1 INTRODUCTION

Energy is an inherent characteristic of human progress, be it socially or technologically, and is probably the most fundamental feature of modern day life. Energy literally "makes the world go round". It enables economic growth and stability, significantly contributes to human development, and its cost and availability influences the competitiveness of an economy and the cost of living for the country's citizens (DME, 2007). The consumption of energy, and therefore also the availability and affordability of energy, correlates well with the human development index (HDI) and shows that energy is required for the social well-being of a country. To illustrate this, Figure 1-1 shows the human development index (a composite measure based on health, longevity, education and economic standards of living) as related to the per capita consumption of electricity (UNDP, 2005 as stated in IAEA, 2006).

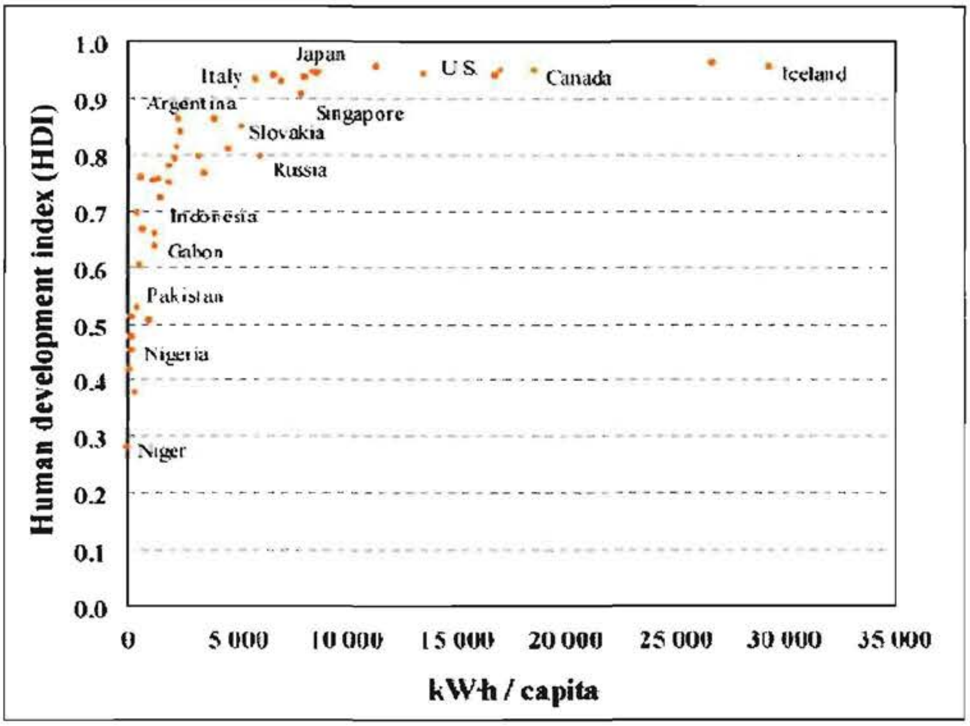
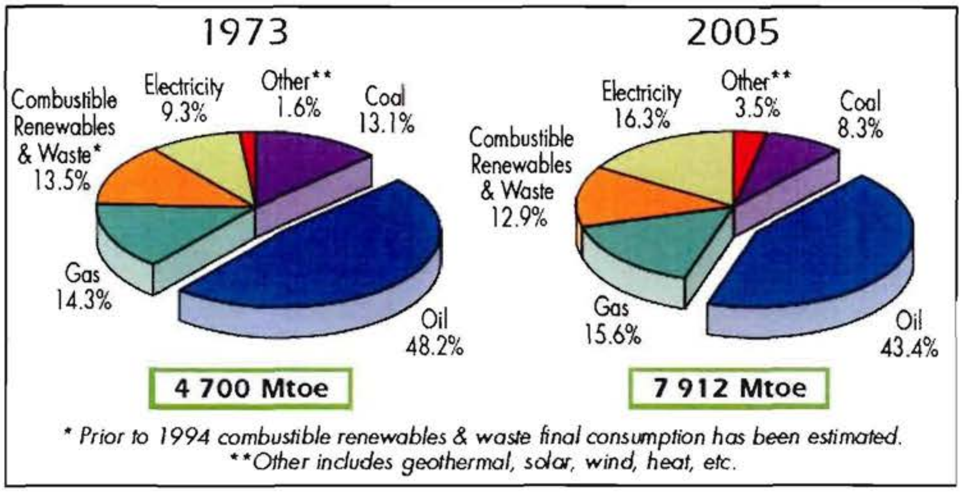


Figure 1-1: HDI per capita electricity consumption (UNDP, 2005 as given in IAEA, 2006)

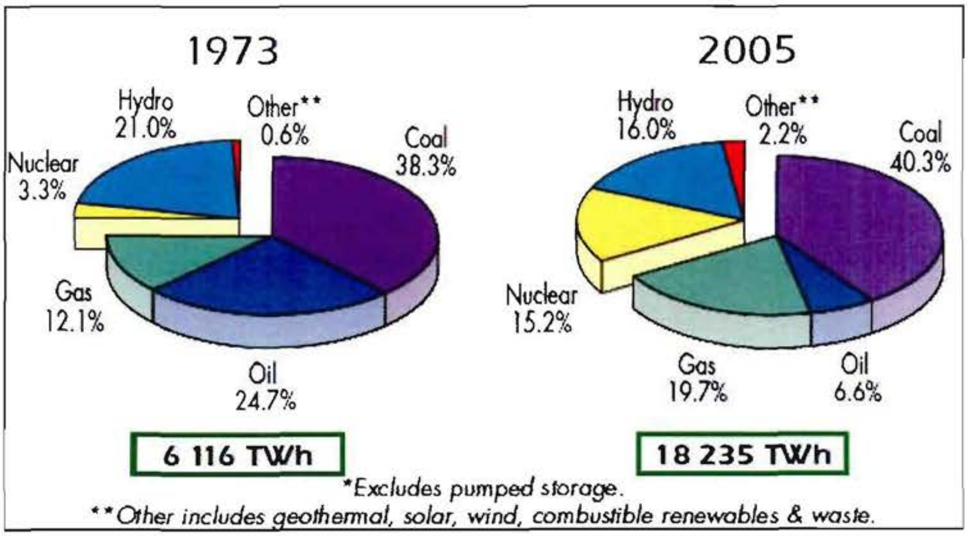
However, the energy issue is not simply to increase the procurement of energy in order to sustain human and economical growth and development, but includes the efficient generation and use thereof, as well as being sensitive to the harmful effects that energy generation have on the environment and human health.

The current energy sector (see Figures 1-2 and 1-3) is heavily dependent on fossil fuels such as coal, oil and natural gas, and while they are relatively inexpensive and have huge reserves, they are finite and are being depleted by the growing energy demand. Moreover, fossil fuels release huge amounts of carbon dioxide during the combustion process utilized to generate energy, and therefore significantly contribute to polluting the environment and affecting human health. Add to these aspects the geopolitical sensitivity and location of the reserves and the ever-increasing price of crude oil, it is no surprise that severe concerns regarding energy security have arisen.



** Prior to 1994 combustible renewables & waste final consumption has been estimated.*
***Other includes geothermal, solar, wind, heat, etc.*

Figure 1-2: 1973 and 2005 Fuel Shares of Total Final Consumption (IAE, 2007)



**Excludes pumped storage.*
***Other includes geothermal, solar, wind, combustible renewables & waste.*

Figure 1-3: 1973 and 2005 Fuel Shares of Electricity Generation (IAE, 2007)

The unit Mtoe (mega ton oil equivalent) relates energy to oil quantity (by mass) or *vice versa* and is very informative when evaluating the feasibility and practicality of replacing or supplementing oil with alternative sources of energy. The following table (Table 1-1) contains the conversion factors associated with Mtoe and the main units of energy (IAE, 2007).

Table 1-1: Conversion factors for energy (IEA, 2007)

To:	TJ	Gcal	Mtoe	MBtu	GWh
From:	*multiply by:*				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

1.1 ENERGY SECURITY

Energy security of a country or region is primarily concerned with ensuring their energy supply through managing demand- and supply chains. It is not restricted to countries that are net importers of energy (such as South Africa) but extends to net exporters of energy as well and is recognized in the IEA's World Energy Outlook 2005 (DME, 2007):

> *"Concerns among consuming countries about security of supply are matched by concerns among producing countries about security of demand. Consuming countries will continue to seek to diversify their energy mix, while producing countries will continue to seek to diversify their economies."*

While countries that are net importers of energy focus on diversifying their energy supply and acquiring sufficient amounts of energy at acceptable rates, the World Bank's definition of energy security incorporates socio-economic considerations and states (DME, 2007):

> *"Energy security means that a country can steadily produce and consume energy at reasonable prices in order to promote economic growth and, by*

> *doing so, to reduce poverty and directly improve the population's living standards by expanding access to modern services in the energy sphere."*

However, these definitions focus on the physical security of energy (supply and demand) and socio-economic responsibilities (reasonable prices, economic growth and poverty alleviation) but neglect to incorporate issues regarding the environment and climate change, both aspects which play a vital role in policy decision-making. A definition of energy security that considers these issues is that of the World Energy Council, which emphasizes energy sustainability by asserting that (DME, 2007):

> *"Energy sustainability embraces access, reliability and security, and environmental impacts."*

In light of these definitions, and considering the increasing convergence among economic sectors, the South African government proposes the following definition regarding energy security (DME, 2007):

> *"Energy security means ensuring that diverse energy resources, in sustainable quantities and at affordable prices, are available to the South African economy in support of economic growth and poverty alleviation, taking into account environment management requirements and interactions among economic sectors."*

1.2 SUSTAINABLE DEVELOPMENT

Sustainable development connects economic development with environmental protection and is defined as (WCED, 1987 as quoted by IAEA, 2006):

> *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

In light of this definition, the IAEA (2006) further elaborates that:

> *"(sustainable development) emphasizes the importance of economic development to satisfy needs, and the importance of the natural environment as both a resource provider and waste absorber. And it requires that we judge today's options not only by today's immediate political, economic or*

environmental implications, but also from the perspective of future generations who will benefit from our successes in achieving sustainable development, or suffer from our failures."

Probabilistic values for the projected growth in population (Figure 1-4) and energy requirements (Figure 1-5) are informative with regard to future energy needs and the rate at which capacity additions may be required. However, these projections cannot determine which energy-generating technologies will be successful in future energy markets, for instance if fusion will become a viable, economic source of electricity. A more practical policy is that of sustainable consumption according to which there should be no net loss of total energy resources at the current operating values.

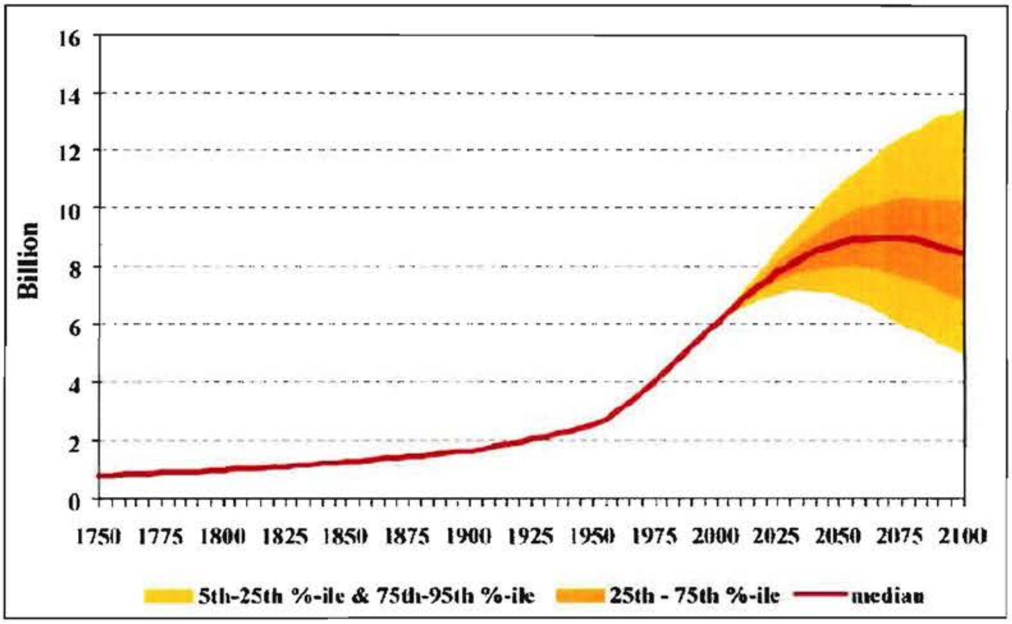


Figure 1-4: Probabilistic global population projections to 2100 (IAEA, 2006)

Thus, the energy technology should be able to supply in the needs of the growing population and economy, as well as conform to the definitions of sustainable development and energy security. Since these definitions are not limited to the generation of energy but span the entire life cycle of energy, the final consumption of energy should also conform to these definitions as far as practically possible. In this regard, liquid fuels play a major role since the transportation sector constitutes a significant portion of the world's primary energy consumption. Although (conventional) liquid fuels are also produced via coal liquefaction and biomass conversion processes, they are primarily produced from crude oil, making them a fundamental concern regarding energy security and the environment.

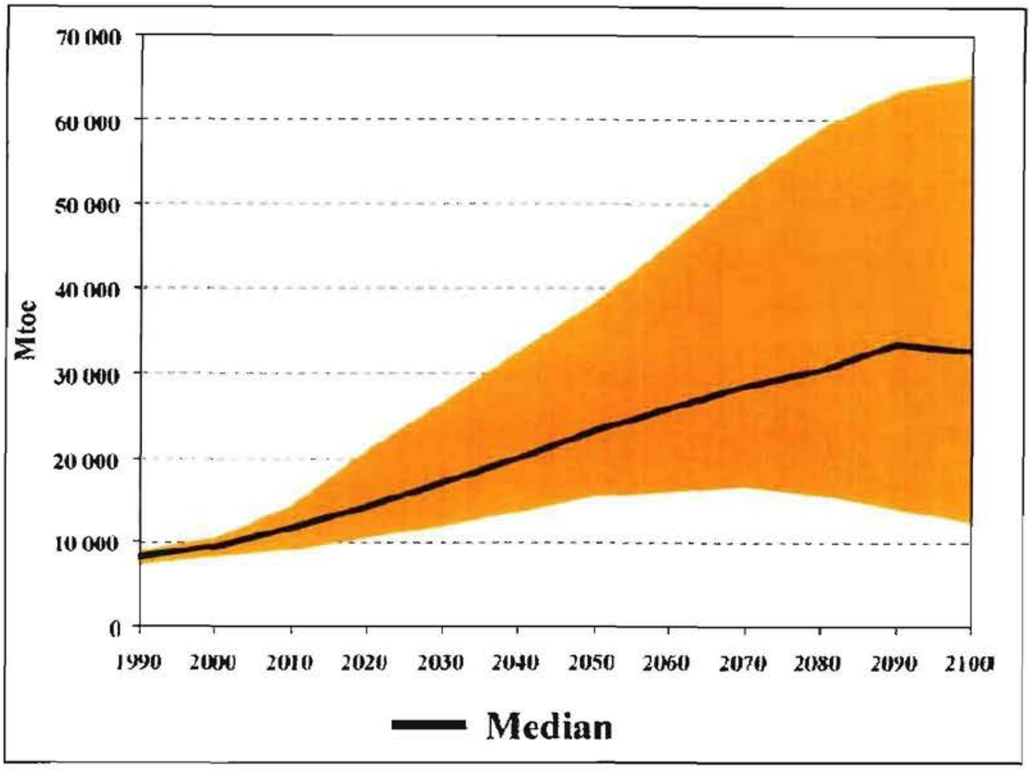


Figure 1-5: Projected global primary energy use through 2100 (IAEA, 2006)

Therefore, the energy issue becomes the development and implementation of an energy cycle (primary energy source and energy carrier) that is capable of conforming to the constraints imposed by the definitions of sustainable development and energy security.

1.3 NUCLEAR ENERGY AS PRIMARY ENERGY SOURCE

Nuclear energy is a mature technology with 443 nuclear power reactors operating globally as of April 2006, generating a total of 370 GW(e) and supplying approximately 16% of the world's electricity (IAEA, 2006). Therefore, nuclear fission energy can be considered a proven, technologically- and economically feasible primary energy source. However, since the great majority of these reactors are PWRs and BWRs (to a lesser extent), the lack of large-scale operating experience and commercial application of HTGRs and other advanced nuclear reactor systems may result in uncertainties regarding their ultimate feasibility at the desired scale of operation. Although not without merit, these concerns mainly arise from misconstruing the lack of commercial experience as a sign of unfeasibility while not taking into account the public and political attitude towards nuclear energy after the TMI and Chernobyl accidents. Furthermore, the significant R&D and testing that have been performed on these advanced reactor systems, especially on gas-cooled reactor concepts (Chapter 2), appear not to enjoy the favour and acknowledgement they have earned and should have been attributed with.

The following figure (Figure 1-6) shows the nuclear electricity generation and capacity additions since 1960, with the orange bars indicating the additions in new nuclear generating capacity (GW) and the red line representing the annual nuclear electricity generation (TWh).

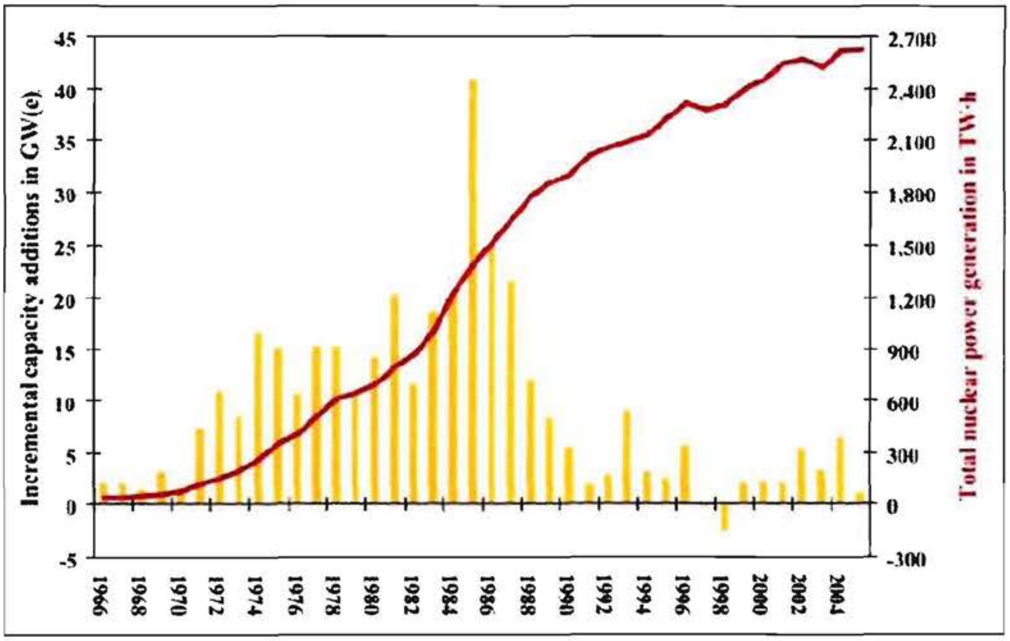


Figure 1-6: Nuclear electricity generation and capacity additions since 1966 (IAEA, 2006)

From this figure, it is clear that the technology is mature and even though the Three Mile Island (1979) and Chernobyl (1986) accidents hampered its implementation (decline in capacity additions), nuclear energy generation still increases due to growth in the Asian markets, improved plant availability and increased generating capacity. Improvements in the design, operating, maintenance and management of nuclear power plants make it extremely improbable that accidents similar to TMI and Chernobyl could occur. Moreover, nuclear energy has significant advantages over competing power-generating options that are shown throughout this section.

Apart from maturity and technical feasibility, another vital aspect to consider is that of economic feasibility, wherein nuclear energy has a considerable advantage over renewable energy sources while being competitive to fossil derived energy options. The following figure (Figure 1-7) graphically illustrates the ranges of new generating cost estimates from seven studies that were performed in the past few years, except for oil-fired generation that was only estimated in one study (IAEA, 2006).

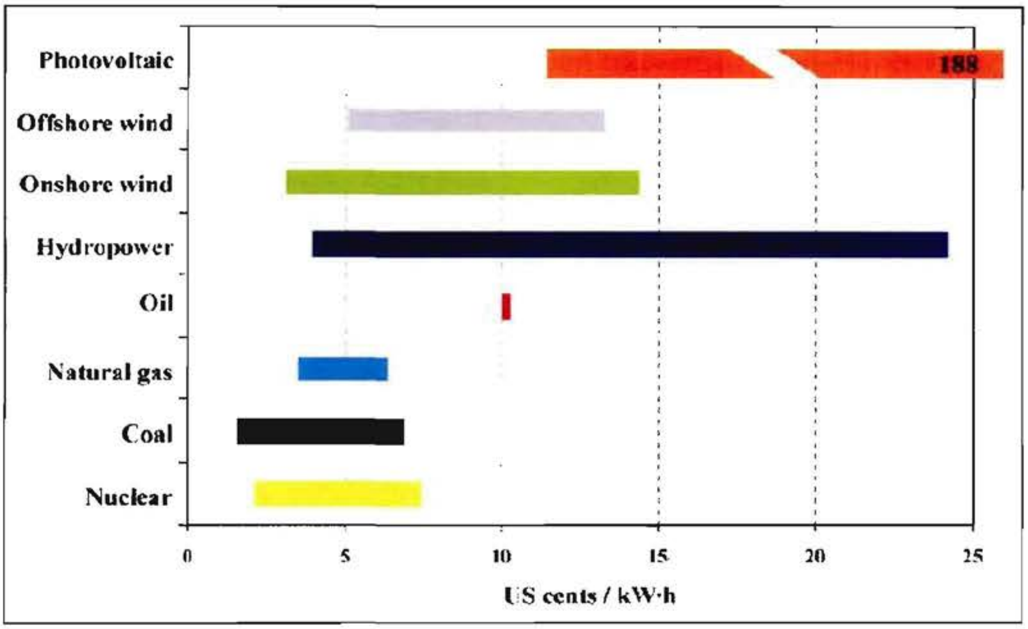


Figure 1-7: Ranges of levelized costs for electricity generating technologies (IAEA, 2006)

From this figure, it is evident that the cost range differs significantly from one study to another, with the high-end value at least 100% greater than the low-end value, which is probably due to different technological assumptions, national factors and regulatory compliances (IAEA, 2006). Considering that the constraints of sustainable development and energy security effectively rules out the conventional fossil derived energy options, nuclear energy is the most affordable (conventional) energy option. In order to promote the use of fossil-fired power stations, their conventional systems have been adjusted to include carbon capture and storage (CCS), which captures and permanently stores the majority of the carbon dioxide and carbon monoxide in the effluent stream of the plant. CCS reduces the emission of GHG into the atmosphere and enables fossil-fired power stations to conform to environmental legislation or to reduce their carbon-taxes when and if these are implemented.

The next aspect to consider is therefore the emission of carbon dioxide and other carbon consisting compounds into the atmosphere. As mentioned previously, this is required due to the correlation between global warming and greenhouse gases, specifically carbon dioxide. To this extent, the entire cycle of the technology should be considered and includes extracting of the resources, building the required facilities, transporting the material, conversion of the resource to energy, and waste management. The following figure (Figure 1-8) shows the carbon-equivalent emission rates of power produced from alternative energy sources.

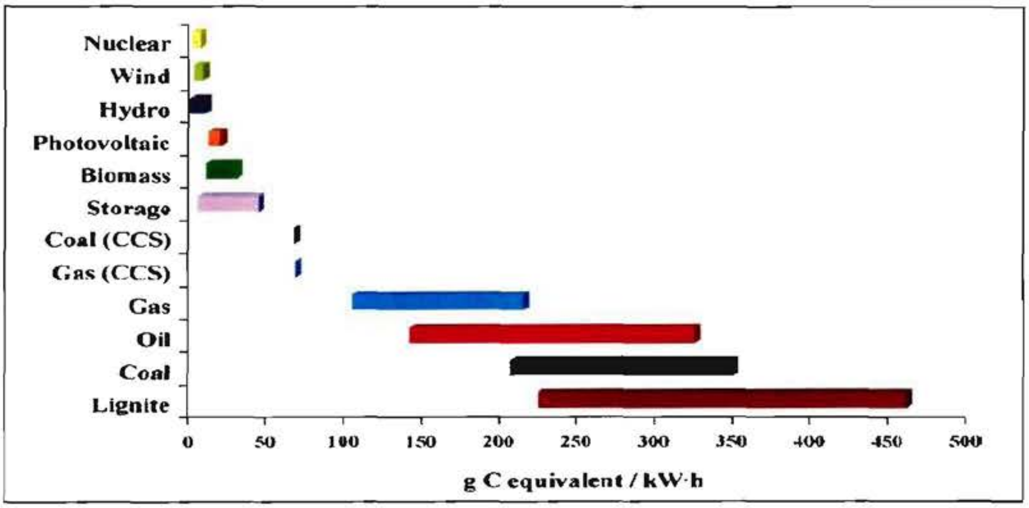


Figure 1-8: CO_2 emission rates for electricity generating alternatives (IAEA, 2006)

If it is assumed that greenhouse gas emissions, specifically CO_2 emissions, will be regulated in the near future, this figure effectively rules out all fossil-fired power plants even if CCS technologies are employed. When this information is combined with that of the costs attributed to each energy option (Figure 1-7), nuclear energy is the most attractive energy option available at present operating conditions and technological standards. However, it would be irresponsible not to consider the external cost attributed to each energy option. External costs are the costs that the public have to suffer but the beneficiaries of the energy option do not have to pay (for instance the health costs due to a highly polluting power plant). A summary of the external costs, including health and environmental costs, for each of the energy options is shown in the following figure (Figure 1-9; IAEA, 2006).

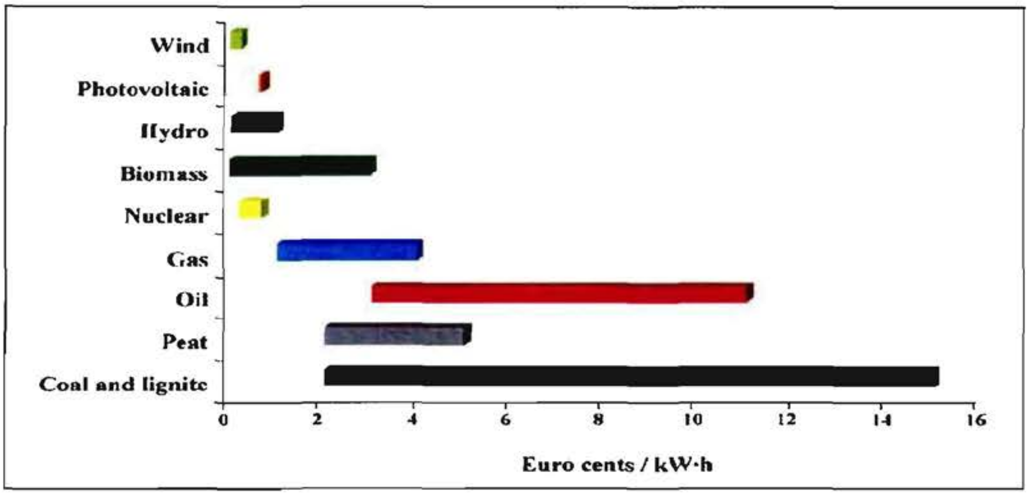


Figure 1-9: Summary of external costs of each energy option (IAEA, 2006)

In light of this information, it is clear that nuclear energy is the most attractive energy option when technological maturity, affordability, sustainability, cost and social responsibility are considered. However, since the entire life cycle should be taken into account, the next issue to address is which secondary energy carrier and fuel component is to be used as alternative to fossil derived energy.

1.4 HYDROGEN AS ENERGY CARRIER

Hydrogen, like electricity, is an energy carrier and does not occur naturally in significant quantities, which necessitates it to be produced. Upon combustion, hydrogen does not release any greenhouse gases, only water, and can be considered as a clean fuel. However, as energy carrier it is only as "clean" as the plants that produce it, which is also true for electricity generation. Therefore, the plants responsible for its production should be as "clean" as possible to allow it to be considered as environmentally benign. This aspect favours its production by nuclear energy or renewable energy sources, but due to the intermittent characteristics of renewable energy sources, its production by nuclear energy is preferred.

Hydrogen as energy carrier has significant advantages over electricity since it can be stored for future use, which is not the case for electricity. Many authors consider the storage and transfer capabilities of hydrogen as its key enabling technologies with regard to the proposed hydrogen economy (Forsberg, 2005; Marban & Valdez-Solis, 2007; BRHS, 2007). A fundamental aspect of the hydrogen economy is that hydrogen and electricity are inter-convertible such that fuel cells covert hydrogen to electricity, while electrolysis converts electricity to hydrogen (Forsberg, 2005). However, the conversion processes are associated with an undeniable lack of efficiency (Marban & Valdez-Solis, 2007). Moreover, implementing a hydrogen infrastructure capable of supplying in the energy demands of the population and economy will require large capital investments and take long to implement, which additionally make it less attractive. Therefore, hydrogen's most promising applications are its use in the automotive industry (as fuel component in internal combustion engines or most probably in FCVs) and as industrial resource. With respect to its automotive application, hydrogen can replace the use of fossil fuels and thereby alleviate concerns regarding energy security and sustainability as well as carbon dioxide emissions. As automotive application, hydrogen can obtain an 18 % share of the global primary energy demand as is illustrated in the following figure (Figure 1-10; Marban & Valdez-Solis, 2007).

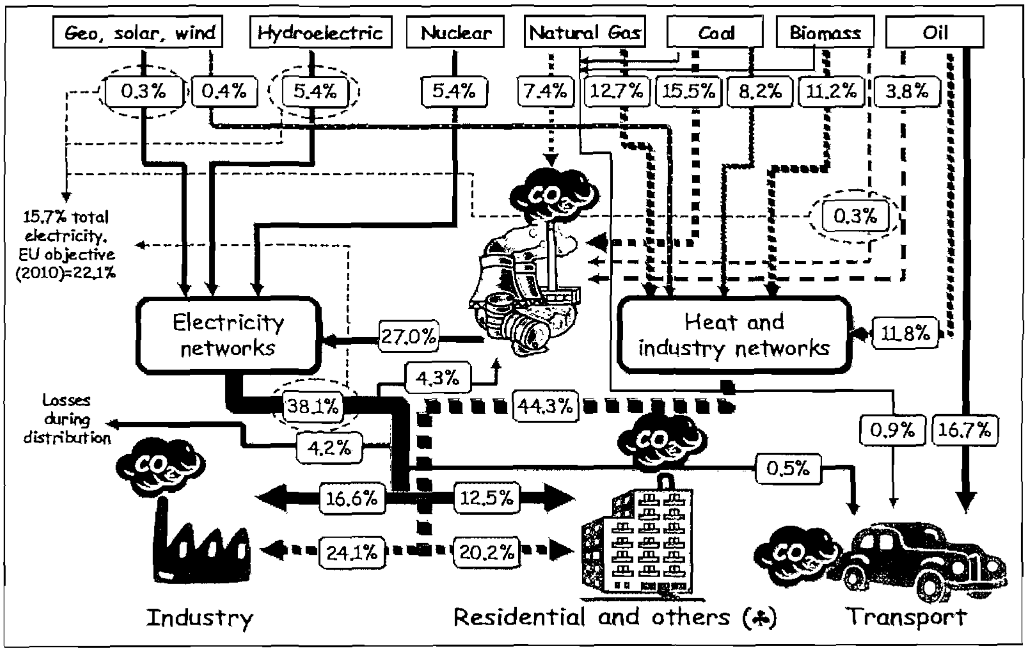


Figure 1-10: Current energy scenario (Marban & Valdez-Solis, 2007)

In addition to its 18 % market share due to the transportation sector, hydrogen can have significant application regarding the heat energy requirements of the industrial sector (24.1 %) by replacing the fossil fuels that are combusted to generate heat. Moreover, the markets of hydrogen not associated with heat energy or the transportation sector are also expected to increase significantly in the near- to mid-term future. These aspects make hydrogen of considerable value and importance to any future energy scenarios and require thorough consideration, especially with regard to the so-called hydrogen economy.

1.5 THE HYDROGEN ECONOMY

Hydrogen has many uses; it is widely applied in the chemical and petrochemical industries such as the refining of fossil fuels, the production of ammonia, methanol and iron units, and can be used as an energy carrier in the transportation sector. The markets for hydrogen can be categorized into current or near-term, mid-term and long-term markets. The near-term markets relate to those that are expected to grow over the next five years, the mid-term markets could develop over the next five to ten years, followed by the long-term markets expected after ten years of development (Yildiz *et al.*, 2005).

1.5.1 CURRENT AND NEAR-TERM MARKETS

The current and near-term markets for hydrogen are primarily those involved with the refining of fossil fuels and production of chemical products, and favour a large, centralized hydrogen production facility.

- **Oil-refining industry**

Hydrogen is used in the oil-refining industry to produce (cleaner) transportation fuels that are able to adhere to environmental regulations (low sulphur content), and for the refining of crude oils by increasing the hydrogen-to-carbon ratio (Yildiz *et al.*, 2005). Thermal cracking or hydro-cracking can accomplish the adjustment to the hydrogen-to-carbon ratio. During thermal cracking, the "excess" carbon is converted to carbon dioxide and released, whereas during hydro-cracking the hydrogen content of crude oil or coal is increased by the addition of large quantities of hydrogen (Forsberg, 2005).

- **Ammonia industry**

Ammonia (NH_3) is generally produced by catalytically reacting hydrogen with atmospheric nitrogen at elevated temperatures and pressures. Additionally, it is an intermediate product used in the manufacturing of various nitrogen fertilizer materials and industrial products (Yildiz *et al.*, 2005).

- **Methanol industry**

Hydrogen is used in the production of methanol, which is primarily an intermediate product used in the manufacturing of materials such as formaldehyde, methyl tertiary-butyl ether (MTBE) and acetic acid. To this extent, formaldehyde and acetic acid are used as adhesives and bonding agents in construction materials, whereas MTBE is an oxygenate in reformulated transport fuel (Yildiz *et al.*, 2005).

- **Direct reduction of Iron (DRI)**

The direct reduction of iron ore (DRI) process is an alternative process for converting iron ores into iron and steel. Whereas the traditional iron production methods use carbon (coke), the DRI method uses synthesis gas or syngas (mixture of H_2, CO and CO_2) to reduce the iron oxides to iron metal according to the following major chemical reactions (Forsberg, 2007):

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \qquad \textbf{Reaction 1-1}$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO \qquad \textbf{Reaction 1-2}$$

The DRI process has lower capital investments than the traditional iron production methods, but a low-cost source of hydrogen is essential to the economic feasibility of the process. The primary market for DRI is to provide a purified iron feed to electric-arc furnaces (EAFs) for the production of various steel mills and are environmentally cleaner operations than blast furnaces (Forsberg, 2007).

- **Oil or tar sands**

Oil or tar sand deposits consist of heavy, viscous oil called bitumen (10-12%), mineral matter such as sand and clay (80-85%), and water (4-6%). After removing the material matter and water, it is sent to an upgrading facility where the bitumen is converted into synthetic crude oil through coking, desulphurization, and the addition of hydrogen (Yildiz *et al.*, 2005). The hydrogen-to-carbon ratio of oil or tar sands may be as low as one and must be increased to two for application as a liquid fuel (Forsberg, 2005).

- **Other chemical applications**

Various other applications for hydrogen are possible and include the manufacturing of edible fats and oils, electronics, metals, float glass, and public utilities (Yildiz *et al.*, 2005). Coal-to-liquid (CTL) processes use hydrogen to convert coal to liquid fuels and are currently employed by SASOL in South Africa, but are generally considered as a mid-term application due to the technology not being widely available and because higher efficiencies with less CO_2 emissions are desired.

1.5.2 MID- AND LONG-TERM MARKETS

The medium- to long-term markets for hydrogen are primarily concemed with the production of liquid fuels and generation of electricity. However, these technologies still require significant improvements and development before they can be implemented on an industrial scale.

- **Coal liquefaction**

There are two classes of coal liquefaction, direct- and indirect liquefaction. During direct liquefaction of coal, the coal is partially dissolved in a liquid solvent at high pressure and temperature to produce a synthetic crude oil. Since coal is hydrogen-deficient, the liquefaction of solid coal requires hydro-cracking to increase the hydrogen-to-carbon ration, a process that is continued during refining of the synthetic oil (Yildiz *et al.*, 2005). Considering that the best direct liquefaction method has an efficiency of 65%, and that a fraction of the remaining coal is used to produce hydrogen, only a small portion (perhaps half) of the original coal forms part of the final liquid fuel product (Forsberg, 2007).

During indirect liquefaction of coal, the carbon, oxygen and water are converted to synthesis gas and thereafter to liquid fuels. All existing commercial liquefaction plants use the indirect process, with the Fisher-Tropsch process the most abundant. This method has three major reactions namely oxidation, water-gas-shift (WGS) and Fischer-Tropsch, which are given below (Forsberg, 2007):

Oxidation reaction:

$$2C + O_2 \rightarrow 2CO$$ **Reaction 1-3**

Water-gas-shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$ **Reaction 1-4**

Fischer-Tropsch:

$$\left(\frac{n}{2} + m\right)H_2 + mCO \rightarrow C_mH_n + mH_2O$$ **Reaction 1-5**

These processes are important since any chemically reduced carbon-containing feed (coal, garbage, natural gas, sewage sludge, biomass and *etcetera*) can be converted to liquid hydrocarbon fuels (Forsberg, 2007).

- **Oil shale**

Huge oil shale resources exist that can be converted to liquid fuels and may potentially be a large hydrogen market in the future. In contrast to the oil or tar sand deposits, the organic compounds in oil shale are solid, do not melt and are not soluble. Therefore, in order to convert oil shale into liquids, the hydrocarbons must be converted from a solid to a liquid state. There are two conventional approaches to achieve this. The first approach in-situ fractures and heats the shale to obtain gases and liquids at wells. Alternatively, the shale is mined, heated and then hydro-cracked to obtain a suitable hydrogen-to-carbon ratio, followed by waste disposal and stabilizing (Yildiz *et al.*, 2005).

- **Peak-electricity**

The variable demand for, and corresponding price of, electricity is a potentially large hydrogen market aimed at generating electricity from hydrogen when the price of electricity is high. Such a peak-electricity nuclear system (PENS) is shown in Figure 1-11 and consists of the following three stages (Forsberg, 2005; Yildiz *et al.*, 2005):

1. Hydrogen production: Nuclear-hydrogen, and optionally oxygen, is produced at a constant rate to minimize the production costs.
2. Hydrogen storage: Economic, large-scale storage of hydrogen and oxygen (optional) in underground storage facilities (only known low-cost storage technology).

3. Peak electricity generation: Fuel cells convert hydrogen to electricity during periods of high demand for electrical power. The fuel cells must be able to store several times the amount of hydrogen produced at constant rate and operate highly variable – from zero to many times the production rate.

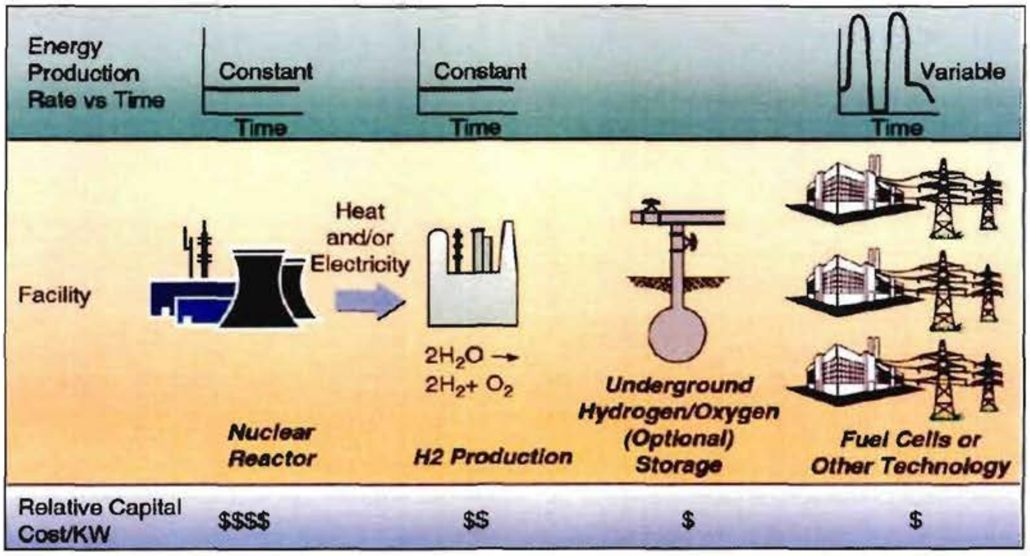


Figure 1-11: Peak-electricity nuclear system (Forsberg, 2005)

The PENS is proposed to operate as a stand-alone facility and its economic feasibility depends on the costs and efficiencies of the fuel cells.

- **Transportation**

Hydrogen fuel cells or hydrogen combustion engines can be used in the transportation sector to replace or supplement the conventional fossil fuel internal combustion engines (ICEs). However, with respect to the mid- and long-term markets, hydrogen fuel cell powered vehicles are already available on the market in some countries (USA and Europe) but wide scale implementation thereof has not been achieved.

- **Other long-term markets**

Other long-term markets for hydrogen include biomass conversion, carbon dioxide vehicle recycle systems, and commercial markets with co-production of heat and energy in buildings (Forsberg, 2005; Forsberg, 2007).

1.6 HYDROGEN PRODUCTION

Hydrogen is a secondary energy carrier and can be produced from various primary energy sources ranging from fossil fuels and nuclear power to renewable energy sources such as wind, tidal and solar power. The annual world production of hydrogen was 5 x 10^{11} Nm^3 in 2005, amounting to approximately 2 % of the world's primary energy demand, with the utilization of fossil fuels contributing 96 % of the total world production (illustrated in Figure 1-12; Ewan & Allen, 2005).

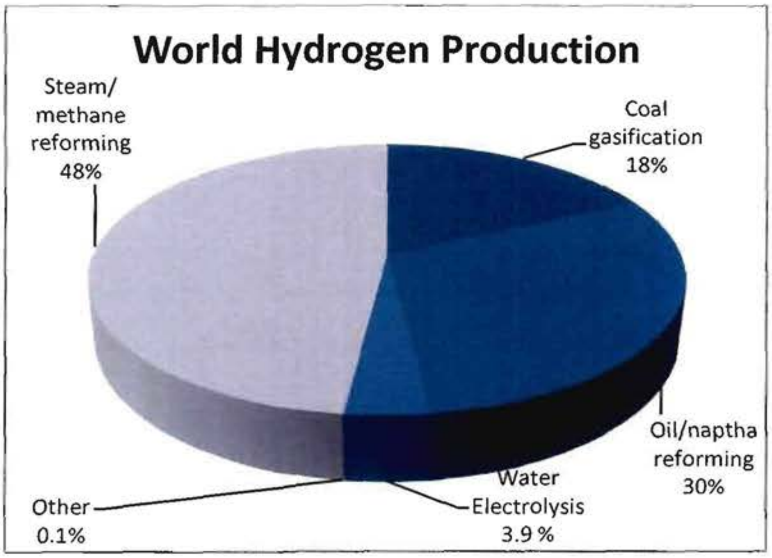


Figure 1-12: World hydrogen production routes in 2005 (Ewan & Allen, 2005)

Even though the reforming of fossil fuels currently dominates the production of hydrogen, several promising alternative production routes exist. A summary of these routes to hydrogen is illustrated in the following figure (Figure 1-13; Ewan & Allen, 2005). The differences in the hydrogen production methods include primary energy source(s), efficiencies, processes, amount of carbon dioxide released, land use required, investment and operating costs, and integration with a nuclear power plant (NPP). Integration with a nuclear power plant is a very significant aspect and effectively means to substitute the heat and/of electric energy generally acquired by the combustion of fossil fuels. In this manner, the fossil fuel requirements and corresponding carbon dioxide emissions are reduced. Keeping in mind the possible depletion of the fossil fuel reserves and subsequent price increases, and that carbon sequestration (capturing) may soon be mandatory, this may be a very important economical aspect.

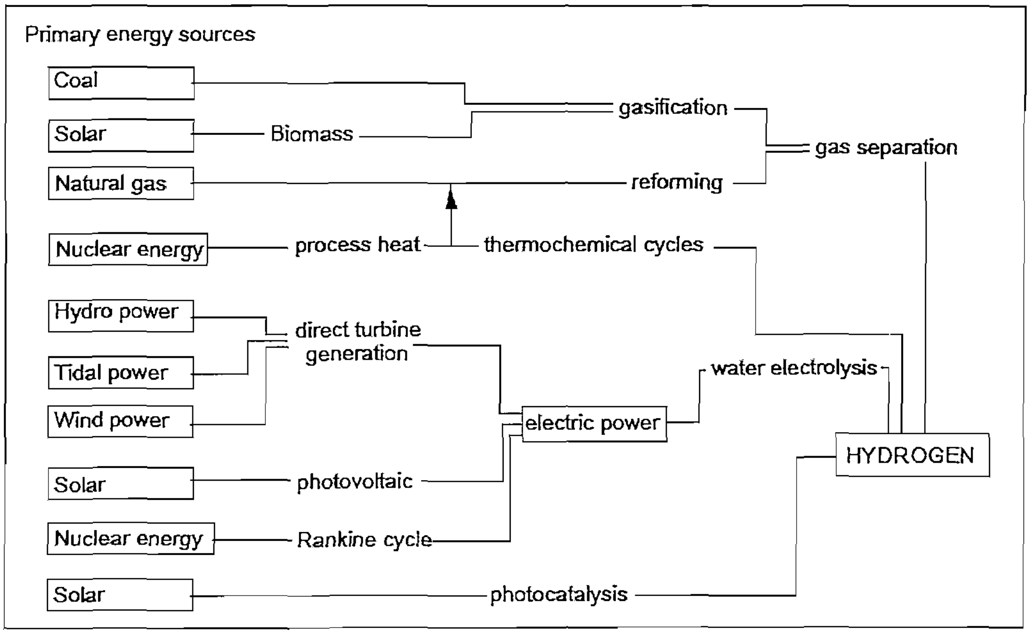


Figure 1-13: The primary energy sources considered and their routes to hydrogen (Ewan & Allen, 2005)

In order to determine which production method is the most promising route to hydrogen, performing a simple figure-of-merit (FOM) assessment may give valuable insight into the efficient use of the primary energy source involved (Ewan & Allen, 2005).

1.6.1 FIGURE-OF-MERIT ASSESSMENT

A FOM assessment considers the carbon dioxide emission reduction, primary energy availability, land use implications and hydrogen production cost such that it reflects the ability of the different sources and processing routes to meet the underlying needs and practical demands of energy on a large scale (Ewan & Allen, 2005). The FOM assessment performed by Ewan & Allen (2005) considered fourteen routes to hydrogen that included additional strategies for carbon sequestration and high-temperature nuclear reactors.

The first FOM is the residual CO_2 following the conversion of 1 GJ of primary energy to hydrogen and is shown in the following figure (Figure 1-14; Ewan & Allen, 2005).

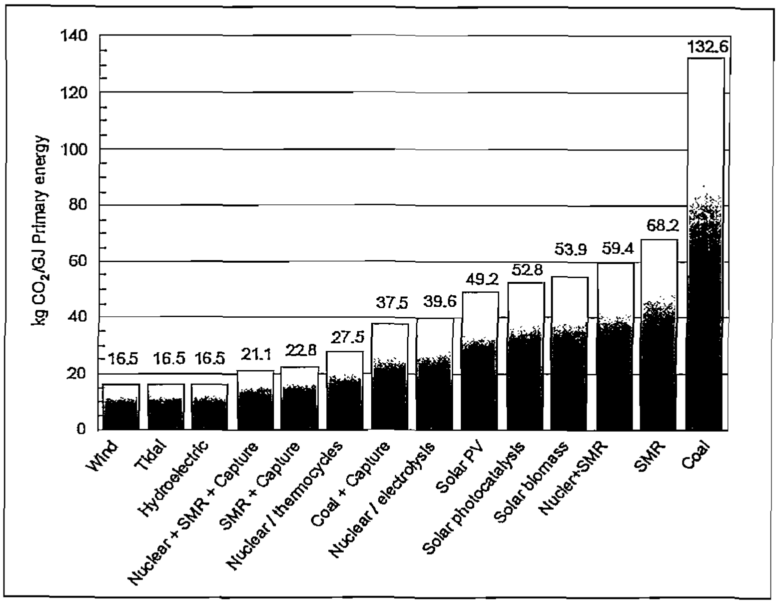


Figure 1-14: Figure-of-merit 1 (Ewan & Allen, 2005)

The second FOM is the route-specific ratio of the maximum collected power available within the national boundary (GW) to the total national average power requirement (Ewan & Allen, 2005). The third FOM is shown in Figure 1-15 below and is the effective area required per MW of hydrogen power generated with the applicable conversion efficiencies taken into account (Ewan & Allen, 2005).

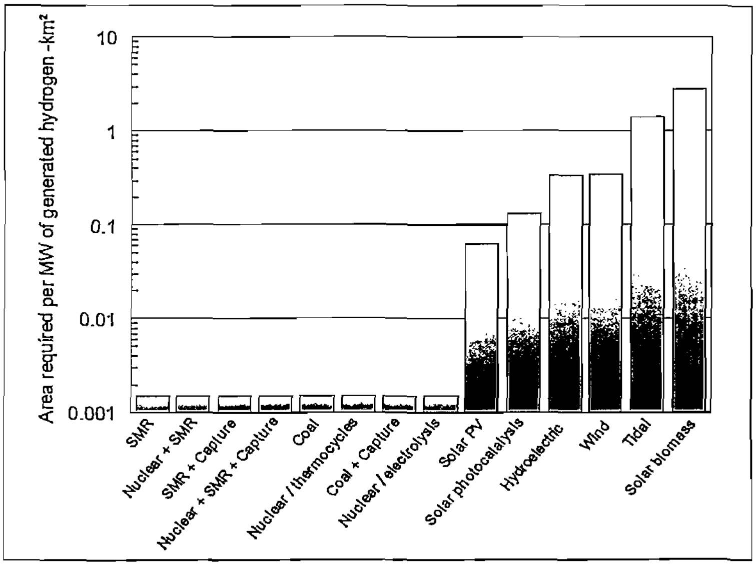


Figure 1-15: Figure-of-merit 3 (Ewan & Allen, 2005)

The fourth FOM is the cost per tonne of hydrogen produced and is illustrated in the following figure (Figure 1-16; Ewan & Allen, 2005).

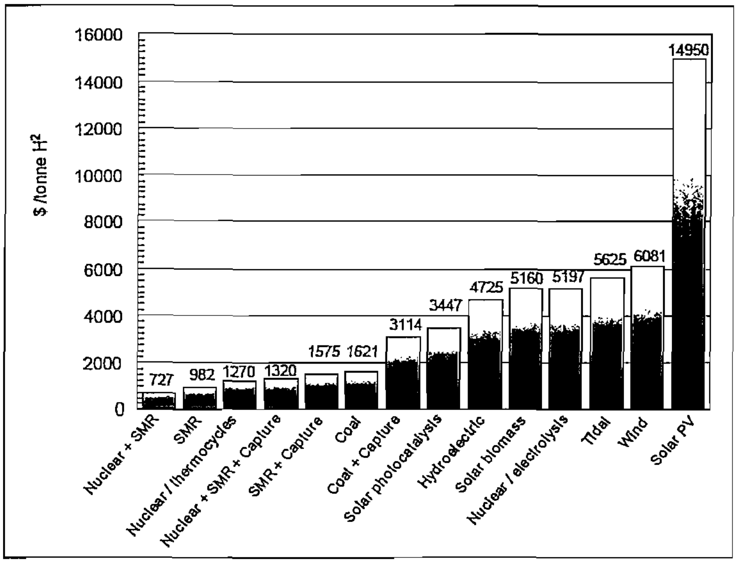


Figure 1-16: Figure-of-merit 4 (Ewan & Allen, 2005)

The overall FOM is shown in Figure 1-17 and is calculated by the following equation (Equation 1-1; Ewan & Allen, 2005):

$$FOM = \prod_{i=4} FOM_i$$ **Equation 1-1**

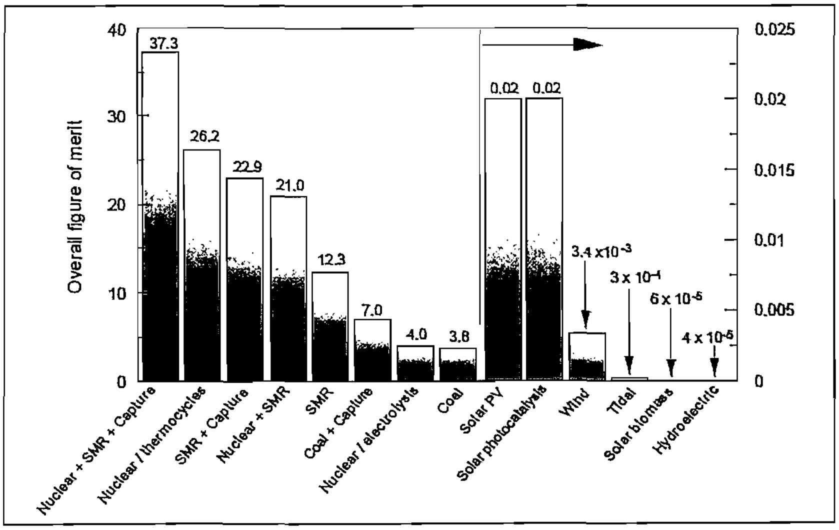


Figure 1-17: Overall figure-of-merit (Ewan & Allen, 2005)

When considering the abovementioned four key measures, the most promising routes to hydrogen are clearly those related to the high-density primary energy sources of nuclear energy and fossil fuels. According to this assessment, the "best" route to hydrogen is the nuclear production of hydrogen by the steam/methane reforming (SMR) process with carbon sequestration (Ewan & Allen, 2005). Taking into account that the CCS technologies and thermo-chemical processes still require further technical and economical development, the next best route to hydrogen is the nuclear production of hydrogen by the steam/methane reforming process without carbon sequestration. Therefore, since the technology applicable to both the nuclear and SMR process is proven and currently available, it forms the base process to be investigated in this study. However, other hydrogen production technologies such as the Hybrid-Sulphur cycle (HyS), partial oxidation of methane (POX) and plasma-arc reforming of methane will also be discussed. It is important to note that the methane requirement of the SMR, POX and plasma-arc reforming processes do not allow them to be sustainable but they are rather considered as transitional technologies while transforming to a sustainable energy sector. This is due to requiring significantly less fossil fuels (methane) and consequently producing less CO_2 emissions than traditional fossil derived energy options such as coal and oil. Moreover, the uranium requirement of nuclear fission reactors may also be of concern in long-term energy scenarios if the expected increase in nuclear-generated energy is realised and additional low-cost uranium sources are not discovered. In this regard, the successful implementation of "breeder" nuclear reactors may be of vital importance since thorium resources are very extensive, even in terms of long-term energy scenarios. Breeder reactors convert the thorium constituent of nuclear fuel into uranium, which could be supplied to traditional nuclear reactors or used within the cycle to generate electricity or process heat.

(Please note that some discrepancies exist between the FOM assessment of Ewan & Allen (2005) and the study performed by the IAEA (2006). For instance, the emission of CO_2 according to Figure 1-14 is less for wind- than nuclear energy, while in Figure 1-8 (IAEA, 2006) nuclear energy produces less CO_2 than wind energy. This could be due to the use of different (specific or limited) data sets or due to differences in investigation methodologies such as assumptions or operational boundaries (inclusion of electrolysis in the analysis of wind energy). However, both studies in their entirety and essence are employed to relate the reasoning behind converting to a nuclear- and hydrogen based energy market.)

1.7 THE SOUTH AFRICAN ENERGY SITUATION

South Africa has large reserves of coal and uranium but limited reserves of natural gas and crude oil. Renewable energy in the form of hydroelectric power plays a very limited role due to low rainfall, while the other renewable energy sources remain largely untapped. The primary energy supply in South Africa is dominated by domestically supplied coal (64%) and imported crude oil (22%) as is shown in Figure 1-18. The large coal reserves (55 367 Mt) is mainly used for electricity generation (40.1%), liquefaction (18.0%) and export purposes (30%). The coal-fired power stations supply more than 90% of South Africa's electricity, complemented by nuclear energy (5.8%), hydroelectric power (1.1%) and pumped storage (0.08%). South Africa relies heavily on imported crude oil for its liquid fuel demands, supplemented by coal liquefaction and the limited reserves of oil and gas off the coast Mossel Bay, with the transport sector accounting for approximately 76% of the consumption of petroleum products (Digest of South African Energy Statistics, 2005).

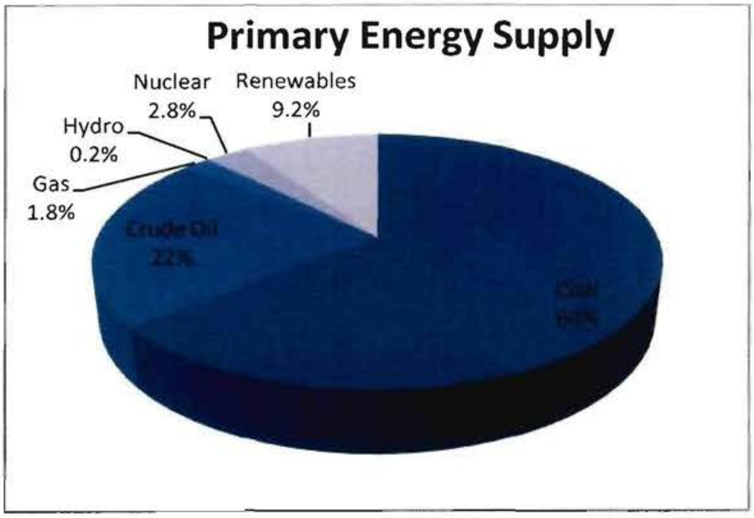


Figure 1-18: South African primary energy supply in 2002 (Digest of South African Energy Statistics, 2005)

Therefore, diversification of energy sources can be achieved by increasing the nuclear energy supply and production of alternative fuel products for the transportation sector. The production of supplementary and/or alternative fuel products are of utmost importance. During December 2005, South Africa experienced a shortage of liquid fuel products, which affected many sectors of the economy and led to an evaluation of the economic impact of such a disruption. A report on petroleum strategic stocks stated that (DME, 2007):

> *"in this context we evaluate the potential downside to the economy if no liquid fuels were available to the various sectors in the economy. By following a conservative approach we quantify the downside to be approximately R 925 million per day in 2005 of Gross Domestic Product (GDP) equivalent value over time."*

Assuming that a disruption in the electricity supply will have a similar (probably increased) negative impact on the economy, the diversification of energy sources are justifiable and of utmost importance. However, diversification of the energy resources must take into account environmental impact as well as being sustainable and affordable.

1.7.1 THE SOUTH AFRICAN ENERGY POLICY

The South African Energy Policy as stated in the White Paper on Energy Policy (1998) has the following five sector policy objectives as foundation (DME, 1998):

1. *"Increasing access to affordable energy services*
    a. *Government will promote access to affordable energy services for disadvantaged households, small businesses, small farms and community services.*
2. *Improving energy governance*
    a. *Governance of the energy sector will be improved. The relative roles and functions of the various energy governance institutions will be clarified, the operation of these institutions will become more accountable and transparent, and their membership will become more representative, particularly in terms of participation by blacks and women.*
3. *Stimulating economic development*
    a. *Government will encourage competition within energy markets.*
    b. *Where market failures are identified government will intervene through transparent, regulatory and other carefully defined and for time delineated mechanisms, to ensure effective delivery of energy services to consumers.*

   c. *Government policy is to remove distortions and encourage energy prices to be as cost-reflective as possible. To this end prices will increasingly include quantifiable externalities.*
   d. *Energy taxation will continue to remain an option within government's fiscal policy, but will be exercised with more consideration for the economic and behavioural impacts of such policies.*
4. *Managing energy-related environmental and health impacts*
   a. *Government will promote access to basic energy services for poor households, in order to ameliorate the negative health impacts arising from the use of certain fuels.*
   b. *Government will work towards the establishment and acceptance of broad national targets for the reduction of energy-related emissions that are harmful to the environment and to human health.*
   c. *Government will ensure a balance between exploiting fossil fuels and maintenance of acceptable environmental requirements.*
5. *Securing supply through diversity*
   a. *Given increased opportunities for energy trade, particularly within the Southern African region, government will pursue energy security by encouraging a diversity of both supply sources and primary energy carriers."*

These policy objectives are beneficial towards the implementation of nuclear energy and associated hydrogen production sectors due to diversification of energy sources, environmental and health impacts, and competition within the energy markets. However, cost effectiveness of these technologies may be of concern to consumers of electricity and/or hydrogen.

1.7.2 THE SOUTH AFRICAN NUCLEAR ENERGY POLICY

The South African Government views nuclear energy as the only economically viable alternative to coal as base load generation on a large scale. This is primarily due to South Africa's large reserves of uranium ore that could be extracted without difficulty by the vibrant and extensive mining community present in the country. Moreover, nuclear energy forms part of the securing of energy by diversification of primary energy sources as called for in the White Paper on Energy Policy of 1998 (DME, 2007).

The Government's Policy on nuclear energy is possibly the most aggressive promotion of nuclear energy in the world and has the following principles as quoted from the Nuclear Energy Policy and Strategy for the Republic of South Africa (DME, 2007):

1. *"Nuclear Energy shall be used as part of South Africa's diversification of primary energy sources to ensure security of energy supply.*
2. *Nuclear Energy programme shall contribute to economic growth and technology development in South Africa through investment in infrastructure, creation of jobs and development of skilled workers.*
3. *Nuclear Energy shall form part of South Africa's strategy to mitigate climate change and global warming.*
4. *All activities undertaken in pursuit of nuclear energy shall be in a manner that mitigates their impact on the environment.*
5. *All Nuclear energy sector activities shall take place within a legal regulatory framework consistent with international best practice.*
6. *Nuclear energy shall be used only for peaceful purposes and in conformity with national and international legal obligations.*
7. *In pursuing a national nuclear energy programme there shall be full commitment to ensure that nuclear and radiation safety receives the highest priority.*
8. *South Africa shall endeavour to use uranium resources in a sustainable manner. To the extent possible technologies chosen for Nuclear Power plant shall be those that allow for maximum utilisation of uranium resources including the use of recycled uranium.*
9. *Government shall encourage the development of appropriate institutional arrangements to ensure the development of human resources competent to discharge the responsibility of managing a nuclear infrastructure.*
10. *South Africa shall strive to acquire technology know-how and skills to enable design, development, construction and marketing of its own nuclear reactor and fuel cycle systems. To this end and industrial support base for the nuclear sector shall be developed as appropriate, taking into account the scale of the national programmes. Technology transfer shall be optimised in any procurement of nuclear and related equipment.*
11. *All facets of the nuclear energy sector shall always be subjected to appropriate safeguards and security measures.*

12. *Government shall support research, development and innovation in the use of nuclear technology. Government shall also support participation in global nuclear energy technology innovation programmes.*
13. *Government shall put in place effective mechanisms to protect and safeguard the South African nuclear energy industry Intellectual Property rights and innovative technology designs.*
14. *Government shall create programs to stimulate public awareness and inform the public about the nuclear energy program.*
15. *Government will ensure that adequate funding will be made available to support the technology development initiatives that are essential to the implementation of this policy. In addition, where appropriate, price support mechanisms can be implemented to enable the ongoing operations of key technologies."*

In light of these objectives, the future of nuclear energy is very promising in the South African political context, at least for the near-term future.

1.7.3 THE SOUTH AFRICAN LIQUID-FUELS POLICY

In the DME's Energy Security Master Plan of Liquid Fuels, energy security is to be obtained by diversification of energy resources, while the country's dependency on foreign oil imports is also to be reduced. Regarding the latter aspect, at least 30% of finished petroleum products are proposed to be manufactured from indigenous raw materials, which relates to an increase of 50 % of locally produced petroleum products. Similar to the energy policy, the environmental impact associated with the production and use of petroleum products are to be reduced while still being economically competitive and affordable to consumers. Considering these aspects, the use of hydrogen as an energy carrier in the automotive industry will comply with these policy objectives.

1.8 IMPORTANCE OF SAFETY

Safety may be the most important aspect of any technology and cannot be understated. Due to their characteristics, all energy systems have inherent risk to some extent. However, the perceived risk associated with these systems or technologies is significantly dependent on their familiarity and extent of implementation. In this regard, nuclear-assisted hydrogen production technologies are relatively unfamiliar (no commercial plants exist) and may be perceived as unsafe by the public or regulating authorities. Since this perception can result in significant delays and even prevent implementation of the technology, concerns regarding safety should receive special attention, especially with regard to the perception thereof by the public and authorities. To this extent, safety should be "proved" and promoted vigorously as soon as it is possible to do so.

1.9 IMPORTANCE OF REGULATIONS

Appropriate regulations and efficient regulatory bodies are of utmost importance in any technology, but even more so in the nuclear industry considering public acceptance and the potential occurrence of a catastrophic hazard such as Chernobyl (even though it is extremely unlikely that a similar event could occur, as will be explained in Chapter 2). Moreover, the importance of these aspects may become even more pronounced in the proposed nuclear-assisted hydrogen production technologies in which two critical facilities are combined and often co-located (thermochemical cycles). While safety is universal, regulatory aspects are local and establishing efficient regulatory bodies will be the responsibility of the local government. Moreover, while safety of the technology is universal, if the safety standards of the local governments are such that safety could be compromised, an accident can occur regardless of the safety of the technology, which will affect the perceived safety and public acceptance of the technology.

1.10 PURPOSE OF STUDY

The purpose of the study is to investigate all safety requirements and the regulatory aspects that have to be adhered to in order to ensure the safe operation of a nuclear-chemical complex which consists of a hydrogen production facility utilizing the heat energy supplied by an adjacent HTGR nuclear power plant.

1.11 ISSUES TO BE ADDRESSED

In view of the purpose of the study and the ultimate objective of ensuring the safe operation of the nuclear-chemical complex, all safety requirements, possible hazards and general regulations applicable to the production of hydrogen via the nuclear-chemical complex need to be investigated. Therefore, the issues to be addressed in the project are:

1. The minimum distance required between a HTGR plant and a hydrogen production facility in order to ensure safe operation of both the facilities.
2. All safety aspects and regulations that have to be adhered to in order to secure the safe operation of a hydrogen production facility adjacent to a PBMR nuclear power plant.
3. All possible risks associated with the production of hydrogen adjacent to a PBMR plant and to describe the actions required to minimize these risks.
4. The general requirements and regulations (safety, health, environmental and *etcetera*) that have to be adhered to when hydrogen is produced by means of the energy supplied by an adjacent PBMR nuclear plant.
5. The importance of CH_4, CO and O_2 in the manufacture of nuclear-assisted hydrogen.

Since such a commercial complex does not exist, these issues are dynamic and their particulars are subject to change as new safety aspects, hazardous issues and operational requirements are identified and investigated. Even the general requirements and regulations (specifically the distance between two critical facilities and the addition of seismic-activity regulations) may be altered in order to be compatible with the "new" technology (Verfondern & Nishihara, 2005; Gürpinar, 2005).

1.12 ASSUMPTIONS

Since the study is research and safety orientated, certain design parameters or operating conditions of the processes involved are required in order to perform the study. These parameters are taken as assumptions and include the following:

1. Assume that a 500 MW_t HTGR (such as the PBMR) nuclear plant is available to supply process heat to an adjacent hydrogen production facility in the form of hot helium gas at a temperature of 900 - 950 ^0C.
2. The hot helium gas is transported by pipeline to an adjacent hydrogen production facility where the high-temperature heat energy is used for the production of either synthesis gas or hydrogen, or both. Additionally, the low

temperature process heat is used for power generation (electricity) that can be used onsite (hybrid thermochemical processes).

3. The reforming of natural gas or methane is the primary method of hydrogen production to be investigated. However, the hybrid sulphur cycle and partial oxidation of methane is also considered.
4. The physical and chemical properties of hydrogen are considered fundamental in planning the optimum layout and positioning of the nuclear-chemical complex, especially considering the separation distance.

These assumptions are made to provide a basis for the investigation and to focus the study on specific issues since there is no use in "reinventing the wheel".

1.13 OVERVIEW OF REPORT

Chapter 2 is an overview of high-temperature gas-cooled nuclear reactors (HTGRs), the leading candidates thereof, and the various nuclear-assisted hydrogen production technologies.

Chapter 3 is a summary of the physical and chemical properties of the hazardous substances present in the different hydrogen production technologies, with the primary focus on hydrogen, methane and carbon monoxide, but all hazardous substances are considered to some extent.

Chapter 4 is a review and evaluation of the accident phenomena and propagation methods associated with the hazards identified in the previous chapter, especially those related to the evolution of a flammable gas cloud, the combustion thereof and the consequences associated with combustion.

In Chapter 5, all aspects pertaining to the nuclear/chemical complex, with special relevance to the safety thereof, were examined and include investigating international R&D projects, the available interfacial equipment and connection technologies as well as previous safety evaluations of similar nuclear/chemical complexes.

In Chapter 6, the regulatory aspects that may be influential during the licensing of a combined nuclear/chemical complex, primarily with regard to South African legislation were examined but international regulatory concerns are also considered.

Chapter 7 commences with a summary of the investigation, after which conclusions and recommendations are given with regard to the safe and successful implementation of nuclear-assisted hydrogen production technologies.