Towards a CO_2-free Energy System in the 21st Century

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1. INTRODUCTION

A world faced with the threat of climate change and characterized by an ever increasing demand for the services which energy can supply will need to develop and make use of CO_2-free forms of energy. Renewable energy sources such as wind, water and sun will ultimately have to play a major role. However, there are limits to the use of renewables. Some of the cost considerations and other barriers to renewable energy are discussed in section 2. Section 3 looks at the issue of fossil fuel availability, and concludes that the probability that mankind will exhaust the reserves at any time in the near future is remote. Section 4 analyzes the likelihood that the carbon constraint will become binding before the reserves are depleted. A CO_2-free energy system based on energy carriers which can be derived from either fossil fuels or renewables is presented in section 5, with special attention for the role that hydrogen might play in such a system. Section 6 describes the steps involved in recovering CO_2 from fuels and flue gases and storing it underground, and presents estimates of the costs associated with each step. Estimates of the costs of producing CO_2-free energy carriers in The Netherlands are presented in section 7. The paper closes with some thoughts about the impact that CO_2 recovery might have on fossil fuel price stability.

2. BRAKES ON THE INTRODUCTION AND UTILIZATION OF RENEWABLE ENERGY SOURCES

It is widely accepted that a sustainable energy system - one which can meet the needs of current and future generations without overtaxing the environment to the point where food supplies, ecosystems or economic development are at risk - will ultimately have to rely largely on renewable sources of energy such as wind, water and sun.

There is also general agreement that the transition to a renewables-based energy system must be made as quickly as possible in order to limit the build-up of carbon in the atmosphere. The greatest obstacles on the road to large scale implementation involve the relative costs of renewable-based energy carriers and the optimization of the necessary technology.

There are a great many measures that governments can take in order to remove these obstacles and most governments are taking them to a greater or lesser degree. In The Netherlands renewables currently account for about 1% of total energy use. The policy target is to increase this share to 3% by the year 2000 and to 10% by the year 2020. As shown in the following table, there are large differences in the costs of producing electricity from the different renewable options. All of them, however, are more expensive than electricity based on the fossil fuels used in The Netherlands, natural gas and coal.

Table 1: Comparative costs of electricity generation with fossil fuels and renewable energy sources, in NL*f*/kWh

fossil fuels	0.08
hydropower	0.15
gasification biomass	0.15
wind	0.17
heat pumps (non-residential buildings)	0.48
heat pumps (households)	0.68
photovoltaic (collective)	1.25
photovoltaic (individual)	1.50

Source: [9, pp. 13, 25]

The differences in the costs of producing electricity with various renewables reflect differences in the stage of development and market penetration. Wind and hydropower, for example, have already undergone a long development history and come the closest to being able to compete with traditional fossil fuel-based generation in The Netherlands. Photovoltaic solar energy, on the other hand, is still in a fairly early stage of development and has a long way to go before it can compete on a commercial basis with more traditional forms of energy. Technology development and experience gained through larger scale application will to some extent result in an autonomous decline in the costs of producing energy with these renewable sources.

The Netherlands uses two types of policy instruments to accelerate and strengthen the autonomous decline in the cost of renewable- based energy: those aimed at technological progress in order to improve the price/performance ratio drastically, and those aimed at fostering the actual application of those renewables for which the costs are only slightly higher than for fossil-based alternatives. Instruments in the former category are largely in the area of research, development and demonstration.

Fiscal instruments are used to foster the application of nearly competitive renewables. At the moment there are four fiscal programs in force in The Netherlands which have the effect of reducing the cost differential between traditional energy sources and renewables: a tax on small scale gas and electricity use with a refund for producers of renewable energy, free depreciation of investments and an investment tax credit in the corporate income tax, and a provision exempting earnings on investments in "green" facilities from the personal income tax. The following table indicates the effect that these fiscal instruments have on the costs of various renewable options.

Table 2: Effects of fiscal instruments in 1997, in NL*f*/kWh

	wind	heat pump (non-residential)	gasification biomass	landfill gas
cost	0.17	0.48	0.15	0.05
energy yield	0.08	0.29	0.08	0.08
tax advantage	0.04	0.10	0.04	0.03
remaining cost	0.05	0.09	0.03	-0.06

Source: [9, p. 25]

As Table 2 shows, even with tax advantages for renewables they are still costlier than their fossil-based competitors. In order to ensure that they are exploited despite their cost disadvantage, The Netherlands is instituting a system of "tradeable green labels". Agreements between the government and energy distribution companies set out each company's share in the total target for 2000 and each company commits itself to being responsible for providing that amount of renewable energy. The objective for an individual company is determined based on its share in the electricity and gas market in 1995. Since the potential for the different forms of renewable energy differs in different areas, the companies are introducing a system to make renewable energy tradeable without actually having to physically transport it.

They have developed a system of "green labels" which represent the renewable "value" of the energy, but not the energy itself. The companies can purchase green labels outside of their own service area, thereby making possible the production of renewable energy elsewhere, and crediting that energy, rightly, against their own commitment.

The energy companies have also found another way to cover the additional costs of producing electricity based on renewables. They have introduced a new product which they call "green current" on the market. The idea behind this approach is to offer a product to "green" customers for whom emission-free electricity has a higher value than regular electricity and who are therefore prepared to pay a premium for it. Customers are offered the possibility of signing a contract for a given amount of "green current" - that is electricity produced with renewables - within a given time period and they pay a higher price for it than they would for regular electricity. "Green current" was first offered on a trial basis about a year and a half ago and is proving much more popular than marketing studies carried out beforehand suggested it would be.

Besides the cost impediments to renewable energy there are also other barriers which are less sensitive to policy solutions. In The Netherlands, for example, the conflicting demands on land use form a particularly acute barrier. Windmill parks take up a lot of space and are noisy. The Netherlands is an extremely densely populated country, where residential, ecological, recreational, agricultural, industrial and infrastructural demands all compete for limited land resources. Other countries are confronted with other kinds of barriers to renewable energy, the most difficult to overcome being climatic conditions which limit the potential of wind and solar power, and geographic conditions which limit the potential of hydropower and biomass.

The combination of cost differentials and other kinds of barriers means that introduction of renewables on a large scale is likely to take a long time. The conclusion is that fossil fuels will have to continue to play a major role even as policy-makers strive to speed the transition to an energy supply system based on renewables.

3. FOSSIL FUEL AVAILABILITY

Having concluded that it will be necessary to continue using fossil fuels in order to meet the needs of current and future generations for energy services, the question arises of whether the remaining reserves are large enough to bridge the gap.

In attempting to answer this question, it is useful to distinguish between proven recoverable reserves and eventually recoverable resources. *Reserves* are estimated based on known geological occurrences, available technologies and current market prices, three elements which are strongly interdependent.

Low prices generally indicate that sufficient reserves are available, so fewer exploration activities are carried out. Moreover, when prices are lower there is no incentive to develop new and better extraction technologies to penetrate new reserves. *Resources* are estimated based on less certain geological occurrences and are not economically feasible to exploit under current market conditions. As market conditions change, technology evolves or advances are made in geology, however, resources can be "promoted" to reserves. Resources are generally expected to become economically exploitable in the near future.

The relationship between reserves and resources can be illustrated by the evolution in the so-called reserves-to-production (R/P) ratio. The R/P ratio provides an indication of how long current reserves will last given current production levels. The R/P ratios for conventional oil and natural gas have been stable or rising throughout most of the post-war period. The R/P ratio for oil hovered around 30 years during the mid-1970's; it is currently about 40 years. This demonstrates that it has been consistently possible to expand reserves faster than production has grown [12, pp. 35-37].

The following table summarizes various estimates which have been made of conventional fossil fuel resources in terms of tons of carbon as well as providing an indication of current annual consumption.

Table 3: Worldwide fossil fuel resources in GtC (10^9 tons carbon)

	WEC/93	Holdren	Skinner	WEC/IIASA	consumption per yr (1990) (WEC/IIASA)
coal	3600	4000	5300	3650	2.4
oil	170	380	300	250	2.6
gas	140	190	170	270	1.1
total	3910	4570	5770	4260	6.1

Source: [11, p. 77 and 12, p. 36]

As Table 3 shows, estimates of fossil fuel resources vary considerably. However, given current levels of consumption it does seem likely that oil and gas resources will be sufficient for at least the next century or so, while coal resources could last for several hundreds of years at the current rate of consumption. And these numbers do not take account of the unconventional oil and gas reserves, of speculative fuels such as the methane hydrates or of growth in the R/P ratio.

4. THE CARBON CONSTRAINT

The carbon present in the known fossil fuel resources is between about 5 and 8 times the present atmospheric carbon content of around 760 GtC. The question facing policy-makers is how much of the carbon in the resources should be allowed to enter the atmosphere, and how fast. Or framed differently: what is a "safe" level of atmospheric carbon? This is the issue which is being addressed by the scientists and policy-makers participating in the Intergovernmental Panel on Climate Change (IPCC) and in the negotiations under the Framework Convention on Climate Change (FCCC).

Policy-makers have not yet chosen a clear and unambiguous indicator of the environmental problem which would provide a starting point for determining a "safe" level of carbon in the atmosphere. Some scientists have suggested that limiting the increase in mean global temperature to 2°C relative to pre-industrial temperatures, and keeping the rate of increase below 0.1°C per decade would achieve the objectives of the Framework Convention on Climate Change. However, these indicators have not yet been embraced by policy-makers. If one assumes for the sake of argument that stabilization of carbon concentrations by the year 2100 at a level that is no greater than twice the pre-industrial level would provide adequate protection against the risks of climate change, then it is possible to put the fossil fuel resources into context.

The IPCC has determined that if concentrations are to be stabilized at about twice their pre-industrial level of about 280 ppmv, then cumulative emissions may not exceed something on the order of 880 to 1060 GtC between 1990 and 2100 [7, p. 16]. This is between 15 and 25% of the carbon present in the fossil fuel resources presented in Table 3, suggesting that the carbon constraint will likely become binding long before the resources are depleted.

In order to get maximum benefit from the remaining fossil fuel resources, there is a need for technologies which make it possible to use them in a carbon-constrained energy supply system. One such technology may be carbon dioxide capture and underground storage. This technology, described in greater detail in section 6, lends itself to use at large point sources of carbon dioxide, such as coal-fired power plants and installations for the production of hydrogen.

5. PRIMARY ENERGY SOURCES VERSUS ENERGY CARRIERS

Energy carriers such as heat, electricity, hydrogen and methanol can provide all the energy services which the world demands: heat, light, mechanical energy and motor fuels. They can be made from either fossil fuels or renewable energy sources, and can therefore furnish the necessary link between the current, fossil fuel-based energy system and the future, renewables-based energy system.

When fossil fuels are transformed into heat, electricity or hydrogen at large point sources, the CO_2 can be recovered and stored underground. Development of an infrastructure optimized to deliver these energy carriers and of products designed to use them (such as methanol-powered vehicles) should be a priority of government and private sector policies aimed at establishing a CO_2-free energy system for the 21st century and beyond.

Hydrogen has been "on the agenda" in the energy world for a long time. Its advantages as a fuel are well known. Since it can be made by electrolysis of water or by gasification of biomass, production can take place almost anywhere in the world. Since it does not emit any CO_2, particulates or sulphur when burned, it offers significant environmental advantages. NO_x emissions are also less of a concern than with fossil fuels since the constraints on lean-burn are much less stringent with hydrogen. Concerns about other environmental aspects (such as contrail formation from aircraft) and safety are lessening with additional research.

Since hydrogen does not occur naturally, it always has to be produced from another energy carrier: fossil or electricity. Production of hydrogen from fossil fuels is the least expensive method, but has not really been part of the discussion in any serious way in recent years because of the fossil CO_2 emissions which it generates. Hydrogen production based on nuclear energy was more or less scrapped from the agenda after the accident with the nuclear plant in Chernobyl and the accent was shifted to production through electrolysis of renewables such as hydropower, wind energy, or photovoltaic solar energy. The development of CO_2 removal and storage technologies adds a whole new dimension to the discussion about the potential role of hydrogen in the global energy supply system, opening up fossil fuels coupled with decarbonization as sources for hydrogen production [2,3].

Up to 15% hydrogen (by volume, 5% by energy share) can be added to the existing gas distribution pipeline without requiring modifications to the current system. New central heating units with ceramic boilers can take up to 50% hydrogen (by volume). In the longer term pure hydrogen could be distributed to final users, but this would require replacement of major elements of the distribution system such as compressors, older pipelines, meters and equipment for use [2].

Hydrogen could also be used in the transport sector. Car manufacturers in Germany are already researching hydrogen driven engines. Mercedes presented a new demonstration vehicle in 1996. Hydrogen is used to fuel busses in Canada. Hydrogen may offer even greater advantages as an aviation fuel. Not only the elimination of hydrocarbon emissions but also the lower weight per unit of energy makes hydrogen particularly attractive for aircraft. The Russian airframe manufacturer Tupolev and engine manufacturer TRUD demonstrated the feasibility of flying a liquid-hydrogen-powered aircraft in 1988. German, Russian and Canadian partners are currently working on a new prototype [8].

The U.S. Department of Energy has estimated comparative hydrogen production costs ranging from US$ 5/GJ for natural gas reforming, to US$ 10/GJ for coal gasification, US$ 15-25/GJ for water electrolysis and US$ 30/GJ for wind/electrolysis [1, Table 2]. In The Netherlands, where virtually all demand for heat is currently met with natural gas, hydrogen purchased on the spot market costs about NL*f* 9.00/GJ (US$ 5.00) and can therefore compete with natural gas purchased by energy distribution companies for delivery to small residential and commercial users, which costs about NL*f* 10.50/GJ (US$ 5.85). Gas purchased for delivery to large, industrial users costs the energy distribution companies something on the order of NL*f* 6.40/GJ (US$ 3.55), so hydrogen is still far from competitive in that part of the market [3].

6. CARBON DIOXIDE RECOVERY AND STORAGE

The first step in CO_2 removal involves its recovery from fuels or from flue gasses during energy conversion processes. It is beyond the scope of this paper to go into recovery technologies or processes in any detail. Extensive information about removal from coal-fired power plants is available in Hendriks [5] and about removal during hydrogen production from fossil fuels in Audus et.al [1]. Hendriks estimates the costs of capture from a conventional coal-fired power plant at between US$ 30 and US$ 70/avoided ton CO_2, which adds between US¢ 2.5 and US¢ 5.0 to the costs of producing a kWh of electricity [5, p. 221].

After the CO_2 has been recovered, it must then be made ready for transport to the storage site. This involves cleaning and dehydration in order to prevent corrosion of the transport system, as well as compression of the gas to a pressure of 60 to 80 bar. Investment costs for compression depend on the capacity of the compressor and the desired pressure. Estimates made in The Netherlands suggest that compression costs amount to something on the order of US$ 4.50/ton CO_2 [3, p.68].

Dry CO_2 can be transported through underground pipelines comparable to those used for natural gas. Pipeline costs are dependent on the length of the pipeline and the pipe diameter. Hendriks has estimated the cost of a 100 kilometer long pipeline which can handle 500 tons of CO_2 per hour at about US$ 2.00 per ton, including the costs of maintenance and extra compression during transportation [3, p.69].

Carbon dioxide may be stored permanently in deep geological formations such as gas and oil fields and aquifers, provided they have an impenetrable upper layer. Given the prevailing pressure and temperatures underground, only locations deeper than 800 meter are suitable for CO_2 storage. Gas fields offer a number of advantages relative to aquifers, one of which is that gas fields have already demonstrated that they have an impenetrable upper layer. Before CO_2 can be stored in aquifers the permeability of the top layer must be thoroughly studied. Another advantage of using gas fields is that much of the infrastructure put in place for exploitation of the field can also be used for CO_2 storage, such as the well head. An advantage of aquifers, on the other hand, is that they are more widely distributed throughout the world [3].

There is wide experience with underground storage of CO_2 in enhanced oil recovery projects in North America. In 1996 Norway's State oil and gas company, Statoil, started with injection of 1 million tons of CO_2 per year into an underground aquifer offshore in the Sleipner area of the North Sea, thereby reducing the CO_2 emissions from their gas operations and saving themselves US$ 55/ton CO_2 in Norwegian carbon taxes. Statoil is also contemplating longer term projects which would involve the export of hydrogen and electricity. Any CO_2 produced would be captured and stored in underground reservoirs [6].

There appears to be considerable potential worldwide for sites which are suitable for underground storage of CO_2. A study carried out under the auspices of the European

Commission's JOULE Program estimated the availability of offshore and onshore underground storage capacity in the European Union and Norway at more than 800 Gt CO_2, while the cumulative emissions of CO_2 from power plants in those countries over 25 years would amount to something on the order of 25 Gt CO_2 [4].

The costs of underground storage consist mainly of drilling and outfitting wells, with smaller additional costs for maintenance and management. Hendriks estimates the costs of storage in natural gas fields at between US$ 0.50 and US$ 3.00 per ton of CO_2, while his estimates of the cost of storage in aquifers vary between US$ 2.00 and US$ 8.00 per ton, excluding the costs involved in determining the suitability of a given aquifer [5, p. 209].

7. SITUATION IN THE NETHERLANDS

The Netherlands has nearly exhausted its No Regret measures for reducing CO_2 emissions. Possibilities for further reductions are quite expensive for a number of reasons.

Because natural gas already has a very large market share in The Netherlands (about 45% of total final energy consumption), there is very little potential for CO_2 reduction from fuel switching to other conventional fossil fuels. The Dutch economy is characterized by a very high proportion of energy intensive industries, which are already among the most efficient in the world. Any gains which could be made from further efficiency improvements would be quite small and very expensive, and due to the fact that these industries compete on a world market it would not be possible to pass on the costs of reduction measures in product prices. As explained in paragraph 2, the transition to a (largely) renewables-based energy system in The Netherlands will take time and the extent to which renewables can ultimately provide all of the energy services demanded in The Netherlands is limited by non-economic constraints which are not sensitive to policy solutions. CO_2 recovery and storage underground, coupled with electricity, heat and hydrogen production, and biomass-based methanol production will likely have to play a major part in the transition to a CO_2-free energy system in The Netherlands in the

21st century.

The capacity for underground storage of CO_2 in gas fields and aquifers in The Netherlands amounts to something on the order of 10 $GtCO_2$ [4, p.107], while CO_2 emissions are currently between 175 and 180 $MtCO_2$ annually. CO_2 storage could therefore provide a backstop for a very long time. There is already a dense system of pipelines in the country due to the high penetration of gas in heating and industrial markets and the ever-increasing application of district heating in most densely populated parts of the country. A great deal of the infrastructure needed to utilize CO_2-free energy carriers is thus already in place.

Table 4 shows some estimates of the cost of CO_2-free energy carriers in the Dutch situation.

Table 4: Comparative costs of traditional and CO_2-free energy carriers, estimates for the Dutch situation

	unit	production cost NL*f*/unit	internal rate of return
Electricity			
1. Reference: natural gas-combined cycle	kWh	0.08	10%
2. natural gas-combined cycle with CO_2 recovery/storage	kWh	0.13	10%
3. Reference: ICGCC	kWh	0.09	10%
4. ICGCC with CO_2 recovery/storage	kWh	0.15	10%
5. wind	kWh	0.17	10%
6. imported biomass	kWh	0.14	10%
Natural Gas			
1. Reference: natural gas	GJ	8	10%
2. hydrogen from gas with CO_2 storage	GJ	16	10%
3. hydrogen from imported biomass	GJ	18	10%
Motor fuels			
1. Reference: gasoline a. production cost excluding distribution and taxes b. retail price including distribution and taxes	GJ	a. 22 b. 60	market prices
2. Methanol from imported biomass excluding distribution and taxes (for use in gasoline engine also suited to methanol)	GJ	34	15%
Passenger cars			
1. Reference: car with gasoline engine a. costs per km excluding fuel taxes and fuel distribution costs b. costs per km including fuel taxes	km	a. 0,38 b. 0,44	15%
2. car with fuel cell based on hydrogen from natural gas with CO_2 recovery/storage	km	0.50	15%
3. car with fuel cell based on methanol from imported biomass	km	0.45	15%

The costs presented here have been calculated by the Ministry of Housing, Spatial Planning and Environment, except for the costs of integrated coal gasification combined cycle (ICGCC), which are based on Hendriks [5]. The numbers presented do not include the costs of modifications to central heating units, pipelines, gasoline engines etc. The energy prices used in the calculations are:

coal	NL*f* 4.00/GJ
natural gas	NL¢ 25.2/m^3
electricity	NL¢ 13.1/kWh
gasoline	NL¢ 72/liter (shadow prices)
	NL¢ 195/liter (retail prices)
biomass	NL*f* 100/ton

8. EFFECTS OF CO_2 STORAGE ON FOSSIL FUEL PRICES

In a carbon constrained world the use of fossil fuels will decrease more slowly if CO_2 recovery and storage is possible. Producing countries (not only OPEC, but also both The Netherlands and the United States) will be able to realize greater value added on their resources if fossil fuels can be made CO_2 free. This will contribute to stability in fossil fuel prices. Price erosion due to an international approach to the issue of climate change is underestimated by policy-makers and analysts. It seems likely that prices for fossil fuels will fall if demand declines. If producing countries react to falling prices by increasing production in order to generate revenue, then prices could fall even further and profit margins could erode entirely. Production of hydrogen from fossil fuels, coupled with decarbonization, could prevent this type of adverse impact from climate change policy.

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