# Ten Steps to a Sustainable Energy Future

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## Introduction

As an economist focusing on energy and environment, I would like to give you some indications, what shape a sustainable energy future could have in the next coming years, why the future I project is a sound economic choice and what extraordinary challenges are ahead. The roles of hydrogen, oil, gas, coal and nuclear are reflected as these are the favorite choices of transnational companies and electricity monopolies.

## The Depletion of Fossil Fuels

It took 150 years to develop the fossil fuel society we are in. In a little over a century, petroleum has grown into the most widely traded commodity in the world – some say, a narcotic – and into one of the prime drivers of violent conflicts. With the election of President George W. Bush, the petroleum system seems to have reached its summit from which a decline is inevitable, and this new direction indeed has already begun.

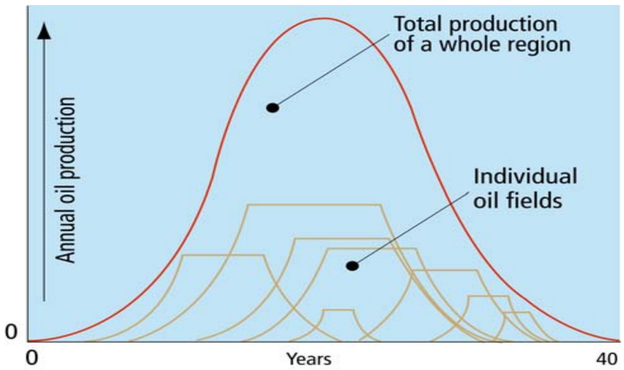


Figure 1    Hubbert curve [1]

Many theories have been spawned regarding petroleum in the ground and its practical availability above ground. The most successful one came from the US oil geologist Marion King Hubbert, who in 1956 predicted that US oil production would peak in 1970 and decline thereafter. The "Hubbert Curve" illustrated above demonstrates empirical experience based on geology and statistics: The practical availability of a region's oil reserves over time describes a bell-shaped curve, similar to the Gaussian (Normal) Curve. Large fields are discovered first, small ones later. After exploration and initial growth in output, production plateaus and eventually declines to zero.

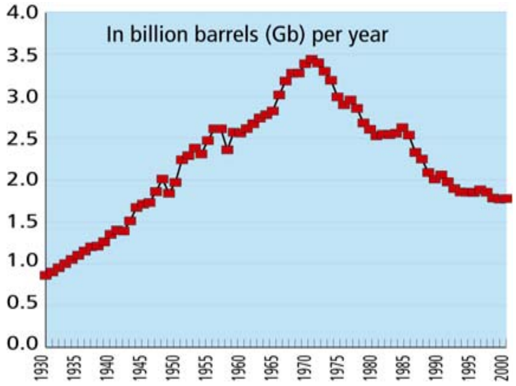


Figure 2 US oil production Lower 48 (USA without Alaska and Hawaii)[2]

In the 1950s Hubbert predicted that global oil production would peak around the turn of the century. OPEC's capping of output for some two decades delayed the peak somewhat. Until 1970 Hubbert was ridiculed and denounced by the US Administration and the oil industry. However, his theories proved exactly correct; beginning in 1971 US oil production declined and has maintained this downward trend steadily. The decline recently was slowed somewhat by tapping off shore and deep-sea oil deposits in the Gulf of Mexico. A steep decline in output is also to be expected there, roughly after 2010.

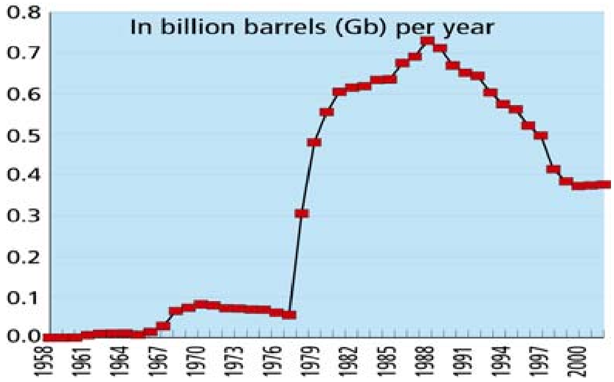


Figure 3 Oil production in Alaska [3]

Hubbert's empirically derived forecasting methods have stood the test of time. Even today new exploration and production technologies can alter, but not undo, the limits dictated by geology. Alaska's giant oil fields mainly were developed after the 1973 oil shock and began producing after 1978. Output reached its peak within ten years followed by the essentially symmetric decline.

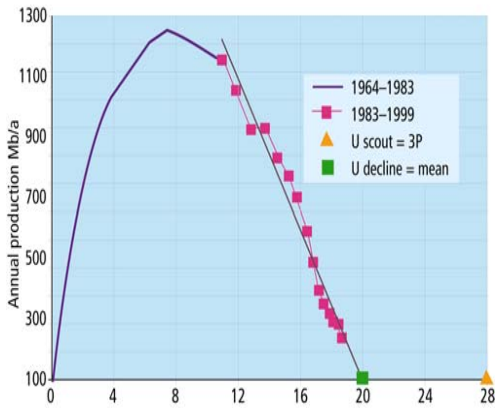


Figure 4  Samotlor, largest known Russian oil field [4]

Samotlor is Russia's largest oilfield. Oil production is declining steadily despite the deployment of secondary and tertiary production technology.

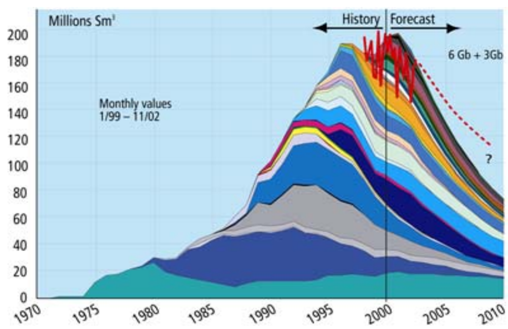


Figure 5  Oil Production off Norway [5]

The bell-shaped output curves work both for major fields and entire regions. Norway presents a similar picture. Production patterns for individual oilfields are particularly well portrayed in this chart. Each of these oilfields describes its own Hubbert Curve that ends up in a steady contraction.

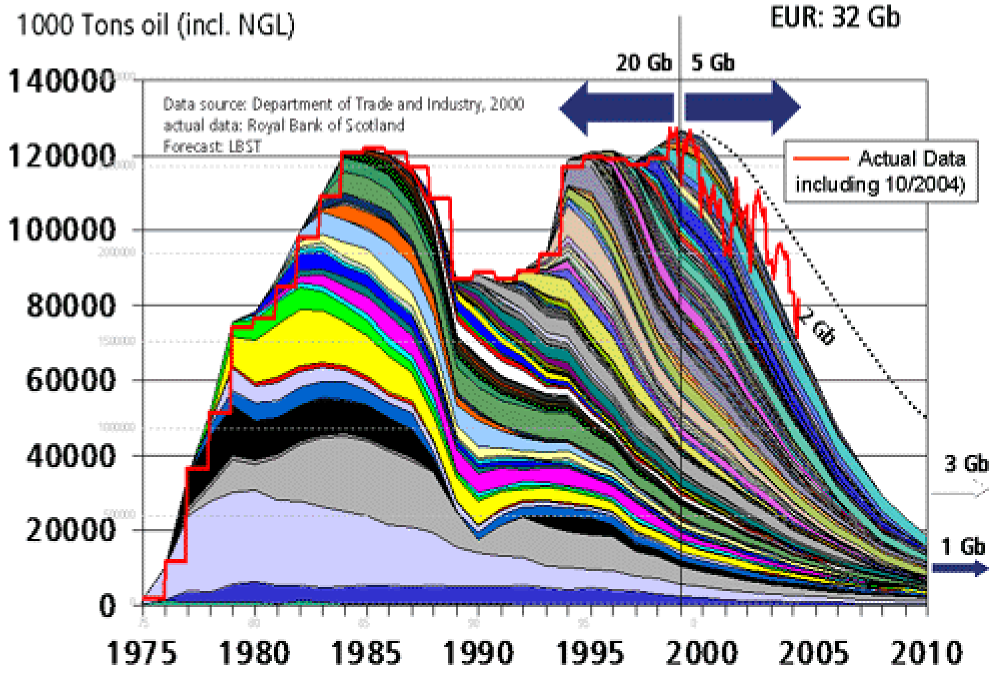


Figure 6 Oil Production Off United Kingdom [6]

In the United Kingdom oil production experienced a dip (shown in the middle of the picture) due to the Piper Alpha oil platform fire. Aside from this disruption the trend conforms well to Hubbert's thesis, reaching a peak of 2.68 million barrels a day (mbd) in 1999. From there, average daily output has already declined 23% (6% per annum) to 2.073 mbd in 2003. By February 2004 production was down to 1.782 mbd---a full 33% below the 1999 average. [7]

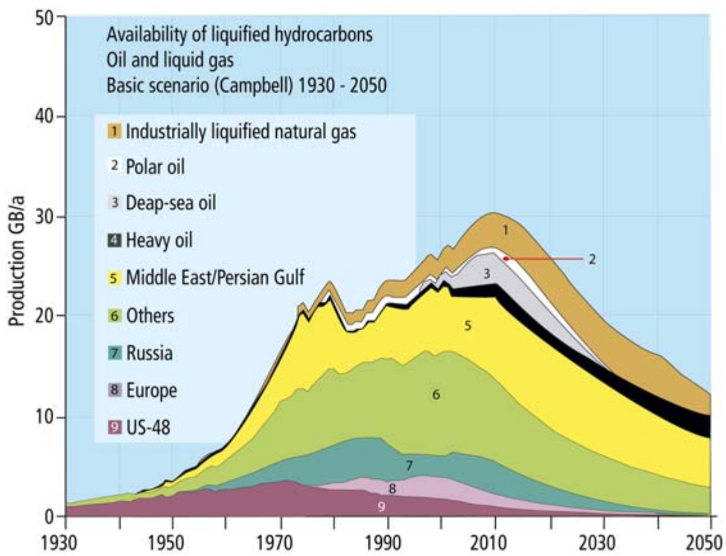


Figure 7 ASPO forecast, all liquids [8]

ASPO (Association for the study of o the Peak of Oil and Gas) is comprised of a group of critical oil geologists that has addressed the issue and has forecast oil production to increase roughly until 2010. Thereafter, production from new fields will no longer be able to offset declines from old fields, let alone contribute to further growth in overall output. [9]

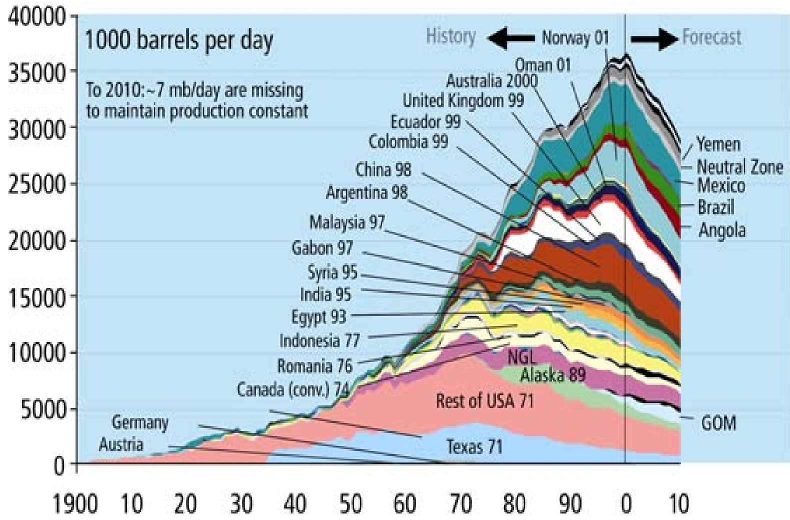


Figure 8 Post peak countries [10]

More drilling does not help. Output in most Non-OPEC nations already has passed their respective peaks. Even for OPEC members the situation is by no means rosy --- Indonesia and Venezuela, for example, can no longer produce at rates to meet their OPEC-allotted quotas. Yet, the world's reliance on lifting OPEC's exports is actually growing because output of all OECD oil exporters has passed peak.

## Rising Energy Prices

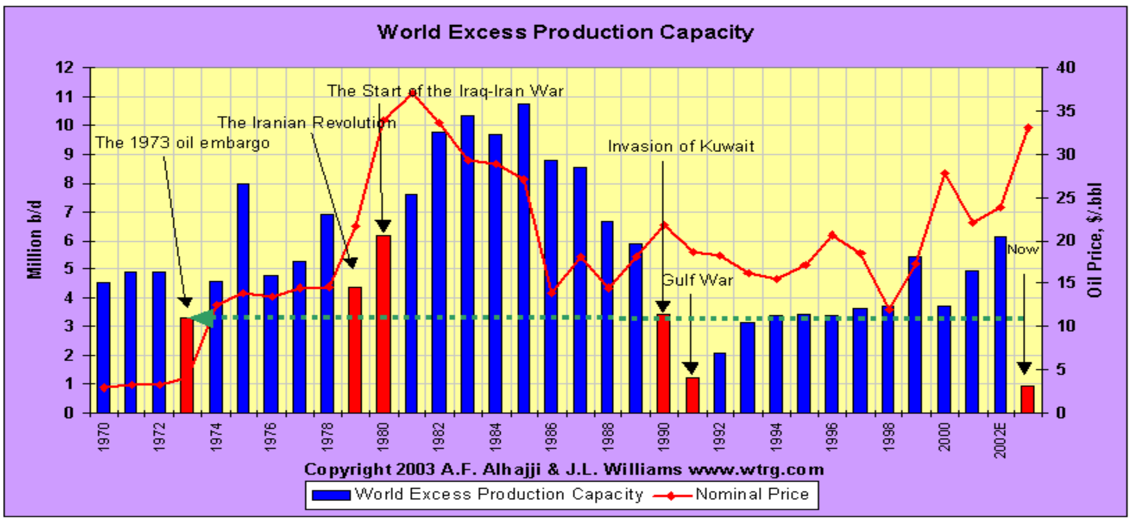


Figure 9 World oil spare capacity [11]

Efforts by the petroleum geology community to nail down the exact date of peak are interesting academically, but the real trouble begins with the loss of oil price stability. This loss is well underway. Price stability would be a reasonable expectation only if there were a good measure of excess production capacity. That is not the case now. Spare capacity is only about 2 mbd --- probably the lowest since World War II.

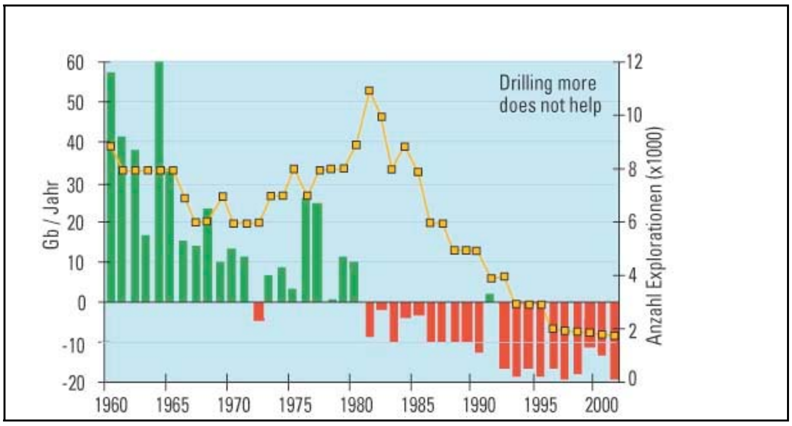


Figure 10 Number of explorations (line) and net increase in oil reserves [12]

Oil indeed will continue to flow for another 75 to 100 years --- but in steadily declining quantities. What's critically important to understand is that the price elasticity of supply is no longer working as it might in other industries. Higher prices no longer can bring forth rapid and significant increases in oil output. As early as in the 1970s it became clear that high prices ($80 to $100/b in 2003 Dollars) might lead to much increased drilling, but not to increases in oil discoveries. This time we cannot drill or militarily conquer our way out of this problem.

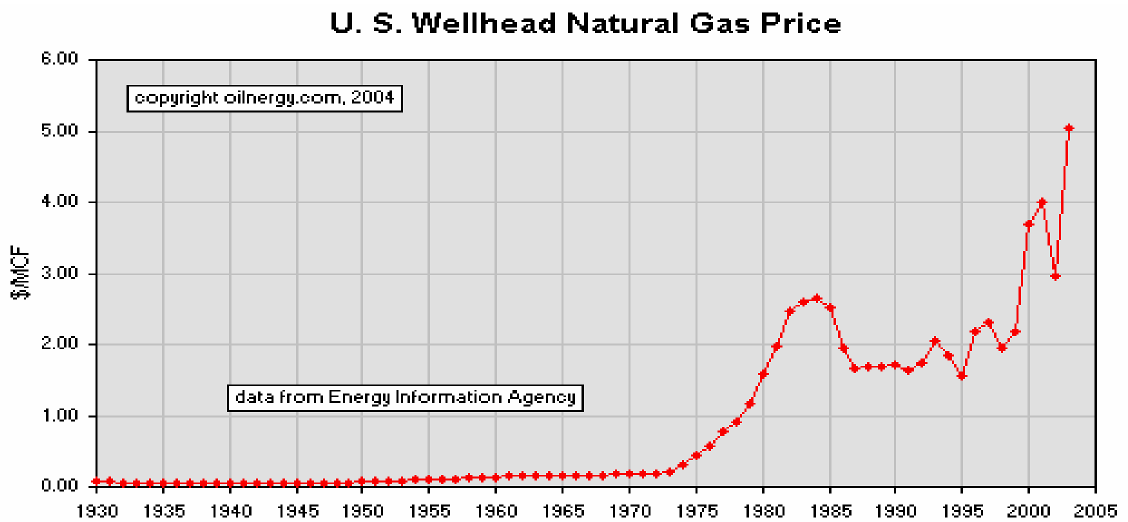


Figure 11 US natural gas prices 1930-2004.

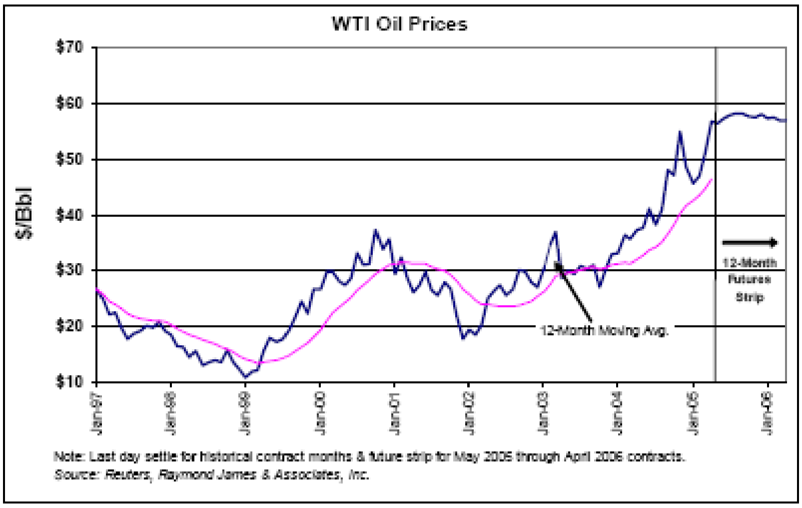


Figure 12: The last 12 WTI contract months, using settlement prices, averaged $46.34/Bbl. The April WTI contract settled at $56.62/Bbl. The May contract is currently down $0.04 at $56.00/Bbl, and the 12-month futures strip is down $0.14 at $57.39/Bb [13]

So oil capitalism will come to an end, an outcome that's beneficial to climate stability. For consumers, however, this will be a bitter end with horrific energy bills, with wars over access to petroleum, with rising costs due to climate change --- killer storms, droughts, floods and unprecedented high temperatures. More damage is to be expected.

## Transition to Efficiency

How will consumers react then? Prices rise to reduce consumption. From a physical perspective it is astounding how inefficient industrialized nations work. In the power sector, 70% of the energy is wasted even before you get it to the home, office or factory, where additional waste occurs.

For the conventional gasoline internal-combustion engine, well to tank combined with tank to wheels, accounts for a total loss of 88 percent. This is great news in a bizarre way, since it means there really is a large untapped efficiency resource.

Take the example of coal energy from coal mine to coal power plant to transmission system to incandescent bulb. You arrive at an energy waste of about 97% of the original source [14]. New LED technology has a very high Lumen/Watt ratio. The same applies to many industries - motors, computers or cars, so with higher prices expect these resources to be tapped!

## Crucial: Energy-Return-on-Energy-Investment

Correctly evaluating future developments requires proper tools for measuring inputs and outputs. With rising cost of fossil fuels The Energy-Return-On-Energy-Investment (EROEI) is such a tool. EROEI reveals the net energy derived from a project after deducting from the project's estimated life-time output all costs of planning, construction, fuels, ongoing operation and decommissioning.

## No Switch Backs in Technical History

Many energy industry experts and international bodies such as the IEA (International Energy Agency) see the solution to our coming exhaustion of oil reserves in returning to, or in stepping up, the use of liquid natural gas, of nuclear power, coal or oil derived from shale or tar sands with lower marginal energy returns than oil. These energy sources offer little hope for solving our problems on a long-term basis.

- Take natural gas: like oil, it faces exhaustion of resources and add greenhouse gases into the atmosphere. In most OECD-countries gas production has peaked and is on the downward slope.
- The IEA's favorite energy sources of the future, oil sands and shale oil have a restricted role in the future. A number of companies working in this sector showed huge cost overruns [15] or fell into bankruptcy [16]. The core of the problem is the low Energy-Return-on-Energy-Investment (EROEI), combined with a huge demand for water, polluting rivers, landscapes and ground water, not to talk about multiplied emissions of $CO_2$ and air pollutants.
- Even with subsidized oil extraction form oil sands, these resources will play a marginal role in replacing conventional oil when new renewable sources with higher EROEI and lower cost will step in.

## The Case for Nuclear Power

For years now we hear of the "Renaissance of Nuclear Power". But market shares of nuclear power are dwindling – and where are the advantages? The high costs of nuclear power have not disappeared since the sixties and seventies. Even the pro-nuclear Bush Administration admits that the costs of nuclear energy exceed those of wind energy, for example.

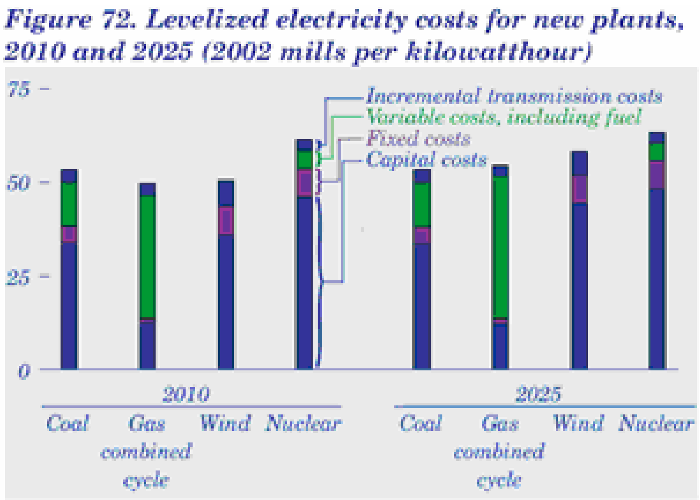


Figure 13 Expected Electricity Cost 2010 and 2025, US-Energy Information Agency [17]

Moreover the hidden costs of nuclear power are not going away: costs associated with nuclear radiation and accidents, misuse of bomb material, terrorist attacks, lack of liability insurance and the issue of radioactive waste.

On purely economic grounds, nuclear power has no easy standing in competitive open markets like in the European Union [18] and will barely grow without subsidies over the coming years [19]. Billions of subsidies are needed to keep nuclear power plants going [20], to clean up old facilities [21] and even more money to construct new ones. These huge investments offer no hope for cost reductions to an extent observable for renewable energy [22]. Nuclear energy is viable only in state monopoly structures where initial costs for capital and fuel conditioning, decommissioning and insurance are transferred to state bodies and paid for by the tax payer.

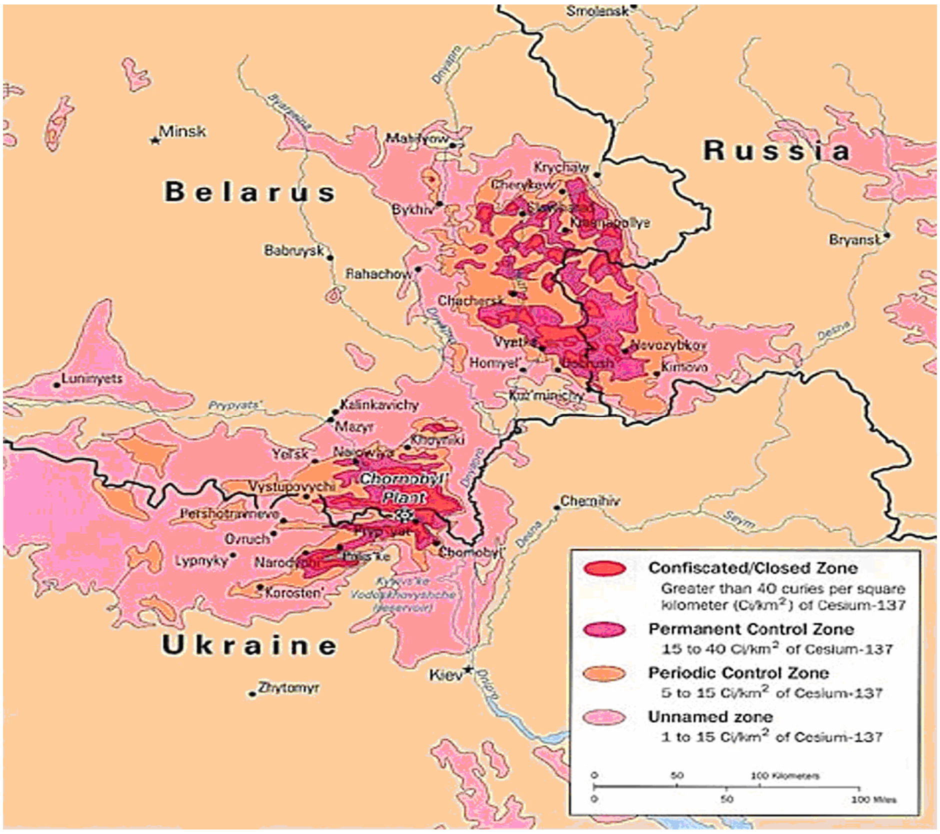


Figure 14 Radiation levels in areas of Belarus, Russia and Ukraine [23]

That nuclear energy is a huge source of financial losses is becoming ever clearer the more the power grids are open to competition and the more electricity monopolies get vertically unbundled. Aside from the fundamental lack of profitability there are the unmeasurable costs of human tragedies such as Sellafield and Chernobyl. In the latter case 2.5 million people are living today on contaminated area, with rising morbidity of children and a range of new, terrible diseases [24].

The phase-out of nuclear power on economic terms has begun in nations like the United Kingdom, Canada or the US. With the next middle sized nuclear accident in a Western nation, this phase-out will proceed even faster. Investors who like to put their money in energy should be aware of this. Sustainable energy solutions are those which do not compromise the well-being of future generations. That rules out all nuclear options.

## Hydrogen: Another Bush Policy Smokescreen

So will hydrogen be the future? In his State of the Union address, President George W. Bush proposed a $1.5bn research and development program for hydrogen-powered fuel cell cars. The "hydrogen economy" is even on the bestseller list; "freedom fuel" is supposed to release us from the grip of the oil barons. There are 985 organizations listed as fuel cell developers, researchers, distributors, associations, government agencies and laboratories in the U.S. alone [25]. But properly analyzed the hydrogen way raises a lot of questions.

Hydrogen is not a source of energy, but an energy carrier like batteries or flywheels, but compared to other energy carriers, a difficult one. Because of the low density and molecular structure of hydrogen, the energy needed to operate a "hydrogen economy" is much bigger compared to the energy consumed within today's oil and gas energy economy or a properly structured sustainable energy economy based on renewable energy sources.

Hydrogen proponents love to cite the efficiency of the hydrogen/oxygen reaction [26] in fuel cells, but sometimes neglect the steps that precede it, which include the manufacture, compression, liquefaction, transport, delivery, bulk storage, transfer to vehicle, and re-expansion of hydrogen fuel. A utilization technology is efficient only if the entire process, and not only a single step within the process, is efficient.

If electricity is generated from natural gas in a large unit, the associated emissions of carbon dioxide are just over 400 g/kWh. When hydrogen is produced by reforming natural gas, the emissions are around 285 g/kWh. If that hydrogen is passed through a fuel cell to produce electricity, the emissions per unit of electricity generated roughly doubled to 550 g/kWh, as the efficiency of a fuel cell system is at best about 50% [27]. In other words, electricity generated directly in a natural gas fired combined cycle plant is more effective in keeping emissions down than a fuel cell running on hydrogen derived from the same natural gas.

It is a fundamental fact of physics that converting energy also consumes some energy. This dictates that we limit conversion steps to situations where they cannot be avoided. Using electricity from renewable energy sources – wind, tidal flows, sunlight, geothermal heat – to break down water in order to get hydrogen for fuel cells to convert it again into electricity is a wholly uneconomic detour.

In all applications, hydrogen energy would compete with its source energy. These original energy carriers can be delivered to the customers much more efficiently in their original form than by using them first for producing hydrogen.

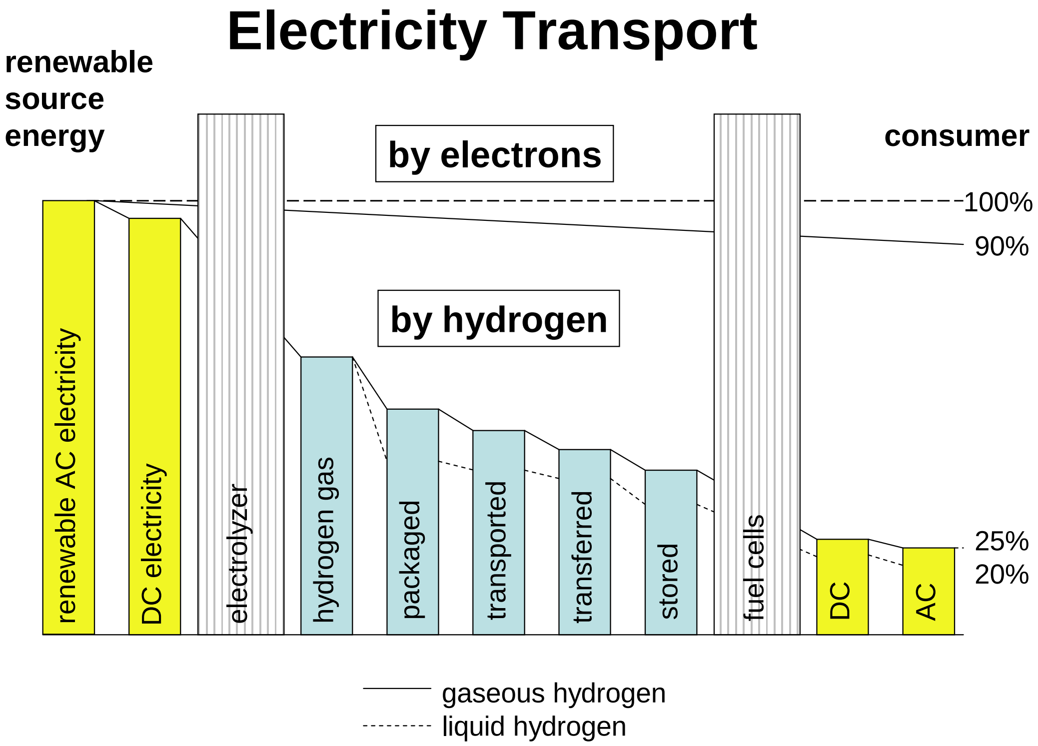


Fig. 15: Energy losses with hydrogen and with direct current from a renewable energy source to the consumer. Source: Bossel 2004 [28]

In summary, for purely physical reasons hydrogen will always be more expensive per energy unit than the energy source used to produce it, and because losses are huge, hydrogen must be put in serious question of solving our energy problems in an economic way. Superior solutions do exist for tackling most energy problems.

The economic implications of this are important. Economic viability is as much part of sustainability as the development of clean, safe technologies and secure supplies. If a hydrogen economy may ever be coming, it will most likely resemble the perfume economy, a market where quantities are so small that unit prices do not matter. It might start with cellular phones or laptop computers, where consumers do not mind paying $10 a kilowatt-hour for electricity from fuel cells, but the options for hydrogen in a global energy market seem very restricted [29].

European Commission Union members Loyola de Palacio and Philipp Busquin followed George W. Bush's call for hydrogen and devoted some 500 million € [30] to a European Hydrogen Program. More programs covering almost 3 billion Euros for hydrogen from fossil fuels with $CO_2$-sequestration and "hydrogen communities are to be followed.

So why are international research organizations so fixated on the introduction of a new energy carrier rather than solving the actual problem: reduction of energy consumption by rational use of energy and by utilization of clean and domestic renewable energy source?

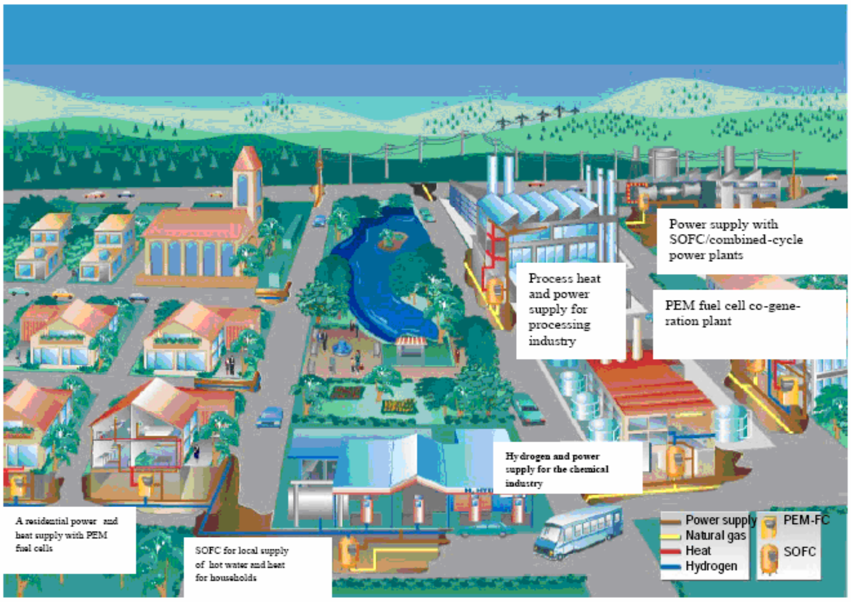


Figure 16 Picture from the hydrogen Report of the EC High Level Group for Hydrogen and Fuel Cells [31]: Lots of fuel cells, no primary energy visible

The hidden aspects of this focus on hydrogen deserve to be illuminated. When the European Commission and various scientists declare that "*Hydrogen opens access to a broad range of primary energy sources, including fossil fuels, nuclear energy and increasingly renewable energy sources*" the sequence of wording is revealing: fossil resources first, then nuclear, renewables later or maybe never.

The hydrogen research budget of the Bush administration comes at the expense of support of renewable energy and of energy efficiency [32]. Wind, biomass, geothermal and efficiency research all lose support. The funding of hydrogen is provided to fill the coffers of nuclear and fossil fuel companies and car makers. They are supposed to produce "clean" hydrogen on their grounds.

The hydrogen campaign is very generously funded by governments and cleverly managed by fossil industries and nuclear. They have hijacked hydrogen for their own gains, with cynical disregard for the economic and environmental downsides of elbowing renewables out of the way.

Today the efficiency gaps of hydrogen are clearly identified [33]. You need four times more primary renewable energy to run a hydrogen system than using electricity directly from wind turbine for example to delivery point. Economics implies avoiding all unnecessary energy conversion steps.

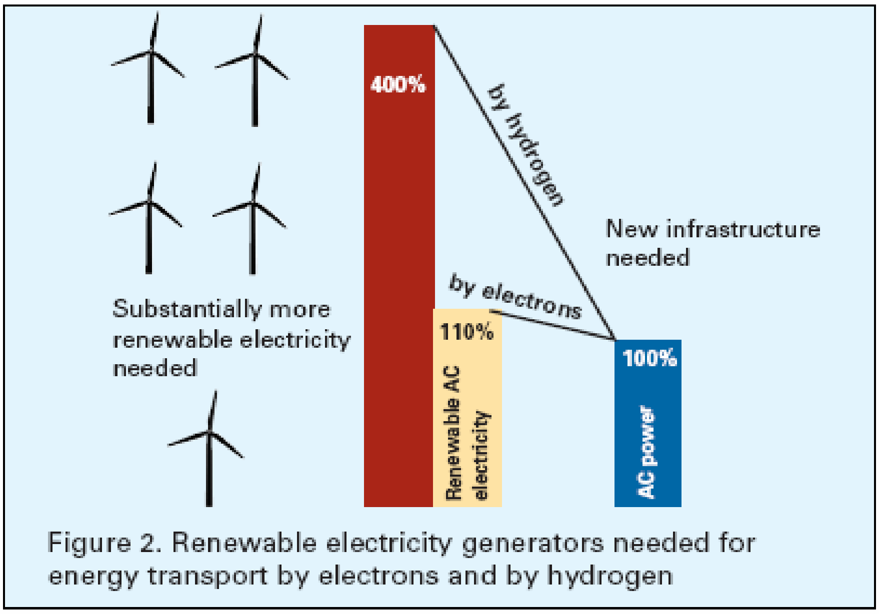


Figure 17 Efficiency of renewable primary sources like wind, solar, hydro; grid transport compared with hydrogen conversion [34]

## The Switch from "Chemical Fuels" to "Physical Fuels"

Compare modern society and its growing scarcity of cheap oil with the functional system of a rain forest. In a rain forest you have extreme mineral scarcity and a huge diversity of specialized organisms find their way of living in recycling and managing materials with solar energy, recycling materials and heat. Our own society must turn away from non-sustainable nuclear or chemical fuels like coal, oil or gas and satisfy its energy demand primarily form sustainable “physical sources" like electricity derived from solar, wind, water, ocean waves or geothermal heat, supplemented by biomass from natural growth and organic waste.

We have both an immediate and a long-term source problem. However, in recent years we have developed and matured a variety of commercially available technologies to relieve it. Wind, solar, geothermal and biomass truly are energy sources with a positive Energy Return on Energy Investment (EROEI). For wind, for example, the EROEI is in the range of 80 to100 [35].

Renewables require an energy investment before they generate a usable fuel. These up-front costs may be quite high, but on a life-cycle basis they are more and more affordable, for there are no fuel costs. Thus, with renewables one attains a high degree of cost stability in an environment that is increasingly volatile. The ongoing flow of primary energy is essentially free – save for maintenance on and for amortization of the equipment costs.

Wind energy is a textbook example for the energy potential, the cost development, and the speed of market introduction that soon could be reached in other fields like geothermal, biomass or solar photovoltaic energy generation.

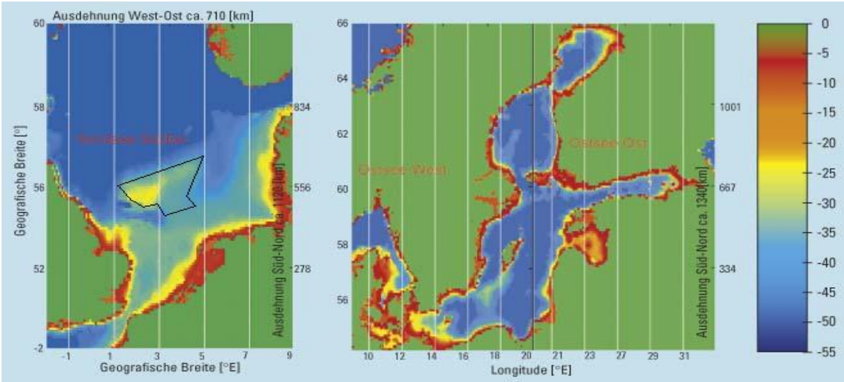


Figure 18 Sea depths in Northern and Baltic see [36]

The potential of wind power is indeed enormous: All the electricity consumed by the former European Union (EU-15) could be produced in an offshore area of 200 km x 200 km (shown by the polygon in the left half of Figure 17) with two 5 MW turbines positioned per km². For stability of supply one will of course avoid putting all these turbines in one place; a more decentralized location strategy with variety of renewable sources will be more practical.

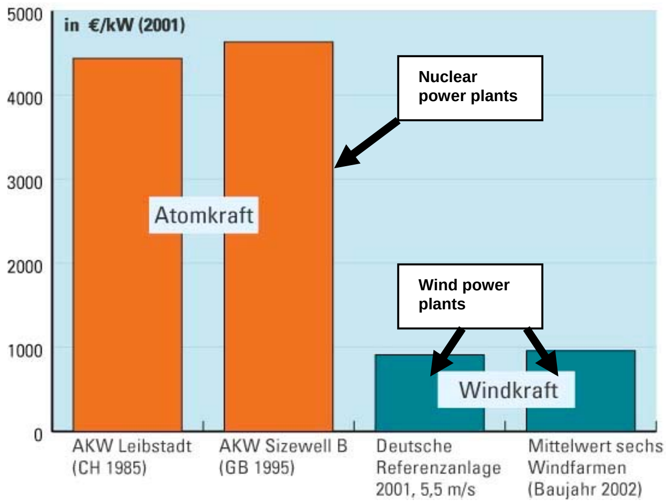


Figure 19 Investment cost of nuclear power and wind energy in €/kW (2001) [37]

Recently, wind power enjoyed dramatic cost reductions. In many locations the generation cost of electricity from new wind power plants are lower than those of new coal or nuclear-fueled plants of equivalent-capacity. Compared with natural gas-fueled plants, European wind power installations deliver energy at equal cost. In the US the cost advantage for wind is even greater.

The economics of wind power are remarkable: investment costs of fairly less than 1€/Watt, short building times (2-20 weeks), winter and summer production peaks (depending on location), global availability, no emissions, no fuels and disposal costs, low maintenance requirements and steadily falling generation costs thanks to increasingly efficient installations and mass production. Wind power is fully immune to oil and gas price fluctuations. Wind hedging is gaining in importance on the US power market because natural gas, the widely preferred power plant fuel supply, is declining and experiencing alarming price rises and fluctuations.

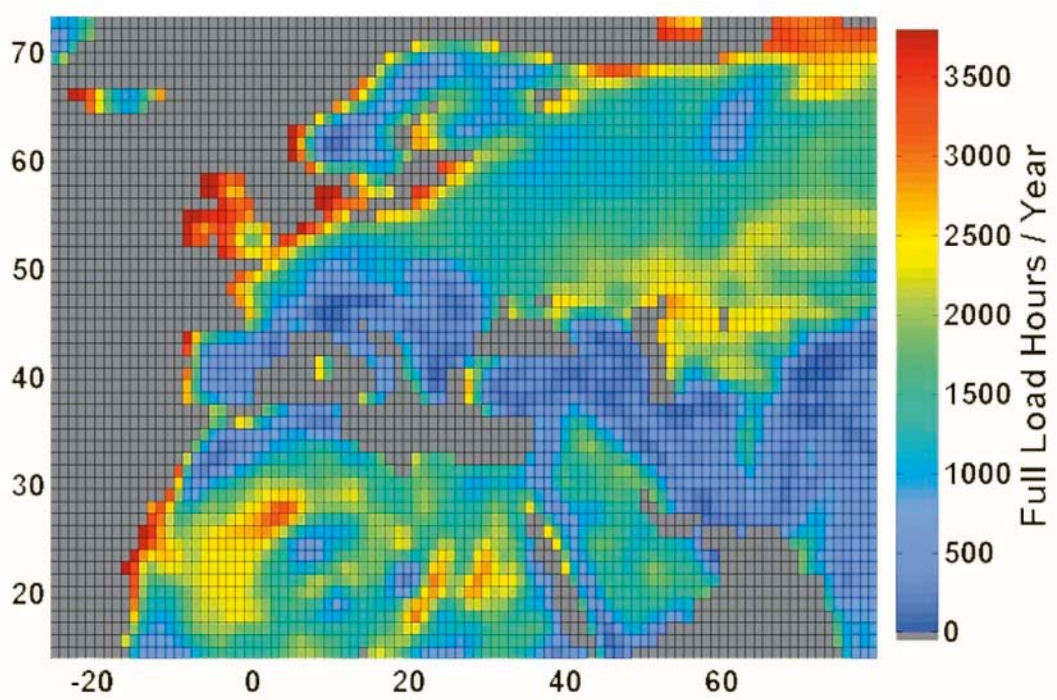


Figure 20 Potential annual electricity production of wind turbines in Europe and ist neighbourhood in full load hours [FLH] per year (NH = 80m, NL = 1.5 MW); Electricty consumption EU-15 and Norway: 2100 TWh; Potential wind energy production on shore with more than 1500 FLH with 4 – 8 MW/km$^2$: 120‘000–240‘000 TWh (Average annual production: 2050 FLH)

Maps of European wind conditions reveal that the continent’s present electric power consumption could be supplied 100-fold with onshore installations alone; offshore installations add enormous additional capacity. Denmark, Germany, and Great Britain are eagerly developing these technologies for delivering clean, inexhaustible electric power that is inexpensive after the initial investment is amortized. The full replacement of conventional electric energy by renewable-source energy is possible, promising lower costs than today's fossil-fuel derived power, not to speak of energy from new nuclear facilities [38].

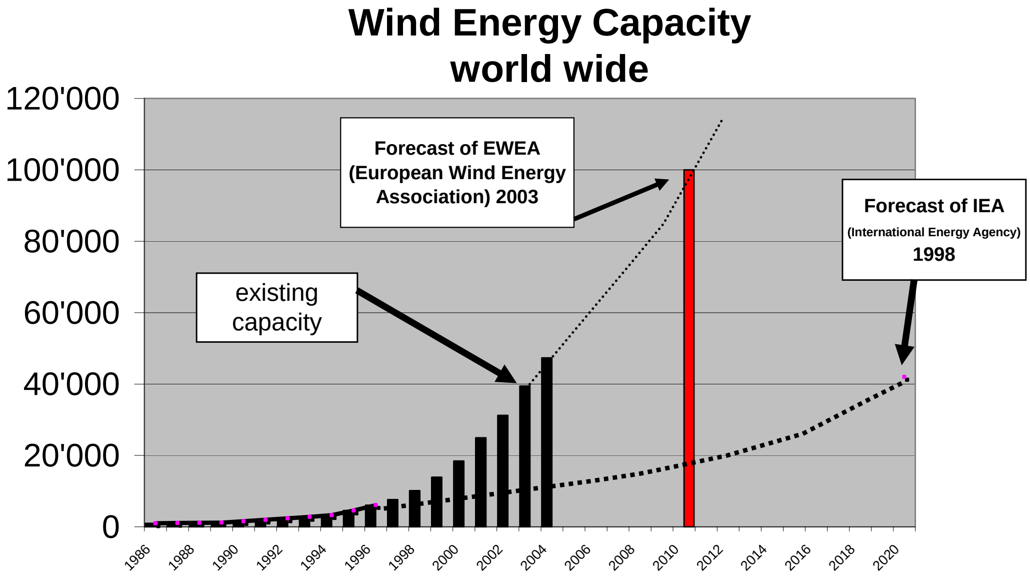


Figure 21 IEA projections on wind power and real development [39]

Despite their compelling advantages, new renewable energy sources are consistently ignored as being economically viable by such organizations as the IEA. In its World Energy Outlook 1998 the Paris based intergovernmental body predicted that by 2020 a total of 45 GW of wind power capacity would be installed. The reality is that wind power in the last five years to 2003 attained a yearly growth rate of 26 percent and is the fastest growing generation technology worldwide. By 2003 the installed capacity already reached 39 GW, and the 2020 goal of 45 GW will be attained in 2004 [40].

It is not a coincidence that wind turbine and photovoltaic companies experienced extraordinary sales for years now, and they are expected to translate these sales into solid market share gains [41]. Sinking cost and a good balance of output versus input are strong positive arguments for most renewables. That's why renewables are called a source of energy – the energy returned is greater than the energy invested. By contrast, an energy carrier is not a new source of energy, but an energy sink.

Renewable energy is harvested as electricity, heat or chemically as biomass. Of these, electricity can be transmitted to the user and converted to energy services with highest efficiency.

Energy losses are least if transmitted by High Voltage Direct Current (HVDC); losses are as low as 4% over a transmission distance of 1000 km. With grids accessible to all, energy producers can compete with little concern for the actual distance to market. Wind farms in Russia or Ireland, hydroelectric peak power from Switzerland and Norway, and solar farms and wind from Mediterranean countries will eventually contribute to a stable electric power supply in Europe. Similar continent-wide interlinks could be realized in the US and other parts of the world.

No other energy carrier can beat electricity from renewable energy with respect to efficiency, environmental friendliness and low cost of transmission. Consequently, electric power should not be converted to another type of energy until its final point of use.

Today, research seems to be hijacked by people like George W. Bush who believe that after oil – a chemical energy resource – we again need to resort to a chemically stored form of energy. But upstream resources will shape downstream infrastructure. The internal combustion engine or oil burning furnaces were a logical outcome of fossil resource. The outcome of renewable energy sources will be different.

It must be adapted and derived from a variety of primary resources whatever locally is most useful and competitive. Any primary source of energy, as far as practical, should be used directly without conversion. We should particularly avoid multiple conversions or wasteful conversions between physical and chemical energy (electrolyzer, thermal power plants, IC engines, fuel cells) for the goal of efficiency. So most probably the future will consist in a higher technical diversity than the oily past:

- Electricity from mechanical energy sources: wind, water, oceans
- Electricity from thermal energy sources: solar, geothermal, solid waste and biomass incineration
- Electricity form solar radiation: photovoltaic conversion
- Heat from solar and geothermal sources for direct use like space heating, hot water and process steam
- Biomass from natural growth, farming and organic waste

Physics and economics must lead our way, to a lesser extent political frameworks and directives. The laws of physics cannot be changed by majority votes of political bodies or by announcements of a president. Renewables will succeed because of their high "source-to-service" efficiency. The sooner, the better. It’s good for all of us.

## Renewables and Mobility

It was pointed out that hydrogen is less efficient for stationary uses than direct use of electricity or of heat from renewable energy. So what about hydrogen for use in mobile appliances?

Here too, the most efficient solution is obtained by an efficient conversion of high-grade mechanical energy into high-grade electrical energy or by converting the hydrocarbon molecules of biomass into hydrocarbon molecules of liquid fuels. In both cases, energy is not converted across the border between physics and chemistry.

The transformation of biomass into methanol or ethanol or the creation of synthetic fuels by processing biomass hydrocarbons creates fewer losses than the conversion of biomass or electricity into hydrogen when all aspects of the energy market are considered. On a volume basis, these fuels store more energy than hydrogen. They even contain more hydrogen than liquid hydrogen itself or hydrogen gas compressed to 800 bar.

Biofuels are traditional hot topics, but battery cars and compressed air cars deserve a closer look than hydrogen.

The French designer, Guy Nègre (see his presentation in this conference), is developing cars with air expansion engines. Compressed air is expanded in four cylinder piston engines to provide power for vehicle propulsion. Compressed air is not a new energy carrier, but it is the first time that a modern compressed air vehicle has been designed. Compressed air cars have some positive attributes: Air motors are small and lightweight for the power they produce, and also substantially cheaper; compressed air tanks can be refilled much faster than hydrogen tanks or batteries. They last almost indefinitely with any number of recharging cycles and without losing capacity. The engine can be made from lightweight aluminum, because it is operated near ambient temperature.

As to cost and density of stored energy, it's hard to say what the driving range of compressed air or battery cars will eventually be. Experts on battery cars claim that 300 km are possible with up-to-date battery technology (Lithium-Ion) at no prohibitive cost [42]. It is by no means clarified if fuel cell cars have a better driving range. For this range electric vehicles will be superior to hydrogen fuel cell cars with respect to initial costs and overall economy. This aspect should be recognized by the hydrogen fuel cell community.

In any event, if renewable electricity from solar, wind or hydro is available from a 90%-efficient intercontinental power grid, and air tank or battery losses (loading-unloading) are in the range of 20 percent, and recuperative braking is applied, an overall car efficiency of 50 percent or more appears attainable - a great leap from today's gas guzzlers or from hydrogen car's "well-to-wheel" or "power-plant-to-wheel" efficiency in the range of 9 to 22 percent [43, 44].

Hydrogen proponents point out that the low driving range of electric cars will not be accepted by consumers and that battery and compressed air systems are not getting mature. This evidently was true in an economy with very cheap gasoline. But with higher prices and with the growing success of the Toyota Prius, things could turn out well for electric vehicles (EV) very fast.

There has been some disappointment expressed that battery technology for electric vehicles hasn't progressed nearly as much as had been hoped. The reality is that battery technology has progressed significantly in the last decade. But vehicle manufacturers haven't been applying that technology in new products [45]. So with rising fuel prices expect these technologies to be adapted for automotive use.

The Prius includes most of what is needed to make a basic EV – electric drive-train, electric power steering, electric power brakes, 4-door lightweight body, low rolling resistance tires, all for a retail price of $20,000. Considering the lack of hydrogen fuel stations and the easy access to electricity, driving with batteries or compressed air could soon be a better choice that could be developed without much additional research or nation-wide new infrastructure.

Think about a good battery and a battery maintenance network at reasonable cost, maybe with permanent service and ownership of the battery by the car maker. In any way, it must be pointed out that cars driven by hydrogen electrolyzed from electricity show a much bigger consumption of energy than today cars. Such a strategy for cars could only be viable in the case that abundant cheap and clean renewables were available. If hydrogen is derived from fossil fuels, $CO_2$ emissions will grow higher than with today's car fleet and would be very much higher than with bio-fuels, battery cars or compressed air cars. The electric vehicle turns out to be far more efficient than any fuel cell car; even more when the weaknesses of batteries are eliminated and confidence into a service network would be built, by reasonable guarantees for ranges and life-time of such appliances.

Also, there are opportunities for using a wide range for using biomass-derived fuels like ethanol, methanol or synthetic bio-fuels in automotive fuel cells. And let us not forget electrical rail transport – a highly efficient means of mobility for personal and freight traffic that could solve a number of problems in urban areas; air pollution, excessive noise, road construction and maintenance, traffic congestions and losses due to accidents.

## Hydrogen as a Storage Medium for Renewables?

In the not so distant future renewable energy sources will contribute a sizable percentage of power to the integrated power grid, even if developed within the conservative visions of current energy policies. Fortunately, the reality is ahead of politics. The need for new energy storage schemes and load management becomes apparent. However, electrochemical energy storage with batteries or hydrogen using reversible fuel cells will not necessarily be the most practical or the most economic solution.

Physical energy storage systems appear to be the better solution. Electrical energy is best stored in electron storage devices like super capacitors, as potential energy in hydro power storage facilities, as pressure energy in compressed air storage tanks and alike. But above all, much energy can be stored in form of useful energy (e.g. ice reservoirs in refrigerators, heat reservoirs in buildings). Furthermore, HVDC transmission lines can carry electricity from regions of oversupply to regions of shortages to balance differences caused by weather or daytime changes [46]. Also, wind energy generators can be easily stopped if the stability of the power grid is threatened by too much wind in one area. This requires that the installed wind power is above the actual power requirement of the grid. All these physical energy storage and management schemes compete in economic terms with equally clean hydrogen storage solutions.

The dwindling fossil fuel resources come in as an additional source for capacity management: It might soon be more economical to spare natural gas for capacity management in integrated wind driven grids than to burn it as prime energy source in thermal base load power plants. As long as certain amounts of fossil fuels are tolerated and used, it seems better to use them for this purpose rather than to convert them to hydrogen to replace fossil fuels in the transportation sector. Why take the long and expensive way detour when the short and less expensive straight road can be used?

Hydrogen does not provide a solution to the energy problems we face today, and, in all likelihood, it will not do so in future. The Bush Freedom Fuel Initiative will have the overall effect of creating a hydrogen economy with more of the same old fossil fuels. Rather than reducing the overall $CO_2$ levels this solution would only shift the emission of pollutants from one activity to another and from one location to another, but the emission of greenhouse gases would grow faster than ever before. We really should put hydrogen aside and look for economical and risk-free, clean technologies that are readily available.

## Ten Necessary Steps for Sustainable Energy

Oil was the principal driver of our economic prosperity. Renewables and electricity will be the keys for the future. Electricity is the most efficient power source for trains, fixed route transport and homes. Electricity is the most effective power source for illuminating, especially with the emerging LED technology. Communication depends almost entirely on electricity. Electricity could be used with high efficiency for space heating if electric heat pumps were used together with solar energy heat sources. In a future "Electron Economy" based on electricity from renewable sources, electric heat pumps could become real "energy multipliers", while the replacement of natural gas by synthetic hydrogen in stationary gas heaters would lead to an intolerable waste of energy.

As we leave oil behind as our dominant energy technology we will more and more convert our energy system from a chemical to an electrical base. Electric power will be the reference energy against which all other forms of energy will be compared. The cost of synthetic hydrogen will be compared against the cost of electricity needed to obtain this hydrogen. It is clear that this hydrogen is more expensive than the electricity “burned” in producing it. Applying the principles of this simple comparison may well lead to new technologies focused on energy **use** more than on energy production and distribution. Engineers will make choices that are quite different from those made a generation or two ago. Electrical systems with their proven high efficiencies will gradually displace chemical energy conversion systems saddled with inferior efficiencies.

Efficient electric systems will replace inefficient chemical energy converters like thermal power plants, IC engines or fuel cells. This is not a vision or personal view, but it is directly related to the physics of the future energy supply and the necessity for rational use of the energy that mankind is able to harvest from renewable sources.

Energy production will become more regional. Wind energy and biomass conversion offers a certain measure of choice on where and when to produce electricity. Wind farms are located on the basis of decisions that take account of where suitable wind conditions exist, where land is available and where the customers are. By contrast, there is no choice possible on where to locate an oil field --- it must be where the oil deposits are, and that may be half a world away from where most oil consumers live.

The enormous infrastructure for transporting oil and gas will take on diminished utility in competition with super-efficient HVDC systems for bringing electric energy to industrial and personal consumers. By 2050 we might not be transporting energy as chemical commodity at all. Instead we will transport energy as pure energy itself.

We are heading into a new energy world. Energy is the core of virtually every problem facing humanity. We cannot afford to make mistakes. We should not assume that the existing energy industry will be able to provide solutions on its own. Somehow we must find a basis for energy prosperity for ourselves and for worldwide peace. Energy needs to be available, affordable and secure for all. To do this we need to improve or adapt the existing technology. We also need new policies to for a sustainable solution:

1. Wind energy seems to be at the threshold of becoming the least-cost-technology for electricity generation. But other technologies for renewable energy are still more expensive than electricity from paid-off thermal power plants.
   To attain a diversity of electricity from primary renewable energy sources it seems crucial that operators of all renewable energy systems, to recover their sometimes high up-front investment costs, get guaranteed feed-in tariffs which cover their specific generation costs, with regressive tariffs over time as applied in the German "Erneuerbare-Energien-Gesetz" [47]. The energy consumer, in particular the industry will eventually benefit from investments made in the renewable area, considering that once paid-off renewable energy installations produce energy extremely cheap as can be seen with older hydro power plants. And with mass production renewable electricity will be much cheaper than power from ever more expensive natural gas or nuclear.
   Therefore this tariff system should be applied for all renewable technologies with no or very low externalities and with good potential for cost regression by mass production and further technical improvements. So far, most renewable energy installations, professionally managed with respect for nature, do fulfill these conditions. Unfortunately, there are also exceptions: certain large hydro dams and deforestation as practiced in the Third World.

2. Models should be developed which apply guaranteed feed-in-tariffs for electricity imports, too. This can give access to cheap primary resources for mutual benefit of export and import countries. The energy system therefore will not be more expensive than today [48].

3. Massive long distance HVDC electrical power transmission will promote energy security and access to least cost production areas from renewable sources. Such schemes work for all industrialized regions of the world. Instead of a one-way supply structure from the power plant to the user, the electrical power grid of the future will be a multi-way network with electrons moving back and forth at different times to balance local or regional supply and demand.

4. To a certain extent production of electrical power needs to be done locally – for security reasons and for protection of essential life line services. We need a balance between locally produced energy and cheap imports. A

standard for mandatory use of renewables in situ by every household or business might be an incentive for more security, for controlling efficiency of electricity use (minimizing stand-by-losses for example) and for reducing costs.

5. Managing these energy flows economically requires price signals by real-time tariffs so the system can optimally use the generating capacity. Modern information technology could help to manage demand side and to improve the match between production and consumption of electricity in time. This will reduce the requirements for stand-by capacity to follow peaks in demand and reduce overall costs.

6. With proper incentives most electricity will be consumed synchronous with production, so that there is no need for storage. Facilities like electric cars, many heating or cooling appliances or private washing machines can be programmed to draw power from the grid during off-peak hours. Even laptop computers and other electronic devices with storage batteries can be programmed to go off-grid at certain times during the day. Storage and time management of electrical energy is critical for the stability and robustness of a grid depending on solar and wind as dominant primary power sources.

7. Where storage is nevertheless needed it is best provided locally near the point of use. Imagine that by 2050 every house, every business, every building and every car has its own local electrical energy storage device, an uninterruptible power supply capable of handling the entire needs of the owner for 24 hours [49]. Based on yesterday's lead-acid storage batteries, a 100 kWh electrical energy storage for a typical apartment house would require a small room and cost over $ 20,000. But it is possible to shrink the size of such installations and to drop cost. Super capacitors may provide a better solution.

8. This energy system, based on renewable energy, will be a market system in its fundamentals. Energy will be produced where it is cheapest and most available in terms of capacity and time. Therefore we should stop subsidies for non-renewable energy that do not cover their cost. We need a strong foothold in government action – this time not for subsidized nuclear energy or coal, but for correct pricing and for a strong power transmission system.

9. Zero emissions building technology is readily available. We therefore should not forget the cheapest resource we have: energy efficiency. Stringent standards should be enacted for all energy-consuming products, standards analogous to electrical safety standards but aimed at wasteful use of energy. The ecological tax reform should be advanced, harmonized step by step, and be a part of WTO treaty. Energy cost should be sufficiently high to punish wasteful behavior while honoring efficient energy use.

10. Last but not least: Start research efforts devoted to harvest and distribute energy from renewable sources, to systems for efficient energy storage with superconducting magnets, super capacitors, advanced batteries, compressed air, and to practicable methods for converting biomass into synthetic liquid hydrocarbon energy carriers.

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