Towards a Sustainable Energy Future

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Abstract

Energy use, and its impact on the environment, is one of the most important technical, social, and public-policy issues that face mankind today. Our overwhelming reliance on fossil fuels to provide most of our energy requirements has resulted in ever-increasing levels of global CO2 concentrations, leading to increased global temperatures. In this presentation a systems approach to energy use is introduced in which the complete energy conversion chain is used to link primary energy resources through to the ultimate end-use. Using this simple analysis the complete consequences of choosing a particular energy source, or energy conversion system, can be seen. An overview of global energy demand and supply is then presented, followed by a discussion of the challenges of meeting future energy demand from the three primary sources of energy; fossil fuels, renewable energy, and nuclear power. The difficult problems of developing a more sustainable transportation energy system are addressed in some detail, including a comparison of possible energy carriers for the automobile of the future. Finally, some projections are made about how a sustainable global energy balance might be achieved over the remainder of this century.

Introduction

The debate about whether or not climate change is real has gone on too long and the time has come to develop practical solutions. Governments in many countries have now established targets for reduction of greenhouse gases, and some jurisdictions have introduced carbon taxes or cap-and-trade schemes to limit emissions of carbon dioxide into the atmosphere. There has been very little discussion, however, of plans and policies which show how these targets might actually be achieved. In the broadest terms there are only three ways to reduce our over-reliance on fossil fuels in order to combat climate change. Simply put, these are; choosing to use less energy, using energy more efficiently, and switching from fossil fuels to other primary sources of energy. The first of these approaches is reliant on individual action rather than on any new technology, while the remaining two responses require a more technological approach. Choosing to use less energy just means that each one of us can reduce our contribution to climate change by changing our lifestyle through activities such as walking or cycling rather than driving, or by turning down the heating and cooling systems in our houses and offices.

The second approach to reducing fossil fuel consumption, and therefore reducing our carbon dioxide emissions, will rely on a dedicated effort to increase energy efficiency. This will reduce the demand for energy in industrial processes, in consumer products such as cars and appliances, and in the heating and cooling systems for commercial and residential buildings. Although the energy efficiency of buildings and industrial processes has been increasing over many years, there is still a long way to go before we can say that we are not needlessly “wasting” energy and producing more greenhouse gas emissions than we need to. Increasing energy efficiency is often seen as the “low-hanging fruit” in plans to reduce fossil fuel consumption, and can often result in significant economic benefits to industry and consumers alike. There is not usually any new technology required to aggressively pursue energy efficiency, as most techniques, such as increasing building insulation, replacing single-glazed windows with new double-glazed units, or replacing old furnaces with new high-efficiency condensing furnaces are already well established. There are often financial barriers, however, since in most cases there is a considerable "up-front" capital cost, while the savings accrue over time from the reduced cost of energy.

The third option to combat climate change relies primarily on new technology aimed at "fuel-switching" away from fossil fuels, which now supply 80% of global energy needs, to more sustainable primary energy sources, such as renewable energy and nuclear power. One promising way to reduce the emission of greenhouse gases from automobiles is to switch to the use of electricity as the main energy carrier rather than using gasoline or diesel fuel. The next step in the evolution of hybrid vehicles will see the introduction of "plug-in hybrids" with an increased battery capacity and the ability to re-charge the battery from an electrical outlet overnight, or when the vehicle is not in use. Studies have shown that this approach can reduce carbon dioxide emissions by more than 50% if the electricity used to charge the vehicle overnight has been generated using fossil fuels. If the electricity is generated primarily from renewable sources, then a dramatic reduction in greenhouse gas emissions of some 85% can be achieved. This paper focuses on the strategy of "fuel-switching" by outlining some of the opportunities for switching from liquid fossil fuels to electricity as the transportation energy carrier of choice. Widespread adoption of this strategy will usher in a new "electricity economy", in which electricity is increasingly used as a substitute for fossil fuels. A systems approach to energy use is introduced in which the complete energy conversion chain is used to link primary energy resources through to the ultimate end-use. Using this simple analysis the complete consequences of choosing a particular energy source, or energy carrier, can be easily seen. The difficult problems of developing a more sustainable transportation energy system are addressed in some detail, including a comparison of possible energy carriers for the automobile of the future. Finally, some projections are made about how a sustainable global energy balance might be achieved over the remainder of this century.

Energy Conversion Chain Analysis

There is a great deal of discussion in the popular press about energy issues, some of which paint a very pessimistic picture for future generations, while others point to a bright future through the use of sustainable energy technologies. Unfortunately, many proposals to change the way in which we use energy take only a partial view of the consequences of doing so, without regard to the overall efficiency of primary energy use, the effects on the environment, or the costs to society as a whole. As engineers, however, we know that a systems approach is essential for developing a clear understanding of such complex technical, economic, and environmental issues. Every time we use energy, we need to be aware of the impacts of such use, all the way from the primary energy source through to the final end-use. When we use energy, whether it's to heat our home, or fuel our car, we are converting one form of energy into another, or into useful work. To heat our buildings, for example, the chemical energy in natural gas or fuel oil is converted into heat by the furnace. And, when we drive our car, the engine converts the chemical energy in the gasoline into mechanical work. These are just two examples of the 'energy conversion chain' which is always at work when we use energy in our homes, offices, and factories, or on the road. In each case we can analyze the complete process which tracks a source of primary energy and its conversion into the final end-use form. In this paper we will use energy conversion chain analysis to examine energy use in the road transportation sector.

A schematic of the complete energy conversion chain described by Evans [1] is shown in Figure 1. The chain starts with just three 'primary' energy sources, and ends with only a few end-use applications such as building heating and cooling, transportation, and industrial processes. In between the primary source and the ultimate end-use are a number of steps in which the primary source is converted into an energy ‘carrier’, or is stored for use at a later time. To take a familiar example, in order to drive our car, we use a fossil fuel, crude oil, as the primary energy source. The crude oil is first converted in a refinery into gasoline, the energy carrier for this case, with some loss of energy availability, as indicated by the branched arrow joining the processing block to the energy carrier block in Figure 1. The gasoline is then stored in a fuel tank, ready for use by the engine in the final end-use conversion step, again with losses of energy availability as indicated by the branched arrow. This is, of course, just one example, but any use of energy can always be tracked through the complete energy conversion chain in this way. One important lesson to be taken from Figure 1 is that there are only 3 primary sources of energy; fossil fuels, nuclear energy, and renewable energy, and only 3 energy carriers that are of significance today; refined petroleum products, natural gas, and electricity. Hydrogen, often billed erroneously in the popular press as an energy source of the future, is just a potential energy carrier.

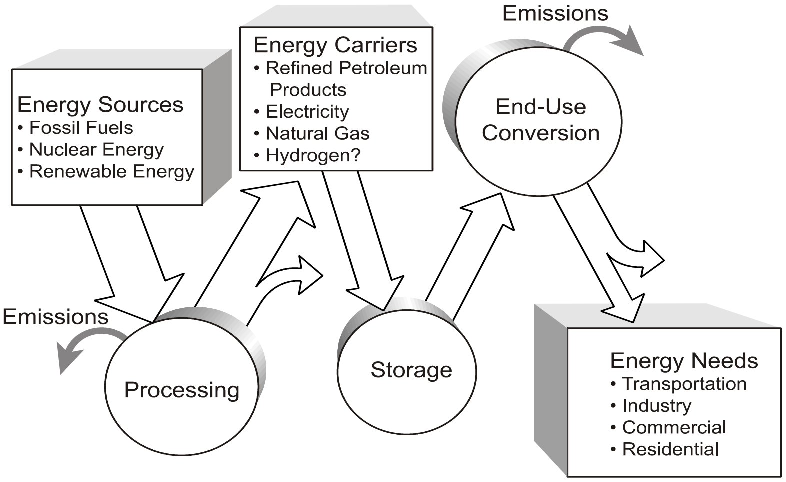


Figure 1 The Complete Energy Conversion Chain

The benefit of using the complete energy conversion chain as an analysis tool can best be seen in an example. And, since transportation accounts for just over a quarter of the global demand for energy, it provides an ideal example of the type of analysis which can be done. Liquid petroleum fuels are ideally suited to transportation applications because of their inherently high energy density, and ease of transportation and storage. The problem with using fossil fuels, of course, is that they are a non-renewable resource and result in large quantities of CO_2, the principal greenhouse gas. The search is continuing, therefore, to find alternative energy sources for transportation, so that the very large contribution to greenhouse emissions from this sector can be minimized. Proponents of the 'hydrogen economy' claim that the use of hydrogen as a transportation fuel would eliminate the production of any harmful exhaust emissions from vehicles on the road. This is true for the vehicle itself, but if we consider the complete energy conversion chain, hydrogen is just an energy carrier, and would need to be 'manufactured' from one of the three primary energy sources. If produced from hydrocarbons, such as natural gas or coal, all of the carbon in the primary energy source would still end up as CO_2 at the point of hydrogen production. If, on the other hand, the hydrogen was produced from a more sustainable primary energy source, such as renewable energy or nuclear power, then there would indeed be no production of greenhouse gases. The energy conversion chain for this case, from primary energy source to end-use, is illustrated by the schematic shown in Figure 2.

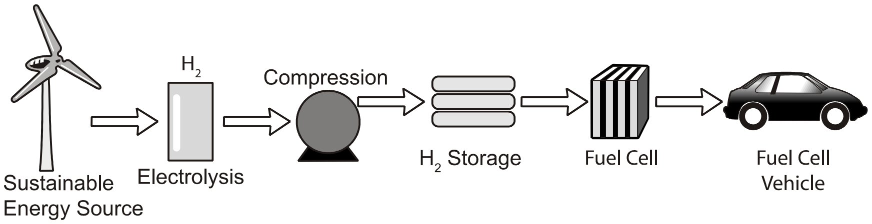


Figure 2 Energy Conversion Chain for a Fuel Cell Vehicle

The first step in the chain is the generation of electricity as an initial energy carrier. The electricity would use electrolysis of water to produce hydrogen, which would then be compressed, or converted into liquid form, for storage on board the vehicle. An all-electric drive would power the vehicle, with a fuel cell generating electricity on-demand from the hydrogen. In this case the first energy carrier, electricity, is converted into hydrogen as a secondary carrier, and stored on-board the vehicle. In other words, there is a “double conversion” into energy carriers, first from electricity into hydrogen, and then from hydrogen back into electricity again by the fuel-cell. A battery electric vehicle takes a much simpler approach, with a battery used on-board the vehicle to store the electricity directly. The two approaches can be summarized by comparing the partial energy conversion chains shown in Figure 3. This shows the two different approaches, starting from the point at which the primary energy source produces electricity, and ending where electricity is again used to power the vehicle’s electric traction motor. It can be seen that the equipment required for the fuel cell vehicle, including hydrogen production and storage, as well as the fuel cell, is really just an electrical energy storage device. The advantage of this approach over that of using a simple electrical storage battery, however, is the fact that the energy storage capacity on-board the vehicle can be much greater using hydrogen.

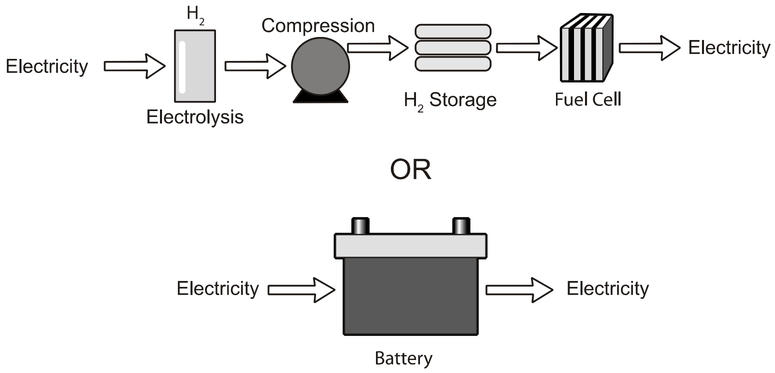


Figure 3 Alternative Electrical Energy Storage Concepts

Although strictly speaking not all of the process steps shown in Figure 3 are energy conversion processes, there is a loss of available energy associated with each step in the chain. To account for these energy losses we may assign an “in-out” efficiency value to each step in the two equivalent conversion chains.

The efficiency for each of the steps for the complete hydrogen “electricity storage” process is then shown on the left-hand side of Table 1. For example, electrolysis of water has an efficiency of nearly 75%, while compressing hydrogen to a pressure suitable for the storage cylinders has an efficiency of about 92%. The efficiencies of each individual step are then multiplied together to get the final “overall efficiency” of the complete process, going from electricity “in” from the primary source to electricity “out” to the traction motor. With an assumed fuel cell efficiency of 50%, the overall “in-out efficiency” for the hydrogen energy conversion chain is approximately 34%. For the battery, there is only one step between the input to the energy storage and output to the vehicle, as shown on the right-hand side of Table 1, and since about 10% of the input energy is normally lost in the form of heat during the battery charging process, we can assign an “in-out efficiency” of 90% to the battery. This simple analysis indicates that if a battery with sufficient energy storage capacity to provide a reasonable vehicle range were available, then battery electric vehicles would be a very attractive option.

Table 1 Electricity Storage “In-Out” Efficiencies

Efficiency Comparison of Equivalent Energy Storage Schemes			
Hydrogen and Fuel Cell		**Battery**	
Electrolysis	75%	Battery	90%
Compression	92%	—	—
Fuel Cell	50%	—	—
Overall Efficiency	***34%***	Overall Efficiency	***90%***

Unfortunately, batteries are not yet able to compete with liquid fuels in terms of either energy density or specific energy, and pure battery electric vehicles will likely be suitable only in specialized short range applications for the foreseeable future. Much of the recent development work on batteries has been driven by the successful introduction in the last few years of hybrid electric vehicles. Hybrid vehicles have been very successfully introduced into the market, initially in compact cars, but the technology is now spreading to larger cars and sport utility vehicles where the benefit of much greater fuel economy is particularly welcome. The current design of hybrid vehicles may be classed as “stand-alone” or “grid-independent” hybrids, because although they incorporate an electrical powertrain, and storage battery, they obtain all of their primary energy from the fuel carried on-board the vehicle, and do not need to be plugged into the electrical grid to re-charge the battery. However, with the expected advances in battery energy density, and the desire to minimize the use of fossil fuels, these vehicles have set the stage for a transition to the next generation of vehicles, the so-called “grid-connected” hybrids, sometimes also referred to as “plug-in hybrids”. A simple schematic of this concept, which incorporates the advantages of both battery electric vehicles and hybrid vehicles, is shown in Figure 4. In this concept, the battery pack in an otherwise conventional hybrid vehicle would be much larger, and could be fully charged when not in use by being plugged into the electrical grid. The engine, however, would be smaller, and would still operate on some form of liquid fuel. In this way, the vehicle could operate for a significant range, perhaps somewhere between 50 and 100 kms, as a completely electric vehicle, and would use the engine to re-charge the battery only when it was necessary to exceed this distance or perhaps when climbing steep hills. For commuters the vehicle would then be capable of operating as a pure battery electric vehicle for most trips. Recent studies have shown that a plug-in hybrid vehicle with a 90km range could provide up to an 85% reduction in CO_2 emissions for many drivers.

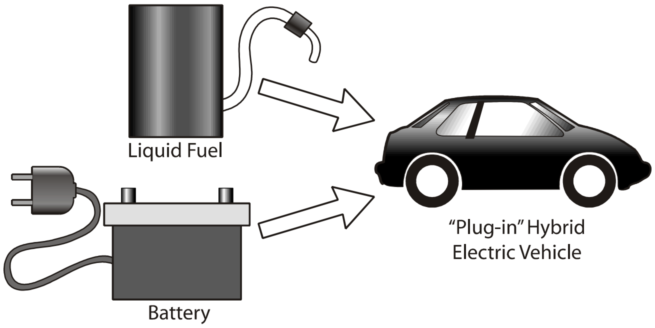
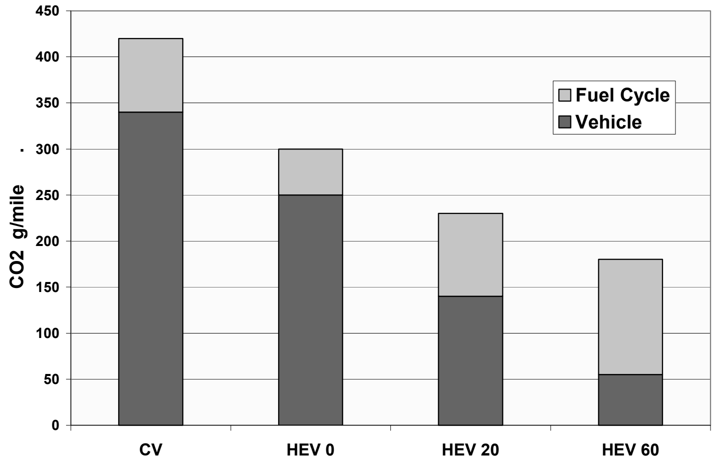


Figure 4 The "Plug-in Hybrid" Electric Vehicle

Of course once significant numbers of these vehicles enter the market, shifting much of the transportation energy requirements from petroleum to electricity, there would need to be a significant expansion of electrical generation capacity. If the electricity used to charge the battery is generated primarily by sustainable primary energy sources, such as renewable energy or nuclear power, then road transportation would no longer be a significant factor in contributing to greenhouse gas production. A benefit to utilities of such a shift, however, would be an improvement in the load factor by spreading the electrical load more evenly during the day. With many commuters plugging their cars in for recharging overnight, the increased electrical load, which is normally low at these times, would ensure that electrical generation capacity is better utilized. This "load-levelling" could provide a significant improvement to utility load factors, with the result being a reduction in electricity generation costs. The successful development and introduction into the marketplace of the "grid-connected" or "plug-in" hybrid vehicle would mark the beginning of a significant new transportation paradigm, eliminating the need for road vehicles to use hydrocarbon fuels, at least for the majority of miles travelled.

The Electric Power Research Institute [2] conducted a study comparing the performance of a stand-alone hybrid electric vehicle and a plug-in hybrid electric vehicle to a conventional vehicle powered by a gasoline engine. The four different configurations were referred to as a conventional vehicle (CV), a hybrid electric vehicle with no all-electric range (HEV 0), and two plug-in hybrid vehicles, one with an all-electric range of 20 miles (HEV 20), and one with an all-electric range of 60 miles (HEV 60). All of the HEV's were assumed to use nickel-metal hydride (NiMH) batteries and regenerative braking, and to have similar performance, including a minimum top speed of 90 mph and a 0-60 mph acceleration time of less than 9.5 seconds. All vehicles were assumed to have sufficient gasoline storage to provide a range of 350 miles. In considering the overall energy consumption of the vehicles the study examined the complete energy conversion chain, and included the energy obtained from the gasoline on-board the vehicle and the energy required to process the crude oil to produce the gasoline, as well as the electrical energy required to re-charge the batteries for both of the plug-in hybrid vehicles, the HEV 20 and the HEV 60. The energy required to produce the gasoline, and the primary energy required to produce the electricity required for recharging the two plug-in hybrids was referred to as the "fuel cycle" energy. For the battery re-charging part of the process, the study assumed that electricity would be generated from natural gas using a combined cycle power plant, with an overall thermal efficiency of approximately 50%. The main results of the study are summarized in Figure 5, showing the CO2 emissions per mile travelled, assuming a real-world driving schedule.



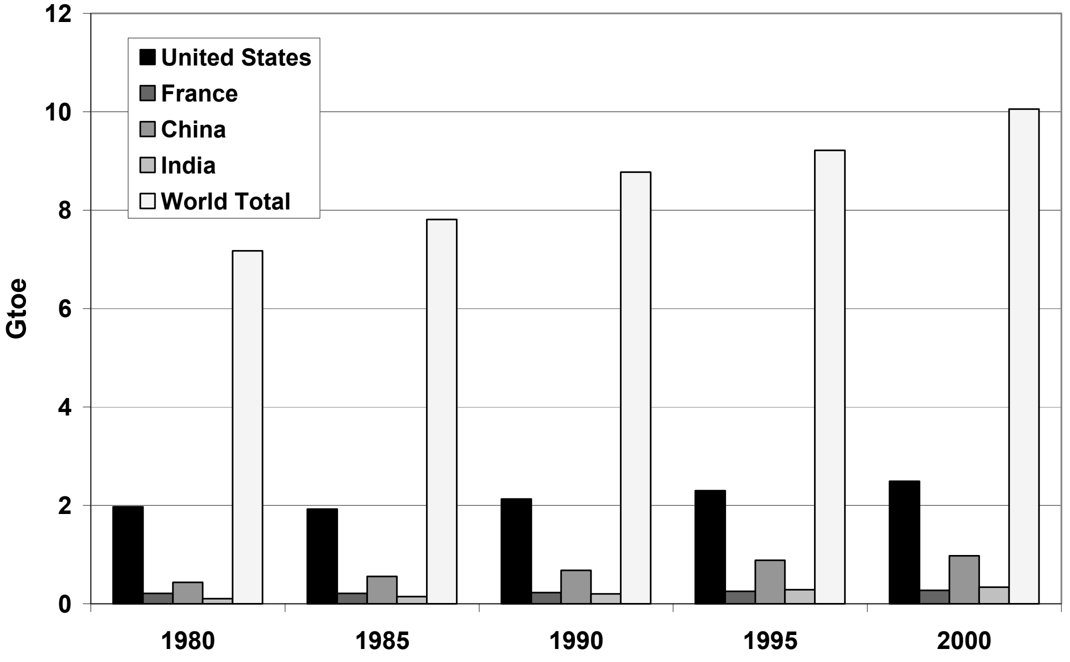
Source: EPRI

Figure 5 CO_2 Emissions from EPRI Study

The total CO_2 emissions shown in Figure 5 provide a measure of the overall energy conversion chain efficiency of the vehicle and fuelling system, as well as the overall contribution to greenhouse gas emissions. For the CV the total CO_2 emitted per mile driven includes the energy used in processing the crude oil into gasoline, as well as the gasoline used by the vehicle's engine. This is the same situation for the stand-alone hybrid vehicle, HEV 0, since only gasoline is used, and the fuel-cycle energy represents the same proportion of total energy used as in the CV. However, because of the much higher efficiency of the HEV 0 compared to the CV, the total emissions are reduced by nearly 30%. By moving to the HEV 20 vehicle, the total CO_2 emissions are now just over half those of the CV, while for the HEV 60 they are reduced by nearly 60%. However, it can be seen that in this case 70% of the total emissions are derived from the production of electricity, which is assumed to use natural gas as the primary energy source. These results point to the importance of moving to a plug-in hybrid vehicle strategy in conjunction with a sustainable electrical energy supply system. If, for example, the was generated from some combination of renewable energy and nuclear power, then the only CO_2 emissions would be those due to the on-board consumption of gasoline, and a small amount for fuel processing, so that the total CO_2 emissions for the HEV 60 would be about 65 g/mile. This would then mean that by moving from a vehicle fleet of all conventional vehicles, to one with all HEV 60 vehicles, together with a zero-emission electricity system, CO_2 emissions would be reduced by some 85%, from 420 g/mile to 65 g/mile. The widespread use of plug-in hybrid vehicles, therefore, together with a move to a zero CO_2 emission electricity grid, would go a long way towards eliminating the greenhouse gas contribution from motor vehicles.

Global Energy Supply and Demand

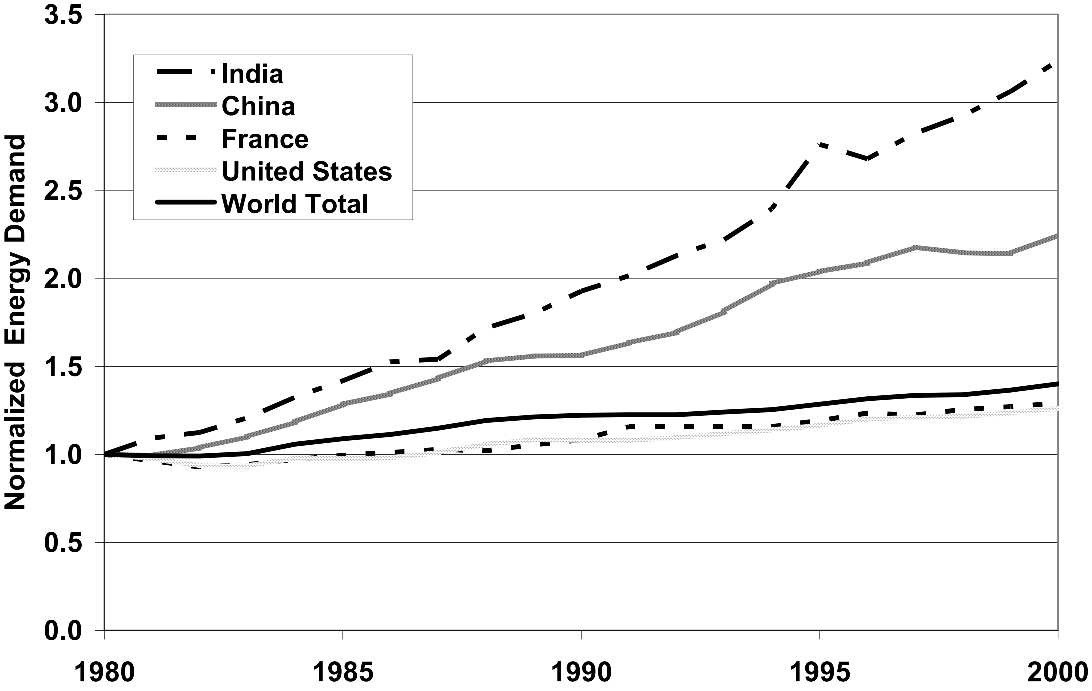
Worldwide demand for energy has been steadily increasing over time, certainly since the beginnings of the industrial revolution in the 18th century. The evolution of this increase in demand is shown for the 20 years between 1980 and 2000 in Figure 6 for the world as a whole, and for a few selected countries. The global consumption of all primary energy forms in 2000 was just over10 Gtoe (gigatonnes, or billions of tonnes, of oil equivalent), with the United States accounting for some 25% of the total worldwide demand. The growth in worldwide energy demand for this short period has been some 40%, as can be seen in Figure 6, although the growth rates in some individual countries have been much higher. Although the total demand for energy in absolute terms from China and India, for example, has been much less than that of the US, the growth rate in demand over this period has been very high.



Data: US DOE Energy Information Agency

Figure 6 Growth in Total Energy Demand – 1980-2000 (Gtoe)

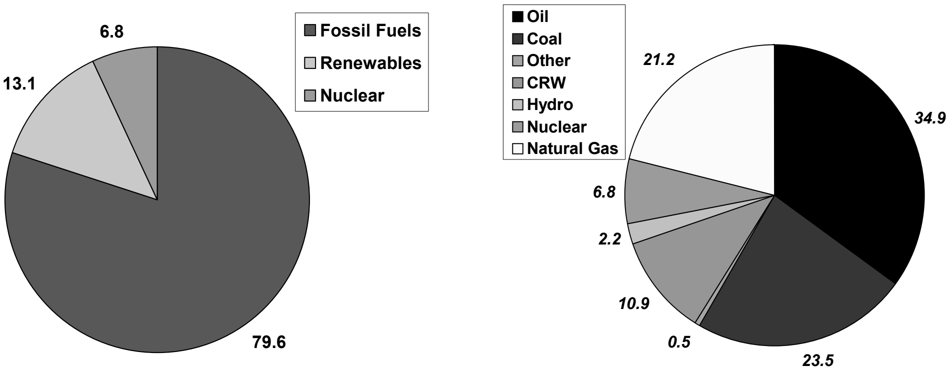
The normalized growth in demand (with demand in 1980 set to 1.0) for the same countries over this 20 year period can be seen in Figure 7, compared to the world total growth in demand. It can be seen that the major industrialized countries, such as the United States and France, have been fairly modest during this period, but those of the two largest 'developing' countries, China and India have been very much higher. The average annual compound growth rate over this 20 year period has been 1.2% in the US, and 1.75% for the world overall, but in China it has been 4.1% and in India 6.0%. These very large growth rates for the large, rapidly growing, emerging economies will put enormous pressures on worldwide energy resources in the years to come. If the 6% growth rate were to be sustained in India, for example, the total demand for energy would double every 12 years. If these rates were to continue until the middle of the century, China would overtake the US as the largest energy consumer by the year 2030, and India would similarly overtake the US by 2043. High energy demand growth rates will also put increasing strain on the global environment, unless action is taken to significantly change energy end-use patterns and the way we use our primary energy resources.



Data: US DOE Energy Information Agency

Figure 7 Normalized Total Energy Demand – 1980-2000 (1980 =1)

The percentage of total world demand for energy in 2002 supplied by each of the 3 primary energy sources; fossil fuels, renewable energy, and nuclear power, is shown in Figure 8. It can be seen in Figure 8a that nearly 80% of all of our primary energy needs are supplied from fossil fuels. The distribution of energy supply by source is further broken down in Figure 8b, which shows the largest fossil fuel component of the overall global supply to be oil, followed by natural gas and finally coal. In the renewable energy category by far the largest component is for combustible renewables and waste, which includes wood-waste and ‘black liquor’ used to fuel boilers in the pulp and paper industry, for example, as well as other combustible bio-fuels such as firewood gathered by hand in developing countries. The remainder of the renewable energy supplied in 2002 consisted of hydroelectric power, accounting for 2.2% of global demand, while only about 0.5% of total energy demand (shown as ‘other’ in Figure 8b) was supplied from wind, solar and geothermal power. These figures illustrate the overwhelming reliance that the world places on fossil fuels to satisfy our energy needs. Although crude oil is the largest source of energy, and is used primarily to provide fuel for transportation, we also consume large quantities of natural gas and coal, mainly to provide space heating and to generate electricity.



8a

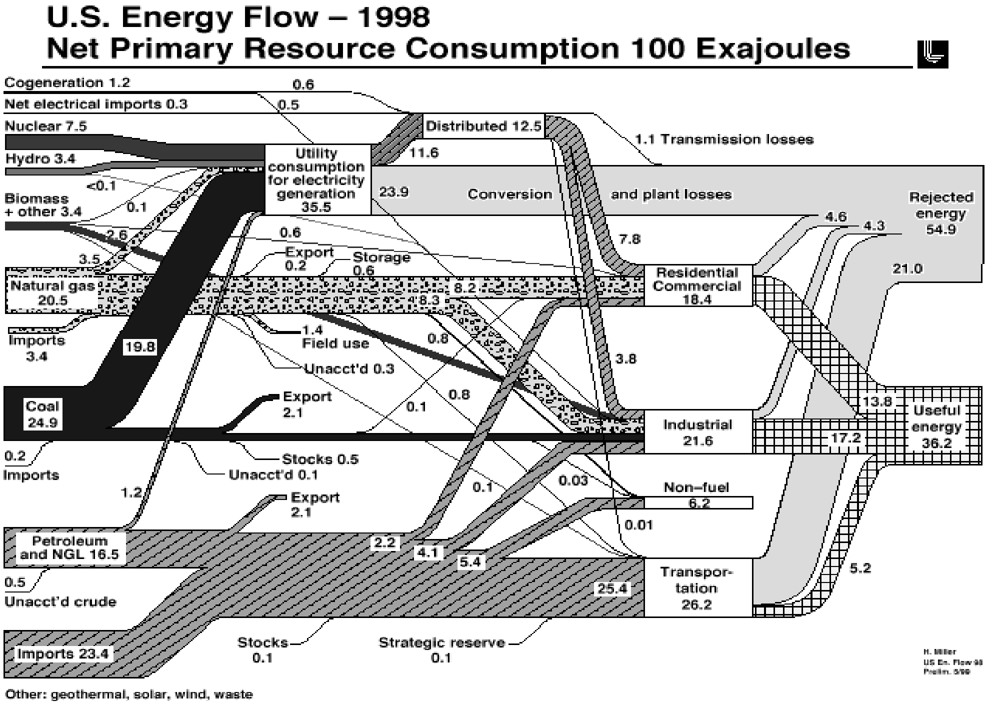
8b

Source: IEA

Figure 8 World Primary Energy Consumption by Source – 2002
CRW = Combustible Renewables & Waste
Other – Geothermal, Solar, Wind,etc.

The overall energy demand-supply balance for any region or country may be summarized very succinctly by a “Sankey” diagram, which is just a more detailed version of the energy conversion chain diagram shown in Figure 1. Figure 9, which has been prepared by the Lawrence Livermore Laboratory of the U.S. Department of Energy, shows the energy flows for the complete U.S. economy in 1998. This particular year is very useful because the total amount of primary energy consumed, including that consumed for non-energy uses, such as the petroleum used for chemical feedstock and asphalt production, just happens to total 100 EJ (Exajoules, or 10^{18} joules). This then makes it very easy to determine the percentage flows of energy directed to various end-uses, as well as to waste heat or “rejected energy”. For example, the diagram clearly shows the various flows of primary energy being used to generate electricity, with the largest source being coal, accounting for 19.8 EJ, followed by 7.5 EJ of primary energy input in the form of nuclear energy, 3.5 EJ from natural gas, and 3.4 EJ from hydro power. However, of the total of 35.5 EJ used for electricity generation, only 12.5 EJ ends up as electricity, while 23.9 EJ ends up as rejected energy, primarily in the form of waste heat from thermal power stations.

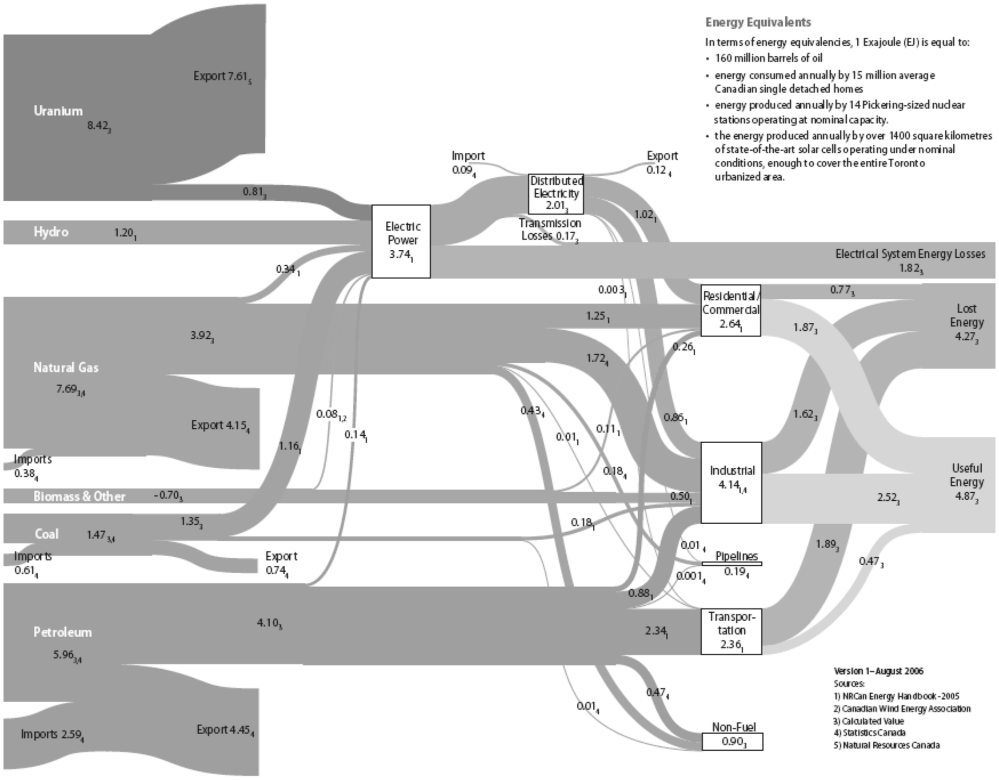
Similarly, it can be seen that in the transportation sector, which relies primarily on petroleum as a source for the 26.2 EJ of primary energy used, just under 20% or some 5.2 EJ, is turned into “useful energy” to propel all the cars, trucks, ships and aeroplanes. In total, then, of the 100 EJ of all forms of primary energy used in the U.S. in 1998, only 36.2 EJ was “useful energy” to provide heat and power to homes, factories and automobiles, while some 54.9 EJ was “rejected energy”, or unavailable energy, which was primarily in the form of waste heat.



Source: *U.S. DOE*

Figure 9 Energy Flow Diagram for the U.S. – 1998

A similar Sankey diagram for the complete Canadian economy, prepared by Natural Resources Canada for the year 2003, is shown in Figure 10. The total domestic consumption of primary energy totals 10.96 exajoules, corresponding to approximately 10% of U.S. consumption, as expected from the relative size of the two economies. The percentage of total energy represented as “lost energy” is 56%, which is nearly exactly the same as for the U.S. The striking difference between this figure for Canada and the one for the U.S., however, is the very large flow of energy exports from Canada in the form oil, natural gas and uranium.



Energy Equivalents

In terms of energy equivalencies, 1 Exajoule (EJ) is equal to:

- 160 million barrels of oil
- energy consumed annually by 15 million average Canadian single detached homes
- energy produced annually by 14 Pickering-sized nuclear stations operating at nominal capacity.
- the energy produced annually by over 1400 square kilometres of state-of-the-art solar cells operating under nominal conditions, enough to cover the entire Toronto urbanized area.

Version 1–August 2006
Sources:
1) NRCan Energy Handbook -2005
2) Canadian Wind Energy Association
3) Calculated Value
4) Statistics Canada
5) Natural Resources Canada

Source: *NRCan*

Figure 10 Energy Flow Diagram for Canada – 2003

Primary Energy Sources for the Future

Fuel-switching between primary energy sources, as illustrated above, can lead to a much more sustainable energy future. However, the continuing growth in global energy consumption, particularly in rapidly developing economies, will provide major challenges to achieving sustainability. Many organizations, such as the International Energy Agency (IEA), have suggested that total energy consumption at the end of this century will be nearly two and a half times the level at the beginning of the century. If most passenger cars end up as plug-in hybrid vehicles the energy carrier of choice will be electricity, rather than gasoline and diesel fuel. This shift in use of energy carrier would require a very large increase in electricity generation capacity, ushering in an "Electricity Economy", rather than an "Oil Economy". The choice of primary energy sources to generate this electricity will be the key to achieving sustainability. It is difficult, of course, to predict how the balance between the three primary energy sources of fossil fuels, renewable energy, and nuclear power, will change, but two possible scenarios are shown in Figures 11 and 12. Both these figures assume that the consumption of primary energy resources by the end of the century will grow to a total of about 25 Gtoe (gigatonnes of oil equivalent) from the total of some 10 Gtoe in the year 2000, in line with projections from the IEA. In the "Clean Coal Scenario" illustrated in Figure 11, for example, the assumption is made that carbon capture and storage will be well advanced, and suitable repositories will be found for the nearly 7 billion tonnes of CO_2 that mankind generates each year from burning fossil fuels. Under this scenario there would be a very large expansion in the electricity infrastructure, with most of the new generation coming from cleaner coal technologies, such as integrated gasification combined cycle powerplants. These would have a much higher thermal efficiency than conventional coal-fired plants, and would make it much easier to separate CO_2 from the combustion products, ready for sequestration in underground repositories.

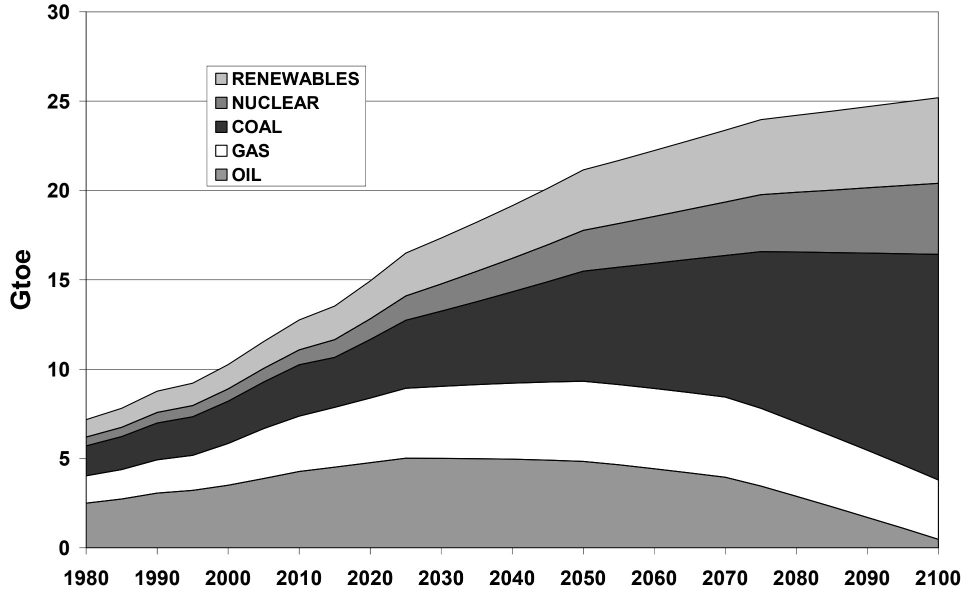


Figure 11 World Primary Energy Supply – Clean Coal Scenario

In the “Nuclear and Renewable Energy” scenario illustrated in Figure 12, much of the growth in primary energy consumption would be supplied from renewable and nuclear energy sources. Again, most of this energy would be converted into electricity as the main energy carrier, but in this case there would be very little additional production of CO_2 so that the need for carbon sequestration would be greatly reduced. This scenario provides its own unique set of challenges, however, since the low energy density of most renewable energy sources means that a great deal of land needs to be devoted to energy production, while the public acceptance of nuclear power is still very much in question in many jurisdictions. These two scenarios are, of course, pure speculation, and the actual split between the three primary energy sources will likely be some combination of both scenarios.

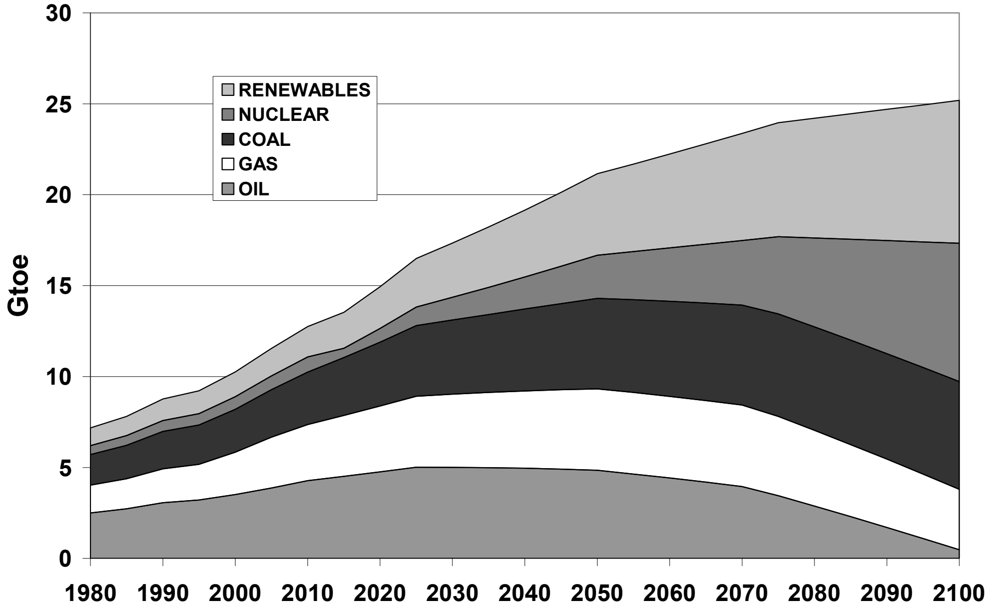


Figure 12 World Primary Energy Supply – Nuclear & Renewable Energy Scenario

Conclusions

There are only 3 sources of primary energy, and just 3 ways to curb our use of fossil fuels in order to reduce greenhouse gas emissions. We can cut back on fossil fuel use by reducing our overall energy demand and increasing energy efficiency, or by “fuel-switching” from fossil fuels to one of the other two primary energy sources, renewable energy and nuclear power. In this paper the complete energy conversion chain has been shown to be an important tool for analyzing energy use. This concept has been used to compare the overall energy utilization efficiency of two different proposals for sustainable road transportation. The results have shown that the use of electricity directly as an energy carrier to power a vehicle is nearly three times more efficient than using electricity to generate a secondary carrier, hydrogen, which is stored onboard the vehicle and converted back to electricity using a fuel cell. The successful development and introduction into the marketplace of the “grid-connected” or “plug-in” hybrid vehicle would mark the beginning of a significant new transportation paradigm, eliminating the need for road vehicles to use hydrocarbon fuels, at least for the majority of miles travelled. If electricity were to be generated primarily from sustainable primary energy sources, then road transportation would also become sustainable resulting in an “Electricity Economy”, rather than a “Hydrogen Economy”. Finally, even with widespread “fuel-switching”, estimates of future energy consumption show that we will likely continue to rely heavily on fossil fuels to the end of the century, even as we move to greater use of renewable energy and nuclear power.

References

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[2] EPRI (2001). *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options.* Electric Power Research Institute, Report 1000349, Palo Alto, CA.