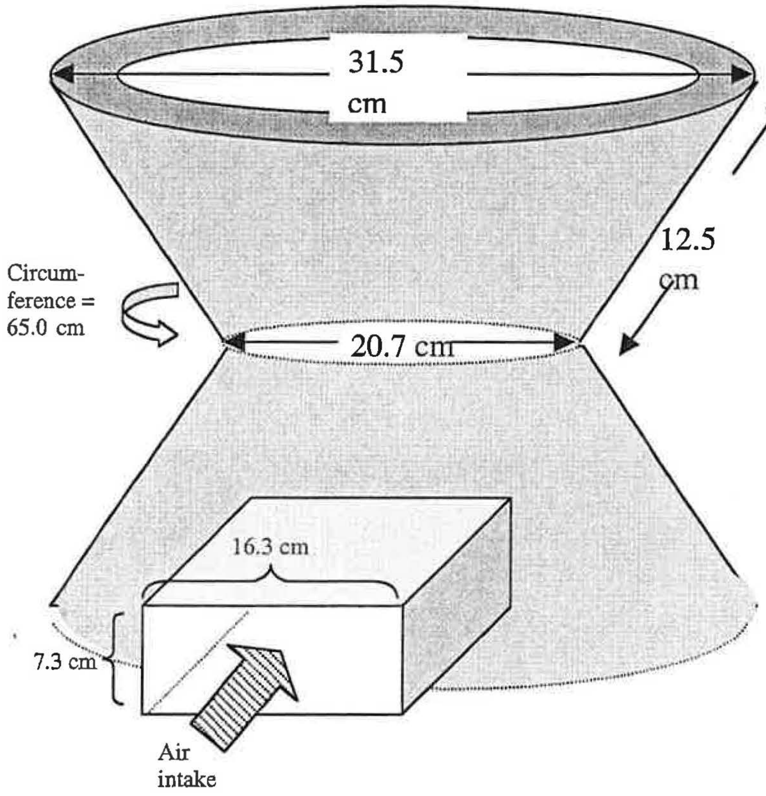
After the 30-minute period was up we obtained a new 2 kg of cold water and somewhat refilled the stove with charcoal. We re-suspended the pot in the same position as before and had the computer take data for another 30 minutes.

MASS DATA FOR WATER, POT, AND LID

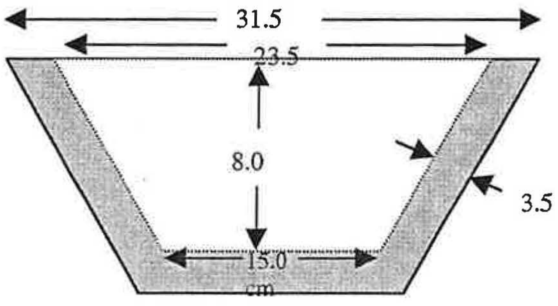
	TRIAL 1	TRIAL 2
Mass pot with lid (kg)	0.895	0.895
Initial mass of pot with lid and water (kg)	2.897	2.897
Mass of pot with lid and water after 30 minutes on the stove(kg)	2.297	2.534
Initial mass of water (kg)	2.002	2.002
Final Mass of water (kg)	1.402	1.639
Mass of water turned to steam (kg)	0.600	0.363

DIMENSIONS FOR STOVE, POT, and LID

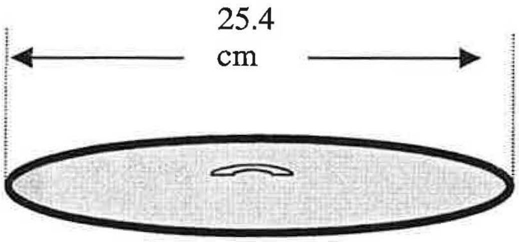
The data below are for the dimensions of the stove.
The lab handout states that the mass of the stove is 8 kg, and that its specific heat capacity is 0.835 kJ/kg K



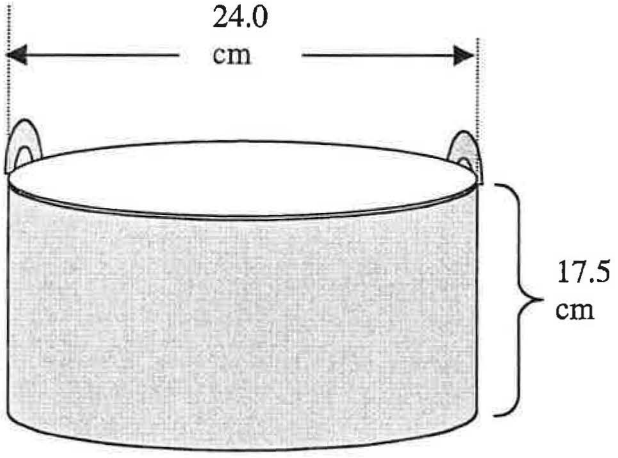
STOVE DIMENSIONS



STOVE—Interior Dimensions



POT LID DIMENSIONS



POT DIMENSIONS

THEORY: HEAT BALANCE IN THE EXPERIMENT

The source of energy in the experiment is the burning charcoal. All of the heat released from the charcoal is considered to have been transferred into one of five basic "places":

1. Energy radiated by
   a. the stove sides,
   b. the pot sides, and
   c. the pot lid.
2. Energy transferred by convection from
   a. the stove sides,
   b. the pot sides, and
   c. the pot lid.
3. Energy that goes into heating up
   a. the water
   b. the pot
   c. the pot lid
   d. the stove
4. Energy that goes into vaporizing water
5. Energy that goes into the exhaust gases.

The first four can be calculated from the lab data using the general methods described below. The energy that goes into the exhaust gases can be considered to be all of the original energy available in the charcoal that can NOT be accounted for by any of the other means.

CALCULATIONS SECTION:

1. NET ENERGY RADIATED BY A HOT SURFACE

In general the net power radiated from a hot surface (in watts) is given by

$$P = \varepsilon \sigma A (T_{hot}^4 - T_{ambient}^4)$$

where

ε is the emissivity of the surface

σ is the Stefan constant (5.67E-08 $W\ m^{-2}\ K^{-4}$)

A is the area of the radiating surface, and

T_{hot} and $T_{ambient}$ are the temperatures of the radiating object and its surroundings, respectively, in Kelvin

In our particular case we have measured the temperature of various hot objects once every minute over a thirty-minute period. The total energy radiated should be given by

$$H = \int P\, dt$$

In practice the way we evaluate this integral is:

- ⇨ Calculate the *average* value of P for any given time interval
- ⇨ Multiply that average value by the time length of the interval (60 seconds, in this case), and
- ⇨ Sum up the energies from the thirty one-minute intervals.

That is, $H = (P_o + P_1)/2\ \Delta t + (P_1 + P_2)/2\ \Delta t + \ldots + (P_{29} + P_{30})/2\ \Delta t$

$$= [0.5\ P_o + (P_1 + P_2 + \ldots + P_{29}) + 0.5\ P_{30}]^*\ \Delta t$$

2. NET ENERGY TRANSFERRED FROM A HOT SURFACE BY CONVECTION

In general the net power lost to convection from a hot surface (in watts) is given by

$$P = h\ A\ (T_{hot} - T_{ambient})$$

where

h is the heat transfer coefficient (taken to be 8 W m^{-2} K^{-1})
A is the area of the radiating surface, and
T_{hot} and $T_{ambient}$ are the temperatures of the hot object and its surroundings, respectively, in Kelvin

The method of calculating the <u>total</u> heat transferred from a surface by convection is entirely analogous to the one for radiation above, except that the expression for each P is different.

3. HEAT ENERGY "SPENT" IN WARMING UP AN OBJECT

The energy required to raise the temperature of an object of mass m by an amount ΔT is given by;

$$H = m\ c_p\ \Delta T$$

where c_p is the specific heat capacity of the material

4. HEAT ENERGY "SPENT" IN TURNING WATER TO STEAM

The energy required to convert a mass m of water at its boiling point to steam is given by

$$H = m\ L_v$$

where L_v is the latent heat of vaporization of the water (2260 KJ/kg)

Details of calculations **(for radiation and convection the integrations are carried out on the spreadsheet):**

CALORIFIC INPUT FROM THE CHARCOAL:

The energy provided by the burning charcoal is simply

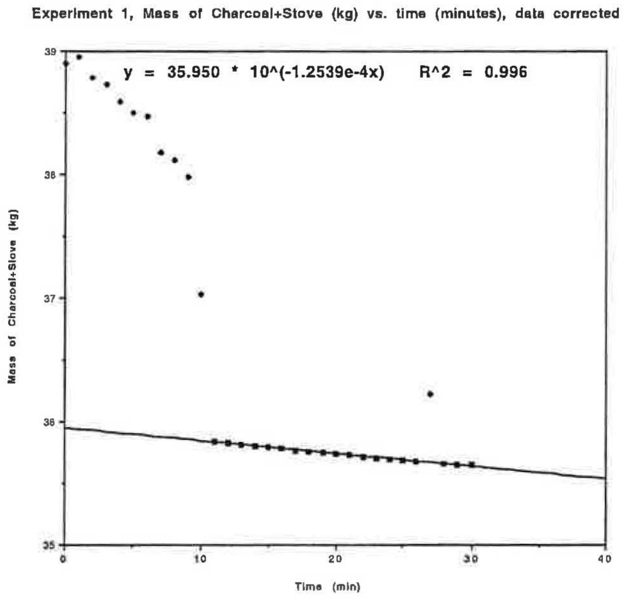
$$\left(\begin{array}{l}\text{Mass of}\\ \text{charcoal}\\ \text{burned}\end{array}\right) \times \left(\begin{array}{l}\text{Calorific}\\ \text{value of the}\\ \text{charcoal}\end{array}\right)$$

Under ordinary circumstances one would calculate:

$$\begin{array}{l}\text{Mass of}\\ \text{charcoal}\\ \text{burned}\end{array} = \left(\begin{array}{l}\text{Mass of}\\ \text{stove +}\\ \text{charcoal}\end{array}\right)_{\text{final}} - \left(\begin{array}{l}\text{Mass of}\\ \text{stove +}\\ \text{charcoal}\end{array}\right)_{\text{initial}}$$

In our second trial (starting with the stove already hot) this is not a problem. Unfortunately, for the first trial we started out with the pot sitting on top of the charcoal. Thus, until about 12 minutes into the trial (when Dr. Fulford jiggled the pot so that the charcoal settled into the stove) the mass being recorded by the sensor included the mass of the pot.

We decided to plot the mass data anyway and use the masses from t=12 minutes and beyond to work backwards to find the original mass of the stove + charcoal, which turns out to be 35.95 kg. The graph is shown below:

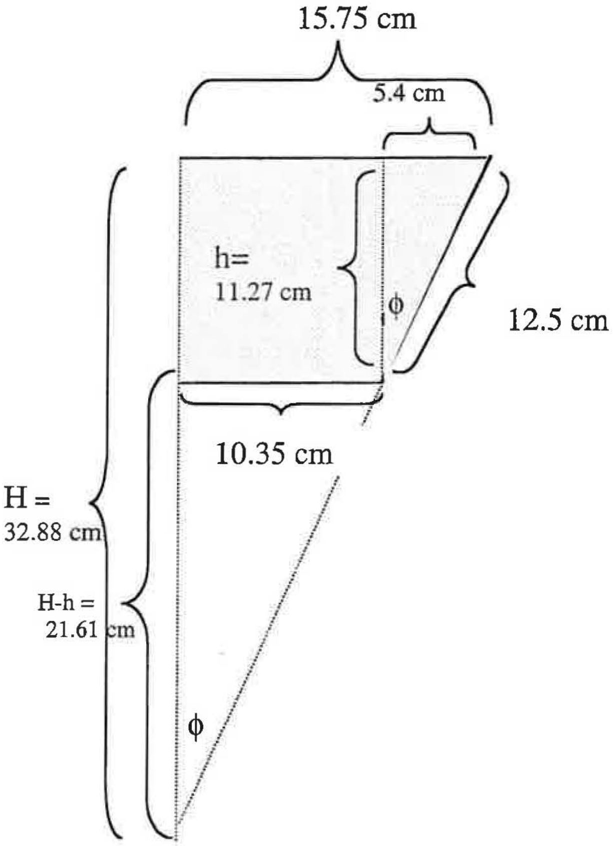


This gives, for trial 1, H = (35.95-35.65) kg x 31000 kJ/kg = 9300 kJ
For trial 2 we get H = (35.497 – 35.355) kg x 31000 kJ/kg = 4402 kJ

Details of calculations (continued):

1a. Energy radiated by the stove sides:

$\varepsilon_{\text{stovesides}} = 0.98$
radius of top of stove = 15.75 cm
radius of "waist" of stove = 10.35 cm

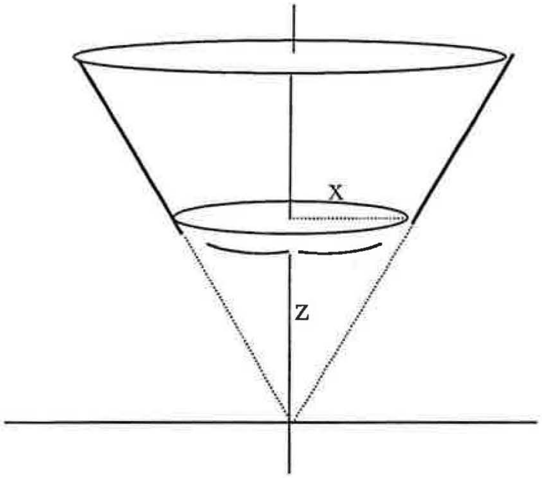


Bits needed to get the area of the stove sides (shown in ray on the diagram):

$\phi = \sin^{-1}(5.4/12.5) = 25.6^\circ$

Height H of the cone defined by the stove:
$H = 15{,}75\ \text{cm} / \tan\phi = 32.88\ \text{cm}$
Height h of the "stove section" of the cone
$h = \sqrt{(12.5^2 - 5.4^2)} = 11.27\ \text{cm}$

Surface area of a cone.



dA (surface area of the strip) $= 2\pi x\, dz/\cos\phi = 2\pi(z\tan\phi)\, dz/\cos\phi$

To find the area of the exterior stove wall we evaluate the integral between the limits 21.61 and 32.88 cm

$$A_{\text{stove surface}} = \int_{H-h}^{H} 2\pi(z\tan\phi)\, dz/\cos\phi = \pi z^2(\tan\phi/\cos\phi)\Big]_{21.61}^{32.88} = 1024\ \text{cm}^2 = 0.1024\ \text{m}^2$$

1b. Energy Radiated by the pot walls

$\varepsilon_{\text{pot walls}} = 0.7$
diameter of pot = 24.0 cm
height of pot = 17.5 cm

Surface Area of pot walls = π x diameter x height
$= \pi * 24.0\ \text{cm} \times 17.5\ \text{cm} = 1319\ \text{cm}^2 = 0.1319\ \text{m}^2$

1c. Energy radiated by pot lid

$\varepsilon_{\text{pot walls}} = 0.7$

diameter of lid = 25.4 cm

Surface Area of the lid = $\pi * (0.254\ \text{m}/2)^2 = 0.05065\ \text{m}^2$

2a,b,c Energy transferred by convection

Use $h = 8\ \text{W m}^{-2}\ \text{K}^{-1}$ and the areas calculated for 1a,b,c.

3a. Heats involved in warming up the water

Trial 1 $\left\{ \begin{array}{l} m_{\text{water}} = m_{\text{water+pot+lid}} - m_{\text{pot+lid}} = 2.897\ \text{kg} - 0.895\ \text{kg} = 2.002\ \text{kg} \\ T_{\text{initial of water}} = 19.2\ ^\circ\text{C} \\ T_{\text{final of water}} = 100.4\ ^\circ\text{C} \end{array} \right.$

H (trial 1) = 2.002 kg x 4.186 KJ/kg °C x (100.4 °C - 19.2 °C) = 680.5 kJ

Trial 2 $\left\{ \begin{array}{l} m_{\text{water}} = m_{\text{water+pot+lid}} - m_{\text{pot+lid}} = 2.897\ \text{kg} - 0.895\ \text{kg} = 2.002\ \text{kg} \\ T_{\text{initial of water}} = 32.8\ ^\circ\text{C} \\ T_{\text{final of water}} = 100.5\ ^\circ\text{C} \end{array} \right.$

H (trial 2) = 2.002 kg x 4.186 KJ/kg °C x (100.5 °C – 32.8 °C) = 567,4 kJ

3b, 3c . Heat involved in heating up the pot and lid

Although we did not measure the mass of the pot and lid separately for purposes of this calculation I will assume that the mass of the lid is 1/3 of the total measured mass (this shouldn't make too much difference in that the temperature change difference between the pot and the lid is not very great).

$c_{p\ \text{pot}}$ (aluminum)= 0.900 kJ/kg °C

Trial 1 $\left\{ \begin{array}{l} m_{\text{pot}} = (2/3) \times 0.895\ \text{kg} = 0.597\ \text{kg} \\ T_{\text{initial of pot}} = 19.2\ ^\circ\text{C} \\ T_{\text{final of potl}} = 100.4\ ^\circ\text{C} \end{array} \right.$

H (trial 1) = 0.597 kg x (0.900 kJ/kg °C) x (100.4 °C - 19.2 °C) = 43.6 kJ

Trial 2 $\left\{ \begin{array}{l} m_{\text{pot}} = (2/3) \times 0.895\ \text{kg} = 0.597\ \text{kg} \\ T_{\text{initial of pot}} = 32.8\ ^\circ\text{C} \\ T_{\text{final of pot}} = 100.5\ ^\circ\text{C} \end{array} \right.$

H (trial 2) = 0.597 kg x (0.900 kJ/kg °C) x (100.5 °C – 32.8 °C) = 36.4 kJ

3c. Heat involved in heating up the lid

$c_{p\ \text{lid}} = 0.835$ kJ/kg °C

Trial 1 $\left\{ \begin{array}{l} m_{\text{lid}} = (1/3) \times 0.895\ \text{kg} = 0.299\ \text{kg} \\ T_{\text{initial of lid}} = 18.9\ ^\circ\text{C} \\ T_{\text{final of lid}} = 89.1\ ^\circ\text{C} \end{array} \right.$

H (trial 1) = 0.299 kg x (0.900 kJ/kg °C) x (89.1 °C – 18.9 °C) = 18.9 kJ

Trial 2 $\left\{ \begin{array}{l} m_{\text{lid}} = 0.299\ \text{kg} \\ T_{\text{initial of lid}} = 31.5\ ^\circ\text{C} \\ T_{\text{final of lid}} = 97.3^\circ\text{C} \end{array} \right.$

H (trial 2) = 0.299 kg x (0.900 kJ/kg °C) x (97.3 °C – 31.5 °C) = 17.7 kJ

3d. Heat involved in heating up the stove

ASSUME that the average temperature of the stove at any moment is the numerical average of the inner and outer wall temperatures.

$c_{p\ stove}$ = 0.835 kJ/kg °C

m_{stove} = 8.0 kg

$T_{\text{initial of outside wall of stove}}$ = 18.9 °C

$T_{\text{initial of inside wall of stove}}$ = 32.2 °C

$T_{\text{final of outside wall of stove}}$ = 171.2°C

$T_{\text{final of inside wall of stove}}$ = 490.2°C

H (trial 1) = 8.0 kg x (0.835 kJ/kg °C) x [(490.2°C + 171.2°C)/2 - (32.2 °C + 18.9 °C)/2]

= 2038 kJ

$T_{\text{initial of outside wall of stove}}$ = 186.6 °C

$T_{\text{initial of inside wall of stove}}$ = 422.8 °C

$T_{\text{final of outside wall of stove}}$ = 173.1 °C

$T_{\text{final of inside wall of stove}}$ = 334.0 °C

H (trial 2) = 8.0 kg x (0.835 kJ/kg °C) x [(334.0 °C+173.1°C)/2 - (422.8 °C + 186.6 °C)/2]

= -341.7 kJ

4. Heat involved in vaporizing water at 100°C to steam.

Mass of water + pot + lid $_{\text{initial}}$ (trial 1) = 2.897 kg

Mass of water + pot + lid $_{\text{final}}$ (trial 1) = 2.297 kg

Heat to vaporize water (trial 1) = (2.897 kg – 2.297 kg) x (2260 kJ/kg) = 1356kJ

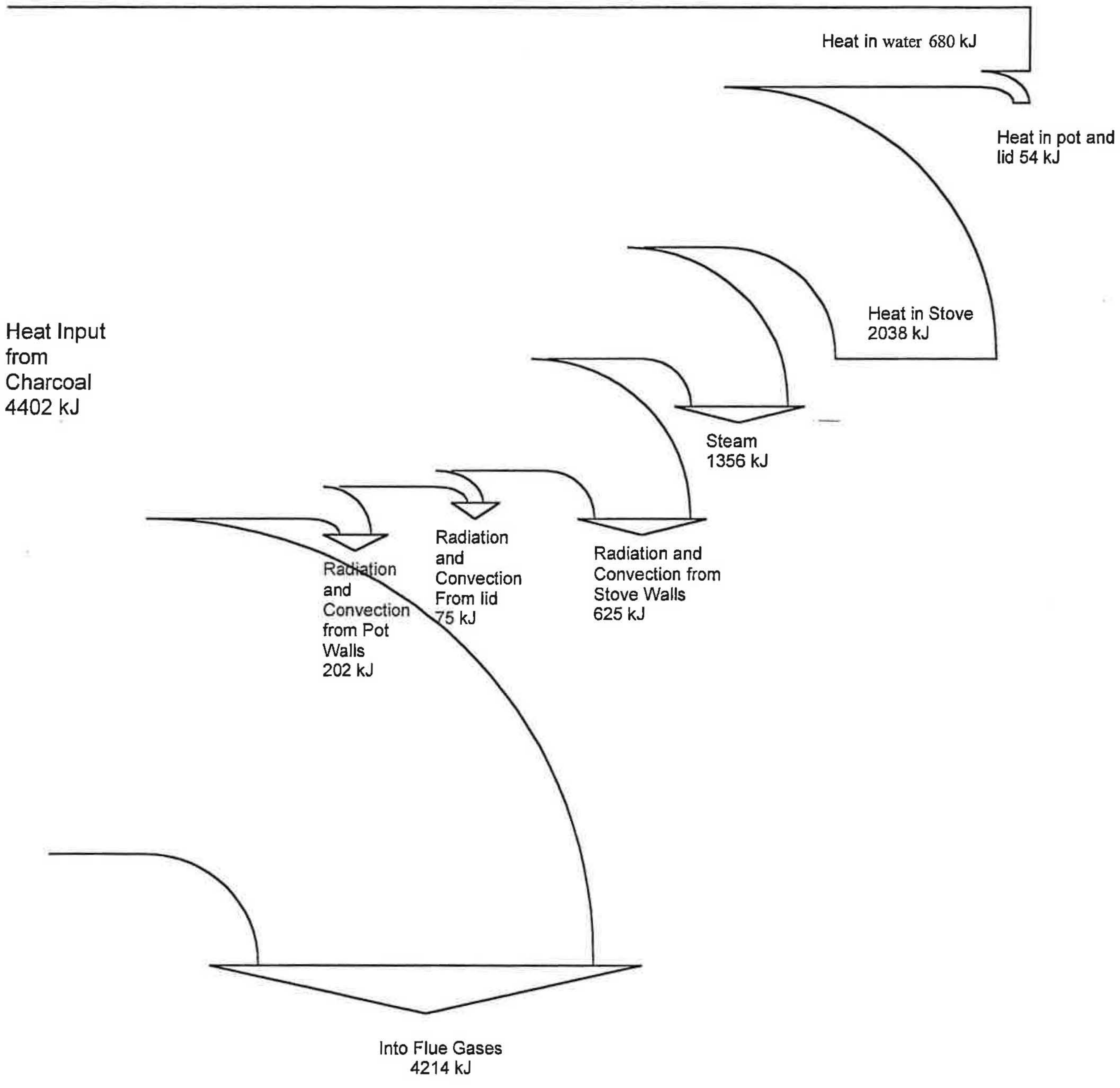
Mass of water + pot + lid $_{\text{initial}}$ (trial 2) = 2.897 kg

Mass of water + pot + lid $_{\text{final}}$ (trial 2) = 2.534 kg

Heat to vaporize water (trial 2) = (2.897 kg – 2.534 kg) x (2260 kJ/kg) = 820.4 kJ

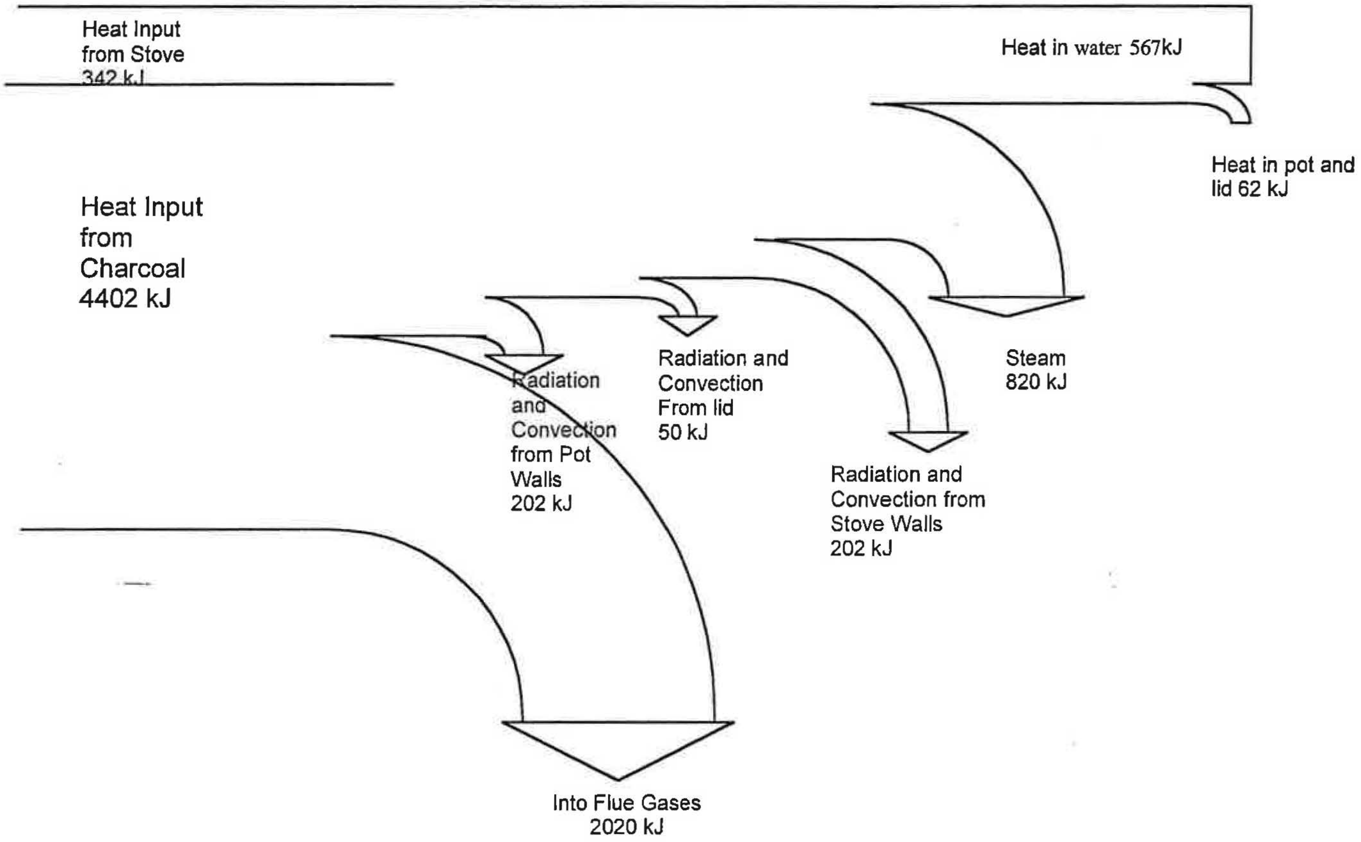
HEAT BALANCE RESULTS		**TRIAL 1**		**TRIAL 2**	
Calorific Value of the charcoal		9300 kJ		4402 kJ	
		Energy	%	Energy	%
Energy into	Heating the water	680 kJ	7.3	567 kJ	12.9
	Heating the stove	2038 kJ	21.9	(-342 kJ)	(-7.7)
	Heating the pot and lid	62 kJ	0.7	54 kJ	1.2
Energy "lost" from the stove walls	By radiation	380 kJ	4.1	109 kJ	2.5
	By convection	245 kJ	2.6	93 kJ	2.1
Energy "lost" from the pot lid	By radiation	37 kJ	0.4	21 kJ	0.5
	By convection	48 kJ	0.5	30 kJ	0.7
Energy "lost" from the pot walls	By radiation	106 kJ	1.1	91 kJ	2.1
	By convection	34 kJ	0.4	118 kJ	2.7
Energy "lost" in making steam		1356 kJ	14.6	820 kJ	18.6
Energy "lost" into the flue gases		4214 kJ	45.3	2020 kJ	45.9
STOVE "EFFICIENCY"		**7.3 %**		**12.9%**	

A Sankey diagram for the Ethiopian stove (Trial 1, starting with a cold stove):



OVERALL EFFICIENCY
= 680/9300 x 100 = 7%

A Sankey diagram for the Ethiopian stove (Trial 2, starting with a hot stove):



OVERALL EFFICIENCY
= 567/4402 x 100 = 13%

Heat Transfer from the charcoal fire to the pot

There are two main mechanisms whereby heat is transferred from the charcoal to the pot: convection and radiation. *THE PURPOSE HERE IS TO GAUGE THE RELATIVE IMPORTANCE OF THE TWO HEAT TRANSFER MECHANISMS.*

CONVECTION:

The net power lost to forced convection from a hot surface (in watts) is given by

$$P = \underbrace{h} \times \underbrace{A_c} \times \underbrace{(T_{\text{hot gases}} - T_{\text{bottom of the pot}})}$$

① h is the heat transfer coefficient, given by

$$h = 0.662 \times (\underbrace{k}_{④} / \underbrace{L_c}_{⑤}) \times \underbrace{Re_L^{1/2}}_{⑥} \times \underbrace{Pr^{1/3}}_{⑩}$$

④ k = the termal conductivity of the air ($W\ m^{-1}\ K^{-1}$) which is a function ~~of~~ the temperature of the air

⑤ L_c = a "characteristic length"
= (4 x Cross-sectional area of the pot) / Perimeter of that area
= diameter of the pot (for a circular pot)

⑥ Re_L = the Reynold's number. "*When the number is small there will be little tendency towards eddy production, because the viscous forces are large compared with the inertia ones; when the ratio is large there will be a great tendency for eddies to occur.*" (Francis, 1975) In our case it tells us whether the air is going to tend to "hug" the pot (a lower Reynold's number) or swirl along the pot surface (a higher Reynolds number). It depends upon the velocity of the air, a characteristic length (see below) and the "dynamic viscocity" of the air and is calculated as

$$Re_L = \underset{⑦}{u_\infty} \times \underset{⑤}{L_c} / \underset{⑨}{\nu}$$

⑦ u_∞ is the "free stream velocity" of the air which can be calculated by

= flow rate (m^3/s) / the cross sectional area of the stove at a point just below the pot

$$⑧ \quad \text{flow rate} = \text{velocity of the air entering the stove} \times \text{cross-sectional area of the stove's air intake} \times \frac{T_{\text{understove}}\ (K)}{T_{\text{intake air}}\ (K)}$$

⑨ ν = the "kinematic viscocity" which is the ratio of the "molecular viscocity" of the fluid (which indicates how strongly the intermolecular forces in the fluid resist shear) and the density of the fluid. (Francis 1975) *It describes the diffusion of momentum in a fluid.* (Weisstein 2002)

⑩ Pr is the Prandtl number, which *"is a dimensionless parameter of a convecting system that characterizes the regime of convection. It is defined as*

$$Pr = \frac{\nu}{\kappa}$$

where ν *is the kinematic viscosity and* κ *is the thermal diffusivity. In order of increasing Prandtl number, modes of convection are as follows.*

1. *Rolls,*
2. *Three-dimensional steady pattern in which flow occurs in interlocking polygons which are often hexagons or squares,*
3. *Irregularly shaped cells,*
4. *Narrow rising regions characterized by isothermal circulation, and*
5. *Turbulent convection in which no cells are present."*

(Weisstein 2002)

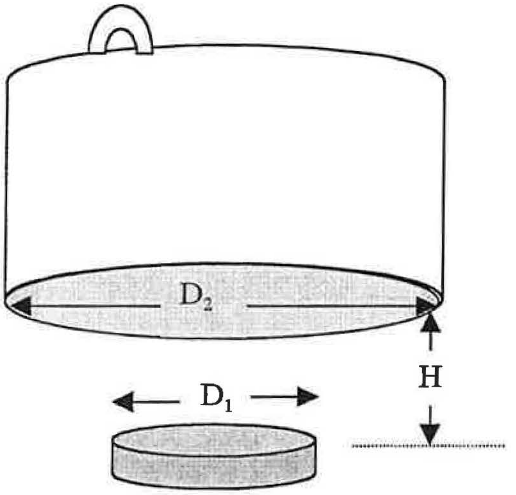
② A_c is the effective area of the pot in contact with the hot rising gas. I will take this to be the area of the bottom of the pot plus 1/3 the area of the side of the pot $= \pi \times (.24\ m/2)^2 + 1/3 \times (0.132 m^2) = 0.0892\ m^2$

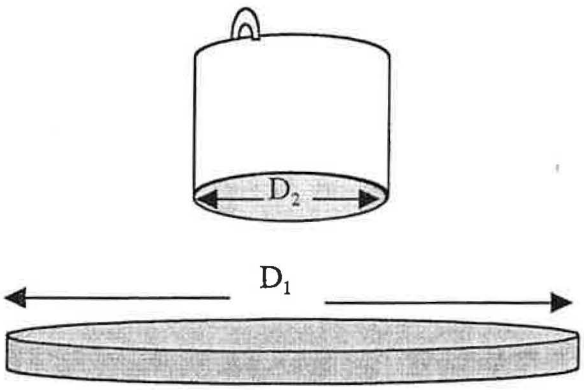
③ $T_{\text{hot gases}} - T_{\text{bottom of the pot}}$ is the difference between the temperature of the hot gases reaching the bottom of the pot and the temperature of the bottom of the pot itself.

I will calculate the convective heat transfer at two different points in each of the two trials respectively, one where the water is at 60°C (halfway between its initial temperature and boiling) and again after it has been boiling for five minutes. I will also calculate the radiative heat transfer at those same times and temperature.

THE CALCULATIONS ARE DONE ON THE SPREASHEET. I WILL SUMMARIZE THE RESULTS AT THE END OF THE NEXT SECTION ON RADIATIVE HEAT TRANSFER.

RADIATION:





There is a net transfer of energy by radiation from the hot charcoal to the not-as-hot pot bottom. The amount of energy transferred to the pot depends on

- ⇨ the ratio D_1/D_2. If $D_1 < D_2$ then the pot bottom subtends a larger solid angle of the radiation emitted by the hot charcoal than if $D_2 > D_1$, so the transfer of energy by radiation from the hot coals to the cooler pot is relatively more efficient.
- ⇨ the ratio D_1/H, which likewise determines what solid angle of the radiation from the coals is subtended by the pot.
- ⇨ the relative temperature of the coals and pot. If the pot is cooler it radiates less energy relative to what it receives from the hotter coals
- ⇨ the emissivity of the coals and pot. The emissivity of the hot coals determines how much energy they radiate. The emissivity of the pot determines the rate at which the radiated energy from the coals is absorbed by the pot.

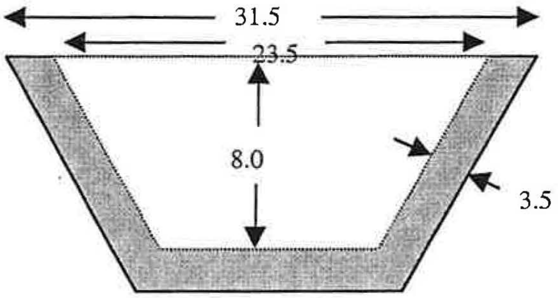
The geometries contribute to a "geometric form factor" F′ which can be obtained from the graph provided in the lab handout. The geometry and the emissivities together contribute to the total form factor $F'_{1\text{-}2}$ given by:

$$F'_{1-2} = \left\{ \frac{1}{F} + \left(\frac{1}{\varepsilon_2} - 1 \right) \frac{D_1^2}{D_2^2} + \left(\frac{1}{\varepsilon_1} - 1 \right) \right\}^{-1}$$

Here ε_1 is taken to be 1 for the charcoal, and ε_2 is taken to be 0.9 for the partially blackened aluminum pot bottom.

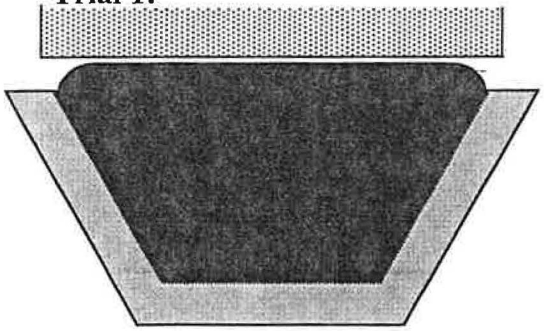
Determination of D_1 and H:

For the first trial the charcoal was filled up to the top of the stove. Indeed, the pot was sitting on top of the charcoal until 10 or 12 minutes into the trial. For purposes of calculating D_1 and H I will assume that the height of the charcoal in the stove decreases linearly with time, and that the top of the charcoal bed is the location of the radiating surface.

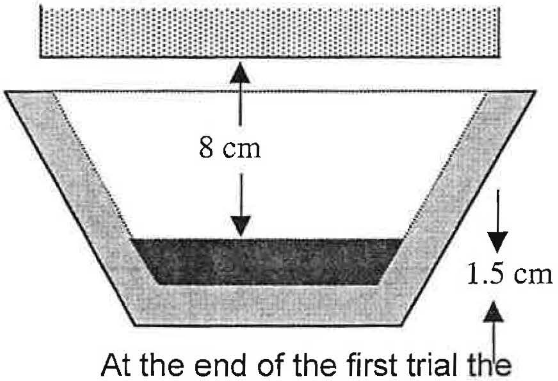


NOTE: IN ALL TRIALS THE POT WAS SUSPENDED 1.5 CM ABOVE THE TOP OF THE STOVE.

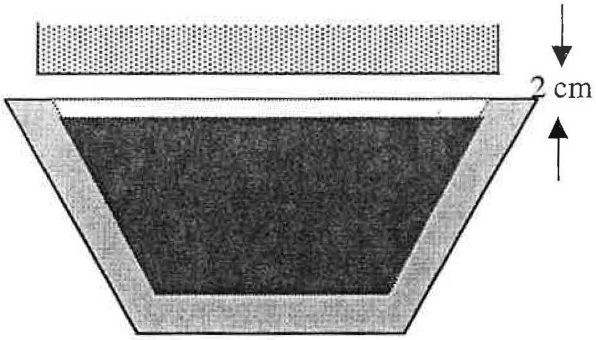
Trial 1:



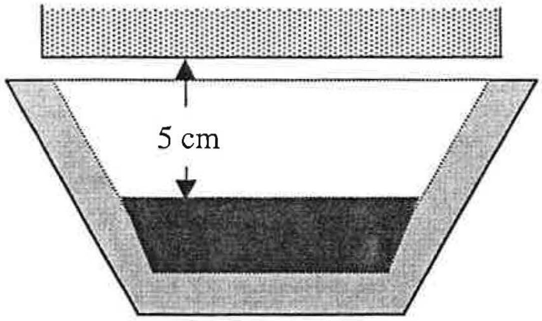
At start of the first trial the pot was sitting directly on top of the charcoal . . . .



At the end of the first trial the charcoal was about 1.5 cm deep in the stove



SO: 8 minutes into the first trial the charcoal would have burned down 8/30 of 8 cm total change in bed depth (2.13 cm)



AND: 19 minutes into the first trial the charcoal would have burned down 19/30 of 8 cm total change in bed depth (about 5.06 cm)

EXAMPLE CALCULATION OF D_1 and H:
Eight minutes into the first trial the top of the coal bed would have been $2.13 - 1.5 = 0.63$ cm below the top edge of the stove, Also, the upper inner diameter of the stove is 23.5 cm and the diameter of the base of the stove is 15 cm

So the diameter of the top of the charcoal bed 8 minutes into the first trial would have been:

$$15 \text{ cm} + [(8 \text{ cm} - 0.63 \text{ cm})/8 \text{ cm})] \times (23.5 \text{ cm} - 15 \text{ cm}) = 22.8 \text{ cm}$$

and the ratio

$$D_1/H = 22.8 \text{ cm}/ 2.13 \text{ cm} = 10.7$$

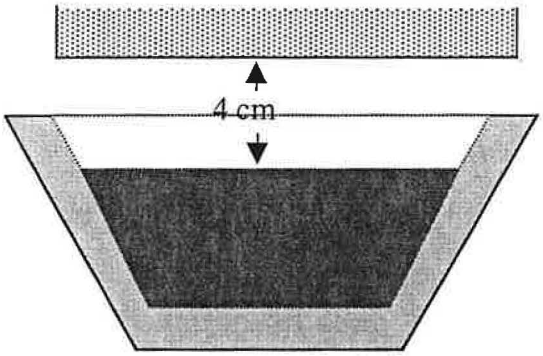
Extrapolating from the graph on page 5 of the lab handout the Geometric Form Factor would be about 0.9.

Then $F'_{1\text{-}2} = \{(1/0.9) + ((1/0.9) - 1)(22.5/23.5)^2 + ((1/1) - 1))\}^{-1} = 0.822$
And the rate of energy transfer from the charcoal to the pot would be:
$P = F'_{1\text{-}2}\ \sigma A_c (T_{\text{charcoal}}^4 - T_{\text{pot bottom}}^4)$

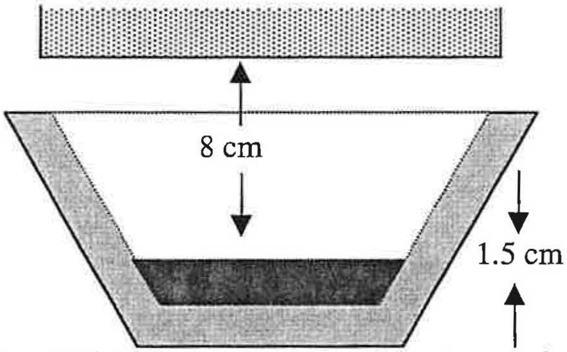
$$= 0.822 \times 5{,}6697\text{x}10^{-8} \times \pi \times (0.228/2)^2 \times ((660.3+273.2)^4 - (63.5\ +273.2)^4) = 1420 \text{ Watts}$$

SIMILAR CALCULATIONS WERE CARRIED OUT ON THE SPREADSHEET FOR THE OTHER TEMPERATURES AND TRIALS

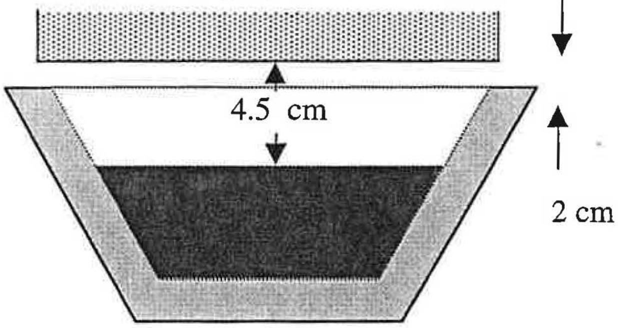
Trial 2:



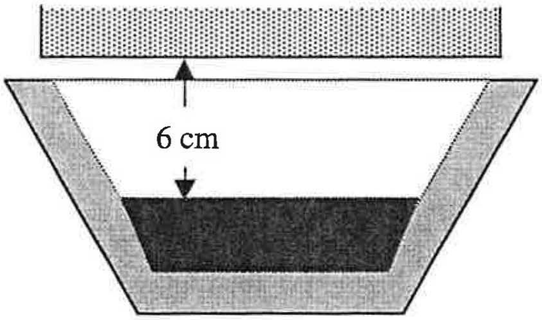
At start of the second trial the pot was sitting about 4 cm away from the pot bottom (bed 5.5 cm deep)



At the end of the second trial the charcoal was about 1.5 cm deep in the stove



SO: 4 minutes into the first trial the charcoal would have burned down 4/30 of 4 cm total change in bed depth (about 0.5 cm)



SO: 14 minutes into the first trial the charcoal would have burned down 14/30 of 4 cm total change in bed depth (about 2 cm)

COMPARISON OF CONVECTIVE AND RADIATIVE HEAT TRANSFER:

	Convective Heat Transfer to pot	Radiative heat Transfer to Pot	RATIO Radiation/Convection
TRIAL 1, 8 minutes in, Twater ~ 60°C	44.7 Watts	1420 Watts	~32
TRIAL 1, 19 minutes in, Twater ~ 100°C	64.8 Watts	2350 Watts	~36
TRIAL 2, 4 minutes in, Twater ~ 60°C	59.0 Watts	1540 Watts	~26
TRIAL 1, 14 minutes in, Twater ~ 100°C	36.9 Watts	1190 Watts	~32

A REALITY CHECK:
For trial 1 at 19 minutes the total power gained by the stove+pot+water is ~2400 Joules/sec.

The calculated power radiated and convected by the stove, pot and lid was
68.9 + 85.3 +13.8 +19.9 = 187.9 Watts
so there is about 2200 Watts to account for.

The water started boiling at minute 14 and we turned 600 grams of water total into steam in the first trial. That works out to about 40 grams of steam per minute on average, or about 2/3 gram of steam per second. At 2260 J/gram, that's about 1500 J/sec or 1500 watts.

So, there is about 2400 Joules per second leaving the charcoal for the pot.
I can account for 1700 of those Joules per second being used to turn the boiling water to steam. That leaves about 900 watts unaccounted for. Given the assumptions made in the calculations, that is not bad. It's not a great agreement, but at least it tells us that we are in the right ballpark as far as estimating the relative quantities or heat transferred by convection.

IN THE CONCLUSIONS SECTIONS I'LL SUGGEST REASONS WHY THE NUMBERS DO NOT AGREE EXACTLY.

CONCLUSIONS / POSSIBLE IMPROVEMENTS TO THE STOVE:

1. Efficiency of the Ethiopian stove: We calculated the efficiency of the stove by determining what proportion of the calorific value of the charcoal burned went into raising the cold water to its boiling point. By this definition the stove was 7% efficient when the stove was initially cold, and 13% efficient when the stove was already hot. This difference in efficiency can be ascribed to radiation from the burning charcoal striking the stove walls and being re-emitted to the pot when the walls were hot as opposed to the radiation being absorbed by the walls when the walls were cold

In reality the efficiency really should be ascribed to a particular stove/pot combination. The most efficient stove/pot combination would be one that raised the water to its boiling point and then kept it there. **The apparent efficiency of the stove could have been increased by:**

a. **Using a very shiny lid and a pot with very shiny walls and a very black bottom.** This would ensure that the emissivities of the pot surfaces that radiate heat would be very low, so that the radiative losses from the pot and lid would be minimized. Since the emitted radiation is all in the infrared portion of the spectrum, glass walls and a glass pot lid might have had a similar effect at least in terms of keeping the water from radiating infrared light out of the pot). Having the pot bottom have $\varepsilon = 1$ would ensure that radiative heat transfer from the charcoal to the pot was optimized.

b. Although we did not discuss conduction at all in this experiment, **having a pot with evacuated double walls and an insulated lid** might help minimize the required heat input as well. (This is NOT, however, something that would likely be within the budget of anyone who was cooking on one of these stoves!)

c. In the second trial (starting with the already-hot stove) we burned less than half of the amount of charcoal but still kept the water boiling. This indicates that;

   (1) **We could use less charcoal.** We could have put the same energy into heating the water and spent a lot less of it in keeping it at the boiling point. Most of the excess heat was wasted in making steam or into the flue gases.

   (2) After the water was boiling we really just needed to SIMMER the pot. **Once the water was boiling** we could have **cut off most of the primary air supply** to slow the rate of charcoal burning. Since virtually all of the heat was transferred to the pot by radiation and NOT by convection, lowering the rate of air flow from the charcoal to the pot wouldn't have affected the heat transfer to the pot very much. We need just enough air getting to the charcoal to keep it burning. If we are using the stove out-of-doors the extra CO being produced wouldn't be a safety issue.

d. Over 20% of the energy from the charcoal in the first trial went into heating up the stove. In the second trial we may have recovered some of the heat that went into the stove in the first trial. If we were to **insulate the stove** then a stove used to cook breakfast might still retain a large proportion of it's heat when it came around to lunchtime.

e. If we were to **make the stove with a shiny metal exterior** then the emissive losses from the stove might have been reduced. This may be impractical in that soot and grease would soon blacken the stove anyway.

Other possible changes one might comtemplate in the stove/pot design might be:

a) If we were to **make the stove into a cylinder** instead of a cone we could possibly lower the pot to keep it very close to the charcoal as the charcoal burned down. I suspect that this would make only a very minor difference in that the geometric form factor is not particularly sensitive to marginal charges in the pot-charcoal distance. It would also make the pot subtend a smaller solid angle of the radiative output of the charcoal. Probably this would NOT be an improvement.
b) **Don't change the pot size**! The pot was used was just the right size to intercept virtually all of the upward-directed radiation from the charcoal and inward-directed radiation from the hot stove wall. A smaller pot might have allowed more convective heat transfer, but we have already determined that this is not a significant mode of heat transfer for this stove.
c) **Make the ceramic sides of the stove less thick**. This would mean that there was less energy required to heat the stove, but it might also mean that the stove got hotter, and that the radiative and conductive losses from the sides of the stove might increase. This might also make the stove more fragile.

ALL of these other changes would require testing to see what effect they had on the stove efficiency.

2. As already mentioned, only about 10% or so of the calorific value of the charcoal went into heating up the water.
   Large amounts of energy went into turning the already boiling water into steam, or heating up the stove, or into the flue gases.

3. The dominant form of heat transfer from the charcoal to the pot is through radiation. Radiation transferred about 30 times more energy to the pot than convection did.

SOURCES of ERROR and UNCERTAINTY in the EXPERIMENT and CALCULATIONS: HEAT BALANCE

There are two main classes of errors built into the lab. In one category are measurement errors associated with the various sensors and meauring tools. In the other category lie all of the assumptions that went into calculating the various derived quantities in the lab.

Example of measurement errors are:
Lengths : ± 2 mm
Temperatures: ± 1°C
Masses: ± 2 grams

For example, looking at the power radiated by the stove walls we have:

$P = \varepsilon\,\sigma\,A\,(T_{hot}^4 - T_{ambient}^4)$

ε : Here we assume that since the walls are black that ε can be taken as close to 1. Although this is true for visible light, **in general the value of ε is a function of wavelength.** My experience teaching labs is that when you put boiling water into two cans that are in all ways identical except that one is painted white and the other black, they cool at exactly the same rate. An radar physicist who served as an adjunct lab instructor commented that in his experience with radar antennae it is the paint base material rather than the bits of pigment that get added that determines the emissivity of the material. SO: Dark black does NOT mean that emissivity = 1. So, $\Delta\varepsilon = .02$ (at least!)

σ: no uncertainty here

A: Each height, length, angle, and diameter used to calculate A has an uncertainty of around 1%. Since several of these go into calculating A, ΔA is probably ±3%

T: each Temperature is measured as a voltage at a thermocouple and intepreted by an A/D converted at the computer. I don't know the uncertainty of the thermouple or A/D conversion but it is probably safe to assume that it is at least ± 1°C. Since we are calculating T^4 the uncertainty in our value for T^4 is $4T^3\Delta T$. The uncertainty in $(T_{hot}^4 - T_{ambient}^4)$ will be approximately $\sqrt{2}\,(4T_{avg}^3\Delta T)$, so the fractional uncertainty in the temperature part of the calculation is about $6\Delta T/T_{avg}$. Taking $T_{avg} = 350$ K and $\Delta T = 1°$ gives a percent uncertainty in $(T_{hot}^4 - T_{ambient}^4)$ of around 1.5%.

Putting all of these uncertainties together gives a total uncertainty in the power radiated by a surface to be at leat $\sqrt{([0.02)^2+(0.03)^2+(0.015)^2]} = .033$ or 3.3% or 1 part in 30.

For the convection numbers we have

$$P = h\,A\,(T_{hot} - T_{ambient})$$

h: is taken to be about 8. Since this should depend at least in part on the orientation of the surface (vertical vs. horizontal or slanted) this value has to be ± at least 2%

A: suffers from the same uncertainties as for the radiating area. ± 3%

T: is probably ± 1° so the uncertainty in $(T_{hot} - T_{ambient})$ is about $\sqrt{2}\,^{\circ}$ so the percent uncertainty in $(T_{hot} - T_{ambient})$ is about $\sqrt{2}$ our of 2 to 160° or between 70% and 1%

So the uncertainty in the convected power can range probably works out to be around 3 to 5 watts for each calculated value. For an experiment running 1800 seconds that works out to 5400 to 9000 Joules of uncertainty, or around 6-8% of the total value.

HEAT QUANTITIES:

The mass of the stove is given to be 8 kg. Not 8.0 kg or 8.00 kg, but 8 kg. We can assume an uncertainty of at least ± 2%

I assumed that the temperature of the stove walls at the beginning and ending of each trial could be taken to be the arithmetic averageof the outer and inner wall temperatures.

Most of the masses are pretty dependable. I assumed that the lid made up 1/3 of the total mass of the lid+pot combination, which may throw off the calculation of the heat that went into the pot. By a percent or two.

I assumed that the specific heat capacity of the water was 4.186 kJ/kg°C for ALL water temperatures because the uncertainty such an assumption introduced was less that any of the other uncertainties in the calculations.

SOURCES of ERROR and UNCERTAINTY in the EXPERIMENT and CALCULATIONS: CONVECTIVE and RADIATIVE HEAT TRANSFER

CONVECTION:

There are many quantities that go into calculating the convective heat transfer.

Temperature of the air under the pan: this is only as good as the sensor (±1°?) and how close it actually is to the bottom of the pan

Temperature of the pot bottom: We assume that this is the same as the temperature of the water in the pot, but if it really were the same no heat would flow from the pot bottom into the water and the water would not boil. I do not have an easy and immediate way of estimating how big the difference actually is.

The Air flow velocity sensor was out. The meter in the air intake varied between 0.14 and 0.20 m/s. I took the value to be 0.17 m/s for the entire experiment.

Area in contact with the hot gas I took to be the pot bottom area plus 1/3 of the pot side area. Had I chosen 1/2 instead or 1/3 that would have changed the value for the convective heat transfer by about 15%.

All together these contribute to a relative uncertainty of at least 20% in the convective heat transfer values.

RADIATION:

The biggest uncertainties here come from assuming that the heat is radiating from the TOP of the charcoal bed at a temperature measured at the BOTTOM of the charcoal bed. The situation is made worse by raising this uncertain value it to the fourth power.

The geometric from factor is calculated assuming that all of the heat is radiating from the top surface of the charcoal. From a practical point of view it would be hard to design a robust temperature sensor that moved down as the charcoal burned, but it does mean that the temperature we are calculating with is probably not the "real" one,

I also assumed that the height of the charcoal bed decreased linearly with time, that the charcoal can be treated as a perfect blackbody ($\varepsilon = 1$) and that the pot bottom has $\varepsilon = 0.9$, although that value is just a reasonable guess. Finally, I assumed that the temperature of the pot bottom was the same as that of the water (see comments on CONVECTION errors above), and there is some uncertainty associated with reading numbers off of the geometric form factor graph.

All of these uncertainties might lead to errors as large as 50% or more, but as I point out in the "reality check" of the radiation heat transfer calculations, the numbers are of the right order of magnitude.

Ultimately we are trying to determine which heat transfer method dominates, and even if the convection were twice as much and the radiation half as much the radiative heat transfer would still clearly dominate.

References:

Unless otherwise stated, all equations and value used in this lab come from the Biomass Module—Stove Practical lab handout attached to the back of this lab report.

Francis . 1975

Francis, J.R.D. Fluid Mechanics for Engineering Students, 4th ed. Edward Arnold (Publishers) Ltd. London. 1975

Weisstein 2002

http://scienceworld.wolfram.com/physics from Eric Weisstein's World of Physics

Biomass Module—Stove Practical lab handout (attached)

Data for Lab Group D—Nikos, Julian, Seyhan, and Phil
Biomass Stove—Trial 2 (start with hot stove)

ewall	0.98
sigma	5.67E-08
deltaT	1
Wall Area (m2)	0.1024

epotsides	0.76	elid	0.76
Apotsides	0.1319	Alid	0.05065

	CHANNEL 1		CHANNEL 2				CHANNEL 3	CHANNEL 4	CHANNEL 5	CHANNEL 6				CHANNEL 7				CHANNEL 8	CHANNEL 11
Time into the Experiment (minutes)	AMB. DEG.C	Ambient Temperature (Kelvin)	O-S WALL DEG.C	Stove Outside Wall (Kelvin)	Power Radiated by Stove Walls (Watts)	Power Convected from Stove Walls (Watts)	I-S WALL DEG.C	BED DEG.C	U-PAN DEG.C	WATER DEG.C	Water Temperature (Kelvin)	Power Radiated by Pot Walls (Watts)	Power Convected from Pot Walls (Watts)	LID DEG.C	Lid Temperature (Kelvin)	Power Radiated by Pot Lid (Watts)	Power Convected from Pot Lid (Watts)	AIR IN DEG.C	CHARCOAL kg
0	19.9	293.0	186.6	459.8	212.3	136.6	422.8	753.3	210.3	32.8	306.0	7.9	13.7	31.5	304.6	2.7	4.7	23.6	35.5
1	19.8	293.0	187.2	460.4	213.7	137.1	462.2	778.9	298.1	36.9	310.1	10.7	18.0	34.6	307.7	3.5	6.0	23.6	35.5
2	19.8	293.0	187.6	460.8	214.5	137.4	492.9	780.0	346.6	46.2	319.4	17.3	27.9	39.2	312.4	4.7	7.8	23.6	35.5
3	20.1	293.3	186.8	460.0	212.6	136.6	503.7	771.2	333.7	54.8	328.0	23.7	36.6	44.6	317.8	6.1	9.9	23.3	35.5
4	20.3	293.5	187.2	460.3	213.3	136.7	505.8	753.3	339.7	63.8	337.0	31.1	45.9	51.2	324.3	8.0	12.5	23.3	35.5
5	20.5	293.6	186.7	459.9	212.2	136.2	498.0	777.8	345.7	71.2	344.4	37.7	53.6	59.0	332.2	10.3	15.6	23.3	35.5
6	20.2	293.4	187.1	460.2	213.1	136.7	496.0	777.9	345.5	79.1	352.3	45.4	62.1	67.5	340.6	13.2	19.1	23.3	35.4
7	20.3	293.4	187.9	461.1	215.0	137.3	492.9	769.9	349.9	87.7	360.8	54.2	71.1	75.8	349.0	16.2	22.5	23.2	35.4
8	20.4	293.6	188.3	461.4	215.6	137.5	461.7	761.3	345.8	94.3	367.5	61.4	78.0	83.9	357.0	19.2	25.7	23.3	35.4
9	20.1	293.3	188.9	462.1	217.3	138.3	478.3	765.7	332.3	100.4	373.6	68.6	84.7	93.6	366.8	23.4	29.8	23.2	35.4
10	20.1	293.3	190.1	463.3	220.0	139.3	478.3	747.8	317.2	100.5	373.7	68.8	84.9	96.1	369.3	24.5	30.8	23.4	35.4
11	19.9	293.0	190.6	463.7	221.1	139.8	463.5	785.3	313.3	100.5	373.6	68.9	85.1	96.1	369.2	24.5	30.9	23.3	35.4
12	19.8	293.0	190.2	463.4	220.4	139.6	450.4	783.5	301.5	100.5	373.6	68.9	85.1	96.5	369.7	24.7	31.1	22.9	35.4
13	19.8	293.0	190.4	463.6	220.8	139.8	439.5	767.5	297.5	100.5	373.6	68.9	85.1	96.6	369.8	24.7	31.1	23.0	35.4
14	19.8	293.0	189.9	463.0	219.6	139.3	435.2	772.9	280.7	100.5	373.6	68.9	85.1	96.9	370.0	24.8	31.2	22.6	35.4
15	19.8	293.0	189.9	463.0	219.6	139.3	426.6	803.4	272.1	100.5	373.6	68.9	85.1	96.9	370.0	24.8	31.2	22.7	35.4
16	19.8	292.9	190.0	463.1	219.8	139.4	418.2	787.7	265.8	100.5	373.6	68.9	85.2	97.0	370.1	24.9	31.3	64.3	35.4
17	19.9	293.1	189.8	462.9	219.3	139.1	409.6	777.9	263.0	100.5	373.7	68.9	85.0	97.0	370.2	24.9	31.2	22.5	35.4
18	20.3	293.4	189.1	462.2	217.5	138.3	402.0	772.9	262.2	100.5	373.7	68.7	84.7	97.1	370.3	24.9	31.1	22.5	35.4
19	20.0	293.1	188.1	461.2	215.4	137.7	396.2	770.8	245.5	100.5	373.7	68.9	85.0	97.3	370.4	25.0	31.3	22.6	35.4
20	19.7	292.8	187.2	460.3	213.7	137.2	391.7	759.9	235.4	100.5	373.7	69.0	85.3	97.1	370.2	25.0	31.4	22.6	35.4
21	19.8	293.0	186.5	459.7	212.1	136.5	384.6	739.9	225.3	100.5	373.7	68.9	85.1	97.0	370.1	24.9	31.3	22.8	35.4
22	19.8	293.0	185.3	458.5	209.5	135.6	378.4	725.5	219.6	100.5	373.7	68.9	85.2	97.1	370.3	25.0	31.3	23.0	35.4
23	19.9	293.0	184.2	457.4	207.1	134.7	374.5	709.7	230.7	100.6	373.7	69.0	85.2	97.3	370.5	25.0	31.4	22.7	35.4
24	19.7	292.9	182.9	456.0	204.2	133.6	367.8	696.1	223.8	100.6	373.7	69.1	85.3	97.2	370.4	25.0	31.4	22.7	35.4
25	19.8	293.0	180.9	454.0	199.8	131.9	362.0	682.9	220.9	100.5	373.6	68.9	85.1	97.2	370.4	25.0	31.4	22.7	35.4
26	19.9	293.1	179.3	452.4	196.4	130.5	357.2	665.6	212.6	100.5	373.7	68.9	85.0	97.2	370.4	25.0	31.3	22.7	35.4
27	19.9	293.0	177.7	450.9	193.2	129.3	351.0	652.7	201.5	100.6	373.7	69.0	85.2	97.1	370.3	24.9	31.3	22.5	35.4
28	20.1	293.3	176.1	449.2	189.6	127.7	345.8	635.0	199.0	100.5	373.6	68.7	84.8	97.2	370.4	24.9	31.2	22.6	35.4
29	19.9	293.1	174.7	447.9	187.0	126.8	339.9	616.6	196.6	100.5	373.7	68.9	85.1	97.2	370.4	25.0	31.3	22.6	35.4
30	19.8	293.0	173.1	446.3	183.7	125.6	334.0	604.9	191.8	100.5	373.7	69.0	85.2	97.3	370.4	25.0	31.4	22.6	35.4
					Energy Radiated by Stove Walls (Joules)	Energy Convected from Stove Walls (Joules)						Energy Radiated by Pot Walls (Joules)	Energy Convected from Pot Walls (Joules)			Energy Radiated by Pot Lid (Joules)	Energy Convected from Pot Lid (Joules)		
					3.799E+05	2.448E+05						1.060E+05	1.337E+05			3.694E+04	4.750E+04		

	Temp (oC)	1	2	3	4	5	6	7	8	9	10	
Trial		h (W m-2 K-1)	Ac m2	Thot gases – T bottom of the pot K	k (W m-1 K-1)	Lc m	ReL	u∞ m/s	flow rate m3/s	ν m2 s-1	Pr	Power
2 (t = 4 min)	63.8	2.40	0.0892	275.9	0.0476	0.24	429	9.74E-02	4.22E-03	5.45E-05	0.686	59.0
2(t = 14 min)	100.477	2.29	0.0892	180.2	0.0441	0.24	458	8.82E-02	3.82E-03	4.62E-05	0.683	36.9

	D2	distance (top of charcoal to bottom of pot)	D1	D1/h	Geometric Form Factor	ε2(pot)	ε1(charcoa	Total form factor	Tcharcoal (K)	Tpot-bottom (K)	Power radiated from charcoal to pot bottom
2 (t = 4 min)	0.235	0.0453	0.20281	4.47695916	0.82	0.9	1	0.76789	1026.498	336.975	1.54E+03
2 (t = 14 min)	0.235	0.0653	0.18156	2.78034074	0.72	0.9	1	0.68719	1046.012	373.627	1.19E+03

Biomass Stove—Trial 1 (start with cold stove)

ewall 0.98
sigma 5.67E-08
deltaT 1
Wall Area (m2) 0.1024

epotsides 0.76 elid 0.76
Apotsides 0.1319 Alid 0.05065

Time Into the Experiment (minutes)	CHANNEL 1 AMB. DEG.C	Ambient Temperature (Kelvin)	CHANNEL 2 O-S WALL DEG.C	Stove Outside Wall (Kelvin)	Power Radiated by Stove Walls (Watts)	Power Convected from Stove Walls (Watts)	CHANNEL 3 I-S WALL DEG.C	CHANNEL 4 BED DEG.C	CHANNEL 5 U-PAN DEG.C	CHANNEL 6 WATER DEG.C	Water Temperature (Kelvin)	Power Radiated by Pot Walls (Watts)	Power Convected from Pot Walls (Watts)	CHANNEL 7 LID DEG.C	Lid Temperature (Kelvin)	Power Radiated by Pot Lid (Watts)	Power Convected from Pot Lid (Watts)	CHANNEL 8 AIR IN DEG.C	CHANNEL 11 CHARCOAL kg
0	18.4	291.6	18.9	292.0	0.3	0.4	32.2	30.2	110.2	19.2	292.4	0.5	0.9	18.9	292.0	0.1	0.2	20.2	38.9
1	18.4	291.6	19.1	292.2	0.4	0.5	76.2	50.0	177.1	35.7	308.9	10.6	18.2	27.8	300.9	2.1	3.8	20.1	39.0
2	18.5	291.7	19.3	292.5	0.5	0.7	152.9	80.5	210.1	36.0	309.2	10.8	18.4	28.4	301.6	2.3	4.0	20.2	38.8
3	18.9	292.0	19.7	292.9	0.5	0.7	244.2	125.0	231.4	39.7	312.8	13.1	22.0	31.6	304.7	2.9	5.1	20.1	38.7
4	19.0	292.1	20.2	293.4	0.7	1.1	342.5	203.9	240.9	42.4	315.5	15.0	24.7	33.8	307.0	3.5	6.0	20.2	38.6
5	19.2	292.4	21.2	294.4	1.1	1.6	416.9	340.5	250.1	46.2	319.4	17.6	28.5	36.2	309.4	4.0	6.9	20.1	38.5
6	19.2	292.3	23.2	296.3	2.3	3.3	469.8	487.5	260.3	51.6	324.8	21.8	34.3	38.5	311.6	4.6	7.8	20.1	38.5
7	19.3	292.4	27.1	300.3	4.7	6.4	506.9	586.0	268.9	57.8	330.9	26.6	40.6	41.4	314.6	5.4	9.0	20.2	38.2
8	19.3	292.5	34.3	307.4	9.2	12.2	522.8	660.3	281.5	63.5	336.6	31.4	46.6	39.1	312.3	4.8	8.0	20.2	38.1
9	19.6	292.7	44.6	317.7	16.2	20.5	553.3	704.6	298.0	69.6	342.8	36.7	52.8	38.9	312.0	4.7	7.8	19.8	38.0
10	19.6	292.8	54.8	328.0	24.1	28.9	578.6	780.3	318.2	75.7	348.8	42.4	59.2	43.1	316.2	5.8	9.5	20.2	37.0
11	19.2	292.3	60.6	333.8	29.1	34.0	547.0	830.8	354.4	78.9	352.1	45.8	63.1	42.0	315.1	5.6	9.2	20.4	35.8
12	19.2	292.4	65.0	338.2	32.8	37.5	510.2	847.5	378.3	84.1	357.2	51.0	68.4	48.8	322.0	7.5	12.0	20.5	35.8
13	19.2	292.4	66.8	340.0	34.4	39.0	507.0	856.3	391.9	91.6	364.8	59.1	76.4	52.0	325.1	8.4	13.3	20.2	35.8
14	19.2	292.3	68.4	341.6	35.9	40.3	521.6	887.3	392.3	100.4	373.5	69.1	85.7	60.6	333.7	11.1	16.8	20.6	35.8
15	19.4	292.6	73.4	346.5	40.4	44.2	540.8	888.7	391.1	100.4	373.5	69.0	85.4	60.1	333.3	10.9	16.5	20.7	35.8
16	19.4	292.6	77.0	350.2	43.9	47.2	571.6	889.9	400.9	100.4	373.6	69.0	85.5	65.2	338.4	12.6	18.6	20.8	35.8
17	19.6	292.8	82.2	355.3	48.9	51.2	569.3	883.8	404.6	100.4	373.5	68.9	85.2	62.7	335.8	11.7	17.4	21.0	35.8
18	19.7	292.8	89.6	362.7	56.7	57.3	563.2	866.1	401.6	100.4	373.5	68.9	85.2	62.0	335.1	11.5	17.2	21.1	35.8
19	19.6	292.7	96.7	369.8	64.7	63.2	562.9	889.0	392.8	100.4	373.6	68.9	85.3	68.7	341.9	13.8	19.9	21.1	35.7
20	19.6	292.8	107.5	380.6	77.6	71.9	563.4	910.6	387.4	100.4	373.6	68.9	85.2	81.5	354.7	18.5	25.1	21.1	35.7
21	19.5	292.6	116.4	389.6	89.3	79.4	569.6	921.4	388.3	100.4	373.6	69.0	85.4	84.5	357.6	19.7	26.4	21.3	35.7
22	19.5	292.6	124.6	397.7	100.7	86.1	565.8	926.9	385.4	100.4	373.5	69.0	85.4	86.5	359.7	20.5	27.2	21.3	35.7
23	19.6	292.8	133.6	406.7	113.9	93.3	549.0	926.3	369.2	100.4	373.5	68.9	85.2	87.4	360.5	20.8	27.4	21.8	35.7
24	19.5	292.6	140.3	413.5	124.6	99.0	535.4	900.7	357.3	100.4	373.6	69.0	85.4	88.2	361.3	21.2	27.8	22.0	35.7
25	20.0	293.1	147.1	420.2	135.5	104.2	525.9	871.3	355.2	100.5	373.6	68.8	85.0	88.1	361.2	21.0	27.6	22.3	35.7
26	19.6	292.8	153.4	426.6	146.6	109.6	517.7	849.2	346.2	100.4	373.6	69.0	85.3	88.5	361.6	21.3	27.9	22.3	35.7
27	19.7	292.9	158.5	431.6	155.6	113.6	515.9	825.0	329.0	100.4	373.6	68.9	85.2	88.8	362.0	21.4	28.0	22.4	36.2
28	19.9	293.0	162.9	436.1	163.8	117.2	503.5	797.9	326.9	100.4	373.5	68.8	85.0	88.8	362.0	21.4	27.9	22.3	35.7
29	19.9	293.1	167.2	440.4	172.0	120.7	494.3	777.2	321.2	100.4	373.5	68.7	84.9	88.8	362.0	21.4	27.9	22.4	35.7
30	19.8	292.9	171.2	444.3	179.9	124.0	490.2	761.4	321.7	100.4	373.6	68.8	85.1	89.1	362.2	21.5	28.1	22.3	35.6

Energy Radiated by Stove Walls (Joules)	Energy Convected from Stove Walls (Joules)	Energy Radiated by Pot Walls (Joules)	Energy Convected from Pot Walls (Joules)	Energy Radiated by Pot Lid (Joules)	Energy Convected from Pot Lid (Joules)
1.089E+05	9.282E+04	9.116E+04	1.176E+05	2.108E+04	2.977E+04

	Temp (oC)	1	2	3	4	5	6	7	8	9	10	
Trial		h (W m-2 K-1)	Ac m2	Thot gases – T bottom of the pot K	k (W m-1 K-1)	Lc m	ReL	u∞	flow rate	v m2 s-1	Pr	Power
1 (t = 8 min)	63.5	2.30	0.0892	218.0	0.0441	0.24	459	8.84E-02	3.84E-03	4.62E-05	0.683	44.7
1(t = 19 min)	100.401	2.49	0.0892	292.4	0.0506	0.24	405	1.06E-01	4.60E-03	6.28E-05	0.692	64.8

	D2	distance (top of charcoal to bottom of pot)	D1	D1/h	Geometric Form Factor	ε2(pot)	ε1(charcoa	Total form factor	Tcharcoal (K)	Tpot-bottom (K)	Power radiated from charcoal to pot bottom (Watts)
1 (t = 8 min)	0.235	0.0213333	0.22827	10.7001953	0.9	0.9	1	0.8224	933.461	336.622	1.42E+03
1(t = 19 min)	0.235	0.0506667	0.1971	3.89021382	0.8	0.9	1	0.75292	1162.199	373.551	2.35E+03

M.Sc. and Diploma in Renewable Energy and the Environment

Biomass Module - Stove Practical

OBJECTIVES

- To investigate the characteristics of an Ethiopian stove in a simulated cooking exercise.
- To use the measurements to calculate the overall efficiency of the stove.
- To calculate a heat balance and draw a Sankey diagram.
- To suggest possible improvements that could be made to the design to improve overall efficiency, taking into account the cost, the use of local materials and crafts and the purpose for which the stove is used.

BACKGROUND

Rice should be brought from cold to the boil quickly (within 10 to 15 minutes) and then simmered for a further 15 minutes to ensure it is well cooked. In this test, 2 kg of water are used (sufficient to cook rice for a family of 4); it will be brought to the boil and simmered for a further 15 minutes. The amount of energy (in the form of charcoal or wood) that is used will be continuously measured, together with temperatures at various positions around the stove. A data logger is used to record this information every minute, and the results printed out and recorded on disk. A large amount of data is generated. Part of the exercise is to determine what data is useful.

SUGGESTED PROCEDURE

The first step is to take detailed measurements of the stove and the pan. These measurements will be required in order to calculate the heat transfer between the stove and the pan and the heat losses from the stove and the pan. The stove is supported on an aluminium plate that can be lowered onto the pan of an electronic scale, or lifted up above it. With the stove lifted up, and the scale setting at 12 kg, measurements can be taken of the weight of the pot, the weight of the pot plus water and the weight of charcoal to be added to the stove. The scale setting should be reset to 120 kg before the stove is lowered onto the pan.

Charcoal (about 400 g) or wood is placed in the stove and lit with the aid of a piece of paraffin soaked paper. When the fuel is well alight, the pan of water is placed over the stove and the data logger started. The programme is called MSC STOVE and it is RUN on an Apple II computer. The data is recorded on disk in a binary-coded decimal format, but can be "printed" out to disk as an ASCII file once the data recording has finished. It can then be transferred to a PC and imported into Excel.

The data logger is programmed to log the data once a minute for 31 minutes. The performance of the stove will vary with the temperature of the stove at the start of the test. The first test will be with a cold stove, so the test should be repeated with a warm stove.

GENERAL INFORMATION

	Charcoal
Calorific value	31,000 kJ kg^{-1}
Carbon content	86%
Hydrogen content	2%
Moisture content	5%
Ash content	1%

Specific heat of stove material: $C_P = 0.835$ kJ $\text{kg}^{-1}\text{K}^{-1}$

Mass of stove = 8 kg

DETAILED CALCULATIONS

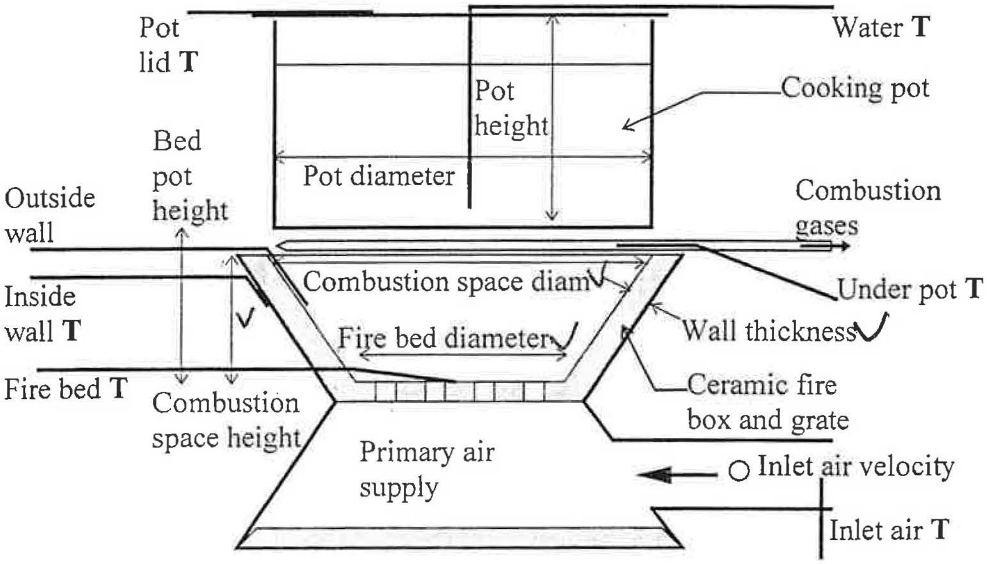
Heat Balance and Efficiency

In order to draw the Sankey diagram it is necessary to calculate :

- Heat output from the charcoal;
- Heat stored in the stove wall;
- Heat lost through stove wall by convection and radiation;
- Heat into steam;
- Heat lost from pan lid;
- Heat stored in the water (the useful output heat);
- The heat lost in the flue gas is assumed to be any heat not identified in the above calculations;
- and the overall stove efficiency (useful heat divided by input heat).

Also the heat transferred to the pan by convection and radiation should be estimated.

Measurements of Apparatus



Stove Heat Transfer Equations

The dimensions measured above are used to determine the geometrical values of the variables used in the heat transfer equations below, such as the areas of stove and pot walls and the area of the pot lid.

Heat loss by convection from stove and pot walls is given by:

$$Q_c = hA_w \Delta T$$

where A_w is the wall area (m^2)
h is the heat transfer coefficient (on average = 8 W m^{-2} K^{-1}) and
ΔT is the difference in temperature between the wall and the air (K)

Note: the aluminium pot wall temperature will be the same as the water temperature.

Heat losses by radiation

Heat lost from the stove wall and pot sides and lid by radiation is given by:

$$Q_r = \varepsilon \sigma A\left(T_{wall}^4 - T_{amb}^4\right)$$

where σ = Stefan constant = 5.6697×10^{-8} (W m^{-2} K^{-4})
T = Temperatures (absolute) (K)
A = Area of wall (m^2) and
ε = emmisivity

Values for emmisivity:

Use: $\varepsilon = 0.98$ black paint on stove wall and
$\varepsilon = 0.76$ for lid (commercial aluminium sheet)

Combustion Efficiency

Measurements of the proportion of CO_2 to CO produced should give the efficiency of the combustion process, but analyser has failed, so this part of the experiment cannot be done.

Heat stored in the stove

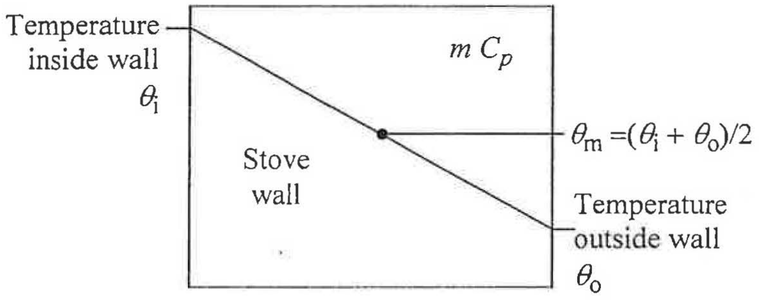
The heat stored in the stove wall during the test period will be:

$$Q_s = mC_p \Delta\theta$$

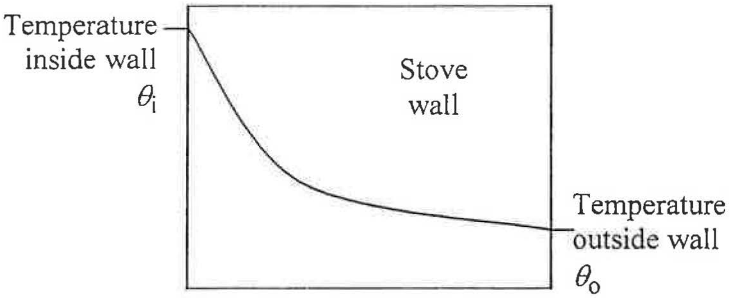
where m = mass of stove wall (= 8 kg)
C_p = Thermal capacity of stove wall (= 0.84 kJ kg^{-1} K^{-1})
$\Delta\theta$ = difference between the mean temperature at the start (s) and finish (f) of the test.

So:
$$Q_s = \frac{mC_p}{2}\left[(\theta_{if} + \theta_{of}) - (\theta_{is} + \theta_{os})\right]$$

where i = inside wall and o = outside wall.



The temperature profile will only approach the above condition after the stove has been running for some time and the wall temperatures are fairly stable. While temperatures are changing, the temperature profile will be more like this:



The mean temperature is not a simple mean, so the above equation should only be used when temperatures have reached a steady state. This is usually the situation at the beginning and end of the test.

Heat Transfer from the charcoal fire to the pot

Since the temperatures are variable and somewhat uncertain, the following will only give an approximate result to the magnitude of the heat transferred by convection and radiation, but will show if one or the other is dominant. Choose average or optimum conditions. **These results should not be used in the calculation of the overall efficiency of the stove.**

Heat transfer coefficient for forced convection

$$h_{av} = 0.662 \frac{k}{L_c} \mathrm{Re}_L^{1/2}\ \mathrm{Pr}^{1/3}$$ where Re = Reynolds Number, Pr = Prandtl number.

The above equation is for a laminar boundary layer over the whole plate, and will give a pessimistic value for the conditions under consideration.

$$\mathrm{Re}_L = \frac{u_\infty L_c}{\nu}$$ Use values of the properties of air at the film temperature.

Film temperature = average of the air temperature and the surface temperature.

u_∞ = free stream velocity (m s^{-1})

Calculate this from the measured airflow rate at the temperature of the gas under the pan. e.g. if the flow rate of air is 3 l/s at 20°C (293 K) then the flow rate at a gas temperature of 800°C will be:

$$\dot{V} = 0.003 \times \frac{1073}{293} = 0.011\ \mathrm{m^3 s^{-1}}$$

Therefore: u_∞ = 0.011/Cross sectional area of stove at point just under pot.

L_c = Characteristic length = $\frac{4 \times \text{Area}}{\text{Perimeter}}$

k = Thermal conductivity

ν = Kinematic viscosity

Heat transferred by convection:

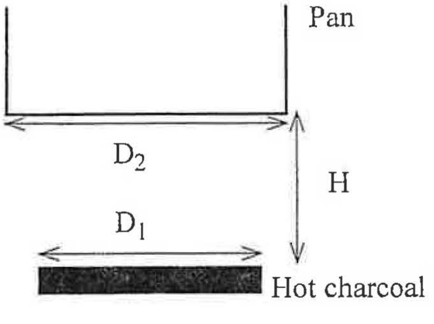
$Q_c = h_{av} A_c \Delta T$

A_c = effective area of pan in contact with the hot gas (a reasonable estimate in this case would be the area of the pan up to the water line)

ΔT = temperature difference between the pan and the hot gas

Heat transfer by radiation

The heat transfer by radiation is the direct transfer from the hot charcoal plus the radiation from the hot walls of the stove. It is assumed that all the heat that is radiated to the wall is reradiated and that the losses from the wall are supplied by convection from the hot gas.



Emissivity of charcoal: $\varepsilon_1 = 1$ (black body)

Emissivity of the pan bottom $\varepsilon_2 = 0.4$ (blackened aluminium)

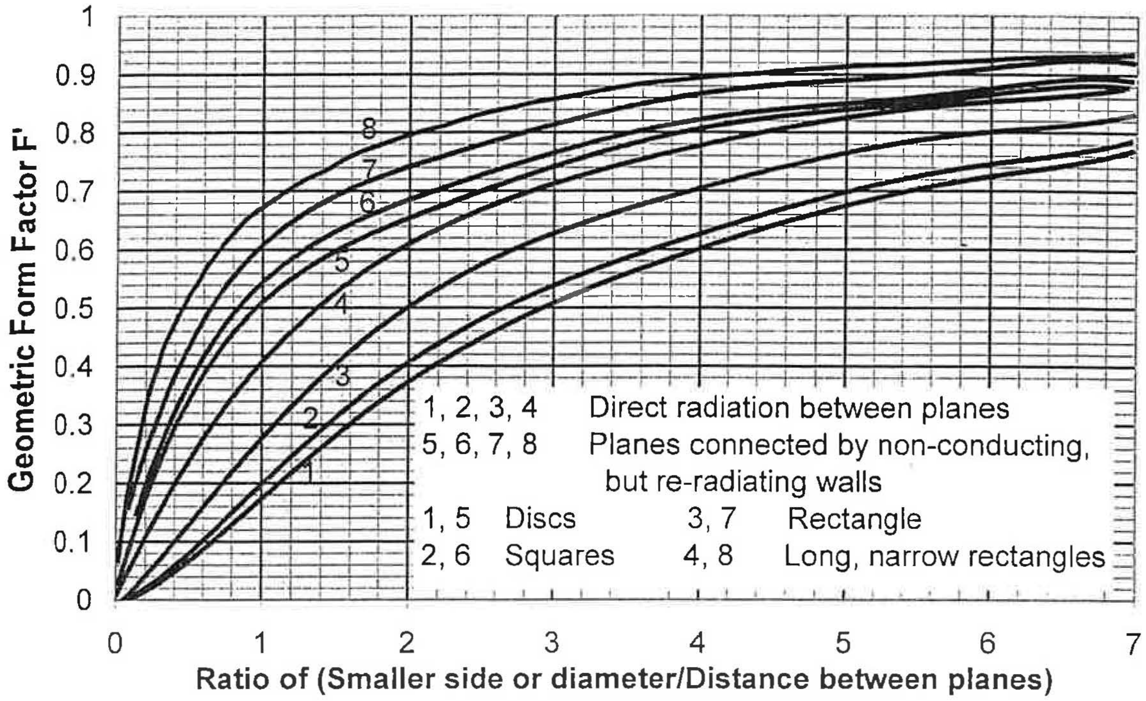
View factor ratio = $\frac{D_1}{H}$

From graph (over page) obtain the geometric form factor F (curve 5), then:

$$F'_{1-2} = \left\{ \frac{1}{F} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{D_1^2}{D_2^2} + \left(\frac{1}{\varepsilon_1} - 1\right) \right\}^{-1}$$

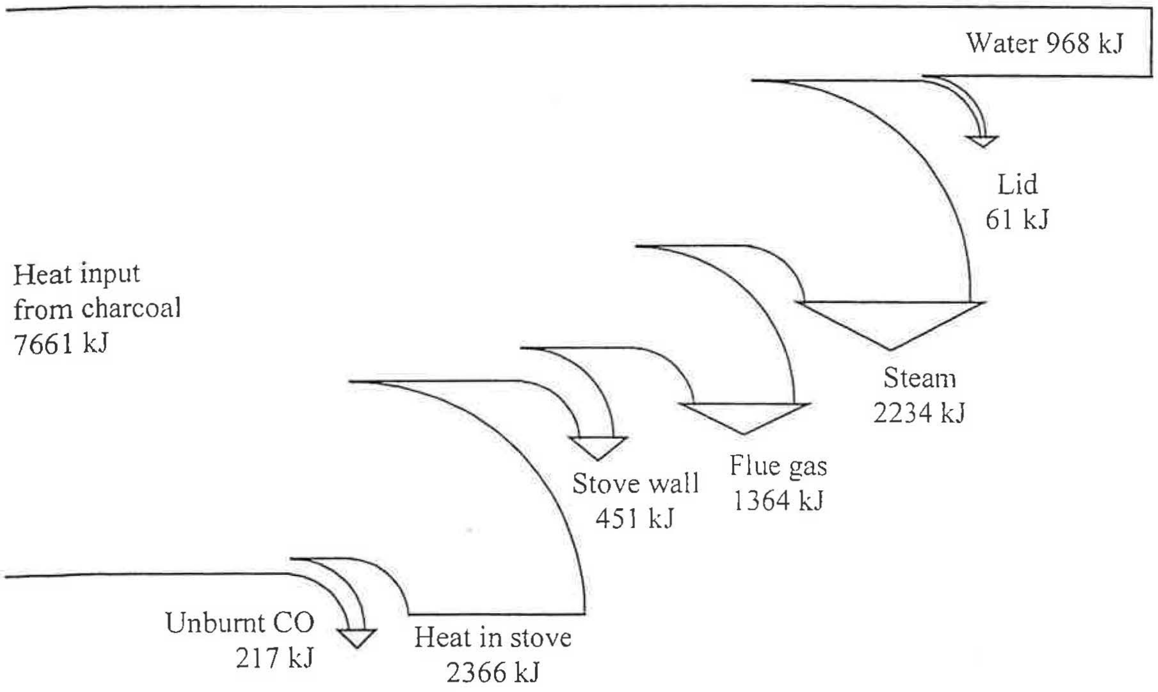
Then from this the radiation heat transfer (Q_r) is given by: $Q_r = F'_{1-2}\sigma A_c\left(T_1^4 - T_2^4\right)$

σ = Stefan-Boltzman constant = 5.6697×10^{-8} W $m^{-2}K^{-4}$ A_c = Area of hot charcoal



Geometric Form Factor *F'* for opposed parallel shapes: discs, squares and rectangles

A Sankey diagram shows values expressed as widths on a graphical presentation:



A **Sankey diagram**, showing heat balance in a Thai charcoal stove.

Overall efficiency = 968/7661 × 100 = 12.6%

Note: "Heat in stove" not shown as "lost", but it is difficult to recover as useful heat.

Properties of matter

Thermal Properties of Air

Temperature (K)	100	150	200	250	300	350	400
Density (kg m^{-3})	3.5562	2.3364	1.7458	1.3947	1.1614	0.995	0.8711
Heat Capacity (J kg^{-1}K^{-1})	1032	1012	1007	1006	1007	1009	1014
Kinematic Viscosity (m^2 s^{-1})	2.00E-06	4.43E-06	7.59E-06	1.14E-05	1.59E-05	2.09E-05	2.64E-05
Thermal Diffusivity (m^2 s^{-1})	2.54E-06	5.84E-06	1.03E-05	1.59E-05	2.25E-05	2.99E-05	3.83E-05
Thermal Conductivity (W m^{-1} K^{-1})	0.00934	0.0138	0.0181	0.0223	0.0263	0.03	0.0338
Prandtl Number	0.786	0.758	0.737	0.72	0.707	0.7	0.69

Temperature (K)	450	500	550	600	650	700
Density (kg m^{-3})	0.774	0.6964	0.6329	0.5804	0.5356	0.4975
Heat Capacity (J kg^{-1}K^{-1})	1021	1030	1040	1051	1063	1075
Kinematic Viscosity (m^2 s^{-1})	3.24E-05	3.88E-05	4.56E-05	5.27E-05	6.02E-05	6.81E-05
Thermal Diffusivity (m^2 s^{-1})	4.72E-05	5.67E-05	6.67E-05	7.69E-05	8.73E-05	9.80E-05
Thermal Conductivity (W m^{-1} K^{-1})	0.0373	0.0407	0.0439	0.0469	0.0497	0.0524
Prandtl Number	0.686	0.684	0.683	0.685	0.69	0.695

Thermal Properties of Water

Temperature (°C)	0	20	40	60	80	100
Density (kg m^{-3})	999.8	998.2	992.2	983.2	971.8	958.4
Heat Capacity (J kg^{-1}K^{-1})	4215.32	4182.49	4177.29	4185.35	4198.37	4214.16
Kinematic Viscosity (m^2 s^{-1})	1.79E-06	1.01E-06	6.60E-07	4.80E-07	3.70E-07	3.00E-07
Thermal Diffusivity (m^2 s^{-1})	1.31E-07	1.43E-07	1.51E-07	1.55E-07	1.64E-07	1.68E-07
Thermal Conductivity (W m^{-1} K^{-1})	0.55	0.6	0.63	0.65	0.67	0.68
Prandtl Number	13.7	7	4.34	3.07	2.23	1.76
Thermal Expan coeff. (β) (K^{-1})	-2.40E-05	1.44E-04	3.81E-04	6.90E-04	1.04E-03	1.49E-03

Wind Turbine Experiment

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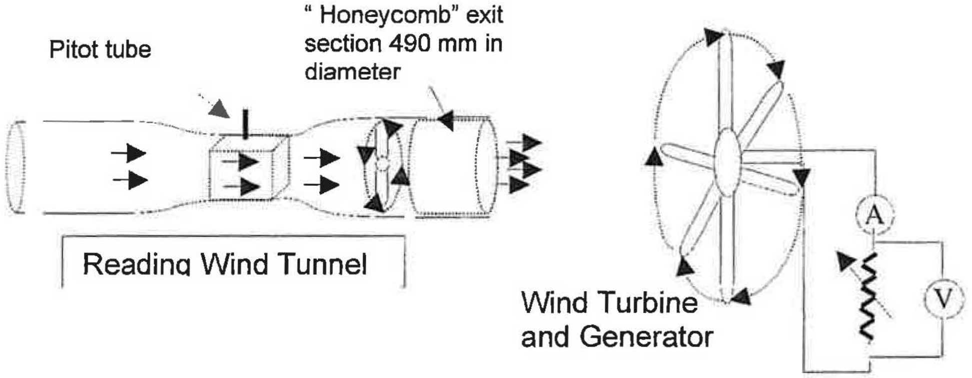
University of Reading
School of Construction Management and Engineering

9 December, 2002

CONTENTS

Introduction

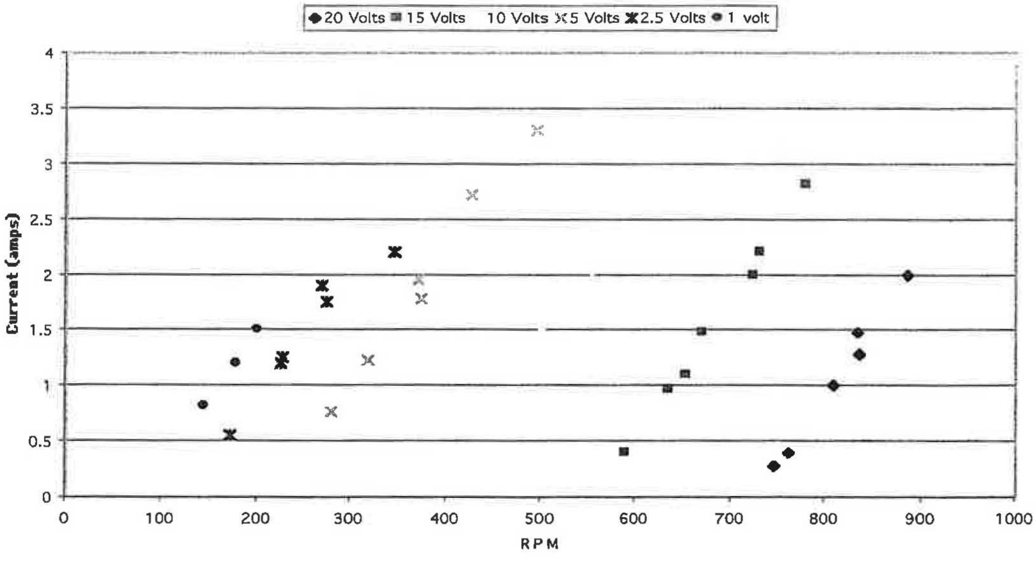
We tested a Rutland 910 6-bladed wind turbine placed 1.8 meters from the output of a wind tunnel. The turbine itself is 900 mm in diameter and is designed to charge batteries.



We can adjust the velocity of the air leaving the wind tunnel and use rheostats to vary the load resistance on the turbine generator (which lets us adjust the output voltage of the generator). A voltmeter and ammeter were connected to the generator output as shown.

1. Characterising the turbine performance for a constant voltage output.

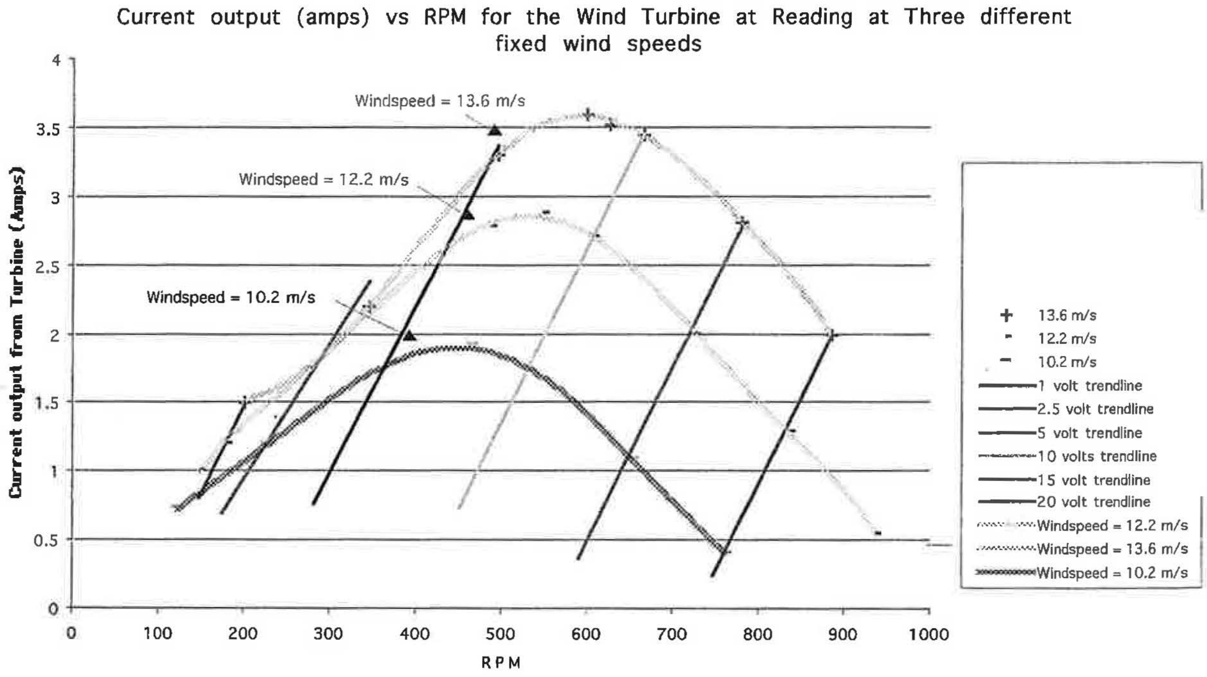
Here we adjusted the wind velocity from the wind tunnel and the resistance load on the turbine to keep the voltage of the turbine output constant and measured the current output from the turbine in each instance. Our results are plotted below. (The data table is included in the Appendix at the end of this report).


Characterisation of a Rutland 910 Wind Turbine (Reading)--Current (amps) vs. RPM for a fixed output voltage

2. Characterising the wind turbine performance at constant wind speed.

For the next plot we kept the wind tunnel at three different, constant wind speeds and varied the electrical resistance load on the turbine. For each wind speed we measured the current output of the turbine and the turbine's rate of spin in RPM. These performance lines are superimposed over the "constant voltage" performance lines of the previous graph.

Since the current from the generator is proportional to the torque it requires ~~provides~~, this graph is a sort of plot of torque for various RPM for the wind turbine under various wind speed conditions. also a plot of available torque for various RPM –, –



3. Plot of $\frac{I}{\Delta p} vs. \frac{n}{\sqrt{\Delta p}}$

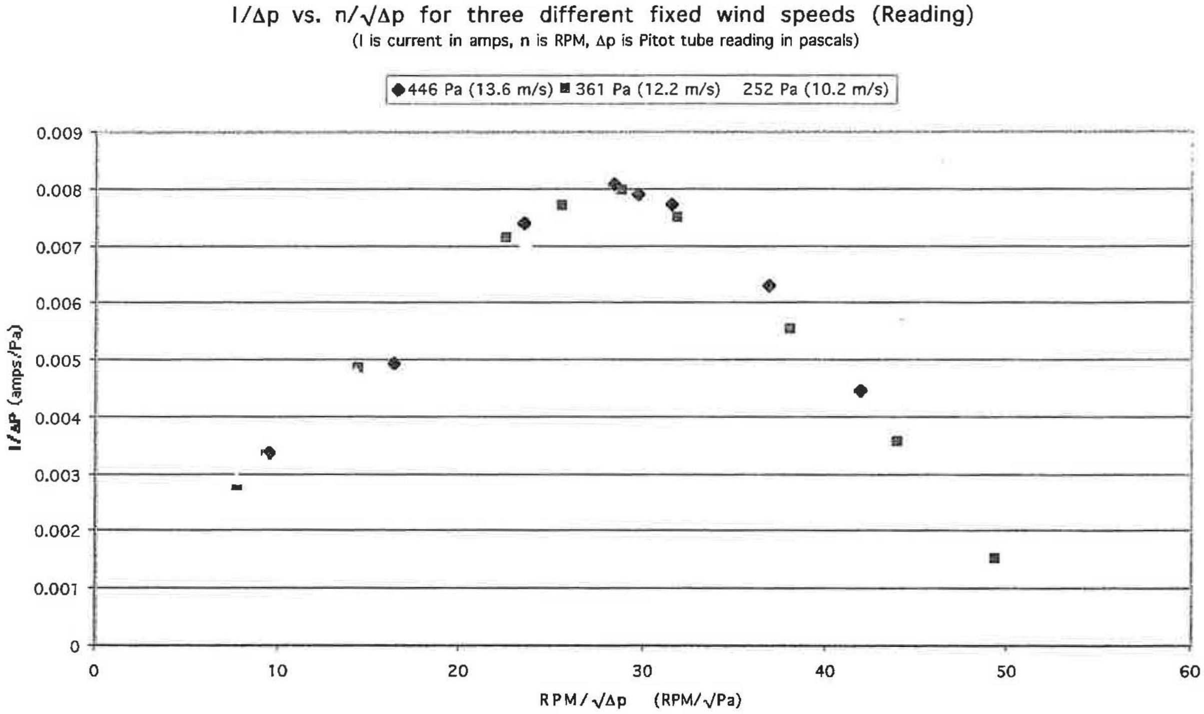
Since

$$\frac{I}{\Delta p} \alpha \frac{\tau}{v_\infty^2} = \frac{C_\tau(\frac{1}{2}\rho A v_\infty^2 \frac{D}{2})}{v_\infty^2} = C_\tau \times \text{some constants}$$

and

$$\frac{n}{\sqrt{\Delta p}} \alpha \frac{\frac{2\pi\omega}{60}}{v_\infty} = \frac{\frac{2\pi}{60}(\frac{v_{tip}}{\frac{D}{2}})}{v_\infty} \alpha \frac{v_{tip}}{v_\infty} = \lambda$$

a plot of $\frac{I}{\Delta p} vs. \frac{n}{\sqrt{\Delta p}}$ is essentially the same as a plot of C_τ vs. λ. By setting up the ratios as we have this eliminates the particular wind speeds and provides a way to interpret the data that is independent of particular operating conditions.



4. Plot of $\frac{EI}{\sqrt{\Delta p^3}}$ $vs.$ $\frac{n}{\sqrt{\Delta p}}$

Since $\frac{EI}{\sqrt{\Delta p^3}} \alpha \frac{\eta P}{v_\infty^3} = \frac{\eta C_P(\frac{1}{2}\rho A v_\infty^3)}{v_\infty^3} = C_P \times some\,cons\tan ts$

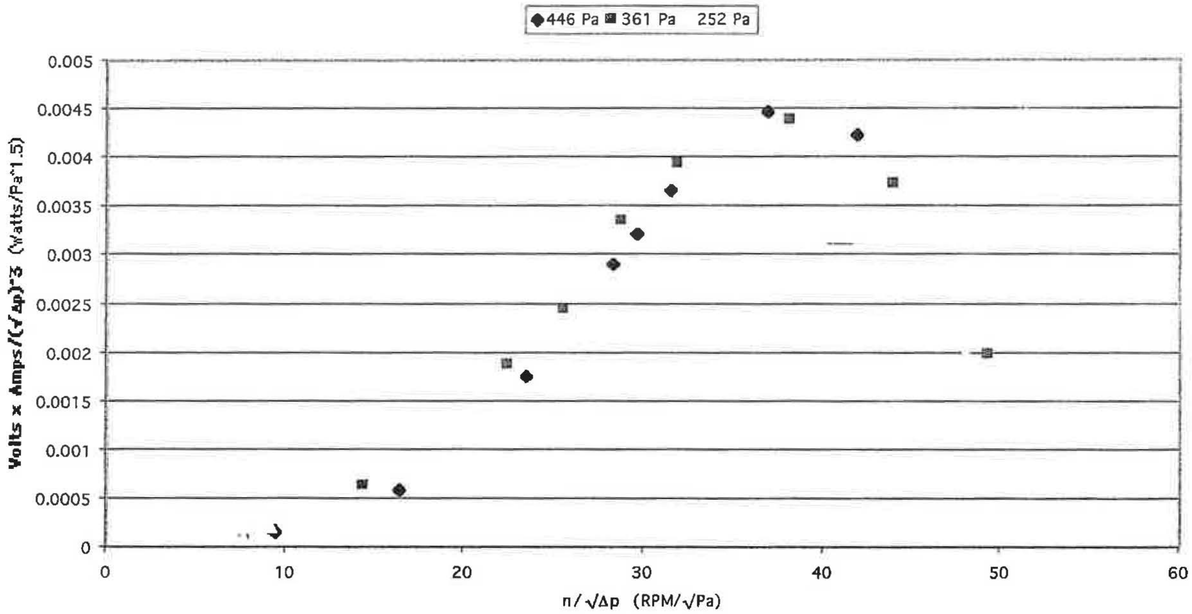
{ Provided that the $\eta_{electrical}$ is assumed constant.

and

$$\frac{n}{\sqrt{\Delta p}} \alpha \frac{\frac{2\pi\omega}{60}}{v_\infty} = \frac{\frac{2\pi}{60}(\frac{v_{tip}}{\frac{d}{2}})}{v_\infty} \alpha \frac{v_{tip}}{v_\infty} = \lambda$$

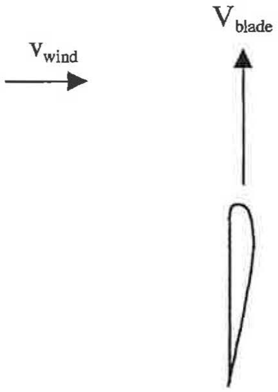
a plot of $\frac{EI}{\sqrt{\Delta p^3}}$ $vs.$ $\frac{n}{\sqrt{\Delta p}}$ is essentially the same as a plot of C_p vs. λ. Setting up the ratios as we have eliminates the particular wind speeds and provides a way to interpret the data that is independent of particular operating conditions.

Electrical Power/(√Δp)^3 vs n/√Δp for the Wind Turbine at Reading at three different wind speeds
(Δp is pitot tube reading on wind tunnel)



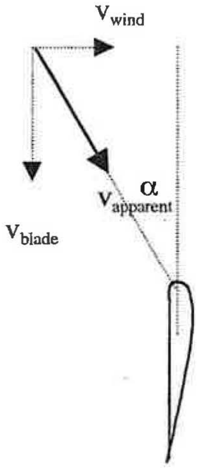
The physical reason why we are able to "collapse" the data for three different wind speeds into a single graph has to do with the fact that the tip speed ratio λ is in a sense a "stand in" for the angle of attack of the turbine blade with the wind.

For example, in the lab frame the blade moves in a direction perpendicular to the incoming wind from the wind tunnel:



From a frame of reference fixed on the blade, however, the incoming wind velocity is given by $v_{apparent}$:

It should be clear from the diagram that the angle of attack α is given by:



$$\alpha = \cot^{-1}\left(\frac{v_{blade}}{v_{wind}}\right)$$

If we choose to measure v_{blade} at the tip of the turbine we get

$$\alpha = \cot^{-1}\lambda$$

where λ is our tip-speed ratio.

The lift and drag coefficients for a particular wing profile are a function of the angle of attack, and the angle of attack is directly related to the tip speed ratio rather than to a particular wind or blade speed. So as far as the turbine blade is concerned, it cannot "tell" the difference between turning slowly in a gentle wind or turning more rapidly in a faster wind as long as the wind speeds are slow enough that the air flow over the wing can be considered smooth. Thus the power and torque characteristics of such a turbine blade can be related to λ independent of the particular wind speed.

5. Data for the Marlec 910 for the Bristol Wind Tunnel

The Bristol wind machine is the same as the one we have in Reading, but was tested in a larger wind tunnel. For the Bristol machine we are given Shaft Power vs. RPM data for various wind speeds and are asked to produce a plot of ηC_p vs. λ,

We can say $\eta C_p = \frac{\eta P}{P_0} = \frac{Shaft\ Power}{\left(\frac{1}{2}\rho A v_\infty^3\right)} = \frac{Shaft\ Power}{\left(\frac{1}{2}\times 1.18\pi\left(\frac{0.9}{2}\right)^2 v_\infty^3\right)}$

and $\lambda = \frac{v_{tip}}{v_\infty} = \frac{\frac{2\pi}{60} n \frac{D}{2}}{v_\infty} = \frac{n\pi\left(\frac{0.9}{30}\right)}{v_\infty}$.

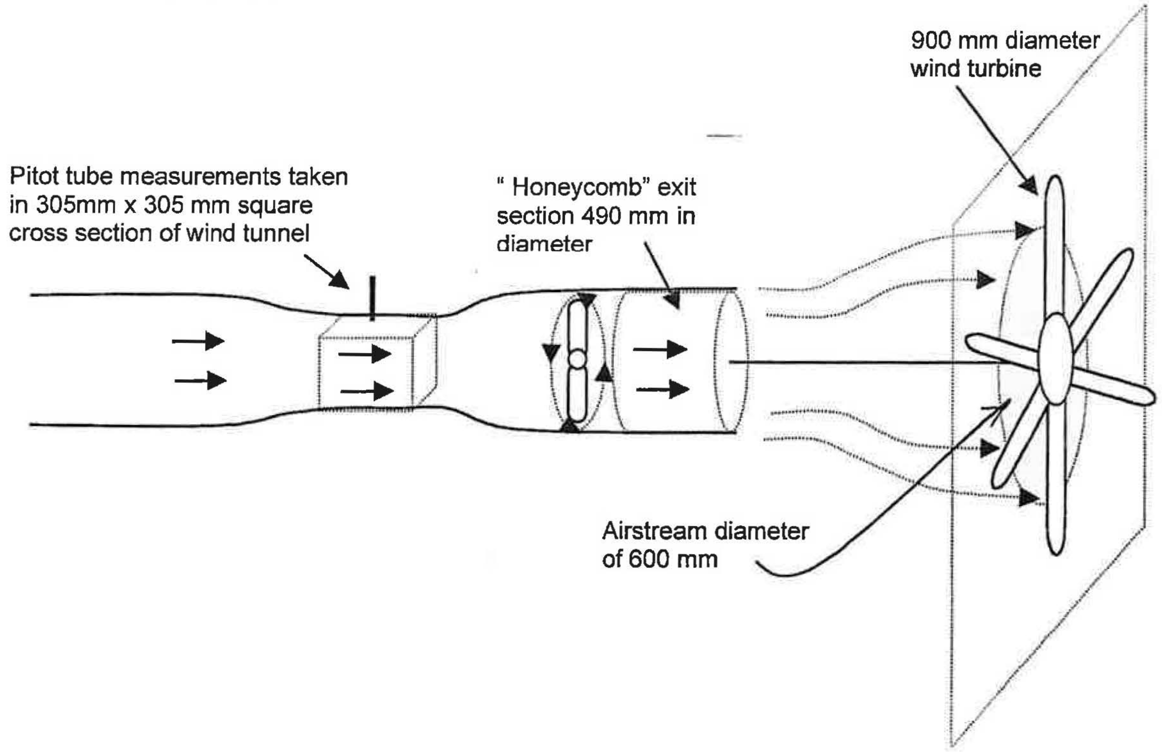
so we can calculate the required quantities from the data taken off of the graph (see the Appendix for the data tables).

We can calculate the same quantities for the wind turbine at Reading. Here

- shaft power will be given by Voltage x Current ,
- v_∞ can be calculated from the Pitot tube measurements and knowing the dimensions of the wind tunnel.

$$v_\infty = \sqrt{\frac{2\Delta p}{\rho}} \times \frac{Area\ of\ exit}{Area\ working\ section}$$

$$= \sqrt{\frac{2\Delta p}{\rho}}\left(\frac{(305)^2}{\pi\left(\frac{490}{2}\right)^2}\right) = 0.642\sqrt{\Delta p}$$



According to the actuator-disk model, the air leaving the wind tunnel should slow down and spread by the time it hits the turbine. Ideally, the velocity of the wind at the turbine should be 2/3 of v_∞.

The continuity equation says that $A_{\text{wind tunnel exit}} v_\infty = A_{\text{airstream at turbine}}(2/3\ v_\infty)$.

This leads to:

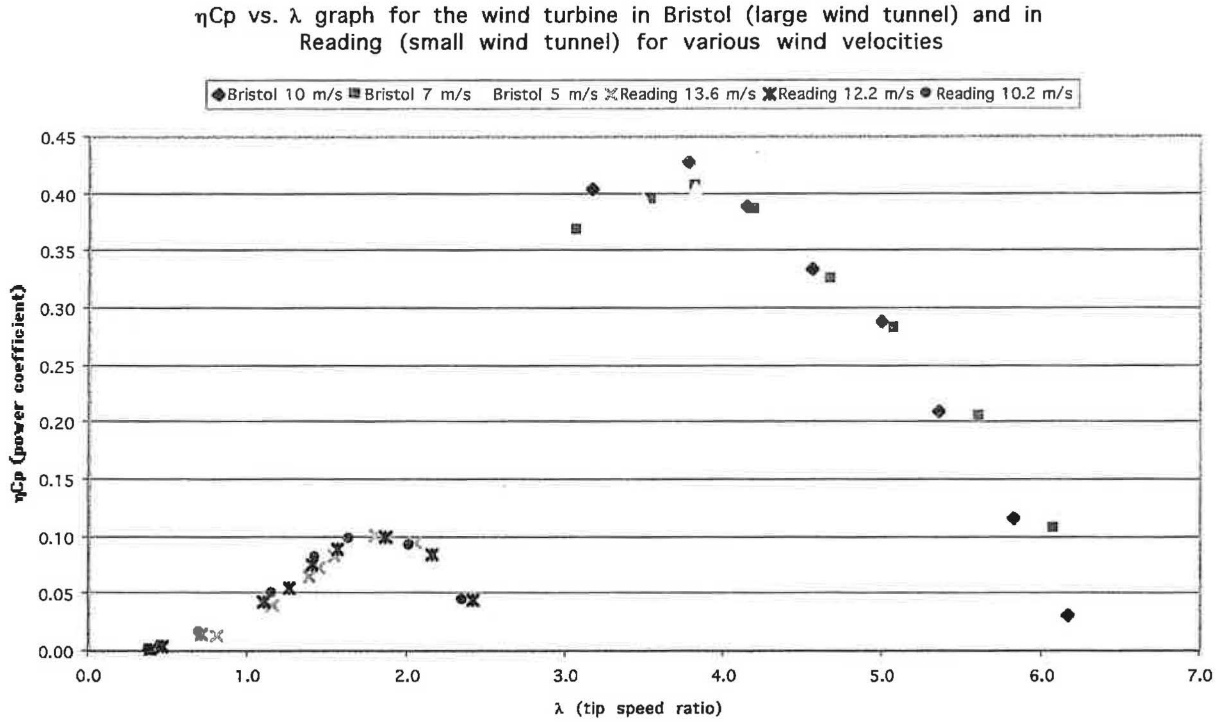
$$\pi\left(\frac{490\,mm}{2}\right)^2 = \frac{2}{3}\pi\left(\frac{D_{effective}}{2}\right)^2.$$

Solving gives

$$D_{effective} = 600\,mm$$

Thus, even though the real diameter of the wind turbine is 900 mm, only 600 mm of it is actually receiving any wind. In "real life" the turbine would be facing the full force of a full wind, but because of the limitations of our wind tunnel this leaves roughly half of each blade out of the wind and producing drag rather than power. We should expect that the C_p values for our turbine in Reading should be lower than those for the same turbine tested in the much larger wind tunnel in Bristol.

In addition, when we go to calculate the tip speed ratio for the Reading turbine we need to use a diameter of 600 mm rather than the 900 mm we use for the Bristol turbine.



The data matches what we would expect—For each turbine the data lie on essentially the same curve, but the values for ηC_p and λ are lower for the Reading turbine because of the extra drag on the Reading turbine from the "extra" blade length and the smaller diameter (leading to a smaller tip speed ratio for the same rotational frequency.

The smaller diameter shouldn't influence Cp–λ

Large & small wt of same design & solidity will have almost identical Cp~λ characteristics.

Reading Turbine data

Voltage	n (rpm)±3 rpm	I (amps, analog)±0.02A	I (amps, digital)±0.08A
20	884.8	1.99	2
20	834.9	1.28	1.31
20	808.9	1.00	1.03
20	761.3	0.399	0.4
20	745.9	0.275	0.27
20	832.5	1.48	1.50
15	779.4	2.81	2.83
15	730.9	2.20	2.24
15	724.3	2	2.04
15	669.5	1.48	1.51
15	652.6	1.09	1.1
15	634.4	0.96	0.97
15	588.5	0.39	0.39
10	665.3	3.45	3.47
10	614.1	2.88	2.91
10	605.7	2.7	2.72
10	552	1.98	2
10	533.8	1.72	1.76
10	500.4	1.5	1.51
10	448.7	0.71	0.71
5	494.3	3.3	3.3
5	427.7	2.72	2.74
5	373.7	1.78	1.77
5	371	1.95	2
5	318.1	1.23	1.26
5	279.9	0.76	0.76
2.5	345.6	2.2	2.15
2.5	273.6	1.75	1.76
2.5	268.8	1.9	1.9
2.5	227.9	1.25	1.26
2.5	225.9	1.2	1.22
2.5	172.1	0.549	0.58
1	200.1	1.5	1.52
1	178.7	1.2	1.28
1	145.6	0.82	0.82

Data for wind speed equivalent to $\Delta p = 446$ Pa ±0.02 Pa

V	n	I(analog)	I(digital)	v (m/s)	lambda	PO(Watts)	P(watts)	Cp
20	884.8	1.99	2	13.6	2.05	416	39.8	0.096
15	779.4	2.81	2.83	13.6	1.81	416	42.2	0.101
10	665.3	3.45	3.47	13.6	1.54	416	34.5	0.083
8.6	626.3	3.52	3.58	13.6	1.45	416	30.3	0.073
7.6	598.5	3.6	3.63	13.6	1.39	416	27.4	0.066
5	494.3	3.3	3.3	13.6	1.15	416	16.5	0.040
2.5	345.6	2.2	2.15	13.6	0.80	416	5.5	0.013
1	200.1	1.5	1.52	13.6	0.46	416	1.5	0.004

Data for wind speed equivalent to $\Delta p = 361$ Pa ±0.08 Pa

25	937.2	0.54	0.54	12.2	2.41	303	13.5	0.045
20	834.9	1.28	1.31	12.2	2.15	303	25.6	0.085
15	724.3	2	2.04	12.2	1.87	303	30.0	0.099
10	605.7	2.7	2.72	12.2	1.56	303	27.0	0.089
8	547.2	2.87	2.93	12.2	1.41	303	23.0	0.076
6	486	2.78	2.84	12.2	1.25	303	16.7	0.055
5	426.3	2.58	2.6	12.2	1.10	303	12.9	0.043
2.5	273.6	1.75	1.76	12.2	0.70	303	4.4	0.014
1	178.7	1.2	1.28	12.2	0.46	303	1.2	0.004
0.45	147.9	1	1.06	12.2	0.38	303	0.5	0.001

Data for wind speed equivalent to $\Delta p = 252$ Pa ±0.04 Pa V

20	761.3	0.399	0.4	10.2	2.35	177	8.0	0.045
15	652.6	1.09	1.1	10.2	2.01	177	16.4	0.093
10	533.8	1.72	1.76	10.2	1.65	177	17.2	0.097
7.5	464.2	1.92	1.97	10.2	1.43	177	14.4	0.082
5	373.7	1.78	1.77	10.2	1.15	177	8.9	0.050
2.5	225.9	1.2	1.22	10.2	0.70	177	3.0	0.017
1	145.6	0.82	0.82	10.2	0.45	177	0.8	0.005
0.53	122.2	0.735	0.73	10.2	0.38	177	0.4	0.002
	770	0		10.2	2.37	177	0.0	0.000

Data for the Marlec 910 Wind turbine at Bristol

Marlec Pitot Measurements

RPM	(Del p)^0.5	Del P
225	6	36
280	7	49
325	8	64
385	9	81
445	10	100
510	11	121
560	12	144
620	13	169
675	14	196
755	15	225
780	16	256

v0	shaft power	rpm	lambda	PO	Cp
10	138	650	3.1	375	0.37
10	148	750	3.5	375	0.39
10	153	810	3.8	375	0.41
10	145	890	4.2	375	0.39
10	122	990	4.7	375	0.33
10	106	1075	5.1	375	0.28
10	77	1190	5.6	375	0.21
10	40	1290	6.1	375	0.11

v0	shaft power	rpm	lambda	PO	Cp
7	52	470	3.2	129	0.40
7	55	560	3.8	129	0.43
7	50	615	4.1	129	0.39
7	43	675	4.5	129	0.33
7	37	740	5.0	129	0.29
7	27	795	5.4	129	0.21
7	15	865	5.8	129	0.12
7	4	915	6.2	129	0.03

v0	shaft power	rpm	lambda	PO	Cp
5	18	340	3.2	47	0.38
5	18.5	370	3.5	47	0.39
5	19	405	3.8	47	0.40
5	16	450	4.2	47	0.34
5	9	535	5.0	47	0.19
5	4	575	5.4	47	0.09
5	1	610	5.7	47	0.02

Fa WIND TURBINE EXPERIMENT

1. OBJECTIVES

The objective is to examine the behaviour of a small battery-charger wind turbine of 900 mm diameter.

2. PROCEDURE

2.1 Before the date of the test:-

(a) Read the general description and the technical data.
(b) Examine the apparatus and take note of units in which the instruments will provide the variables to be measured. Also make note of the range for each variable.
(c) Read the theoretical background.
(d) Read the test procedure and operating instructions. You need to prepare a test data sheet with the appropriate formulas so that you can process the measurements immediately.

2.2 During the test:

Make a note of the stability in readings and estimate the reading errors and include any observations you might consider useful.

The test work is divided into two parts.

(i) The performance of the electrical generator is first examined by varying the electrical load at constant voltage (5v; 10v; 15 v and 20 v) and recording the rotational speed (RPM) and current (I) delivered.

Plot by hand I versus RPM at each fixed voltage.

(ii) The performance of the wind turbine-generator at two fixed wind speeds, recording electrical power should next be examined.

3.0 GENERAL DESCRIPTION

The wind turbine is located 1.8 m downstream of the exit of the wind tunnel, which is of the open suction type, with a driving fan downstream of the working section. The working section of 305 mm x 305 mm (12 inch x 12 inch) has a Pitot-static tube mounted in it to enable the wind speed at that section to be measured. The exit duct on the downstream side of the fan is of 490 mm diameter. Here the flow is quite disturbed and issues as a free jet of air to impinge on the wind turbine placed in its path. Not only is the free jet disturbed, it is also of a smaller diameter than the 900 mm turbine. For this reason only qualitative results of wind turbine performance can be made.

3.1 Technical Data

Rutland 910 Wind charger

• diameter	900 mm
• blade numbers	6

Plint 12" x 12" Wind tunnel

• working section (square)	305 mm x 305 mm
• exit section (circular)	490 m diameter

Pitot tube + manometer

- digital display (Pa)

Electrical resistances: two off

35.6 Ω 3.3A

Avometers to measure current and voltage
Tachometer to measure rotational speed.

3.2 Starting the wind tunnel

(a) make certain the on/off switch on the horizontal control panel is **OFF** and the variable speed setting is at the lowest value.
(b) turn the key in the control box clockwise.
(c) push to green button and then turn the on/off switch to the **ON** position.
(d) increase the speed of the wind tunnel.

3.3 Theoretical Background

For turbomachines

$$\frac{gH}{n^2D^2};\frac{Q}{nD^3};\frac{Psh}{pn^3D^5}$$

For turbines these are usually re-structured as:

$$\frac{nD}{\sqrt{gH}};\frac{Q}{D^2\sqrt{gH}}\text{and}\frac{Psh}{pD^2(gH)^{\frac{3}{2}}}$$

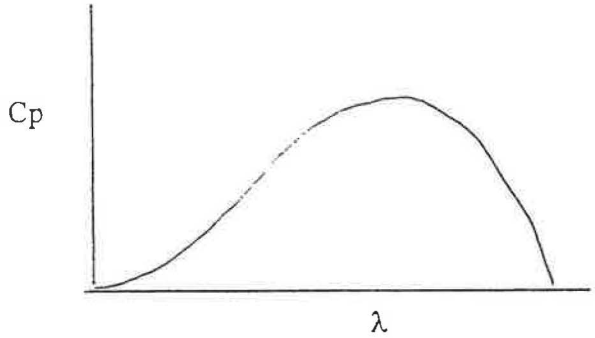
In the case of the wind turbine, or free stream propeller the energy supply gH (J/kg) is no more than the kinetic energy of the stream $V^2/2$ (J/kg) so the groups can be re-written as:-

$$\frac{\pi n D}{V} = \lambda \quad \text{(Tip speed ratio)}$$

$$\frac{Psh}{\left(\frac{1}{2}\right)\rho A V^3} = Cp \quad \text{(Power coefficient)}$$

where A is the swept area of the wind rotor (αD^2)

The figure shows a typical performance Cp-λ curve.

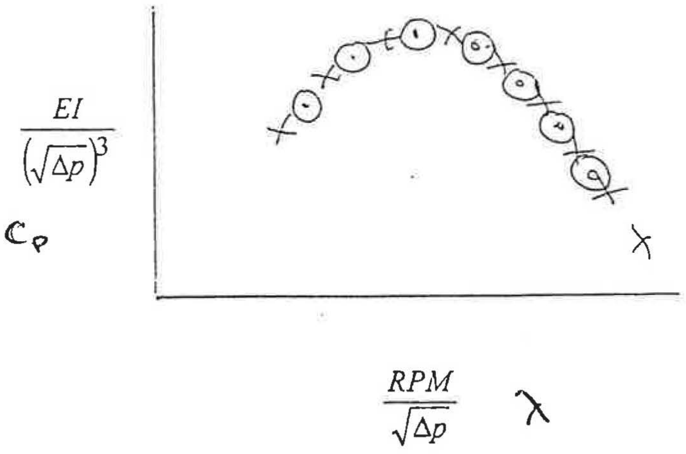


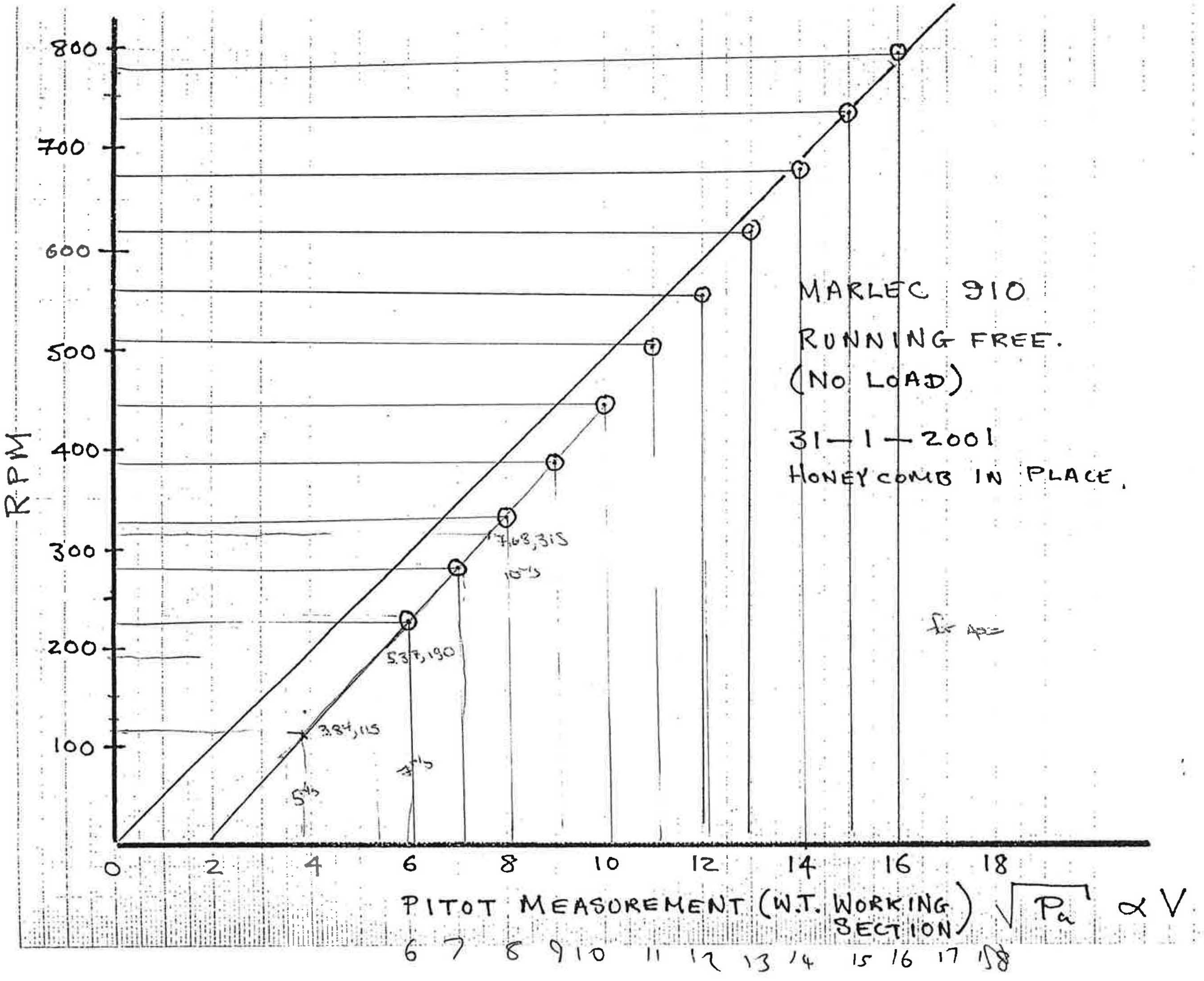
In the case of the test arrangement

$V \alpha \sqrt{\Delta p}$ (where Δp is the Pitot tube measurement in the working section)

and the power P_{sh} α EI (Volts x amps).

For the different wind speeds therefore $\frac{EI}{\left(\sqrt{\Delta p}\right)^3}$ versus $\frac{RPM}{\sqrt{\Delta p}}$ should plot out as a single curve.

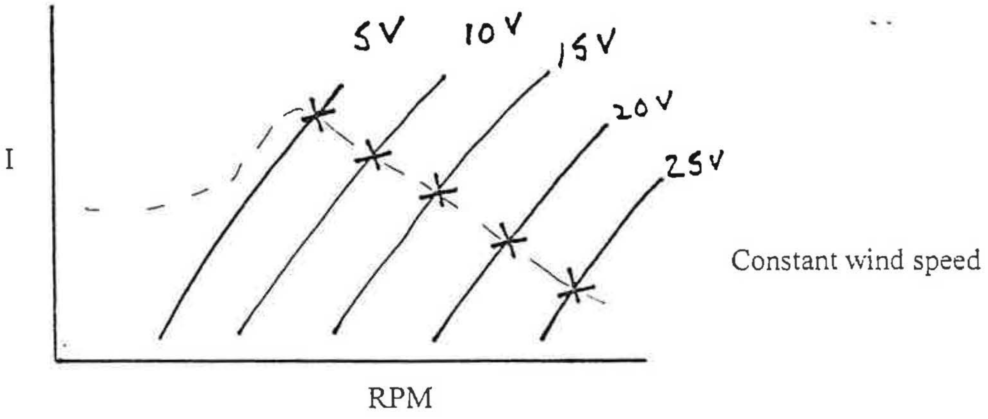




MARLEC 910
RUNNING FREE.
(NO LOAD)

31 — 1 — 2001
HONEYCOMB IN PLACE.

Provided that the raw data at constant wind speed includes observations taken when the voltage is 5v; 10v; 15v and 20 v; then the behaviour of the wind turbine can be plotted on the generator characteristic, and will show the general form of the C_T - λ curve.



4.0 THE WRITE-UP

The attached figure show tests performed on the WG 910 in a large Wind Tunnel at Bristol.

$C_{pmax} \approx 0.375$ $\lambda_{max} = 6.43$ $\lambda_o = 3.86$

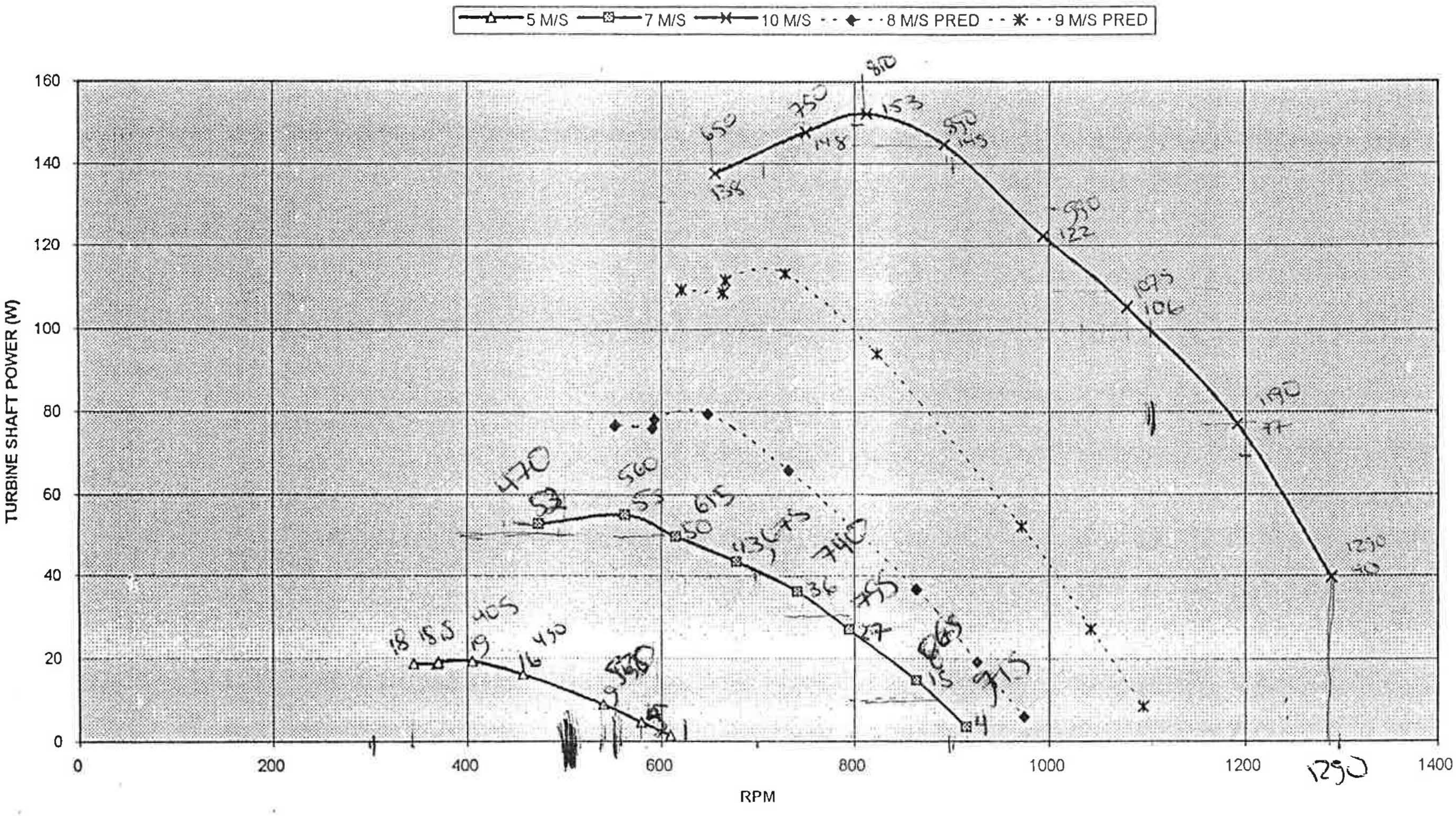
If it is assumed that the jet stream in which the wind turbine is placed in the Reading tests, expands in an optimum manner after leaving the 490 mm exit diameter, then only about 600 mm* of the rotor is in the flow. It is suggested that C_p and λ values for the Reading tests be calculated assuming that the **effective** rotor diameter is 600 mm and the wind velocity is that which exists at the 490 mm exit duct.

Compare these results with the Bristol data

* Note $490^2\ V = 600^2 \left(\frac{2}{3}V\right)$

WG910 TURBINE CHARACTERISTIC

WIND TUNNEL TESTS



Bristol Polytechnic Wind Tunnel Tests 05/03/92

Turbine Blade 01-100 NACA 4409 Modified

Integrated Biosystems for Sustainable Development

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9 May, 2003

CONTENTS

no. This is an industrial not agricultural process.

INTRODUCTION

not necessarily monoculture.

In the developed world, agricultural production typically uses fossil fuels to produce inorganic fertilisers that are then applied to an intensive monoculture system. The wastes from the system are collected and "deactivated" using complex, costly systems, often involving extensive investment in infrastructure. In economic terms, the whole system "works" (when it does work) because farmers can purchase the required inputs on credit, and the production yields and profits are high enough to cover the costs of the inputs. Such systems give preference to short-term financial profits and do not consider natural resource degradation. (UNDP)

Such a process is not environmentally sustainable, in that one is constantly "mining" the environment for energy and mineral inputs, and then paying to dispose of the resulting wastes. It may also not be economically sustainable in that if market conditions change so that the price for their product drops, farmers can find that the price of system inputs and waste treatment can be more than what they can get for their goods.

reference?

Applying this intensive model of agriculture to the developing world is bound to cause problems, both environmentally and economically. Farmers there do not generally have the resources to purchase the prepared feeds and fertilisers used by their counterparts in the developed world. Development schemes that have tried to mimic the "Western" model can collapse as soon as the donor aid is withdrawn.

At the other end of this agricultural model is the problem of waste disposal "Conventional water treatment systems - highly specialized, costly and based on high amounts of inputs and energy - are beyond the means of most small and medium-scale farmers in the developing world." (UNDP) In much of the developing world "livestock waste management is still in its infancy or rudimentary stages. For example many commercial pig producers simply drain pig manure or effluent into creeks, streams and rivers. To, them, this is the easiest, most efficient, cheap and practical method of waste disposal." (Ajuyah, 1998) This has resulted in water "contaminated with sediments, pesticides, animal manure, fertilizers and other sources of organic and inorganic matter being dumped into streams, which deteriorates water quality, limits its use downstream and causes a loss of valuable resources."(UNDP)

it would be more than just yield for example what about working?

is this assuming a subsistence system?

Ideally, a successful and sustainable agricultural system for the developing world would be one that gives sufficient yields to support a family (or community) based on inexpensive, locally available, sustainable inputs, and whose wastes could be treated with low-tech, inexpensive methods to meet healthy water standards. Even better, if the wastes could be used as a valuable input into the agricultural system farmers would have an economic incentive to manage their wastes in a more environmentally responsible way. This is the essence of an Integrated Biosystems approach to agricultural production.

An integrated biosystem approach is one that seeks to take a waste product and transform it from a liability to something of value. At its best it substitutes cheap, readily available, locally produced materials for expensive materials that must be brought in from outside. It aims to extract nutrients and energy from the wastes of one process, and recycle them into another process. As such it is the antithesis of a monoculture approach, in that you end up producing more than one product, and your inputs and outputs are related to interwoven processes. In such an approach a series of biological processes are used to destroy pathogens and reduce nutrient load in the discharge. Each of these processes uses the waste from one step of the process as inputs into another step of production. A schematic representation of the process is shown below in figure 1:

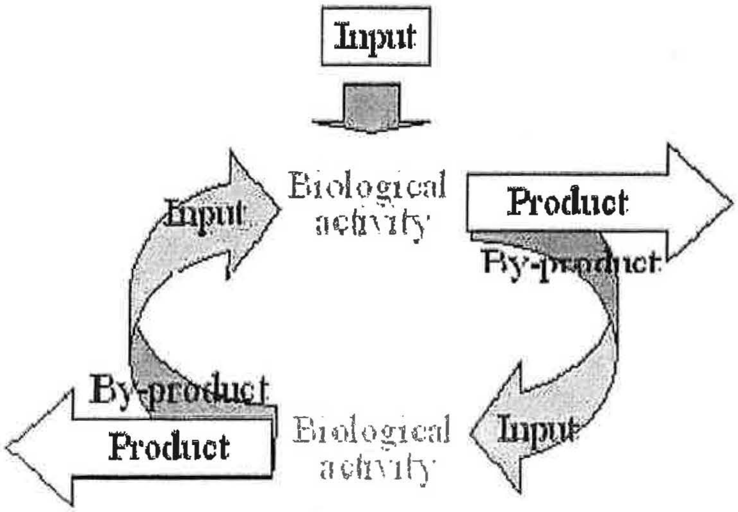

Figure 1. Schematic Diagram on the Material Flow in an Integrated Bio-System (Foo)

only the technical advantages? what about other advantages?

In this paper I intend to review several such integrated systems, starting with the most simple and progressing to more complex systems requiring higher levels of technical and economic resources; to highlight their technical advantages for sustainable development; where available, to look at the indicators that suggest the efficacy of such systems; and finally to examine the social, economic and technical impediments to their acceptance and success in the developing world.

Indicators used to evaluate the success of integrated biosystems

There are several indicators that might be used to ascertain the quality of a water supply or wastewater stream, the "richness" of waste as a feed source, or the productivity of a particular integrated system. For water quality we can consider:

Total Suspended Solids—A measure of what level of particulates are in suspension per litre of water

Biochemical Oxygen Demand (BOD or BOD_5)-This is an indirect measure of the level of nutrients in a sample of water, Typically one takes a water sample and measures the amount of dissolved oxygen in it, puts the sample in a dark place, and then remeasures the level of dissolved oxygen in it five days later. Assuming that some microorganisms exist in the water, the amount of decrease in oxygen in the water indicates in some sense the amount of cellular respiration that has taken place, and thus how much nutrient was available in the water. It is typically measures in mg/litre or ppm. For particularly polluted samples the BOD may exceed the amount of oxygen actually present in the water, and so the sample must be diluted before the measurement can occur.

Faecal Coliform count—This measures the number of *E.coli*-type bacteria in a water sample. Fresh animal and human excreta can be expected to have rather high levels. WHO has set the acceptable level for agricultural applications at 1000 per 100 ml, whereas the level for drinking water is less than 100 per 100 ml. (SANDEC)

Concentration of Helminth eggs—Parasitic intestinal worms (helminths) lay their eggs in their host's gut, and the eggs are passed with the faeces. If these get into the water supply they can reinfect new hosts. WHO standards are ≤1 per 100 ml (SANDEC)

Yes but the form of the element is [illegible] also important

Inorganic fertilisers contain phosphorus, potassium and nitrogen in forms that are biologically available to plants and microorganisms. One way to judge the "richness" of organic fertilisers is to measure the availability of these same elements.

Yields from aquaculture typically are expressed in terms of kilograms (or tonnes) per hectare/year. Economic yields can be expressed in terms of profit per hectare per year, profit/expense ratios, or any number of similar ways.

Examples of Integrated Biosystems

Waste-Fed Pond systems

In the simplest systems cow, pig, or chicken manure is applied directly to a pond as a slurry. In some parts of the Far East this can include "night soil" (human excreta) as well as refuse, snails, grass. Fish (mostly carp and/or tilapia) either feed directly on the waste or on algae and zooplankton that feed on the wastes. Other variations of the system include building duck or pig pens with slatted floors directly over the pond or building a latrine right over the pond and allowing the fish to feed on whatever manure and food wastes fall into the water. Results from China suggest that typical fish yields can range from 2-6 tonnes/ha/year. (Wolfarth)

The advantages of such a system from a waste treatment point of view is that the BOD of the manure can be reduced from its initial value of around 25,000 mg/l to a much lower value (Waste Treatment in Agriculture). Too much manure can lower the amount of dissolved oxygen in the water, limiting plant growth. Too deep of a pond will limit the ability of sunlight to penetrate the pond and allow photosynthesis by the algae that consume some of the wastes and provide food for fish and for zooplankton. Optimising the performance of the pond involves balancing the flow of waste and water into the pond and harvesting fish at an appropriate rate to maximise fish growth. Although the amount of dissolved oxygen could be monitored, in practice application rates of manure are based on empirical rules involving the depth and area of the pond and the numbers and type of fish present in the pond. (Hobson, 1977). From an economic point of view, nuisance substances are transformed into something that can enhance nutrition and income.

[illegible] dated reference

Virtually all of these pond systems involve some form of polyculture. This is analogous to intercropping of crops in fields, but in this case one is stocking a variety of fish species in single pond rather than sowing a variety of plant crops in a single field. A single fish species can only feed on a part of the "food" available from the wastes in the pond, and will produce wastes that can build up to toxic levels. By using multiple species of fish, one species can feed on the wastes from another in such a way that there is an almost complete conversion of wastes to food:

> *"The most widely used combinations are those involving Chinese carp... Grass and silver carp are herbivorous. Grass carp consume aquatic vegetables and will also feed on terrestrial plant residues such as vegetable tops and grass clippings. Silver carp, by means of their special filtering apparatus, consume large quantities of phytoplankton. Bighead carp feed primarily on zooplankton, and black carp consume snails and on the benthos. Common carp feed on benthic animals and detritus. In scavenging pond bottoms, common carp stir up sediments which create turbidity and help prevent excessive growth of undesirable aquatic vegetation. Perhaps more important, organic particles are suspended that are enriched through colonisation by bacteria and filtered from the water column by fish such as the silver carp."* (NAP, 1981)

Although the yield of any particular species of fish will be lower than the yield obtained from an intensive monoculture, the overall yield of fish will generally be two or three times higher. (NAP, 1981) A schematic of such a polyculture system is shown below (Figure 2).

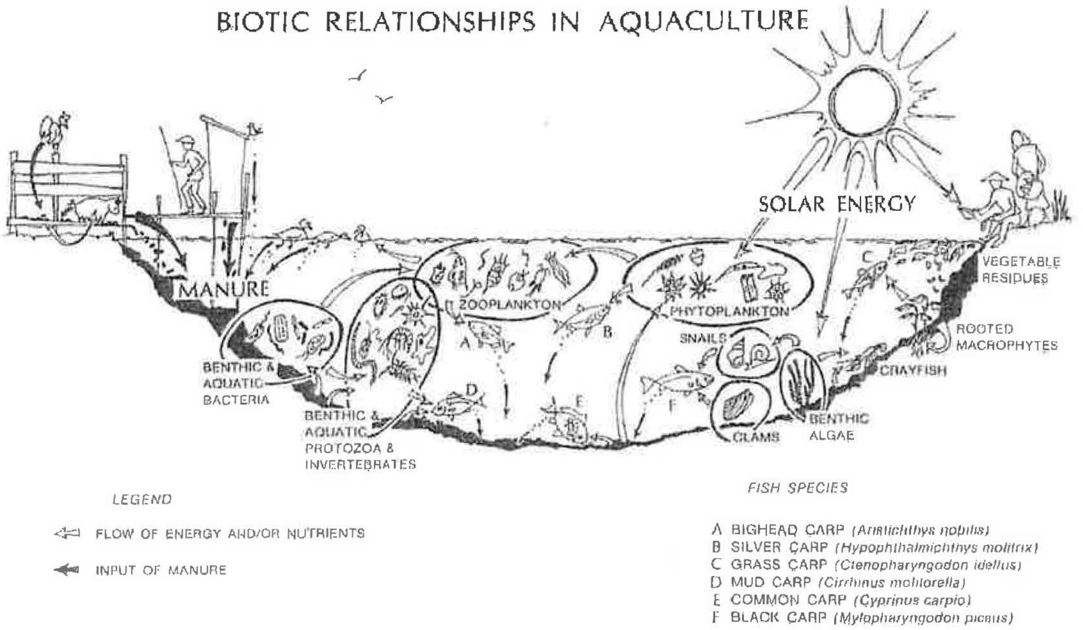

Figure 2. Interrelationships in a carp polyculture system (NAP, 1981)

Anaerobic Digestion as part of an Integrated Biosystem

Another level of sophistication is to include an anaerobic digester as part of the integrated system. Anaerobic digestion is a process whereby bacteria transform the carbohydrates, fats and proteins in food or waste into methane gas and carbon dioxide, leaving the potassium, phosphorus, and nitrogen in forms that are biologically available. (Fulford) The resulting effluent has virtually no odour and has highly reduced biochemical oxygen demand and pathogen levels. (Ajuyah, 1999) The "biogas" produced in the process is approximately 60% methane, and can be used for cooking, heating, lighting, process heat, or fed into an internal combustion engine to produce electricity and heat. Adding an anaerobic digester to the agricultural cycle serves the triple purposes of reducing the toxicity and pathogenicity of the wastes, rapidly (in a period of 1-3 weeks) transforming wastes into forms that can be used as fertiliser, and providing families or communities clean fuel for cooking that can replace purchased or collected wood.

One example of such a system is a livestock-biogas-fruit system employed in South China:

> "*Pomelo (Citrus grandis) farming was the most profitable component of the system. Pomelo litterfall and pig dung were fed into the biogas digester underneath the pigsty. The digester supplied biogas a domestic fuel and sludge as fertiliser. Chickens were raised in the orchard where they fed on weeds and pests, and deposited excreta as fertiliser. Recycling of wastes improved soil texture, and thereby decreased input of chemical fertiliser.*"

Such a system is illustrated diagrammatically below (Figure 3).

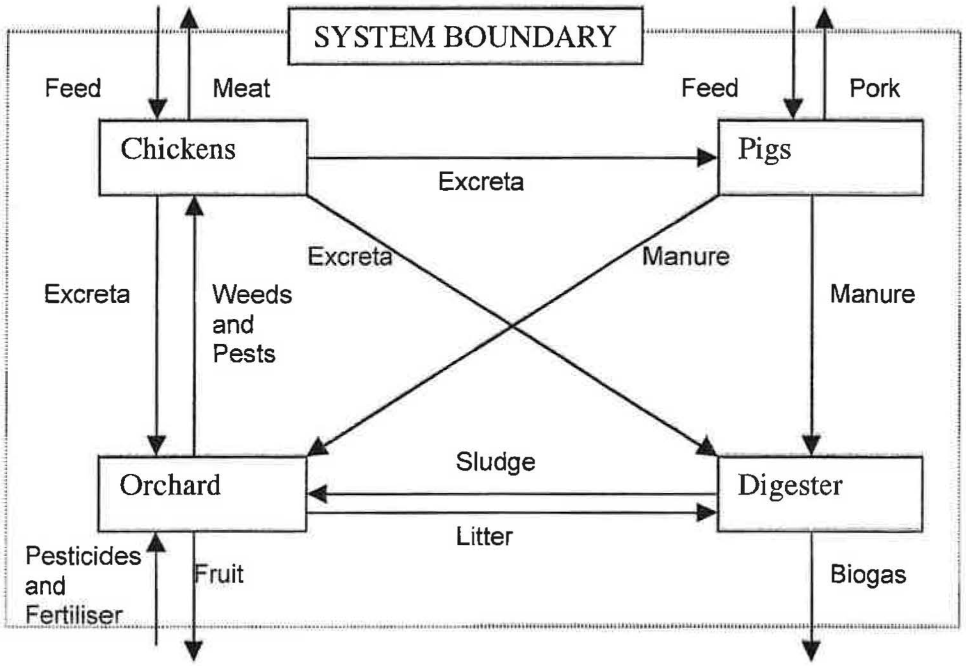

Figure 3. Structure of a typical livestock-biogas-fruit system (taken from Chen, 1977)

There were many advantages to such a system (taken from Chen, 1997):

Before anaerobic digestion	After anaerobic digestion
"Pig dung smells foul and . . . very few farmers wanted to carry it onto farmland. It was discharge everywhere and polluted the environment"	*"All digester sludge was pumped up to the orchard through a pipeline. The soils were gradually improved and became loams [after 4 years]"*
External fertiliser application per plant was 40.6-47.9 kg per plant	External fertiliser application per plant was an average of 5.9 kg per plant
Pesticide use cost an average of 19,3 yuan per plant	Pesticide use cost an average of 2.4 yuan per plant
An average family spent 803 yuan per year on coal for cooking	No money spent for coal. (A digester that could serve a family of five and should function for 15 years could be built for around 800 yuan, so the "pay-back" time was 1 year)

Industrial application of an integrated biosystem

An example of integrated waste treatment at an industrial level is that of the Vorion Distilleries project near Madras, India. The distillery "produces about 33,000 litres of alcohol from molasses releasing about five hundred thousand litres of effluent water every day. The effluent is dark brown coloured with a characteristic offensive odour and with a BOD of 45,000 and COD of 92,000 (mg/litre)". (Vorion) The effluent is anaerobically digested for 5-8 days at 35°C, which reduces the BOD to between 3000-4000 and produces about 10,000 m^3/day of biogas which is used as a substitute fuel in the boiler of the distillery. The effluent is then aerated for 4-5 days and algae and bacteria are added to bring the BOD down to about 1000. From there it is fed to 6 hectares of fish ponds which are stocked with male tilapia[†], stocked with fingerlings at a density of 50,000 per acre. The fish are harvested after 6 months and average about 400 grams each, for a fish yield of 50,000 tonnes/hectare/year. The resulting water has no colour or odour. The project is claimed to be profitable. (Vorion)

these be [illegible] with

Integrated Biosystems Involving Duckweed Cultivation

Yet another level or complexity can be achieved by introducing duckweed cultivation into the equation. In carp polyculture the ultimate amount of fish that can be grown is limited by the availability of food, the availability of fish feed stock, and maintaining sufficient levels of dissolved oxygen in the pond. Another limitation is that the cycle is limited by the amount of green food available to grass-eating carp. The "trick" is to balance feeding, so that there is enough food available to promote fish growth but not so much as to lower the amount of oxygen available in the pond.

> *"A well managed, semi-intensive carp polyculture farm in Asia produces between 2 and 8 metric tons/ha/year. Carp production in Bangladesh averages approximately 50 kg/ha/year for all fished inland ponds. Traditional pond*

[illegible]

[†] Populations of all-male tilapia can be produced either by treating the entire fish population with hormones or producing hybrids offspring of two different subspecies of tilapia that turn out to be all male. The advantage of having all male tilapia is that in mixed-sex populations the fish are below optimal marketable size when they reach sexual maturity, and any subsequent increases in fish mass will be due to increases in the number of fish rather than increases in the size of the fish. In an all male population the fish will continue to grow to 2-3 times their "normal" size (www.cherrysnapper.com)

interpreting

> *fisheries average 500 kg/ha/year while improved fisheries, practicing some variation of carp polyculture, show average annual yields of approximately 2.5 metric tons/ha/year. Aeration is needed to exceed the best yields, but is generally beyond the means of most carp producers.*" (Skillikorn)

Normal commercial carp production requires pre-mixed pelleted feeds and technical assistance to maintain the right balance of feeding and oxygen.

In a duckweed-fed model the only food input is duckweed. Grass-feeding carp eat the duckweed, and their faeces provide food for other carp, whose faeces feeds yet another species of carp. Fresh duckweed is placed on the surface of the carp-pond several times a day. The farmer can tell if he is overfeeding if there is duckweed left on the surface. In an experimental site set up in Bangladesh typical yields under this system were 10-15 tonnes/ha/year. The typical cost of duckweed per kg of fish produces is about $0.30-0.40, while the fish itself sells at $1.50 per kilogram, netting a healthy profit for the farmer. (Skillikorn).

> "*Duckweed-fed fish from the* [duckweed-fed] *experimental site had a clear quality edge in the local market. Aesthetically, fresh, green duckweed contrasted favorably with manure and other less appealing inputs to a conventional pond fishery. The consumer's perception appeared to be that because duckweed-fed fish are reared on fresh vegetables and live in higher quality water, they "smell, feel, and taste" better than fish reared conventionally.*" (Iqbal)

this is the key comparison for such systems.

In similar experiments tilapia were raised as a monoculture in duckweed-fed ponds. Typical yields were 7.5 tonnes/hectare per year. The production costs were between $0.40-0.50 per kg of tilapia, and the fish fetched $1-2 per kg at the market, depending on the size of the fish. This allowed even poor Bangladeshis to afford some fish, and netted a healthy profit for the farmer. (Iqbal)

How all of this fits into a integrated biosystem is that the duckweed is grown in ponds fed with either manure or wastes that have undergone anaerobic digestion to liberate nutrients and produce usable biogas. The solids from the digestion can be used for crop fertiliser; the liquid effluent is fed into a duckweed pond. Since duckweed can double its mass in less than two day depending on conditions (Skillikorn) a well-managed duckweed pond will yield about a ton of duckweed (wet weight) per hectare per day, enough to raise about 100 kg of fish or produce about 90 kg of animal feed. Since the duckweed is about 45% protein by dry weight it can be used either directly or compounded with other foods to make animal feed. If the duckweed ponds are arranged in a plug flow system (where the water moves very slowly along a long, narrow canal covered with duckweed) the duckweed can remove 99% of the nutrients in the water and lower the BOD to US water discharge levels, and lower total suspended solids to below 5 mg/litre. (Skillikorn) A diagram of the duckweed-fed system is shown on the next page (Figure 4).

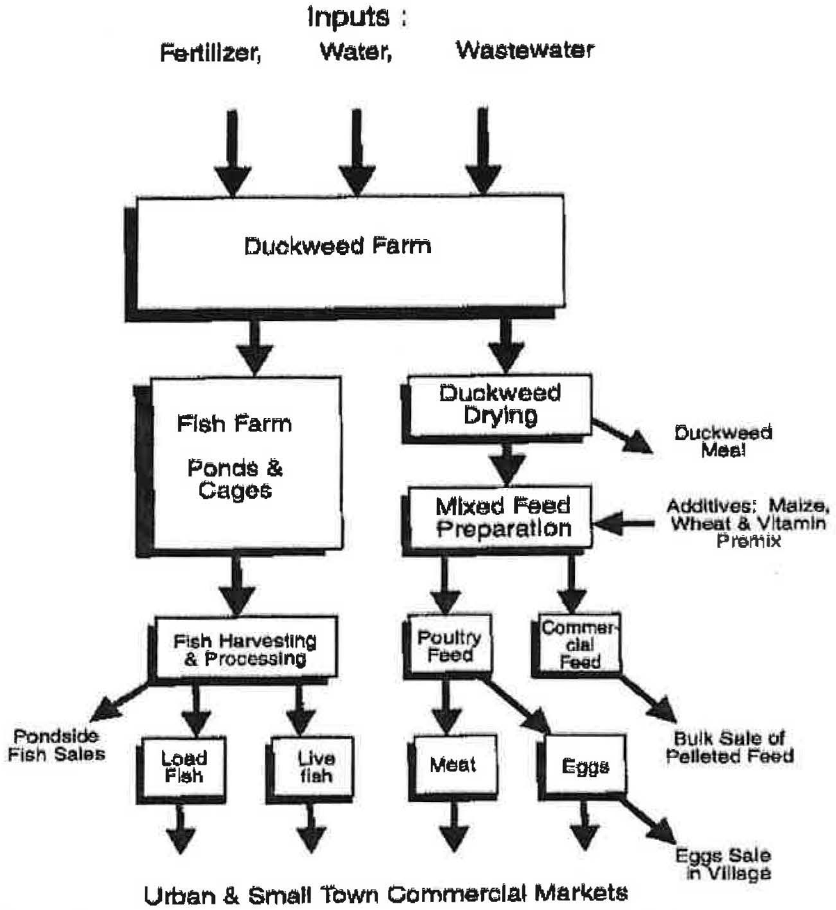

Figure 4. **Product flows in integrated farming of duckweed, fish and poultry** (Skillikorn)

Analysis of Integrated Biosystems for Sustainable Development

Hopefully I have made a case that integrated biosystems are, from a technical point of view, a very sweet solution to the problem of providing food, employment, and waste treatment for the developing world. There are, however, other considerations besides technical elegance that go into a successful development programme. yes.

Technical considerations

In a normal cropping system there are periods of intensive effort (e.g. planting, harvesting) interspersed with periods of relatively low labour demand. Integrated biosystems require constant monitoring and attention. Crop-livestock integration can be a very effective way to help the small farmer who has a small land-base but surplus labour (FFTC 1980). The downside is that integrated biosystems introduce added layers of complexity in that no part of the system can be managed in isolation. Even the "simplest" example given, of a carp pond fed by manure, requires attention to the number, kind, and size of fish in the pond and the quality of the water. Nurseries to provide fry of all of these different species need to be established. Fish harvesting must respect the right balance and size of each species present in the pond.

As the system becomes more complex, farmers have to have a deeper understanding of not only each part of the system, but how each fits into the larger whole. For example, of the tens of thousands of biogas digesters built in China in the 1980's, many of them were abandoned due to shoddy construction or neglected maintenance (Chen, 1997). It is not the "concept" of anaerobic digestion that is at fault. Rather it is a lack of understanding of the overall concept of operation that makes it work. Digesters cannot be treated as "black boxes" that produce effluent and biogas. Successful operation requires balancing the inputs of manure and green-wastes and periodic cleaning out of the system. By the time one gets to integrated biogas-duckweed-fish systems, the level of technical know-how required to operate such a complex system may be beyond the conceptual and intellectual framework of the people for whom it is designed.

very interesting point worth pursuing further

Economic and Land-Use Considerations

Another consideration is that as the level of farming system complexity increases the level of initial capital investment required to establish the system also increases. In the fish-fed duckweed system, the farmer growing duckweed expects to be paid immediately for the duckweed that he delivers to the fish farmer. The fish farmer has to build the pond and stock in with fry or fingerlings, and then wait at least six months before harvesting his first crop, In Bangladesh, the required initial investment is more than an average farmer earns in a typical year (Skillikorn). For such a programme to operate successfully there must be substantial credit available and someone other than the fish farmer (usually an extension worker) who can handle and be responsible for monitoring and disbursing the large sums of money that need to be disbursed over a period of many months. Contracts need to be negotiated between the various parties in the system.

Other issues involve land usage and land ownership. Integrated biosystems involve investment of time, effort, and money into a long-term process of enriching the land and improving the environment. Such an investment only makes sense if the farmer has reasonable guarantees that he will have control of the land long enough to benefit from his investment. (World Bank, 2003)

Environmental/Social Considerations

Integrated biosystems have to be tailored to the particular environment. Soil quality, water availability and climate all can have dramatic effects on what constitutes a "balanced" system in any particular location. There is no single formula that will work equally well in all situations. (Kumar)

There are also cultural issues involved in marketing fish or animals that are fed directly or indirectly with wastes:

> *In several African, American and European societies, human excreta is regarded as repugnant substances best kept away from the sense of sight and smell. Therefore, products which come into direct or indirect contact with excreta are likely to be considered as tainted or defiled in some way (WHO 1989). In such societies where excreta use is regarded as cultural or/and religious taboo, wastewater-based duckweed-fish farming is likely to meet with*

> *strong rejection. In contrast, both human and animal wastes have been used in aquaculture in countries like China, Japan and Indonesia. In such societies, intensive cultivation practices have evolved in response to the need of feeding a large number of people living in an area of limited land availability, and calling for the careful use of all resources available to the community, including excreta (WHO 1989). In such countries, excreta reuse through wastewater-based duckweed-fish farming will probably face less problems of social acceptance. However, the introduction of duckweed aquaculture as a novel farming method in societies where other (piscicultural) techniques have a long-lasting tradition, will probably be met with scepticism. (*Iqbal*)*

It is possible that use of a two-pond system (duckweed is grown on manure in one pond but the fish feed on the duckweed in another pond) may address some of these objections.

Health Considerations

Any time manure or human excreta are involved there is the danger of disease transmission from pathogens in the waste. Use of rubber gloves, breathing filters, rubber wading boots, and vigorous hand washing with soap and hot water are not standard practice in the developing world (Skillikorn). There is good evidence that faecal coliform levels eventually decrease to below the WHO recommended levels for wastewater discharge (Foo) the fact remains that there are several steps throughout the integrated process for human exposure to pathogens. Some intestinal parasites could be transmitted from animals to humans (or vice versa) through the constant recycling of materials. And although the evidence is that disease is not transmitted to people from fish is the fish is gutted properly, washed thoroughly, and properly cooked, there is no way of assuring that all fish grown in manure-based systems is going to be treated appropriately. good point

Consideration Involving Participation

Integrated farming techniques involve a fundamental paradigm shift from the way most farming is done in the developing world. Great care has to be taken to avoid trying to impose such techniques on a community:

> *Historically, notions of Integrated Rural Development (IRD) emerged in the 1970s, when development policies (mostly in what was then known as the 'third world') sought to integrate an increase in agricultural production with improved health, education, sanitation and other social services in rural areas. These approaches were heavily critiqued – not because they were deemed to be founded on incorrect principles, but because the practices which were used to implement them were top-down', economically unsustainable, and did not take account of differences between local community's needs and contexts. (Burkett)*

The investment in training, not just technically, but in the entire "culture" of integrated farming requires not only a large commitment from the farmers, but also from the donor agencies that hope to implement it:

> *"Involving the community can be time-consuming and frustrating, and it is scary for people, who are not naturally disposed to dealing with people and/or have not had relevant training. ... Seen through the prism of technocratic institutional cultures, involving a range of stakeholders in an ill-defined, open ended facilitation process is tedious, its outcomes are often intangible and its cost/benefits debatable. But the complexities of developing new ways of using the land which meet environmental, social and economic objectives mean that genuine stakeholder participation in generating, using and exchanging knowledge, in decision-making, and in resource use negotiation, simply cannot be side-stepped or fudged" (Campbell, 1996).*

CONCLUSIONS

Integrated biosystems offer a technically and economically attractive way of simultaneously improving agricultural production, increasing rural income and employment, building up depleted soils, and reducing pollution of waterways. I have provided a survey of how such integrated systems might work, and looked at some of the other considerations that go into making such schemes work. Technical, economic and social challenges to their widespread acceptance remain. Since each system must be customized to a particular environment, it is not possible to simply set up a successful demonstration site and then "copy" it to various other locales. It is not enough to simply "build" systems and hand them out.

Summary rather than survey.

There are marked parallels between "traditional" farming methods and tradition project funding methods. Both involve short-term, intensive application of external inputs in hopes of yielding large, measurable, immediate gains. Often in both cases the system only "works" as long as the external inputs continue, and collapses as soon as the external inputs are withdrawn.

traditional

There are also marked parallels between integrated farming systems and the type of development aid that is going to be required to make them successful. Integrated biosystems are a radical enough departure from "business-as-usual" agriculture that they will require an equally "non-traditional" approach to development and intervention. Just as integrated biosystems require farmers to look at production as part of a complex and integrated whole, sustainable development of such systems will require donor agencies to provide training and investment to not only establish such systems, but also long-term involvement to administer them. In order for such development to be successful donors will need to engage with the farmers, tailor the development scheme to the locale and culture, and help establish self-perpetuating training and technical support, and develop the appropriate economic and contractual vehicles, institutions and markets. Integrated farming systems can be successful if donors can become intimately involved with getting to know the people they wish to help, and can commit to understanding the relationships between all parts of the system.

OK - a solid summary of such integrated systems. You describe the technical aspects well - with good use of diagrams. While you touch on the broader aspects that influence adoption I would have liked to have seen more on these & perhaps less on the description of their technical function

64%

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Advanced Biomass Assignment #3: Applications using Wood Gas from a rotating retort

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19 March, 2003

INTRODUCTION:

We are given the following mixture of gases:

Gas	Percentage by volume
H_2	31%
CO	52%
CO_2	3%
CH_4	4%
N_2	10%

We are to

⇒ Use it in a 10 kW spark-ignition gas engine with a compression ratio of 18:1
    ⇒ Assuming a stoichiometric air/fuel mixture but ignoring dissociation
    ⇒ Assuming a stoichiometric air/fuel mixture and taking dissociation into account
    ⇒ Assuming a 10% excess of air relative to the stoichiometric air/fuel mixture and ignoring dissociation
  In each case we are to calculate the
    ⇒ Adiabatic flame temperature
    ⇒ Maximum theoretical efficiency of the engine assuming an air-standard Otto cycle
    ⇒ Fuel flow rate by mass and by volume
⇒ Design a 2 kW domestic stove to run on the wood gas above
    ⇒ Find the adiabatic flame temperature
    ⇒ Discuss the concerns of using such a stove with wood gas.

SUMMARY OF RESULTS:

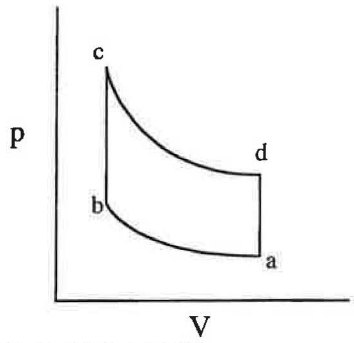
		T (K)	P (bar)	V (relative to BDC)
STOCHIO-METRIC	point A	298	1	1
	point B (end of adiabatic compression)	885.8	62.071	1/18
	point C (end of isochoric combustion)	**3399.17**	209.997	1/18
	Point D (end of adiabatic expansion)	2004.1	17.569	1
	OTTO cycle air standard efficiency	32.1%		
	Fuel Mass flow rate for 10 kW output (kg/hr)	8.79		
	Fuel Volume Flow rate for 10 kW output (m^3/hr)	10.78		
EQUI-LIBRIUM (considering dissociation)	point A	298	1	1
	point B (end of adiabatic compression)	885.8	62.071	1/18
	point C (end of isochoric combustion)	**2432.5**	159.435	1/18
	Point D (end of adiabatic expansion)	1208.04	7.24746367	1
	OTTO cycle airs standard efficiency	41.2%		
	Fuel Mass flow rate for 10 kW output (kg/hr)	12.03		
	Fuel Volume Flow rate for 10 kW output (m^3/hr)	14.75		
10% EXCESS AIR	point A	298	1	1
	point B (end of adiabatic compression)	885.9	61.559	1/18
	point C (end of isochoric combustion)	**3266.995**	1880.9	1/18
	Point D (end of adiabatic expansion)	1880.9	15.368	1
	OTTO cycle airs standard efficiency	33.5%		
	Fuel Mass flow rate for 10 kW output (kg/hr)	8.42		
	Fuel Volume Flow rate for 10 kW output (m^3/hr)	10.33		
STOVE	Adiabatic Flame Temperature	**2430**		

(The numbers in large bold type designate the adiabatic flame temperature for the respective cycles.)

THE OTTO CYCLE

The Otto Cycle involves 4 steps:

- (a-b) An adiabatic compression
- (b-c) A constant volume addition of heat
- (c-d) An adiabatic expansion
- (d-a) A constant volume cooling to the original state



The temperature at point c in the cycle is called the ADIABATIC FLAME TEMPERATURE for the cycle.

The maximum theoretical efficiency for the cycle is given by

$$\eta = 1 - \frac{T_d - T_a}{T_c - T_b}$$

CALCULATING THE ENERGY ABSORBED BY A GAS

For a constant pressure process the energy absorbed by each gas is.

For a constant volume process the energy absorbed is $\int mC_v dT = \int m(C_p - R)dT$

The heat capacities at constant pressure for the gases (in kJ kg^{-1} K^{-1}) are given by the following equations as sixth degree polynomials of the form

$$C_p = a_0 + a_1T^1 + a_2T^2 + a_3T^3 + a_4T^4 + a_5T^5 + a_6T^6$$

The numbers in the table below are the coefficients of the corresponding temperature terms.

	T^0	T^1	T^2	T^3	T^4	T^5	T^6
H_2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22
CO_2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22
CH_4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18
O_2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22
H_2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21
N_2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22

Table of coefficients used to calculate C_p of the various gases at various temperatures.

The $\int C_p dT$ terms can be expressed in the form

$$C_p = b_1T^1 + b_2T^2 + b_3T^3 + b_4T^4 + b_5T^5 + b_6T^6 + b_7T^7$$

	T^1	T^2	T^3	T^4	T^5	T^6	T^7
H_2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23
CO_2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23
CH_4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18
O_2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23
H_2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22
N_2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23

Table of coefficients used to calculate the energy absorbed by the various gases for various changes in temperature. ✓

When multiplied by the number of moles of each gas and its molar mass we can use the above table to calculate the energy required to change the temperature of that amount of gas by evaluating the above polynomial at the beginning and ending temperatures and taking the difference.

COMBUSTION REACTION--STOICHIOMETRY

What we start out with is:

$$0.31H_2 + 0.52\,CO + 0.03\,CO_2 + 0.04\,CH_4 + 0.10\,N_2$$

The balanced reaction is:

$$0.31(H_2 + \tfrac{1}{2}O_2) + 0.52\,(CO + \tfrac{1}{2}O_2) + 0.03\,CO_2 + 0.04(CH_4 + 2O_2) + 0.10\,N_2$$
$$\Rightarrow 0.31H_2O + 0.52\,CO_2 + 0.03\,CO_2 + 0.04\,CO_2 + 0.08\,H_2O + 0.10\,N_2$$

This is a total of 0.155 + 0.26 + 0.08 = 0.495 moles oxygen. Since this oxygen is being provided by the air, it brings along with it 3.762 moles of nitrogen with it for every mole of oxygen, or 1.862 moles nitrogen

So the final balanced equation is:

$$0.31H_2 + 0.52\,CO + 0.03\,CO_2 + 0.04\,CH_4 + 0.10\,N_2 + 0.495\,O_2 + 1.962\,N_2$$
$$\Rightarrow 0.39H_2O + 0.59\,CO_2 + 1.962\,N_2$$

✓

STOICHIOMETRY of DISSOCIATION REACTIONS

Originally we considered:

$$0.31(H_2 + \tfrac{1}{2}O_2) + 0.52(CO + \tfrac{1}{2}O_2) + 0.03\,CO_2 + 0.04(CH_4 + 2O_2) + 0.10\,N_2$$
$$\Rightarrow 0.31\,H_2O + 0.52\,CO_2 + 0.03\,CO_2 + 0.04\,CO_2 + 0.08\,H_2O + 0.10\,N_2$$

For equilibrium we must consider:

	H_2	CO	CO_2	CH_4	O_2	H_2O	N_2
Start	0.31	0.52	0.03	0.04	0.495	0	1.962
Changes	-a				-0.5a	+a	
		-b	+b		-0.5b		
			+c	-c	-2c	+2c	
At equilibrium	0.31-a	0.52-b	0.03+b+c	0.04-c	0.495-0.5a-0.5b-2c	a+2c	1.962

where a, b, and c are the number of moles of H_2, CO, and CH_4 reacting, respectively.

Total number of moles present at equilibrium is:

(0.31-a)+(0.52-b)+(0.03+b+c)+(0.04-c)+(0.495-0.5a-0.5b-2c)+(a+2c)+1.962
=3.357-0.5a-0.5b

If we are ignoring dissociation, we can set a=0.31, b=0.52, and c=0.04.
If we are taking dissociation into account, we will vary the values of a and b (we will still set c = 0.04 because that the temperatures we are considering no CH_4 will be being formed).

At any given point in the reaction the fractional partial pressures of each gas will be given by

$$P_{H_2} = \left(\frac{0.31-a}{3.357-0.5a-0.5b}\right)$$

$$P_{CO} = \left(\frac{0.52-b}{3.357-0.5a-0.5b}\right)$$

$$P_{CO_2} = \left(\frac{0.03+b+c}{3.357-0.5a-0.5b}\right)$$

$$P_{CH_4} = \left(\frac{0.04-c}{3.357-0.5a-0.5b}\right)$$

$$P_{O_2} = \left(\frac{0.495-0.5a-0.5b-2c}{3.357-0.5a-0.5b}\right)$$

$$P_{H_2O} = \left(\frac{a+2c}{3.357-0.5a-0.5b}\right)$$

$$P_{N_2} = \left(\frac{1.972}{3.357-0.5a-0.5b}\right)$$

COMBUSTION REACTION—ENTHALPY CALCULATIONS

For the stoichiometric reaction:

$$\Delta H_{rxn} = \left[0.39\Delta H_f(H_2O_{(v)}) + 0.56\Delta H_f(CO_2)\right] - \left[0.52\Delta H_f(CO) + 0.04\Delta H_f(CH_4)\right]$$

$$= [0.39(-241830) + 0.56(-393520)] - [0.52(-110530) + 0.04(-74870)]$$

$$= 2.542 \times 10^5 \ J/reac\tan t \ as \ written$$ ✓ constant pressure

If we are looking at an equilibrium reaction (i.e., one that does not go to completion) we have:

$$\Delta H_{rxn} = \left[(a+2c)\Delta H_f(H_2O_{(v)}) + (b+c)\Delta H_f(CO_2)\right] - \left[b\Delta H_f(CO) + c\Delta H_f(CH_4)\right]$$

$$= [(a+2c)(-241830) + (b+c)(-393520)] - [b(-110530) + c(-74870)]$$

$$= -241830a + (-393520 + 110530)b + ((2 \times -241830) - 393520J + 74870)c$$

$$= -241830a - 282990b - 802310c \quad (Joules)$$ ✓

CALCULATING THE OTTO CYCLE—Using the spreadsheets

ADIABATIC COMPRESSION:

Consider gases each with number of moles n_i , where n_i

$$= \frac{\underline{\text{(\% of each gas in the original wood gas + added moles oxygen and nitrogen)}}}{\text{total number of moles}}$$

I have assumed in doing the spreadsheet calculations that the TOTAL number of moles of gas present in the cylinder at the start of the cycle is ONE>

For adiabatic compression, for each gas:

$$p_{2i} = p_{1i}\left(\frac{V_{1i}}{V_{2i}}\right)^{\gamma_i} \quad and \quad T_2 = T_1\left(\frac{p_{2i}}{p_{1i}}\right)^{\frac{\gamma_i - 1}{\gamma_i}}$$

which can be rearranged to give

$$p_{2i} = p_{1i}\left(\frac{T_2}{T_1}\right)^{\frac{\gamma_i}{\gamma_i - 1}} \quad and \quad V_{2i} = V_{1i}\left(\frac{T_2}{T_1}\right)^{\frac{1}{1-\gamma_i}}$$ ✓

The reason we have to do this in terms of γ_i is that each gas has a different specific heat capacity, and this value of γ_i changes as a function of temperature.

The plan then is to use a spreadsheet and:

⇒ Start with the initial Temperature, partial pressures, and partial volumes (assuming starting pressures of 1 bar and a starting volume of "1")

⇒ Calculate C_p (and thus γ) for each gas at each temperature.

⇒ Increment the temperature by some amount (say 5°) and use the values from step 2 to calculate the new partial pressure and partial volumes at this new temperature

⇒ Sum the partial pressures and volumes to get the total pressure and volume of the gas

⇒ Go back to step 1 but with the new temperature and partial pressures and volumes, recalculate the C_p and γ values. Increment the temperature again, etc. ✓

Keep this process up until the volume is exactly 1/18 of the initial volume.

For the Stoichiometric Reaction with no dissociation set

a = 0 (no moles H_2 reacting)
b = 0 (no moles CO reacting)
c = 0 (no moles CH_4 reacting)

This gives the final temperature and pressure of the system, which turned out (for the stoichiometric case) to be 885.8 K, 62.071 bar.

For the Stoichiometric Compression taking dissociation into account, this step is exactly the same and gives exactly the same answers.

For the adiabatic compression using 10% excess air in the reaction it is the same as the other two except that we start with 0.5445/3.5927 moles O_2 and 2.1482/3.5927 moles N_2 and end up with 885.9 K, 61.559 bar

ISOCHORIC (constant volume) HEATING

For the stoichiometric mixture assume that we have one mole total of the stoichiometric air/gas mixture. Here we want ΔU for the reaction at 885.8 K, Then we can use this heat to raise the temperature of the product gases. It is complicated by the fact that the numbers of reactant and product molecules are not the same.
What we want is : —

$$\begin{tikzcd}
U_{\text{reactant},886\,K} \arrow[r] \arrow[d, "\Sigma n_{i(\text{reactants})}\int_{886}^{298} C_{vi}\,dT"'] & U_{\text{product},T_{final}} \\
U_{\text{reactant},298\,K} \arrow[r] & U_{\text{product},298\,K} \arrow[u, "\Sigma n_{i(\text{products})}\int_{298}^{T_{final}} C_{vi}\,dT"']
\end{tikzcd}$$

$$\Delta U_{298} = \Delta H_{298} - (n_{products} - n_{reactants})RT_{298}$$

As far as calculating $\Delta U_{reaction,\,298}$ is concerned, we start with (a = 0 b = 0 c = 0)which gives

0.31/3.357 moles H_2
0.52/3.357 moles CO
0.03/3.357 moles CO_2
0.04/3.357 moles CH_4
0.495/3.357 moles O_2
1.962/3.357 moles N_2
set $T_{ambient}$ = 885.8 K
set T_{final} = 298 K

which we cool from 885.8 K to 298 K → -13275.36 (Save this number!)

Then we set (a = 0.31, b = 0.52, c = 0.04) so that we END UP with

0/3.357 moles H_2
0/3.357 moles CO
0.59/3.357 moles CO_2
0.39/3.357 moles CH_4
0/3.357 moles O_2
1.962/3.357 moles N_2

We calculate the $\Delta U_{reaction,\ 298}$ which is → -76032.9736 kJ
The total heat available to heat the products is (76907.407 +13275.36)KJ.

Then we can look at the products that remain:

0.39/3.357 moles H_2O
0.59/3.357 moles CO_2
1.962/3.357 moles N_2 (2.942/3.357 moles total)

and calculate how much hotter they will get given the above amount of heat to absorb:

$$Heat\ available = \Sigma n_{i(\,products)} \int_{298}^{T_{final}} C_{vi} dT$$

We can keep adjusting the value of T_{final} until both sides of the equation are equal.
This gives T_{final} = 3399.17 K

Then p_{final} =

$$p_{final} = \frac{n_{products} T_{final}\, p_{885.8\,K initial}}{n_{reac\tan ts} T_{885.8K}} = 209.997 bar$$

For the equilibrium isochoric reaction this is the same as the stoichiometric adiabatic compression EXCEPT that we must:

- ⇒ Guess at a final temperature
- ⇒ Set value of c = 0.04 (assume that all of the methane reacts to completion)
- ⇒ Guess at values for a (amount of H_2 reacted) and b (amount of C) reacted
- ⇒ Adjust values of a and b until the equilibrium constant ratios equal the values of the equilibrium constant at that temperature
- ⇒ Look at the sum of ($Q_{cooling} + \Delta U_{reaction} + Q_{heating\ to\ final\ temperature}$).
    - ⇒ If the sum is negative, increase the final temperature value
    - ⇒ If the sum is positive, decrease the final temperature value
- ⇒ Adjust the values of a and b again until the equilibrium constant ratios equal the values of the equilibrium constant at this new temperature

Keep repeating the last two steps until the sum of the heats is zero and the equilibrium ratios match the equilibrium constants at that temperature.

Calculate the final pressure as $p = \frac{(moles\ at\ equilibrium)}{(initial\ number\ of\ moles)} \times \frac{T_{final}}{885.8\ K} \times p_{885.8\,K}$
End up at 2432.5 K, 159.435 bar.

For the 10% excess air isochoric reaction we take the same approach as stoichiometric combustion reaction except that we have more moles of gas throughout the reaction and the starting temperature and pressure are slightly different.
ADIABATIC EXPANSION

For the stoichiometric adiabatic expansion it is the same as Adiabatic compression except

- ⇒ (a=0.31, b=0.52,c=0.04)
- ⇒ start at 3399.17 K, 209.997 bar
- ⇒ increment the temperature by –10°C each step

End up at 2004.1 K, 17.659 bar

For the equilibrium adiabatic expansion it is the same as for stoichiometric expansion except

- ⇒ Start out with the a,b, and c values from equilibrium (a = 0.24161, b = 0.19241, c=0.04)
- ⇒ Start out at 2432.5 K, 159.435 bar.
- ⇒ End up at 1208.04 K, 7.247 bar.

For the 10% excess air adiabatic expansion it is the same as stoichiometric adiabatic expansion except start at 3266.995 K, 200.748 bar
End up at 1880.9 K, 15.368 Bar

DISCUSSION—ENGINE CALCULATIONS

At BEST these calculations are a base approximation to the performance of a real engine running on this wood gas. There are several factors that limit the applicability of the analysis done. These are:

THE NON-IDEAL BEHAVIOUR OF THE GASES

The specific heats of each of these gases change with increases in temperature as new vibrational degrees of freedom become available to the gases. Because these changes are non-linear it is not reasonable to use the average value for the temperature range, nor is it reasonable to use the value of the specific heat at the average temperature for the range. For adiabatic processes the problem is doubly non-linear because we are raising values to a power (pV^{γ}) and the γ values themselves don't vary linearly with temperature. I have tried to take this into account by calculating the changes in pressure and volume in 5 or 10 degree temperature increments and recalculating the heat capacities and γ values each time, or calculating the heat involved with constant pressure or constant volume processes by integrating C_pdT rather than using $C_{p\ \text{average}}\,\Delta T$.

Even so, I have still had to assume that the gases behave ideally. Strictly speaking the ideal gas law only applies at low pressures, where we can assume that the interactions between molecules are negligible. This is probably not the case at 200 bar.

For our calculations we assumed an ideal gas going through an air-standard Otto Cycle. Given all of the above, and that the reactions are NOT going reversibly, the calculations we do could (as mentioned in the lab handout) only give the MAXIMUM theoretical efficiency of the engine rather than the actual performance.

CHANGE IN THE NUMBER OF MOLES OF GAS IN THE CYLINDER

All of this is complicated by the fact that the air standard cycle assumes that the number of moles of gas in the cylinder stays constant throughout the process.

In our case we have a combustion reaction that changes the number of moles of gas significantly. The cycle CANNOT return to its starting point, so even the use of the Otto cycle efficiency equation to model our reaction is questionable at best. Better would be to assume some process that brings the combustion products back to 1bar, 298 K, calculate the heat or work involved in each step of the process, and then to calculate an efficiency based on that. ✓

ASSUMPTIONS ABOUT EQUILIBRIUM

In the case of equilibrium we assume that all of the reactions are sufficiently <u>fast</u> as to reach equilibrium during the time of the combustion step, but that AFTER that the reactions are sufficiently <u>slow</u> so that we can assume that the product retain their equilibrium concentrations. One would expect that if the steps were quick enough to reach equilibrium at the end of the constant volume heating, then they would also be quick enough to change concentrations again during at least the initial parts of the adiabatic expansion. If we are assuming that all of the processes are reversible, then they would HAVE to move back towards their initial concentrations. If they are not reversible, then the assumption that the reaction has reached equilibrium (that is, that we can ignore the kinetics of the reaction) is NOT reasonable. ✓

COMPARING CALCULATED EFFICIENCIES

Adding 10% excess air to the cylinder only slightly increased the calculated efficiency of the cycle (33.5% vs. 32.1% for the stoichiometric air/fuel mix). It may be that to the extent the amount of air is much greater than the amount of fuel, the change in the number of moles in the cylinder due to the combustion is proportionally smaller, and the cycle may approach more closely the air-standard Otto Cycle approximation. ✓

Interestingly, the thermodynamic efficiency of the engine under assumptions of chemical equilibrium was quite a bit <u>higher</u> than assuming no dissociation takes place (41.2% vs. 32.1%). This may again be due to the fact that the number of moles of gas changes less, so the cycle is closer to the air-standard Otto Cycle approximation. Despite the engine cycle being more efficient, the engine only combusted about half of the fuel available to it, so in order to get the same energy out of the engine you have to feed through 37% MORE fuel.

STOVE DESIGN PARAMETERS

			COMMENTS
Desired output	2000	Watts	Given
Stove Efficiency	0.5		Assumed
Required output	4000	Watts	=desired output/efficiency
Fuel Energy	254,000	J/mole	From Engine calculations
Required Flow Rate	3.86E-04	m^3/sec	$= \frac{4000W \times 0.0245 \frac{m^3}{kmol}}{254,000 J / mole}$
Required Flow Rate	1.39E+00	m^3/hr	=above*3600 sec/hr
Coefficient of Discharge	0.9		Assumed
Assumed gas pressure	7.2	mbar	75 mmH_20 x $(\frac{1000 \text{ mbar}}{10,322 \text{ mmH}_2 0})$
Specific gravity of gas	0.6914		$= \frac{0.31 \times 2 + 0.52 \times 28 + 0.03 \times 44 + 0.04 \times 16 + 0.10 \times 28}{0.21 \times 32 + 0.79 \times 28}$
Orifice Area	10.241	mm^2	$= \frac{Q(\frac{m^3}{hr})}{0.0467 \times C_d} \sqrt{\frac{specific\,gravity}{pressure(mbar)}}$
Orifice Diameter	3.61096	mm	$= \sqrt{\frac{4}{\pi} A_{orifice}}$
v(gas through orifice)	37.675	m/s	$= \frac{Q(\frac{m^3}{s})}{A_o (mm^2) \times 10^{-6}}$
Throat diameter	12.7	mm	Assumed (1/2" ID)
Entrainment ratio	2.093		Ratio air/fuel. $= \sqrt{s}\left(\frac{d_{throat}}{d_{orifice}} - 1\right)$ Stoichiometric ratio is 2.357:1
Flame port area/throat area	6.280		Refers to last row. Wants to be between 1.5 and 2.2 but not possible with this LCV gas
Flow rate through throat	0.00119	m^3/sec	$= Q_{orifice}(1 + entrainment\ ratio)$
Flow velocity through throat	9.42		$= \frac{Q_{throat}}{A_{throat} (mm^2) \times 10^{-6}}$
density of mixture	1.0597	kg/m^3	$= \frac{(s_{gas} + r)}{(1+r)} \rho_{air} = \frac{(s_{gas} + r)}{(1+r)} \frac{(021 \times 32 + 0.79 \times 28)(\frac{kg}{kmol})}{24.5\left(\frac{m^3}{kmol}\right)}$
viscocity	1.71E-05	Pa s	assumed
Re	7.41E+03		$= \frac{4 \rho Q_{throat}}{\pi \mu d_{throat}}$
f	3.41E-02		$= \frac{0316}{Re^{1/4}}$
pipe length	127	mm	= 10 x throat diameter
Pressure drop in pipe	1.60E+01	Pa	$= \frac{f}{2} \rho v_t^2 \frac{L_{tube}}{d_{throat}}$
Pressure drop in pipe	1.58E-01	mbar	=_p(pa)x(1000 mbar/101325 Pa)
Supply velocity	1.5	m/s	Assumed. Flame speed for the mixture is about 1 m/s, so this supply velocity has to be greater than this to prevent flashback
Port area required	0.0007955	m^3	$=Q_{throat}$/Supply velocity
Port area required	795.56464	mm^3	=Port Area (m^3) x 10^6 (I used 741 mm^2)

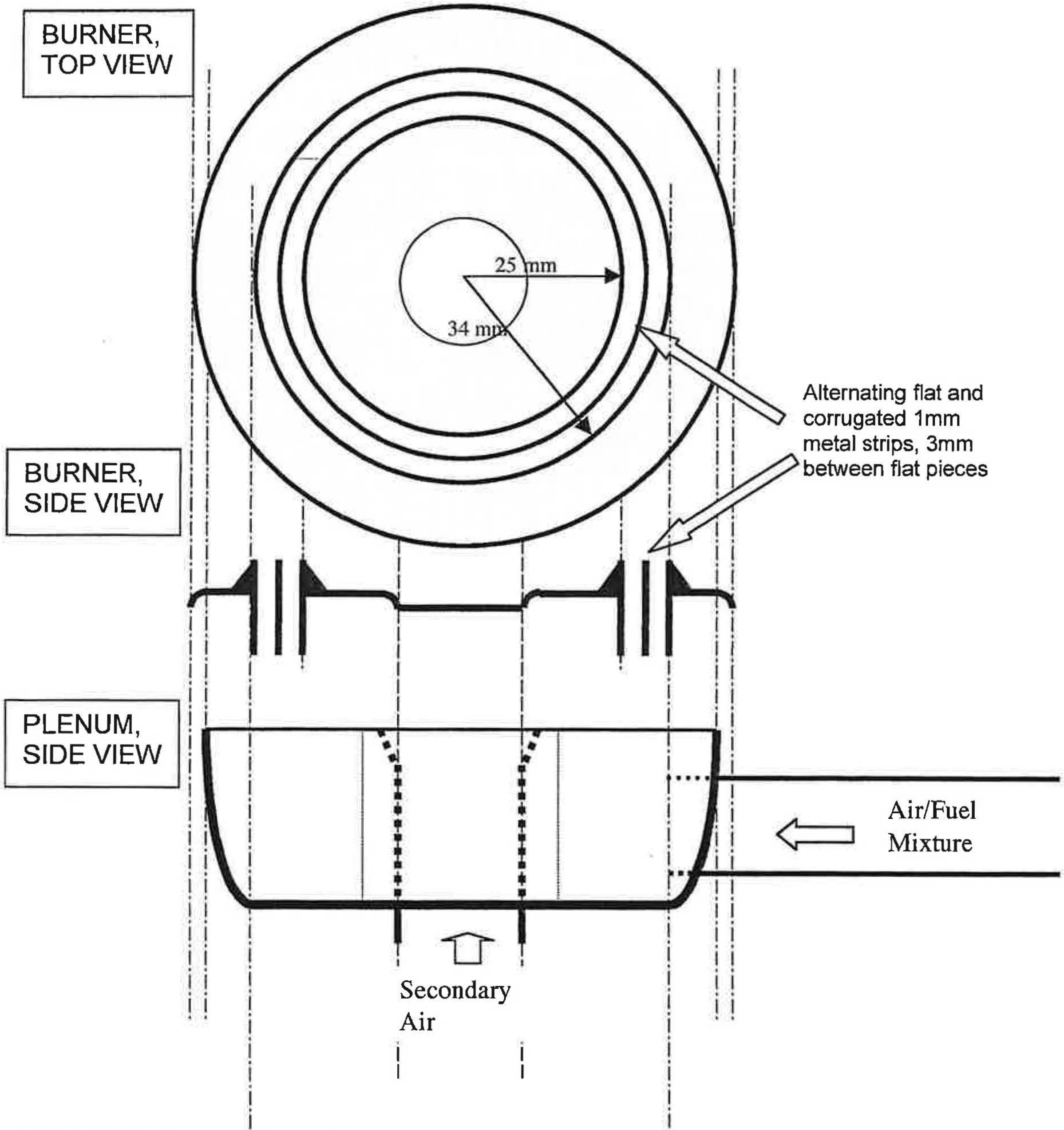
CALCULATING THE ADIABATIC FLAME TEMPERATURE of the STOVE

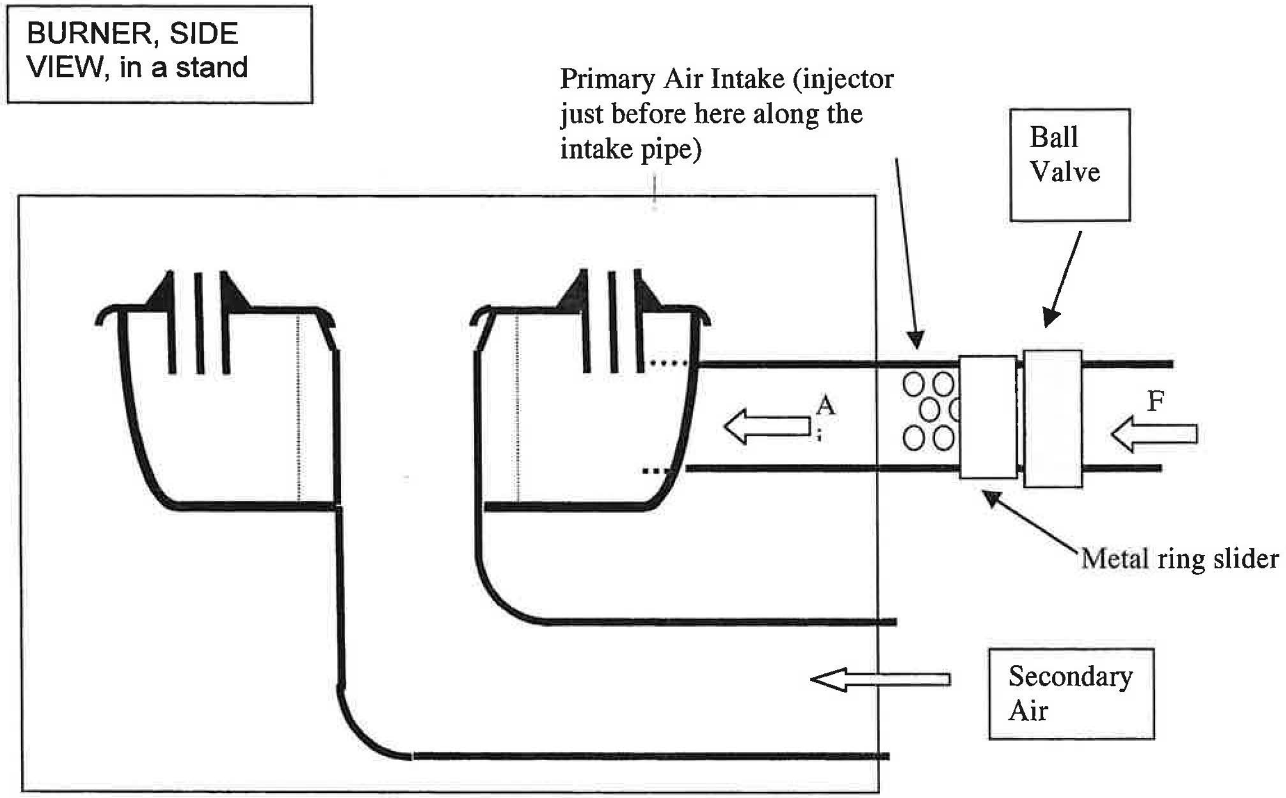
This is the same calculation as finding the final temperature for the constant volume step for the engine except:

- ⇒ The starting temperature is 298 K and the starting pressure is 1 bar (so we can ignore the heat given off by cooling the reactants
- ⇒ We use ΔH instead of ΔU to get the heat evolved in the reaction
- ⇒ When calculating the heat absorbed by the products we use C_p values instead of the C_v values

Putting all of this in gives a final temperature of 2480 K.

BURNER DESIGN




BURNER, SIDE VIEW, in a stand
Primary Air Intake (injector just before here along the intake pipe)
Ball Valve
A
F
Metal ring slider
Secondary Air

DISCUSSION--BURNER DESIGN

The flame ports are made from alternating flat and corrugated 1 mm steel where the gap between the flat bits of steel is 3 mm, with the steel at least 1 cm "deep" vertically. This gives a flame port area of

$$\tfrac{2}{3}\pi\left[(33^2 - 30^2) + (29^2 - 26^2)\right] = 741\ mm^2$$

The design above illustrates the major features of the stove (I am assuming that a ready-for-production drawing is not required). The main features are:

⇒ A ball valve to control fuel flow
⇒ A metal slider to cover (or uncover) the primary air intake holes
⇒
⇒ A secondary air intake to the middle of the burner
⇒ A burner "cap" that sits on top of the plenum and that can be removed for cleaning.
⇒ Corrugated steel should prevent flame liftoff, and the size of the gap between pieces of steel (2 mm maximum) should be small enough to allow flames to quench and to prevent flashback
⇒ The air/fuel mixture is deflected by the internal secondary air pipe to allow some mixing within the plenum.

At this point we'd need to build a model of the burner and see how it deals with lower gas pressures. It may be that I could have designed it for a higher port velocity (or a higher pressure and a slightly smaller burner area) and then used the ball valve to throttle back the pressure for simmering.

The major concerns about using this gas as a domestic fuel are:

⇒ It is highly toxic. An odourant would have to be added to the gas supply.
⇒ It has a high range of flammability limits (12.5-74 for carbon monoxide and 4-75 for hydrogen compared to a range of 5-15 for methane), so a leak is potentially explosive at a much larger range of mixing with the air.
⇒ The possibility of flashback into the stove or into the gas lines is much greater than for methane.
⇒ The hydrogen can diffuse very quickly through the air. Potentially a leak could be ignited by someone smoking a cigarette on the other side of the room.
⇒ Gas connections would have to be tighter for a gas containing this much hydrogen than for equivalent gas lines carrying methane, and hydrogen is chemically more reactive with metal pipes than is methane.
⇒ Because the calorific value of the gas is relatively low compared to methane the flow rates and thus the pipe diameters would need to be bigger for the same desired output.
⇒ Using a pilot light would require that the gas flow to the stove be on all of the time. If the pilot went out the uncombusted gases flowing into the room are much more dangerous than a methane leak would be.

SPREADSHEETS
(CONDENSED)

OTTO CYCLE, STOICHIOMETRIC MIX, ADIABATIC COMPRESSION

moles of. . .	species	MASS	Tambinent	Tfinal	Hrxn	a (# moles H2 reacting)	b(# moles CO reacting)	c (# moles CH4 reacting)	TotalPressure
0.31	H2	2.016	298	300	0.00E+00	0	0	0	1
0.52	CO	28.01							
0.03	CO2	44.01							
0.04	CH4	16.043							
0.495	O2	32							
0	H2O	18.016							
1.962	N2	28							
3.357									

	T0	T1	T2	T3	T4	T5	T6	Cp (kJ/kgK)	Cp (kJ/Kmole
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.41E+01	2.84E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.04E+00	2.92E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	8.45E-01	3.72E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	2.24E+00	3.59E+01
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	9.26E-01	2.96E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	1.87E+00	3.36E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.04E+00	2.91E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

	T1	T2	T3	T4	T5	T6	T7	ENERGYfor Tstart to Tfinal	
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	1.76E+01	
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	3.03E+01	
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	2.23E+00	
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	2.87E+00	
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	2.93E+01	
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	0.00E+00	
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	1.14E+02	1.96E+02
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		4.32E+01	
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		4.62E+01	
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		-3.03E+00	

Denominator	3.357
P H2	0.09234436
P CO	0.15490021
P CO2	0.00893655
P CH4	0.0119154
P O2	0.14745308
P H2O	0
P N2	0.5844504

	so far	should be
K(H2-H2O)	0	5.7609E+18
K(CO-CO2)	0.15024187	1.1742E+20
K(mixed)	0	0.04836726

T	P TOTAL	V TOTAL	1/V TOTAL	Work	
298	1	1	1		
303	1.06035325	0.95891022	1.04285049	-0.0423297	
308	1.12332748	0.92010365	1.08683407	-0.0423706	
313	1.18899632	0.88342005	1.13196435	-0.0424122	
318	1.2574346	0.84871271	1.17825501	-0.0424546	
323	1.32871839	0.81584716	1.22571978	-0.0424977	
328	1.40292501	0.78469995	1.27437245	-0.0425415	
333	1.48013304	0.7551576	1.32422688	-0.0425862	
338	1.56042237	0.72711567	1.375297	-0.0426315	
343	1.64387422	0.7004779	1.42759678	-0.0426777	
348	1.73057114	0.6751555	1.48114028	-0.0427245	
353	1.82059706	0.65106642	1.53594161	-0.0427722	
358	1.91403729	0.62813481	1.59201494	-0.0428206	
363	2.01097859	0.60629043	1.64937454	-0.0428698	
368	2.11150914	0.5854682	1.70803471	-0.0429197	
373	2.21571862	0.56560771	1.76800985	-0.0429704	
378	2.32369822	0.54665288	1.82931442	-0.0430219	
383	2.43554063	0.52855158	1.89196295	-0.0430742	
388	2.55134016	0.51125528	1.95597003	-0.0431273	
393	2.67119268	0.49471879	2.02135036	-0.0431812	
398	2.79519572	0.47889999	2.08811867	-0.0432359	
403	2.92344844	0.46375956	2.1562898	-0.0432914	
408	3.05605175	0.44926079	2.22587865	-0.0433477	
413	3.19310826	0.43536937	2.2969002	-0.0434048	
418	3.33472235	0.42205321	2.36936951	-0.0434628	
423	3.48100025	0.40928224	2.44330172	-0.0435217	
428	3.63205001	0.39702832	2.51871204	-0.0435814	
433	3.78798158	0.38526503	2.59561578	-0.043642	
438	3.94890684	0.37396762	2.67402831	-0.0437034	
443	4.11493964	0.36311281	2.75396509	-0.0437658	
448	4.28619588	0.35267874	2.83544167	-0.043829	
453	4.4627935	0.34264486	2.91847369	-0.0438932	
458	4.64485255	0.33299181	3.00307686	-0.0439583	
463	4.83249527	0.32370139	3.08926697	-0.0440243	
468	5.02584609	0.31475642	3.17705993	-0.0440913	
473	5.22503171	0.30614072	3.2664717	-0.0441592	
478	5.43018116	0.29783903	3.35751836	-0.0442282	
483	5.64142583	0.28983692	3.45021606	-0.0442981	
488	5.85889954	0.28212079	3.54458105	-0.044369	
493	6.0827386	0.27467776	3.64062967	-0.044441	
498	6.31308189	0.26749566	3.73837834	-0.044514	
503	6.55007089	0.26056299	3.83784361	-0.044588	
508	6.79384974	0.25386883	3.93904208	-0.0446632	
868	56.7180511	0.05887406	16.9854079	-0.0545816	
873	58.177012	0.05791984	17.2652399	-0.0548176	
878	59.6705128	0.05698545	17.5483378	-0.0550578	
883	61.1994116	0.05607039	17.8347268	-0.0553022	
885.8	62.0711178	0.05556632	17.9965118	-0.031068	
				-5.5299301	TOTAL WORK

T FINAL P FINAL

OTTO CYCLE, STOICHIOMETRIC MIX, CONSTANT VOLUME COMBUSTION.

FIRST: Use the initial number of moles and calculate the energy given off in going from 885.8 to 298 K (seta,b,and c =0)

The spreadsheet is set up to calculate the Delta Hreaction and then the Deta U using the initial number of moles

SECOND: Put in the final number of moles of each species (set a=0.31, b = 0.52, c = 0.04) and calculate Delta U

THIRD: Put Tambient at 298 and adjust the final temperature until the sum (energy from cooling + delta U + energy into heating up) = 0 (cell K34)

moles of. . .	species	MASS	Tambient	Tfinal	Hrxn	a	b	c	TotalPressure
0	H2	2.016	298	3399.17	2.54E+05	0.31	0.52	0.04	1
0	CO	28.01			7.57E+04				
0.59	CO2	44.01	THIRD						
0	CH4	16.043	298	CHANGE			pfinal	209.996672	
0	O2	32							
0.39	H2O	18.016							
1.962	N2	28							
2.942	TOTAL								

	T0	T1	T2	T3	T4	T5	T6	kj/kg	kj/kmole
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.89E+01	3.82E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.33E+00	3.72E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	2.06E+00	9.06E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	-3.70E+03	-5.94E+04
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	1.27E+00	4.06E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	3.33E+00	5.99E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.10E+00	3.07E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

FIRST	
0.31	H2
0.52	CO
0.03	CO2
0.04	CH4
0.495	O2
0	H2O
1.962	N2
3.357	TOTAL

Del U (reactants)	Del U zero	Del U products
26603.616	-76032.974	8.93E+04
-13275.36027	-76032.974	8.93E+04

Del U (885.9)
0.006003277
89308.340

SECOND	
0	H2
0	CO
0.59	CO2
0	CH4
0	O2
0.39	H2O
1.962	N2
2.942	TOTAL

	T1	T2	T3	T4	T5	T6	T7	ENERGY	
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	0.00E+00	
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	0.00E+00	
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	2.99E+04	
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	0.00E+00	
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	0.00E+00	
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	1.46E+04	TOTAL
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	4.49E+04	
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		-5.60E-02	
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		-2.42E+00	
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		2.38E+00	

Denominator	2.942
P H2	0
P CO	0
P CO2	0.20054385
P CH4	0
P O2	0
P H2O	0.13256288
P N2	0.66689327

	so far	should be
K(H2-H2O)	#DIV/0!	0.94550994
K(CO-CO2)	#DIV/0!	0.08883813
K(mixed)	#DIV/0!	10.7644471

OTTO CYCLE, STOICHIOMETRIC MIX, ADIABATIC EXPANSION

moles of. . .	species	MASS	Tambient	Tfinal	Hrxn	a	b	c	TotalPressure
0	H2	2.016	3399.17	340	2.54E+05	0.31	0.52	0.04	209.996672
0	CO	28.01							
0.59	CO2	44.01							
0	CH4	16.043							
0	O2	32							
0.39	H2O	18.016							
1.962	N2	28							
2.942									

	T0	T1	T2	T3	T4	T5	T6	cp (kJ/Kg K)	Cp (KJ/kmol/K)
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.41E+01	2.85E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.05E+00	2.93E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	8.82E-01	3.88E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	2.34E+00	3.75E+01
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	9.37E-01	3.00E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	1.88E+00	3.39E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.04E+00	2.92E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

	T1	T2	T3	T4	T5	T6	T7	ENERGY	
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	0.00E+00	
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	0.00E+00	
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	-1.15E+05	
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	0.00E+00	
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	0.00E+00	
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	-5.84E+04	
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	-1.99E+05	-3.72E+05 TOTAL
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		4.16E+01	
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		4.44E+01	
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		-2.81E+00	

Denominator	2.942
P H2	0
P CO	0
P CO2	0.20054385
P CH4	0
P O2	0
P H2O	0.13256288
P N2	0.66689327

	so far	should be
K(H2-H2O)	#DIV/0!	1.2027E+18
K(CO-CO2)	#DIV/0!	1.9778E+19
K(mixed)	#DIV/0!	0.06001371

T	P TOTAL	V TOTAL	1/V TOTAL	Work	
3399.17	209.996672	0.05555556	18		
3389.17	206.566814	0.0563159	17.7569739	0.15836629	
3379.17	203.200273	0.05709226	17.5155101	0.15906229	
3369.17	199.895435	0.057885	17.2756323	0.15977598	
3359.17	196.65074	0.05869453	17.0373634	0.16050733	
3349.17	193.464678	0.05952124	16.8007256	0.16125634	
3339.17	190.335793	0.06036555	16.5657406	0.16202299	
3329.17	187.262674	0.06122788	16.3324296	0.16280729	
3319.17	184.243956	0.06210867	16.1008129	0.16360924	
3309.17	181.278322	0.06300836	15.8709104	0.16442885	
3299.17	178.364494	0.06392741	15.6427411	0.16526613	
3289.17	175.501238	0.06486631	15.4163236	0.16612111	
3279.17	172.687358	0.06582552	15.1916757	0.1669938	
3269.17	169.921699	0.06680556	14.9688147	0.16788424	
3259.17	167.203141	0.06780692	14.747757	0.16879245	
3249.17	164.530599	0.06883014	14.5285185	0.16971849	
3239.17	161.903024	0.06987576	14.3111144	0.1706624	
3229.17	159.319399	0.07094433	14.0955592	0.17162421	
3219.17	156.778739	0.07203642	13.8818668	0.172604	
3209.17	154.280091	0.07315262	13.6700503	0.17360181	
3199.17	151.822529	0.07429353	13.4601223	0.17461772	
3189.17	149.405158	0.07545977	13.2520946	0.17565179	
3179.17	147.02711	0.07665197	13.0459783	0.17670409	
3169.17	144.687541	0.0778708	12.841784	0.17777471	
3159.17	142.385637	0.07911692	12.6395213	0.17886372	
3149.17	140.120604	0.08039102	12.4391996	0.17997123	
3139.17	137.891675	0.08169383	12.2408272	0.18109731	
3129.17	135.698104	0.08302605	12.044412	0.18224208	
3119.17	133.539169	0.08438846	11.8499611	0.18340563	
3109.17	131.414168	0.08578183	11.6574809	0.18458807	
3099.17	129.32242	0.08720694	11.4669775	0.18578951	
3089.17	127.263263	0.08866462	11.2784558	0.18701008	
3079.17	125.236055	0.09015571	11.0919206	0.18824991	
3069.17	123.240172	0.09168108	10.9073756	0.1895091	
3059.17	121.275009	0.09324162	10.7248242	0.19078781	
3049.17	119.339977	0.09483825	10.5442689	0.19208618	
3039.17	117.434503	0.09647191	10.3657119	0.19340433	
3029.17	115.558032	0.09814357	10.1891545	0.19474244	
3019.17	113.710022	0.09985424	10.0145976	0.19610064	
3009.17	111.88995	0.10160494	9.8420413	0.19747911	
2999.17	110.097302	0.10339673	9.67148527	0.198878	
2989.17	108.331582	0.10523072	9.50292855	0.20029749	
2979.17	106.592306	0.10710801	9.3363696	0.20173776	
2069.17	20.3219452	0.83207787	1.20181059	0.46771573	
2059.17	19.8930659	0.85560532	1.16876318	0.47307832	
2049.17	19.4714622	0.87991806	1.13646945	0.47852975	
2039.17	19.0570405	0.90504605	1.10491615	0.48407193	
2029.17	18.6497078	0.93102055	1.07409015	0.48970685	
2019.17	18.2493722	0.95787415	1.04397849	0.49543655	
2009.17	17.8559427	0.98564087	1.01456832	0.50126311	
2004.1	17.6590774	1.00008413	0.99991587	0.25647643	38.696291

EQUILIBRIUM (STOICHIOMETRIC MIX), CONSTANT VOLUME COMBUSTION

moles of...	species	MASS	Tambient	Tfinal	Hrxn	a	b	c	TotalPressure
0.06839	H2	2.01	298	2432.5	1.45E+05	0.24161	0.19241	0.04	159.434696
0.32759	CO	28							
0.26241	CO2	44.01							
0	CH4	16.03							
0.19799	O2	32							
0.32161	H2O	18.02							
1.962	N2	28							
3.13999									

	T0	T1	T2	T3	T4	T5	T6
H2	13.33561514	0.003133847	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21
CO	1.025354172	-4.8049E-05	4.194E-07	-2.9716E-10	8.904E-14	-1.2323E-17	6.4626E-22
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22
CH4	2.493536037	-0.00478346	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18
O2	0.83001979	0.000347959	-8.879E-08	-1.996E-11	1.6545E-14	-3.2118E-18	2.0294E-22
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09			
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09			
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10			

Del U (reactants)	Del U zero	Del U products
1.68E+04	-144433.39	5.63E+04
-13269.342	-43024.544	5.63E+04

Sum: 4

	T1	T2	T3	T4	T5	T6	T7	ENERGY
H2	13.33561514	0.001566923	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	1.02E+03
CO	1.025354172	-2.4025E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	5.36E+03
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	8.05E+03
CH4	2.493536037	-0.00239173	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	0.00E+00
O2	0.83001979	0.000173979	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	3.43E+03
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	7.49E+03
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	3.10E+04
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		5.47E+00
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		3.70E+00
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		1.77E+00

TOTAL

Denominator	3.13999
P H2	0.021780324
P CO	0.104328358
P CO2	0.08357033
P CH4	0
P O2	0.063054341
P H2O	0.102423893
P N2	0.624842754

	so far	should be
K(H2-H2O)	236.467176	236.494807
K(CO-CO2)	40.2794628	40.2821993
K(mixed)	5.8706636	5.88099865

EQUILIBRIUM, (STOICHIOMETRIC MIX), ADIABATIC EXPANSION.

moles of. . .	species	MASS	Tambient	Tfinal	Hrxn	a	b	c	TotalPressure
0.06839	H2	2.016	2432.5	340	1.45E+05	0.24161	0.19241	0.04	159.434696
0.32759	CO	28.01							
0.26241	CO2	44.01							
0	CH4	16.043							
0.19799	O2	32							
0.32161	H2O	18.016							
1.962	N2	28							
3.13999									

	T0	T1	T2	T3	T4	T5	T6	Cp (kJ/kg K)	Cp (kJ/kmol K)
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.41E+01	2.85E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.05E+00	2.93E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	8.82E-01	3.88E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	2.34E+00	3.75E+01
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	9.37E-01	3.00E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	1.88E+00	3.39E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.04E+00	2.92E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

	T1	T2	T3	T4	T5	T6	T7	ENERGY		
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	-1.36E+03		
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	-6.97E+03		
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	-9.31E+03		
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	0.00E+00		
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	-4.40E+03		
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	-9.06E+03		
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	-4.06E+04	-7.17E+04	TOTAL
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		4.16E+01		
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		4.44E+01		
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		-2.81E+00		

Denominator	3.13999
P H2	0.02178032
P CO	0.10432836
P CO2	0.08357033
P CH4	0

	so far	should be
K(H2-H2O)	236.467176	1.2027E+18
K(CO-CO2)	40.2794628	1.9778E+19
K(mixed)	5.8706636	0.06001371

T	P TOTAL	V TOTAL	1/V TOTAL	Work
2432.5	159.434696	0.05555556	18	
2422.5	156.314152	0.05643316	17.7200789	0.13855087
2412.5	153.24666	0.05732965	17.4429814	0.13875934
2402.5	150.231373	0.05824553	17.1687006	0.13897432
2392.5	147.26746	0.0591813	16.8972293	0.13919583
2382.5	144.354105	0.0601375	16.6285602	0.13942391
2372.5	141.490508	0.06111466	16.3626856	0.13965857
2362.5	138.675884	0.06211335	16.0995977	0.13989987
2352.5	135.909461	0.06313415	15.8392883	0.14014784
2342.5	133.190483	0.06417765	15.5817492	0.14040253
2332.5	130.518205	0.06524446	15.3269718	0.14066397
2322.5	127.891897	0.06633522	15.0749472	0.14093221
2312.5	125.310843	0.06745059	14.8256664	0.14120731
2302.5	122.774336	0.06859124	14.5791202	0.14148931
2292.5	120.281686	0.06975788	14.335299	0.14177828
2282.5	117.832211	0.07095121	14.0941933	0.14207427
2272.5	115.425243	0.07217198	13.8557929	0.14237733
2262.5	113.060125	0.07342097	13.6200878	0.14268755
2252.5	110.736209	0.07469896	13.3870676	0.14300498
2242.5	108.452862	0.07600678	13.1567218	0.14332969
2232.5	106.209458	0.07734527	12.9290394	0.14366175
2222.5	104.005382	0.07871531	12.7040097	0.14400125
2212.5	101.84003	0.0801178	12.4816212	0.14434827
2202.5	99.7128084	0.08155368	12.2618627	0.14470288
2192.5	97.6231314	0.08302391	12.0447225	0.14506517
2182.5	95.5704236	0.0845295	11.8301889	0.14543524
2172.5	93.5541187	0.08607148	11.6182497	0.14581317
2162.5	91.5736593	0.08765092	11.4088928	0.14619907
2152.5	89.6284966	0.08926893	11.2021058	0.14659304
2142.5	87.7180906	0.09092665	10.9978762	0.14699518
2132.5	85.8419095	0.09262526	10.7961912	0.14740559
2122.5	83.9994298	0.09436599	10.5970377	0.1478244
2112.5	82.1901358	0.09615012	10.4004028	0.14825172
2102.5	80.4135199	0.09797896	10.2062731	0.14868767
2092.5	78.6690819	0.09985386	10.0146352	0.14913238
2082.5	76.9563292	0.10177625	9.82547527	0.14958597
2072.5	75.2747765	0.10374757	9.63877966	0.15004858
2062.5	73.6239458	0.10576936	9.45453435	0.15052035
2052.5	72.0033659	0.10784316	9.27272519	0.15100143
1222.5	7.61045088	0.94943248	1.05326078	0.25627096
1212.5	7.35793101	0.98405632	1.016202	0.25913139
1208.04	7.24746367	1.00001812	0.99998188	0.11656418

OTTO CYCLE, [illegible], ADIABATIC COMPRESSION
10% EXCESS AIR

moles of. . .	species	MASS	Tambinent	Tfinal	Hrxn	a	b	c	TotalPressure
0.31	H2	2.016	298	300	0.00E+00	0	0	0	1
0.52	CO	28.01							
0.03	CO2	44.01							
0.04	CH4	16.043							
0.5445	O2	32							
0	H2O	18.016							
2.1482	N2	28							
3.5927									

	T0	T1	T2	T3	T4	T5	T6		
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.41E+01	2.84E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.04E+00	2.92E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	8.45E-01	3.72E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	2.24E+00	3.59E+01
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	9.26E-01	2.96E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	1.87E+00	3.36E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.04E+00	2.91E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

	T1	T2	T3	T4	T5	T6	T7	ENERGY		
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	4.89E+00		
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	8.44E+00		
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	6.20E-01		
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	7.99E-01		
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	8.98E+00		
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	0.00E+00		
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	3.48E+01	5.85E+01	TOTAL
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		4.32E+01		
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		4.62E+01		
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		-3.03E+00		

Denominator	3.357

T	P TOTAL	V TOTAL	1/V TOTAL	Work	
298	1	1	1		
303	1.06034386	0.95891842	1.04284158	-0.0423211	
308	1.1233069	0.92011936	1.08681551	-0.0423618	
313	1.18896255	0.88344264	1.1319354	-0.0424032	
318	1.25738544	0.84874161	1.17821489	-0.0424454	
323	1.3286514	0.81588182	1.22566771	-0.0424883	
328	1.40283752	0.78473986	1.27430764	-0.042532	
333	1.48002213	0.75520229	1.32414852	-0.0425763	
338	1.56028483	0.72716471	1.37520425	-0.0426214	
343	1.64370656	0.70053088	1.42748881	-0.0426673	
348	1.73036955	0.67521204	1.48101624	-0.0427138	
353	1.8203574	0.65112618	1.53580063	-0.0427612	
358	1.91375506	0.62819746	1.59185616	-0.0428092	
363	2.01064892	0.60635567	1.64919708	-0.042858	
368	2.11112676	0.58553573	1.7078377	-0.0429076	
373	2.21527783	0.56567728	1.7677924	-0.0429578	
378	2.32319286	0.54672425	1.82907563	-0.0430089	
383	2.43496409	0.52862451	1.89170193	-0.0430607	
388	2.55068528	0.51132955	1.9556859	-0.0431133	
393	2.6704518	0.49479422	2.02104221	-0.0431666	
398	2.79436058	0.47897638	2.08778563	-0.0432208	
403	2.92251021	0.46383674	2.15593097	-0.0432757	
408	3.05500093	0.44933861	2.22549315	-0.0433314	
413	3.1919347	0.43544768	2.29648716	-0.0433879	
418	3.33341518	0.42213186	2.36892806	-0.0434452	
423	3.47954785	0.40936111	2.442831	-0.0435033	
428	3.63043996	0.39710728	2.5182112	-0.0435623	
433	3.78620062	0.38534398	2.59508398	-0.0436221	
438	3.94694084	0.37404645	2.67346473	-0.0436827	
443	4.11277355	0.36319143	2.75336893	-0.0437442	
448	4.28381364	0.35275706	2.83481214	-0.0438065	
453	4.46017803	0.34272279	2.91781002	-0.0438698	
458	4.6419857	0.33306929	3.00237828	-0.0439339	
463	4.82935772	0.32377834	3.08853277	-0.0439989	
468	5.02241732	0.31483277	3.17628939	-0.0440648	
885.9	61.55883	0.05555326	18.0007442	-0.0319153	
				-5.5165654	TOTAL WORK

T FINAL　　P FINAL

OTTO CYCLE, 10% EXCESS AIR, CONSTANT VOLUME COMBUSTION.

FIRST: Use the initial number of moles and calculate the energy given off in going from 885.8 to 298 K

FIRST: Use the initial number of moles and calculate the energy given off in going from 885.8 to 298 K (seta,b,and c =0)

The spreadsheet is set up to calculate the Delta Hreaction and then the Deta U using the initial number of moles

SECOND: Put in the final number of moles of each species (set a=0.31, b = 0.52, c = 0.04) and calculate Delta U

THIRD: Put Tambient at 298 and adjust the final temperature until the sum (energy from cooling + delta U + energy into heating up) = 0 (cell K34)

moles of. . .	species	MASS	Tambient	Tfinal	Hrxn	a	b	c	TotalPressure
0	H2	2.016	298	3266.995	2.00E+03	0.31	0.52	0.04	1
0	CO	28.01			5.95E+02				
0.59	CO2	44.01	THIRD						
0	CH4	16.043	298	CHANGE			pfinal	200.747611	
0.0495	O2	32							
0.39	H2O	18.016							
2.1482	N2	28							
3.1777									

	T0	T1	T2	T3	T4	T5	T6	kj/kg	kj/kmole
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.88E+01	3.79E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.33E+00	3.71E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	1.96E+00	8.63E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	-2.75E+03	-4.41E+04
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	1.26E+00	4.03E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	3.28E+00	5.91E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.12E+00	3.15E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

FIRST	
0.31	H2
0.52	CO
0.03	CO2
0.04	CH4
0.5445	O2
0	H2O
2.1482	N2
3.5927	TOTAL

Del U (reactants)	Del U zero	Del U products
84312.950	-842.59537	8.43E+04
-13268.13	-71044.811	8.43E+04

Del U (885.9)
0.00944987

SECOND	
0	H2
0	CO
0.59	CO2
0	CH4
0.0495	O2
0.39	H2O
2.1482	N2
3.1777	TOTAL

	T1	T2	T3	T4	T5	T6	T7	ENERGY
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	0.00E+00
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	0.00E+00
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	9.40E+04
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	0.00E+00
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	4.17E+03
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	4.63E+04
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	1.58E+05
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		9.57E-01
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		-1.28E+00
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		2.25E+00

Denominator	2.942
P H2	0
P CO	0
P CO2	0.20054385
P CH4	0
P O2	0.01682529
P H2O	0.13256288
P N2	0.73018355

	so far	should be
K(H2-H2O)	#DIV/0!	2.60296614
K(CO-CO2)	#DIV/0!	0.27763362
K(mixed)	#DIV/0!	9.45850982

OTTO CYCLE, 10% EXCESS AIR, ADIABATIC EXPANSION

moles of...	species	MASS	Tambient	Tfinal	Hrxn	a	b	c	TotalPressure
0	H2	2.016	3266.995	340	2.54E+05	0.31	0.52	0.04	200.747611
0	CO	28.01							
0.59	CO2	44.01							
0	CH4	16.043							
0.0495	O2	32							
0.39	H2O	18.016							
2.1482	N2	28							
3.1777									

	T0	T1	T2	T3	T4	T5	T6		
H2	13.3356151	0.00313385	-2.974E-06	2.2847E-09	-7.809E-13	1.1949E-16	-6.748E-21	1.41E+01	2.85E+01
CO	1.02535417	-4.805E-05	4.194E-07	-2.972E-10	8.904E-14	-1.232E-17	6.4626E-22	1.05E+00	2.93E+01
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22	8.82E-01	3.88E+01
CH4	2.49353604	-0.0047835	1.4448E-05	1.9652E-09	-2.884E-11	2.727E-14	-8.076E-18	2.34E+00	3.75E+01
O2	0.83001979	0.00034796	-8.879E-08	-1.996E-11	1.6545E-14	-3.212E-18	2.0294E-22	9.37E-01	3.00E+01
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21	1.88E+00	3.39E+01
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22	1.04E+00	2.92E+01
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09					
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	2.41E-09					
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10					

	T1	T2	T3	T4	T5	T6	T7	ENERGY		
H2	13.3356151	0.00156692	-9.91E-07	5.71E-10	-1.56E-13	1.99E-17	-9.64E-22	0.00E+00		
CO	1.02535417	-2.402E-05	1.40E-07	-7.43E-11	1.78E-14	-2.05E-18	9.23E-23	0.00E+00		
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	-1.08E+05		
CH4	2.49353604	-0.0023917	4.82E-06	4.91E-10	-5.77E-12	4.55E-15	-1.15E-18	0.00E+00		
O2	0.83001979	0.00017398	-2.96E-08	-4.99E-12	3.31E-15	-5.35E-19	2.90E-23	-5.33E+03		
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	-5.54E+04		
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	-2.09E+05	-3.77E+05	TOTAL
ln K(H2-H2O)	56.512	-0.049198	1.67E-05	-2.09E-09	0	0		4.16E+01		
ln K(CO-CO2)	61.367	-0.056043	1.91E-05	-2.41E-09	0	0		4.44E+01		
ln K(mixed)	-4.8795	6.88E-03	-2.48E-06	3.19E-10	0	0		-2.81E+00		

Denominator	2.942
P H2	0
P CO	0
P CO2	0.20054385
P CH4	0
P O2	0.01682529

	so far	should be
K(H2-H2O)	#DIV/0!	1.2027E+18
K(CO-CO2)	#DIV/0!	1.9778E+19
K(mixed)	#DIV/0!	0.06001371

T	P TOTAL	V TOTAL	1/V TOTAL	Work	
3266.995	200.747611	0.05555556	18		
3256.995	197.440404	0.05631675	17.756707	0.15154896	
3246.995	194.191803	0.0570937	17.5150673	0.15213964	
3236.995	191.000419	0.05788679	17.2750994	0.15274547	
3226.995	187.86491	0.0586964	17.036821	0.15336643	
3216.995	184.783975	0.05952293	16.8002496	0.15400252	
3206.995	181.756353	0.06036678	16.5654019	0.15465373	
3196.995	178.780826	0.06122839	16.3322942	0.15532007	
3186.995	175.85621	0.06210817	16.1009422	0.15600154	
3176.995	172.98136	0.06300657	15.8713611	0.15669817	
3166.995	170.155165	0.06392405	15.6435655	0.15740996	
3156.995	167.376549	0.06486107	15.4175697	0.15813693	
3146.995	164.644469	0.06581811	15.1933872	0.15887912	
3136.995	161.957913	0.06679567	14.971031	0.15963656	
3126.995	159.3159	0.06779425	14.7505135	0.16040927	
3116.995	156.717478	0.06881438	14.5318467	0.16119731	
3106.995	154.161723	0.06985659	14.3150421	0.16200071	
3096.995	151.647741	0.07092143	14.1001103	0.16281952	
3086.995	149.174661	0.07200947	13.8870616	0.1636538	
3076.995	146.74164	0.0731213	13.6759058	0.16450361	
3066.995	144.347858	0.07425751	13.466652	0.165369	
3056.995	141.992519	0.07541871	13.2593089	0.16625005	
3046.995	139.674852	0.07660555	13.0538844	0.16714682	
3036.995	137.394106	0.07781867	12.8503861	0.16805939	
3026.995	135.149552	0.07905875	12.6488208	0.16898785	
3016.995	132.940482	0.08032648	12.4491951	0.16993228	
3006.995	130.766207	0.08162256	12.2515147	0.17089276	
2996.995	128.626057	0.08294773	12.055785	0.17186939	
2986.995	126.519383	0.08430274	11.8620107	0.17286227	
2976.995	124.445551	0.08568836	11.670196	0.17387151	
2966.995	122.403947	0.0871054	11.4803446	0.17489721	
2956.995	120.393971	0.08855467	11.2924598	0.17593948	
2946.995	118.415042	0.09003701	11.106544	0.17699845	
2936.995	116.466592	0.0915533	10.9225994	0.17807423	
2926.995	114.548069	0.09310443	10.7406277	0.17916695	
2916.995	112.658938	0.09469132	10.5606297	0.18027675	
2906.995	110.798674	0.09631493	10.3826062	0.18140376	
2896.995	108.966768	0.09797623	10.2065572	0.18254812	
2886.995	107.162724	0.09967623	10.0324822	0.18370998	
2876.995	105.386059	0.10141597	9.86038032	0.1848895	
1886.995	15.5865237	0.98216739	1.01815639	0.44850292	
1880.9	15.3676671	1.00000208	0.99999792	0.2760292	35.1353595

Tfinal Pfinal

STOVE, ADIABATIC FLAME TEMPERATURE CALCULATION.

moles of. . .	species	MASS	Tinitial	Tfinal	Hrxn
0.39	H2O	18.02	298	2480	2.54E+05
0.59	CO2	44.01			
1.962	N2	28			

	T0	T1	T2	T3	T4	T5	T6
H2O	1.843517	-0.00023	1.24E-06	-7.40E-10	1.98E-13	-2.50E-17	1.24E-21
CO2	0.471107	0.001564	-1.20E-06	5.00E-10	-1.10E-13	1.36E-17	-6.40E-22
N2	1.041739	-0.00013	4.92E-07	-3.30E-10	9.47E-14	-1.30E-17	6.68E-22

	T1	T2	T3	T4	T5	T6	T7	ENERGY
H2O	1.843517	-0.000115	4.13E-07	-1.85E-10	3.96E-14	-4.17E-18	1.77E-22	3.84E+04
CO2	0.471107	0.000782	-4.00E-07	1.25E-10	-2.20E-14	2.27E-18	-9.14E-23	7.31E+04
N2	1.041739	-0.000065	1.64E-07	-8.25E-11	1.89E-14	-2.17E-18	9.54E-23	1.42E+05
							TOTAL	2.54E+05

THE UNIVERSITY OF READING

SCHOOL OF CONSTRUCTION MANAGEMENT AND ENGINEERING

MSc & PG DIPLOMA COURSES IN RENEWABLE ENERGY & THE ENVIRONMENT 2002/2003

HEAT TRANSFER EXERCISE

A flat plate solar water heater is designed to heat water that is pumped through pipes in the plate at a mass flow rate of 0.01 kg s^{-1}. The 9 pipes, of internal diameter 16 mm, are connected in series. The pipes are soldered into a copper plate with a flat top surface and it can be assumed that the plate and pipes are all at the same temperature. The length of the plate is 1.8 m and the width is 1.4 m.

The heater has a single layer of glass with a thickness of 5 mm placed 30 mm above the copper plate of the same size as the plate. Insulation behind the pipes and the plate is by a block of expanded polystyrene with an average thickness of 50 mm. The edges of the heater are also insulated and the heat transfer through these edges and from the curved connecting pipes within this insulation should be ignored.

The heater is placed at an angle of 30° to the vertical in a constant solar radiation flux (normal to the glass) of 600 W m^{-2}. The ambient air temperature is 20°C. Water at an initial temperature of 30°C is pumped into the heater. Set up a model for the heat gains and losses from the water heater. Find the heat lost from the solar heater and the temperature to which the water increases.

Please write the model as an Excel (or other suitable) spreadsheet and provide a copy of the model electronically either on a floppy disk or as an e-mail attachment, as well as providing a description of the model and results on paper.

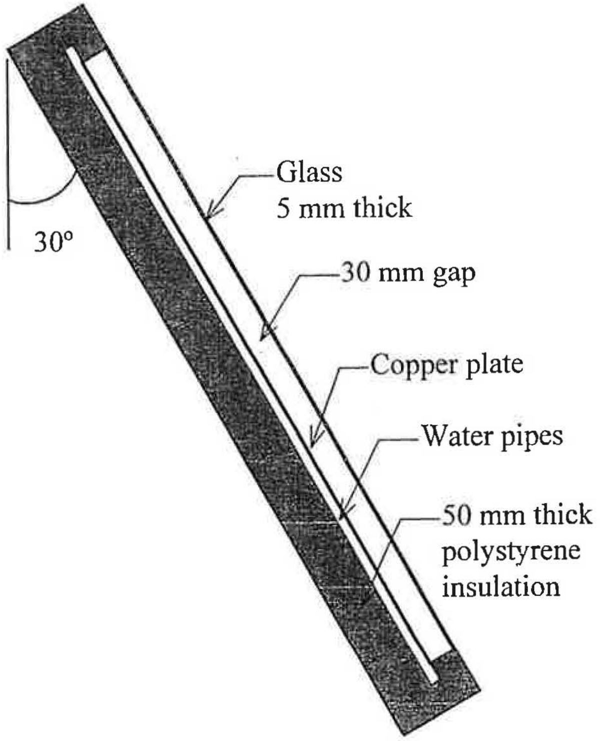


Figure 1 View from side

NOTE: guesses must be made for the water and other temperatures in the system, before the model can be developed.

Scan 30 kb

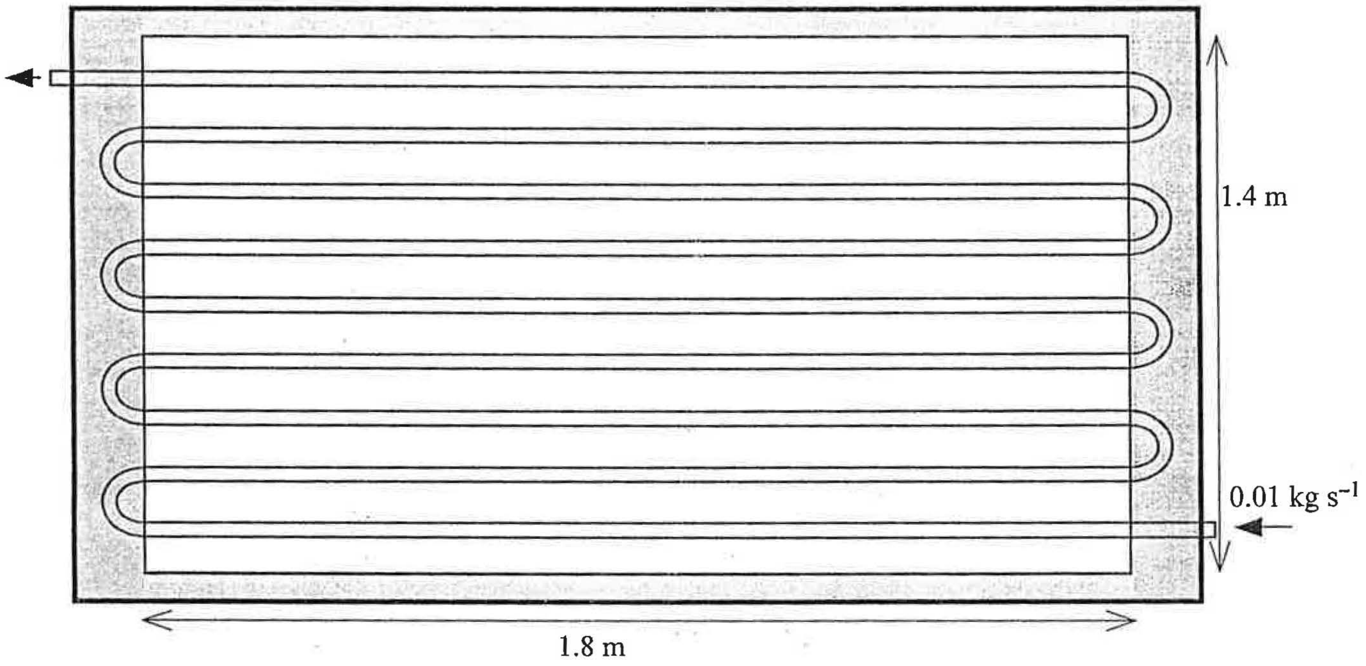


Figure 2 View from top of box

Properties of matter

Stephan-Boltzmann constant	(σ)	=	5.67×10^{-8} W m^{-2} K^{-4}
Thermal conductivity of expanded polystyrene	(k_n)	=	0.027 W m^{-1} K^{-1}
Thermal conductivity of glass	(k_g)	=	1.4 W m^{-1} K^{-1}
Thermal emissivity of glass (around ambient temperatures)	(ε_g)	=	0.94
Thermal emissivity of copper plate (selective surface)	(ε_p)	=	0.1
Solar absorbtivity of copper plate (selective surface)	(α_p)	=	0.92
Solar transmissivity of glass	(τ_p)	=	0.79

Stand-Alone Solar Thermal Project

Prepared by

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University of Reading
School of Construction Management and Engineering

18 February, 2003

CONTENTS:

ENERGY FLOW: Approach to the Project

I am taking a "Conservation of Energy" approach to the project. There are two objects to be concerned with, the absorber plate and the glass cover. Each has energy inputs and outputs. The energy flows into and out of each of these has to sum to zero. My approach is to:

- List all of the ways that energy can flow into or out of the absorber plate and the glass.
- Derive equations to calculate the power involved with each of those heat flows and arrange them on a spreadsheet.
- Manipulate the various temperatures ($T_{\text{absorber plate}}$, $T_{\text{water at the outlet}}$, $T_{\text{bottom surface of the glass}}$, $T_{\text{top surface of the glass}}$) so that the net energy flow is zero for the absorber plate and glass.

Two additional requirements are that

- The "convective/conductive" energy flow from the absorber plate to the water ($hA\Delta T_{log\text{-}mean}$) has to equal the heat gain of the water ($\dot{m}C_p\Delta T_{water}$), and
- The difference between the heat leaving the top of the glass cover and heat arriving at the bottom of the glass cover cannot be more that the amount of the heat the glass absorbs from the sunlight.

Sunlight hits the glass cover plate. 600 W/m^2 x (1.4 x 1.8) m^2 = <u>1512 Watts</u>

1. Some is transmitted (79%) to the absorber plate. = <u>1194.5 W</u>
2. Some is reflected (8.8%), and
3. the remainder is absorbed by the glass (12.2%) = <u>184.5 W</u>

The sunlight hits the absorber plate.

3. Most of it is absorbed (92%). 0.92 x 1194.5 = <u>1099 W</u>
4. The rest (8%) is reflected. We can assume that this reflected visible light passes through the glass and escapes from the collector.

The top of the glass cover will lose energy from:

- Convective losses from the top of the glass
- Net radiative losses from the top of the glass

The bottom of the glass cover will gain energy from:

- Convective gains from the absorber plate
- Net radiative gains from the absorber plate.

In addition, the glass cover will absorb energy from the incoming solar radiation. The absorber plate is going to lose heat to:

- Convection/Conduction into the water flowing through the collector
- Conduction thorough the back of the collector
- Convective losses from the top of the absorber plate.
- Net Radiative losses from the top of the absorber plate to the glass cover.

ENERGY FLOWS: Equations and calculations

For the glass cover:

1. Input from direct sunlight absorption = 0.122 x 600 W/m^2 x (1.4 x 1.8) m^2 = 184.5 W
2. Net radiation loss from the top of the glass cover =

$$\sigma \varepsilon A\left\{\frac{1+\cos S}{2}\left(T_{top}^4 - T_{sky}^4\right)+\frac{1-\cos S}{2}\left(T_{top}^4 - T_{ground}^4\right)\right\}$$

   where S is the angle the collector makes with the horizontal, and

   $\frac{1+\cos S}{2}$ *and* $\frac{1-\cos S}{2}$

   are the form factors between the collector and the sky, and the collector and the ground, respectively.[1] I have taken the sky temperature to be 15°C below ambient, and the ground temperature to be the same as ambient.[2]

3. Net convective loss from the top of the glass:

$$Nu = (Gr\cos\phi\,\mathrm{Pr})^{1/4}\left[\frac{\cos\phi}{1+\left(1+\frac{1}{\mathrm{Pr}^{0.5}}\right)^2}\right]^{1/4}$$

   where ϕ is the angle the collector makes with the vertical.[3]

   $\mathrm{Pr} = 0.707$

$$Gr = \frac{\beta g X^3 \Delta T}{\nu^2} = \frac{\frac{2}{T_{top}+T_{ambient}} \times 9.81 \times \left(\frac{1.4m\times 1.8m}{6.4m}\right)^3 \times (T_{top} - T_{ambient})}{[1.59 + 0.01(\frac{T_{top}+T_{ambient}}{2} - 300)]^2 \times 10^{-10}}$$

$$= 1.198\times 10^{10}\frac{(T_{top} - T_{ambient})}{(T_{top} + T_{ambient})\times[1.59 + 0.005(T_{top} + T_{ambient} - 600)]^2}$$

   Using $\phi = 30^{\circ}$ and substituting into the expression for Nu above gives

   $Nu = 0.550Gr^{0.25}$

$$h = \frac{kNu}{X} = \frac{[0.0263 + 0.000037(T_{top} + T_{amb} - 600)]\times Nu}{0.3938}$$

   So $\overset{Y}{Q} = hA\Delta T = 2.52h\left(T_{top} - T_{amb}\right)$

4. Net convective gain from the air gap:

$$use\,Nu = 1+1.44\left[1-\frac{1708}{Ra\cos\tau}\right]\times\left[1-\frac{1708(\sin 1.8\tau)^{1/3}}{Ra\cos\tau}\right]+\left[\left(\frac{Ra\cos\tau}{5830}\right)^{1/3}-1\right]$$

$$= 1+1.44\left[1-\frac{3416}{Ra}\right]\times\left[1-\frac{3152.4}{Ra}\right]+\left[\left(\frac{Ra}{11660}\right)^{1/3}-1\right]$$

In our case Ra = Pr x Gr

$$Ra = \frac{\Pr\times\beta g X^3\Delta T}{\nu^2} = \frac{0.707\times\frac{2}{T_{bot}+T_{plate}}\times 9.81\times(0.030)^3\times(T_{plate}-T_{bot})}{[1.59+0.01(\frac{T_{bot}+T_{plate}}{2}-300)]^2\times 10^{-10}}$$

$$= 3.741\times 10^6\frac{(T_{plate}-T_{bot})}{(T_{plate}+T_{bot})\times[1.59+0.005(T_{plate}+T_{bot}-600)]^2}$$

Then $h = \frac{kNu}{X} = \frac{[0.0263+0.000037(T_{plate}+T_{bot}-600)]\times Nu}{0.030}$

and $\dot{Q} = hA\Delta T = 2.52h\left(T_{plate}-T_{bot}\right)$

5. Net radiative gain from top of absorber

Form factor between the absorber plate and the glass cover = 1

$$\varepsilon_{effective} = \left[\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right]^{-1} = \left[\frac{1}{0.94}+\frac{1}{0.1}-1\right]^{-1} = 0.0994$$

$$\dot{Q} = A\varepsilon_{effective}\sigma(T_{plate}^4-T_{bot}^4) = 1.42\times 10^{-8}(T_{plate}^4-T_{bot}^4)$$

6. Maximum Conductive flow through the glass =

$$\dot{Q}_{conduction} = \left|\frac{kA\Delta T}{\Delta x}\right| = \left|\frac{1.4\times 2.52\times\left(T_{top}-T_{bottom}\right)}{0.005}\right|$$

$$= \left|705.6\left(T_{top}-T_{bottom}\right)\right|$$

For the absorber plate:

1. Solar gain = 0.92 x (0.79 x 2.52 m^2 x 600 W/m^2) = 1099 W
2. Net radiative loss to glass (same as glass' gain from plate=#5 above)
3. Net convective loss to glass (same as glass' gain from plate = #4 above)
4. Net conductive loss from back panel:

   (We can ignore any convective or radiative losses from the back of the collector.[4])

$$\dot{Q}_{conduction} = \left|\frac{kA\Delta T}{\Delta x}\right| = \left|\frac{0.027 \times 2.52 \times \left(T_{plate} - T_{ambient}\right)}{0.050}\right|$$

$$= \left|1.361\left(T_{top} - T_{bottom}\right)\right|$$

5. Net conduction to water:

$$\mathrm{Re} = \frac{uX}{\nu} = \frac{\dot{m}D}{\rho A \nu} = \frac{4\dot{m}}{\pi D \rho \nu} = \frac{4(0.010)}{\pi(0.016)(997)(1.7 \times 10^{-5})} = 47 \text{ which is laminar}$$

So Nu = 3.66

$$h = \frac{kNu}{X} = \frac{\left[0.63 + 0.01(T_{inlet} + T_{oulet} - 626)\right]}{0.16}$$

$$= 228.75\left[0.63 + 0.01(T_{inlet} + T_{oulet} - 626)\right]$$

$$\Delta T_{\log-mean} = \frac{(T_{plate} - T_{outlet}) - (T_{plate} - T_{inlet})}{\ln\left(\frac{(T_{plate} - T_{outlet})}{(T_{plate} - T_{inlet})}\right)}$$

$$= \frac{(303 - T_{outlet})}{\ln\left(\frac{(T_{plate} - T_{outlet})}{(T_{plate} - 303)}\right)}$$

$$\dot{Q}_{plate-to-water} = hA\Delta T_{lm} = h \times \pi DL \times \Delta T_{lm} = h \times \pi(0.016)(9 \times 1.8)\Delta T_{lm} = 0.8143h\Delta T_{lm}$$

6. Heat gain by water

$$\dot{Q} = \dot{m}C_p(T_{outlet} - T_{inlet}) = 0.010 \times 4180 \times (T_{outlet} - T_{inlet}) = 41.8(T_{outlet} - T_{inlet})$$

Starting Guesses and Results

SHEET Heat Transfer (cold sky)

Starting Guesses:
If ALL the sunlight energy striking the plate went into the water we'd have

1099 W = (0.010 kg/s) (4180 J/kg°C) ΔT_{water} → ΔT_{water} = 26.3°C, T_{outlet} = 56.3°C

If I assume an efficiency of about 60%, this gives T_{outlet} = 45.8°C
Let plate temp be 48°C
Let glass temp be 30°C

I need to adjust the T's such that the net heat flow calculated from conductive/convective losses to the water from the plate is the same as the heat gain by the water, that is

$$hA\Delta T_{\log-mean} = \dot{m}C_p(T_{outlet} - T_{inlet})$$

I adjusted T_{outlet} to 46.75 to make the above condition okay, but then too much heat was being gained by plate, so I needed to adjust the plate and outlet temperature to keep them equal but to give larger heat transfer away from plate.

Increase both by roughly the same amount until get net heat gain/loss from plate = 0

Mess until T_{plate} = 52.21, T_{out} = 50.93. At this point a change in 0.01°C causes changes in the net power fluxes that are greater than the differences between those fluxes and zero.

It turns out that the glass temperature was almost perfect. I adjusted the T_{top} down from 30°C to 29.85°C and T_{bottom} from 30°C to 28.85°C and confirmed that

- The net power flow to the glass was essentially zero.
- The difference between the rate of energy loss from the top of the glass and energy gain from the bottom of the glass was LESS than the sum of the energy input from the sun. (It would have been a physically impossible situation if, say, 500 watts is leaving the top of the glass, 200 watts is entering the bottom of the glass, and the solar input is only 200 watts (instead of the 300 watts necessary).

SHEET Heat Transfer (ambient sky)

If you assume a sky temperature of 20°C (rather than the 5°C I had chosen) you end up with T_{plate} =52.86 T_{outlet} =51.57, $T_{top\ of\ glass}$ =33.89, and $T_{bottom\ of\ glass}$ =33.87

SHEET HT (no glass. abs. amb sky)

This assumes a sky temperature of 20°C and no absorption of sunlight by the glass. You end up with T_{plate} =51.92 T_{outlet} =50.63, $T_{top\ of\ glass}$ =28.7, and $T_{bottom\ of\ glass}$ =28.5

DISCUSSION: Sources of error/uncertainty in results

There are numerous sources of uncertainty in the results. Among them are:

- Assigning $0^{o}C = 273$ K rather than 273.15 K
- Assuming that water and air thermal properties change linearly with temperature.
- Using values for emissivities and absorptivities that have only two significant digits.
- Choice of sky and ground temperatures; assumption that the ground behaves like a perfect blackbody.
- Neglecting heat losses from turns in the pipe, and from the sides of the collector.
- Neglecting convective and radiative losses from the back of the collector.
- Variations in models used for approximating various fluid flow coefficients vary from textbook to textbook.
- Assumption that the plate temperature is uniform. In reality the temperature will be higher between the copper pipes and lower at the location of the pipes, and will be highest at the outlet end of the pipe and lowest at the inlet end. We have taken it as an article of faith that the two-dimensional temperature distribution across the plate does not vary much from a uniform temperature.
- We have ignored the effects of the pipes protruding above or below the absorber plate. If they protrude above the plate the surface area for convection would be greater and result in more convective heat transfer from the absorber plate to the glass cover. If they protrude below the plate the conductive heat transfer from the back of the collector will be greater as the distance between the pipes and back cover will be less.

Possible improvements in Collector Design

Simple changes in collector design could include:

- Reducing the air gap between the absorber and the cover from 30 mm to 10 mm
- Tripling the thickness of the backing insulation from 50 mm to 150 mm, or
- Replacing the glass with "white" glass with a low iron content and a transmissivity of 0.91.[5] The results of these various changes are shown in the table below.

Conditions			Hot Water Outlet Temperature (^{o}C)	Overall Collector Efficiency (%)	Excel Sheet Name
Glass	Air Gap	Insulation			
Original	30 mm	50 mm	50.93	57.86	Heat Transfer (cold sky)
Original	10 mm	50 mm	52.43	62.01	HT (cold sky, 10 mm gap)
Original	30 mm	150 mm	51.47	59.35	HT (cold sky, triple ins)
Original	10 mm	150 mm	53.00	63.58	HT (cold, 3xins, 10 mm gap)
"white" (τ=0.91)	10 mm	150 mm	57.94	77.24	HT (cold,3xins,10mm,whglass)

Simply replacing the glass with clearer glass increases the energy available to the absorber plate by 15%. Changing the air gap and increasing the insulation thickness should be relatively inexpensive changes that could significantly improve the performance of the collector.

REFERENCES

Many of the equations and values came from tables provided by Dr. Fulford as part of the course notes for the Advanced Solar course. Other equations came from:

1. Simonson, J.R. Computing Methods in Solar heating Design. Macmillan Press. London. 1984. ISBN 0-333-32844-2. Page 83.

   "A flat-plate solar collector set at an angle S to the horizontal will see only a portion of the hemispherical sky dome. For this case $F_{1\text{-}2} = (1+\cos S)/2$*, where 1 refers to the collector and 2 refers to the sky. The collector will also see the ground, 3, and for the complete field of view* $F_{1\text{-}2} + F_{1\text{-}3} = 1$.
   It follows that $F_{1\text{-}3} = (1-\cos S)/2$.*"*

2. Ibid, page 86

   "For temperatures achieved I the U.K., the sky temperature is of the order of 10.14 K below ambient in summer, increasing to 20-30 K below ambient in winter."

3. Ibid, page 76.

4. Ibid, page 76.

   "Convection will occur from the upper exposed surface of a collector The underneath surface of the backing insulation will not be significantly above ambient temperature if this surface is exposed."

5. Lunde, Peter J. Solar Thermal Engineering: Space Heating and Hot Water Systems, page 126 1980. John Wiley & Sons, New York.
   ISBN 0-471-08233-3

SPREADSHEETS

I've attached the following spreadsheets. The first includes three scenarios.
The second assumes that one uses a sky temperature of 20°C rather than 5°C.
The third assumes as well that the glass does not absorb any energy from sun, or equivalently, that such absorption has no effect on the temperature of the glass.
The rest of the sheets consider the effect of changes in air gap between the absorber plate and the glass cover, in the thickness of the backing insulation, and/or in the glass that makes up the cover.

Spreadsheet name	**Sky Temperature**	**Glass**	**Air Gap**	**Insulation**
Heat Transfer (cold sky)	*5°C*	Original	30 mm	50 mm
Heat Transfer (ambient sky)	*20°C*	Original	30 mm	50 mm
HT (no glass abs, ambient sky)	*20°C*	Original (but assumes no absorbance of solar radiation)	30 mm	50 mm
HT (cold sky, 10 mm gap)	*5°C*	Original	10 mm	50 mm
HT (cold sky, triple ins)	*5°C* —	Original	30 mm	150 mm
HT (cold, 3xins, 10 mm gap)	*5°C*	Original	10 mm	150 mm
HT (cold,3xins,10mm,whglass)	*5°C*	White glass ($\tau = 0.91$)	10 mm	150 mm

HEAT TRANSFER (COLD SKY)

Solar Thermal Collector Spreadsheet
COLD SKY, Standard Insulation, 30 mm gap between plate and collector, ordinary glass

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value	Kelvin	Celcius	**Fixed Values**	Kelvin	Celcius
Tglass (top)	302.85	29.85	Tinput(water)	303	30
Tglass (bottom)	302.95	29.95	Tambient	293	20
Tabsorberplate	325.21	52.21	Tsky	278	5
Twater (out)	323.93	50.93	Tground	293	20

GLASS COVER

Direct Absorption of Sunlight	184.5						
Radiation Loss from Top	280.698926						
Convective Loss from the top	85.8379699	Gr	80421437.2	Nu	52.08415792	h(conv, top)	3.45814076
Radiative Gain from absorber plate	39.2228705						
Convective Gain from absorber plate	142.84577	Ra	44253.6215	Nu	2.794048438	h(conv, bottom)	2.5464883
TOTAL	**0.03174463**						

Checksum (leaving - coming in)	184.468255	Conduction across glass	71

ABSORBER PLATE

Direct Absorption of Sunlight	1099								
Radiation Loss from Top	39.2228705								
Convective Loss from the top	142.84577								
Conduction through back panel	43.83781								
Conduction loss into water	873.40125	Re	1217.93909	Nu	3.66	h	146.239875	DELT(logmean	7.3343827
TOTAL	**-0.30770088**								

Conduction gain by water	874.874
Efficiency	57.862037

HEAT TRANSFER (AMBIENT SKY)

Solar Thermal Collector Spreadsheet
AMBIENT SKY, Standard Insulation, 30 mm gap between plate and collector, ordinary glass

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value	Kelvin	Celcius	**Fixed Values**	Kelvin	Celcius
Tglass (top)	306.86	33.86	Tinput(water)	303	30
Tglass (bottom)	306.89	33.89	Tambient	293	20
Tabsorberplate	325.86	52.86	Tsky	293	20
Twater (out)	324.57	51.57	Tground	293	20

GLASS COVER

Direct Absorption of Sunlight	184.5							
Radiation Loss from Top	200.997542							
Convective Loss from the top	131.238285		Gr	109586834	Nu	56.27328706	h(conv, top)	3.75748084
Radiative Gain from absorber plate	34.1516992							
Convective Gain from absorber plate	116.379904		Ra	36465.9487	Nu	2.654686013	h(conv, bottom)	2.43450193
TOTAL	**2.79577628**							

Checksum (leaving - coming in)	181.704224	Conduction across glass	21

ABSORBER PLATE

Direct Absorption of Sunlight	1099								
Radiation Loss from Top	34.1516992								
Convective Loss from the top	116.379904								
Conduction through back panel	44.72246								
Conduction loss into water	902.457844	Re	1225.41562	Nu	3.66	h	147.703875	DELT(logmean	7.50327044
TOTAL	**1.28809251**								

Conduction gain by water	901.626
Efficiency	59.6313492

HT (no glass abs, ambient Sky)

Solar Thermal Collector Spreadsheet
AMBIENT SKY, Standard Insulation, 30 mm gap between plate and collector, standard glass but with zero absorbance

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value	Kelvin	Celcius	**Fixed Values**	Kelvin	Celcius
Tglass (top)	301.5	28.5	Tinput(water)	303	30
Tglass (bottom)	301.7	28.7	Tambient	293	20
Tabsorberplate	324.92	51.92	Tsky	293	20
Twater (out)	323.63	50.63	Tground	293	20

GLASS COVER	Watts							
Direct Absorption of Sunlight	0							
Radiation Loss from Top	119.952497							
Convective Loss from the top	71.451223		Gr	70159071.5	Nu	50.33657335	h(conv, top)	3.3357247
Radiative Gain from absorber plate	40.6190031							
Convective Gain from absorber plate	150.74277		Ra	46690.0895	Nu	2.832513491	h(conv, bottom)	2.57616536
TOTAL	**-0.04194639**							
Checksum (leaving - coming in)	0.04194639	Conduction across glass	141					

ABSORBER PLATE	Watts								
Direct Absorption of Sunlight	1099								
Radiation Loss from Top	40.6190031								
Convective Loss from the top	150.74277								
Conduction through back panel	43.44312								
Conduction loss into water	863.171972	Re	1214.44233	Nu	3.66	h	145.553625	DELT(logmean	7.28265722
TOTAL	**1.02313478**								
Conduction gain by water	862.334								
Efficiency	57.032672								

HT (cold sky, 10 mm gap)

Solar Thermal Collector Spreadsheet
Cold Sky, 10 mm gap, normal insulation

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value	Kelvin	Celcius	**Fixed Values**	Kelvin	Celcius
Tglass (top)	300.3	27.3	Tinput(water)	303	30
Tglass (bottom)	300.45	27.45	Tambient	293	20
Tabsorberplate	326.71	53.71	Tsky	278	5
Twater (out)	325.43	52.43	Tground	293	20

GLASS COVER

Direct Absorption of Sunlight	184.5						
Radiation Loss from Top	243.126438						
Convective Loss from the top	59.1159788	Gr	60842504.1	Nu	48.57518457	h(conv, top)	3.21352353
Radiative Gain from absorber plate	46.0732518						
Convective Gain from absorber plate	71.4455202	Ra	6574.05241	Nu	1.186205917	h(conv, bottom)	1.07964192
TOTAL	**-0.2236449**						

Checksum (leaving - coming in)	184.723645	Conduction across glass	106

ABSORBER PLATE

Direct Absorption of Sunlight	1099								
Radiation Loss from Top	46.0732518								
Convective Loss from the top	71.4455202								
Conduction through back panel	45.87931								
Conduction loss into water	936.509437	Re	1235.49694	Nu	3.66	h	149.671125	DELT(logmean	7.68404147
TOTAL	**-0.90751889**								

Conduction gain by water	937.574
Efficiency	62.0088624

HT (COLD SKY, TRIPLE INS)

Solar Thermal Collector Spreadsheet
COLD SKY, Standard Insulation, 30 mm gap between plate and collector, triple backing insulation, ordinary glass

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value			**Fixed Values**		
	Kelvin	Celcius		Kelvin	Celcius
Tglass (top)	302.95	29.95	Tinput(water)	303	30
Tglass (bottom)	303.1	30.1	Tambient	293	20
Tabsorberplate	325.76	52.76	Tsky	278	5
Twater (out)	324.47	51.47	Tground	293	20

GLASS COVER								
Direct Absorption of Sunlight	184.5							
Radiation Loss from Top	282.191837							
Convective Loss from the top	86.9234703		Gr	81172531.7	Nu	52.20534406	h(conv, top)	3.46667745
Radiative Gain from absorber plate	40.063021							
Convective Gain from absorber plate	146.023599		Ra	44817.2489	Nu	2.803132668	h(conv, bottom)	2.55718768
TOTAL	**1.47131315**							
Checksum (leaving - coming in)	183.028687	Conduction across glass	106					

ABSORBER PLATE									
Direct Absorption of Sunlight	1099								
Radiation Loss from Top	40.063021								
Convective Loss from the top	146.023599								
Conduction through back panel	14.86212								
Conduction loss into water	898.252679		Re	1224.24593	Nu	3.66	h	147.475125	DELT(logmean	7.47989176
TOTAL	**-0.20141934**									

Conduction gain by water	897.446
Efficiency	59.3548942

HT (cold, 3×ins, 10 mm gap)

Solar Thermal Collector Spreadsheet
COLD SKY, Triple Insulation, 10 mm gap between plate and collector, ordinary glass

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value	Kelvin	Celcius	**Fixed Values**	Kelvin	Celcius
Tglass (top)	300.35	27.35	Tinput(water)	303	30
Tglass (bottom)	300.5	27.5	Tambient	293	20
Tabsorberplate	327.28	54.28	Tsky	278	5
Twater (out)	326	53	Tground	293	20

GLASS COVER

Direct Absorption of Sunlight	184.5						
Radiation Loss from Top	243.854018						
Convective Loss from the top	59.6207312	Gr	61234399.3	Nu	48.65321626	h(conv, top)	3.21891433
Radiative Gain from absorber plate	47.1282081						
Convective Gain from absorber plate	73.8428861	Ra	6673.61378	Nu	1.20119407	h(conv, bottom)	1.09420211
TOTAL	**1.9963454**						
Checksum (leaving - coming in)	182.503655	Conduction across glass	106				

ABSORBER PLATE

Direct Absorption of Sunlight	1099								
Radiation Loss from Top	47.1282081								
Convective Loss from the top	73.8428861								
Conduction through back panel	15.5516933								
Conduction loss into water	960.854462	Re	1242.19973	Nu	3.66	h	150.975	DELT(logmean	7.81570463
TOTAL	**1.62275046**								
Conduction gain by water	961.4								
Efficiency	63.5846561								

HT (COLD, 3×ins, 10mm, whglass)

Solar Thermal Collector Spreadsheet
COLD SKY, Triple Insulation, 10 mm gap between plate and collector, white glass

SPREADSHEET FOR SOLAR THERMAL COLLECTOR MODELLING--PHIL WOLF

Variable Value	Kelvin	Celcius	**Fixed Values**	Kelvin	Celcius
Tglass (top)	296	23	Tinput(water)	303	30
Tglass (bottom)	296.11	23.11	Tambient	293	20
Tabsorberplate	332.19	59.19	Tsky	278	5
Twater (out)	330.95	57.95	Tground	293	20

GLASS COVER										
Direct Absorption of Sunlight	15.12									
Radiation Loss from Top	181.901059									
Convective Loss from the top	19.5030552		Gr	25896795	Nu	39.23504853	h(conv, top)	2.5797692		
Radiative Gain from absorber plate	63.7464249									
Convective Gain from absorber plate	123.754793		Ra	8956.78601	Nu	1.493155145	h(conv, bottom)	1.36111544		
TOTAL	**1.21710413**									
Checksum (leaving - coming in)	13.9028959	Conduction across glass	78							
ABSORBER PLATE										
Direct Absorption of Sunlight	1375.92									
Radiation Loss from Top	63.7464249									
Convective Loss from the top	123.754793									
Conduction through back panel	17.7791967									
Conduction loss into water	1169.41681		Re	1301.00485	Nu	3.66	h	162.298125	DELT(logmean	8.84853547
TOTAL	**1.22277211**									
Conduction gain by water	1168.31									
Efficiency	77.2691799									

Introduction:

Our carbon management case study is focused on Severn Trent, which, while primarily a water supply and water and waste treatment company, also has substantial investments in the information technology, financial, and insurance sectors. Specifically it consists of:

- Severn Trent Water, which "is the groups regulated water business. It provides water and sewerage services to more than three million households and businesses in England and Wales."
- Biffa, Which "is the largest single supplier of integrated wastes services in the UK. Through its collection, landfill, and special waste treatment activities, it collects, treats, and disposes of municipal and industrial waste nationally.
- Severn Trent Services which "supplies products and services associated with water, wastewater, and contaminated land.
  Severn Trent Systems, which " supplies IT services and software solutions to utilities, particularly in the areas of customer management and work and asset management.
- Property, Engineering, Consultancy and Insurance
  (ST, 2002)

There are two complementary approaches we can take to defining a carbon management strategy for Severn Trent. The first approach is to look at the direct and indirect UK emissions for the water supply, water transport, sewage, and solid waste sectors of the economy. Such an analysis gives the following as the top contributors to GHG's:

1 Water transport
2 Refined petroleum products
3 Transport services
4 Other business activities
5 Electricity production - coal
6 Financial instruments
7 Other transport equipment
8 Renting of machinery
9 Freight transport by road
10 Computer and related activities
11 Solid Waste
18 Electricity production - gas
20 Electricity production - oil
(NAIE)

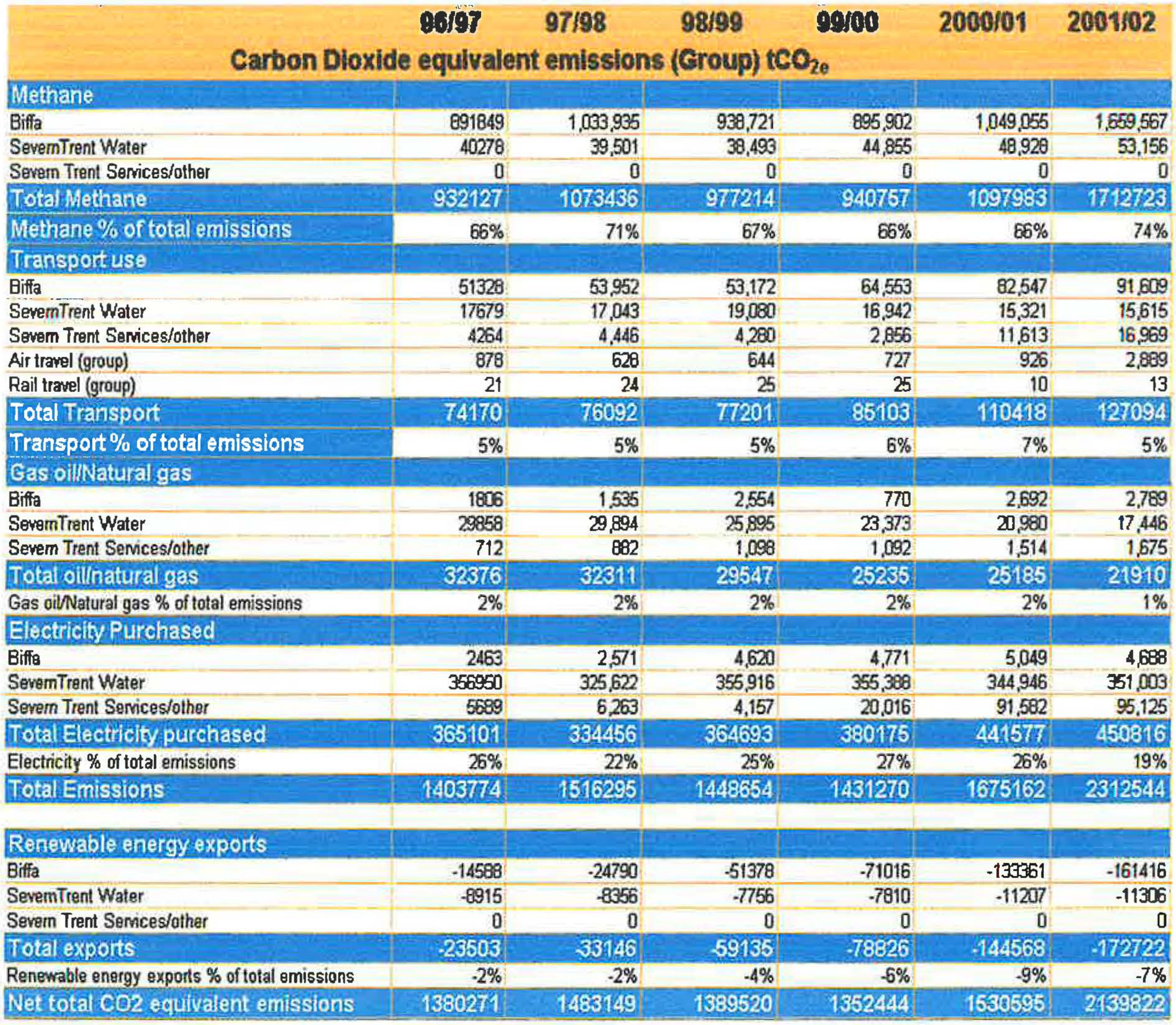
We have chosen to group these as follows:

1. Water Transport and Water Supply
2. Refined Petroleum products, transport services, renting of machinery, and freight transport by road
3. Financial Instruments, computer related activities and other business activities
4. Solid waste, including landfill and sewage treatment

(Electricity was not included as a separate category because it is included in the 1st and 3rd categories above)

This list encompasses the vast majority of both the direct emissions (landfill gas, emissions from transport, etc.) and indirect emissions (purchases of electricity to run operations and maintenance) from Severn Trent.

The second, more direct approach is to look at Severn Trent's 2002 Stewardship report, wherein it lists its greenhouse gas emissions:



Carbon Dioxide equivalent emissions (Group) tCO_{2e}

	96/97	97/98	98/99	99/00	2000/01	2001/02
Methane						
Biffa	891849	1,033,935	938,721	895,902	1,049,055	1,659,567
SevernTrent Water	40278	39,501	38,493	44,855	48,928	53,156
Severn Trent Services/other	0	0	0	0	0	0
Total Methane	932127	1073436	977214	940757	1097983	1712723
Methane % of total emissions	66%	71%	67%	66%	66%	74%
Transport use						
Biffa	51328	53,952	53,172	64,553	82,547	91,609
SevernTrent Water	17679	17,043	19,080	16,942	15,321	15,615
Severn Trent Services/other	4264	4,446	4,280	2,856	11,613	16,969
Air travel (group)	878	628	644	727	926	2,889
Rail travel (group)	21	24	25	25	10	13
Total Transport	74170	76092	77201	85103	110418	127094
Transport % of total emissions	5%	5%	5%	6%	7%	5%
Gas oil/Natural gas						
Biffa	1806	1,535	2,554	770	2,692	2,789
SevernTrent Water	29858	29,894	25,895	23,373	20,980	17,446
Severn Trent Services/other	712	882	1,098	1,092	1,514	1,675
Total oil/natural gas	32376	32311	29547	25235	25185	21910
Gas oil/Natural gas % of total emissions	2%	2%	2%	2%	2%	1%
Electricity Purchased						
Biffa	2463	2,571	4,620	4,771	5,049	4,688
SevernTrent Water	356950	325,622	355,916	355,388	344,946	351,003
Severn Trent Services/other	5689	6,263	4,157	20,016	91,582	95,125
Total Electricity purchased	365101	334456	364693	380175	441577	450816
Electricity % of total emissions	26%	22%	25%	27%	26%	19%
Total Emissions	1403774	1516295	1448654	1431270	1675162	2312544
Renewable energy exports						
Biffa	-14588	-24790	-51378	-71016	-133361	-161416
SevernTrent Water	-8915	-8356	-7756	-7810	-11207	-11306
Severn Trent Services/other	0	0	0	0	0	0
Total exports	-23503	-33146	-59135	-78826	-144568	-172722
Renewable energy exports % of total emissions	-2%	-2%	-4%	-6%	-9%	-7%
Net total CO2 equivalent emissions	1380271	1483149	1389520	1352444	1530595	2139822

(Gill Treanor, Severn Trent, 2003)

It can be seen right away that almost three-quarters of Severn-Trent’s GHG emissions come from methane from landfill gases, and almost a fifth of the emissions come from electricity purchased for its operations, with a smaller contributions from transport. Thus the “groupings” derived from the first approach looking at the water and waste industry as a whole fit very well with Severn Trent’s self-reporting GHG emission sources.

The assumptions that have been made in putting together this report are that what is desired is:

- a summary of the present business-as-usual approach to each greenhouse gas source listed above
- a summary of the “best-practices” in each sector with regards to GHG’s
- an estimate or reasonable set of assumptions about the contribution of each of the above areas to the total GHG output of the company
- an estimate or reasonable set of assumptions about the economic costs of implementing the industry best-practices
- an estimate or reasonable set of assumptions about GHG reductions achievable by switching to industry best practices, and an estimate of the economic benefits that would accrue to the company.
- that all of the above be presented clearly and succinctly.

Our approach will be to look at each of the five grouped sectors following the approach outlined immediately above, then to draw conclusions and summarise recommendations.

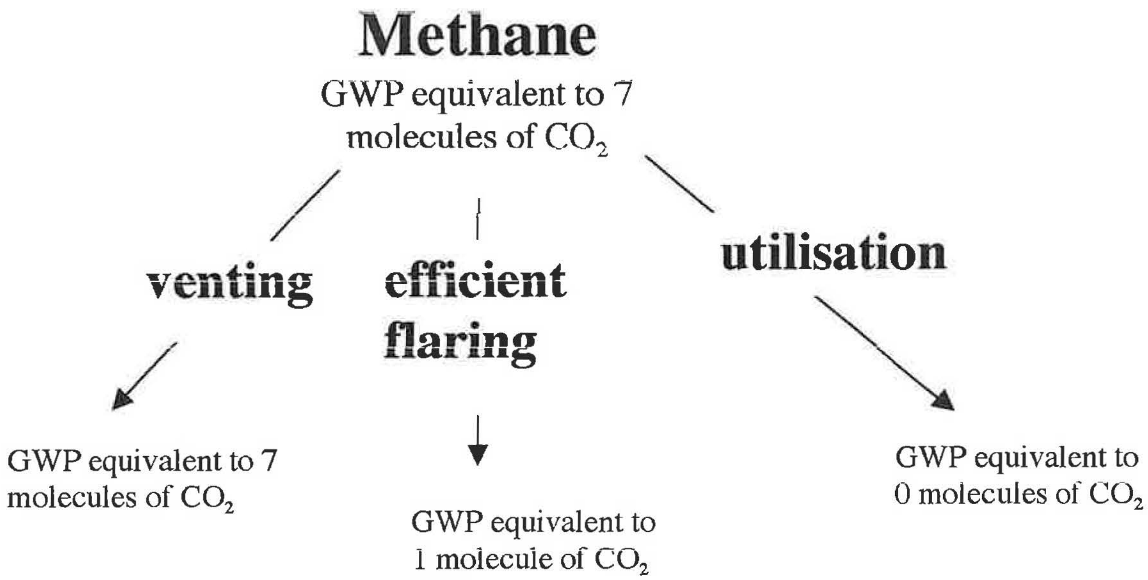
Landfill Gas

Severn Trent through its Biffa subsidiary manages 74 million m^3 of “void space” and takes in a total of 7 million dry tonnes of waste per year at its 33 operational landfill sites. Presently some of the landfill sites are passively vented, while most have some sort of methane collection system for either flaring or power generation. (Biffa, 2002) Below are shown the statistics for Biffa’s methane production, capture, and utilisation:

	Methane in tonnes	% of methane production	Tonnes CO_2 equivalent
Flared	70217	29.6	1474557
Utilised	79053	33.3	1660113
Oxidised	8999	3.8	188979
Vented	79027	33.3	1659567
TOTAL METHANE	237296	100.0	4983216

(Biffa, 2002)

Methane comprises almost 75% of Severn Trent’s GHG emissions (in millions of tonnes CO_2 equivalent). Each molecule of methane that escapes from a landfill is equivalent to 7 molecules of CO_2 as far a global warming potential is concerned. Each molecule of methane that is combusted produces 1 molecule of CO_2. Methane that is combusted to produced energy that would have otherwise been produced by fossil fuels offsets CO production elsewhere, and can be considered “carbon neutral”



Thus any greenhouse gas management strategy for landfill must focus upon:

- Capture of as much methane as possible; burning it to produce carbon dioxide; and claiming carbon credits for the difference in Global Warming Potential between methane and carbon dioxide. Improving the combustion efficiency of the flares ensures the complete combustion of the methane.
- Using the captured methane to produce electricity, and claiming as carbon credits that amount of CO_2 avoided or offset by generating electricity that would otherwise have to be generated by burning fossil fuels elsewhere. These should count as ADDITIONAL credits because:
  - Flaring already converts the methane to CO_2. The electricity produced is a bonus.
  - Electricity production is more expensive than flaring the gas, so the electricity production would only make sense in the context of trying to prevent greenhouse gas production.

So at first glance, it seems that Severn Trent could do very well for itself and generate loads of tradable carbon credits by increasing its methane capture, combustion efficiency and utilisation efficiency.

Unfortunately for this particular scenario, several recent government regulations have changed the situation for Severn Trent.

- Draft legislation requires the use of high temperature, enclosed gas burners. "Open" Bunsen-burner type flares are no longer allowed. Hence, reductions in methane emissions from improvements in burner design have become "business-as-usual" and so do not qualify for carbon credits, (SEPA)
- In addition, Regulation 4 of Schedule 2 of the 2002 Environmental Agency Landfill regulations states that

  (1) appropriate measures must be taken in order to control the accumulation and migration of landfill gas;

  (2) landfill gas must be collected from all landfills receiving biodegradable

> *waste and the landfill gas must be treated and, to the extent possible, used;*
> *(3) the collection, treatment and use of landfill gas under sub-paragraph (2) must be carried on in a manner, which minimises damage to or deterioration of the environment and risk to human health; and*
> *(4) landfill gas which cannot be used to produce energy must be flared.*
> (EA, 2002 guidance_landfill_gas.pdf)

That is, the law REQUIRES that they capture "all" of their landfill gas (or as much as is practicable) and utilise it if possible. Since prior "best practice" has now become "business-as-usual" Severn Trent cannot generate carbon credits by capturing and using methane.

There ARE some steps that Severn-Trent might be able to take to generate carbon credits.

- It is not possible to capture ALL of the gas produced by a landfill. (One study (carbon uk, 2002) suggests that using best practices, landfill managers should be able to capture 85% of the gas produced in a landfill by 2010). Since presently Severn Trent captures about 63% of the gas produced and produces energy from only half of THAT, Severn Trent might ask for clarification from the Environment Agency as to a mandated timeline for achieving the Agency's landfill gas capture and utilisation goals. By exceeding those goals Severn Trent would be able to generate carbon credits.

- Another way out for Severn Trent is to claim (correctly) that the cost of generating electricity from captured landfill gas is greater than present market rates for the electricity so generated ((ST2, 2002), (WM,2001)). Therefore, if they were to go ahead and generate electricity from landfill gas IN SPITE OF the fact that it is not economical to do so, they might be able to generate carbon credits that way.

- Yet another approach is to sell the gas to offsite operators (the gas from their Howley Park landfill is used to fire brick kilns at a local brickworks) and claim carbon credits for the offset CO_2. (www.biffa.co.uk)

All of this is further complicated by the Renewables Obligation, which requires that some percentage of the electricity produced in the UK be from renewable sources (which includes landfill gas). The renewable obligation essentially sets up a *de facto* business-as-usual baseline. In theory, an individual company might only be able to trade carbon credits *after* the aggregate industry-wide target has been achieved. That is, if the target is 4% of energy from renewables and the electricity generation industry is only producing 2% of its energy from renewables, there can be no trading of carbon credits since the carbon credits generated would not be beyond the industry-wide baseline.

However,

> *the government has stated that it will allow individual suppliers who over-comply with their Renewables Obligation to convert that over-compliance into carbon credits for sale into the Emissions Trading Scheme (ETS) (DEFRA 2001 p 38) Note that they may*

> *do this even if suppliers as a whole have not met their targets – i.e. even if the UK has less renewable capacity than required in the Obligation. The baseline for this credit creation is therefore at the supplier level, not the project or UK level.*
> --policyadd.pdf

It is unknown how this would match with the EU trading scheme, and whether that scheme would be willing to grant carbon credits to a UK company when the UK as a whole has not met its own renewables obligation.

The concern is that

> *If the EU rules are more stringent than rules developed earlier for the UK scheme, it is possible that UK projects will not be allowed to sell their credits into the EU scheme. This is because they would threaten the EU requirements for environmental integrity. But if the EU scheme replaces the UK scheme, this means that UK projects will not be able to sell their credits within the UK either. The likely outcome in this instance is that some or all of the anticipated credits from individual UK projects would become invalid when the EU scheme is introduced. Since the EU scheme could be introduced very soon, and well within the crediting lifetime of most projects, this is a critically important issue.—policy add.pdf*

The smartest way to deal with electricity from landfill gas is to ignore the carbon trading scheme entirely and go for Renewable Obligation Certificates, since the value of the ROC's is greater than the expected value of the carbon credits. Waste Management Inc, an American company, estimates that the cost of collecting the landfill gas at 1¢/kWh and the additional cost of generating electricity from landfill gas is about 3¢/kWh (about 2.5p/kWh TOTAL). Renewable Obligation Credits are presently worth at least 4.5p/kWh. Together with the 2p/kWh they can sell the electricity for, Severn Trent can make a tidy profit (see table below).

MWh generated from landfill gas (2002)	391,351
Tonnes CO2 avoided (430 kg/MWh)	168,281
Additional cost to generate electricity (£20/MWh)	£7,827,020
carbon credit value (£20/tonne CO2)	£3,365,619
ROC value including CCL exemption and recycling (£45/MWh)	£17,610,795
Profit from selling electricity	£17,610,795
necessary value of CO2/tonne to make carbon *credits "break even"*	£47
necessary value of CO2/tonne to make carbon credits as profitable ROC's	£151

Since Severn Trent presently flares almost as much methane as they use for electricity generation, they should be able to double their earnings from electricity generation to £34 million/year even without capturing any additional methane. Capturing more methane would be even more profitable.

Methane production can be optimised by reinjecting leachate (fluid dribbling through a landfill and collecting at the bottom) back into the landfill, and adding additional water (or recycling wastewater and sewage sludge) into the landfill. Studies suggest that increasing the moisture content of a landfill can more than double its gas output and more than halve the amount of time that it must be actively managed before it can be returned to other uses. This also adds value to land that might otherwise be made useless. The projected cost of such a move is estimated at £0.5/m^2 (or £5,000/ha). From a carbon management point of view such a move might take landfill whose gas production is marginal and increase it to a point where either the gas is "rich" enough to be flared instead of vented, or to actually be used to generate power. Since present landfill regulations do not require the above steps, Severn Trent may be able to claim carbon credits for the avoided methane emissions

Other steps Severn-Trent might take to decrease their GHG emissions and possibly generate carbon credits include ways to deal with low concentrations of methane in the latter stages of a landfill's life cycle:

- Putting high quality compost on top of their landfills. In some trial studies methane oxidising bacteria in such compost could reduce methane emissions to the atmosphere for the soil underneath by half. (EPA, 2002) This would have the additional benefit of giving them a place to dispose of the greenwaste that they collect.
- Adding biofilters to landfill vents (to do essentially the same thing as the compost above) (WMI)

Landfill issues not involving landfill gas.

At some of its landfill sites Biffa separates waste as it comes into the landfill, and extracts various parts of it for recycling and resale. At most of its sites, however, the waste is simply dumped into the landfill without sorting.

If we assume that they could pull out 6000 tonnes/year of steel and 200 tonnes/year of aluminium from their landfills, and sell the metal for recycling they may be able to claim credits for the avoided CO_2 that would otherwise go into processing virgin materials;

	amount (tonnes)	avoided CO2/tonne	Total avoided CO2 (tonnes)	Tradable carbon credit value (£20/tonne)	Value of recycled scrap/tonne (value + avoided landfill cost)	Total value of recycling
steel	6000	1.4	8400	£168,000	£30	£348,000
aluminium	200	6	1200	£24,000	£410	£106,000
						£454,000

(Data for table calculations taken from IEAgreen (CO2 from steel production), ORNL (energy for Aluminum production), DETR (value of recycled metal))

Another way that Severn Trent might make money is from the Waste Emissions Trading Scheme authorised in the Landfill Directive passed by Parliament in November 2002. The Directive requires that the amount of biodegradable municipal waste going to landfill gradually be reduced to 35% of its 1995 amount by 2020, and establishes a trading scheme similar to the carbon emissions trading scheme but focusing on waste. Diverting organic waste from landfill would allow Severn-Trent to be much more efficient at capturing and using methane from decaying organic material to generate more energy at a lower cost, and might allow it to make money in waste emissions trading. (DEFRA, 2002)

Sewage Waste

Methane is produced as a natural by-product of the anaerobic digestion of municipal sewage treatment, Other means of treating waste do not necessarily produce methane, so Severn Trent Water cannot claim carbon credits for capturing methane that it can essentially choose not to produce.

The issues involving methane use and control are exactly parallel to those that arise in dealing with landfill gas. In 2002 Severn Trent Water exported 26,000 MWh of electricity to the national grid (STW, 2002). The economics are shown in the table below:

MWh generated from sewage biogas (2002)	26,000
Tonnes CO2 avoided (430 kg/MWh)	11,180
carbon credit value (£20/tonne CO2)	£223,600
ROC value including CCL exemption and recycling (£45/MWh)	£1,170,000

Clearly the economics favour using ROC's rather that carbon credits/

Conclusions:
System boundaries, Challenges facing Severn Trent.

Our system boundary comprises
- Direct emissions from burning fuel for transport and construction operations
- Direct emissions of methane from landfill and sewage gas
- Indirect emissions resulting from Severn Trent's use of electricity in its operations

Some of the challenges faced by Severn Trent is that their energy consumption is not entirely within their control. Rather it is "driven by policy decisions affecting what are highly regulated businesses" (Gill Treanor, 2003). Emissions from water services are heavily dependent on water quality standards. Emissions from sewage treatment are directly affected by government regulations about the quality and disposal of sewage sludge. They have no control over the relatively low landfill tax rate (currently about £13/tonne) and so have little leverage to move consumers and industry to reduce waste production

Indeed, waste production and water consumption are increasing at a rate of approximately 3% per year (ST2, 2002). Although Severn Trent's subsidiary businesses are actively engaged in measures to reduce consumption and to increase efficiency, at the end of the day they can neither turn off the taps to their customers nor leave waste rotting on the pavement.

Growth is another issue for carbon management for Severn-Trent. For example, their recent purchase of UK waste greatly increased the number of landfills they operate. Methane release from their landfills increased by 40% overall in spite of an improvement in the percentage of methane captured. (Biffa)

Assumptions used:

In analysing the data, we have as much as possible used data directly from Severn Trent's annual reports and publicly available information. Our approach has been:
- Water—Look at Severn Trent Water's actual production and consumption figures, literature data for energy consumption in pumping and transporting water, and some assumptions about pump output.

- Waste—Look at Biffa and Severn Trent Water's actual methane production figures, literature data for the cost of producing landfill gas and the value of Renewable Obligation Certificates
- Transport—Look at Severn Trent's actual number of vehicles and miles travelled, then assuming industry-wide "business as usual" practices and examining savings possible by moving to best practices
- Systems and Services—Start with the number of employees Severn Trent has, then looking at industry wide space/energy consumption per person on a "business as usual" basis (using Web-based calculators) and examining savings possible by moving to best practices

Suggested cost effective initiatives

- Increase the capture and utilisation of landfill gas and increase the number of anaerobic digestion gas-to-electricity plants at the sewage works.
- Increase the diversion of material from landfill (this is required by law anyway) And sort and recycle (and sell!) material coming to landfill
- Improve the aerodynamics of the truck fleet. The payback time for these improvements was less than a year.
- Change to variable-frequency water pumps for water distribution.
- Distribution of water-saving kits to customers—payback time of less than a year
- Improve lighting and convert computers to flat-screen monitors

Critique of this form of carbon management:

All of the carbon savings suggested are real, in that ultimately they reduce the amount of greenhouse gases being emitted to the atmosphere. The "embodied" energy in new light bulbs, flat screen monitors, aerofoils for trucks, etc. is ultimately less than the amount of energy (and corresponding reduction in greenhouse gas emissions) in the long run.

The emissions reductions we propose can all be monitored in that landfill and sewage emissions are already monitored, as is electricity and fuel consumption. Sales of recycled materials from landfill are also recorded. Water use is recorded. All of our proposed reductions are reflected in quantities that the company already records or can be easily deduced from them,

It is quite possible that Severn-Trent and its subsidiaries are already doing better than the "business-as-usual" assumptions that we have made. Without a detailed knowledge of their actual office technology, transport vehicles, water pumping equipment, and waste disposal trucks it is impossible to do more than make educated guesses and suggestions as to what reductions are possible. Our numbers are really guides to steps to investigate further, rather than any sort of ultimate solution.

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