

The Hydrogen Economy in the Quick Start Programme
of the European Initiative for Growth

***A Large Scale Test Facility
for the Production of Hydrogen and Electricity
The HYPOGEN Project: A JRC-SETRIS Perspective***



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**Sustainable Energy Technologies
Reference and Information System
(SETRIS)**

The objective of SETRIS is to collect, harmonise and validate information on sustainable energy technologies and perform related techno-economic assessments to establish, in collaboration with all relevant national partners, scientific and technical reference information required for the debate on a sustainable energy strategy in an enlarged EU, and in the context of global sustainable development.

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Executive Summary

The HYPOGEN (HYdrogen POwer GENeration) project refers to a large-scale test facility for the co-production of hydrogen and electricity. This project is an integral element of the Quick Start Programme of the European Initiative for Growth, endorsed by the Council in December 2003. The aim of this Initiative has been to mobilize investment in areas that can stimulate growth and boost employment. The transition towards a hydrogen economy has been identified as one of these areas. HYPOGEN, as defined in the Growth Initiative, is a single large-scale facility. The main role of this facility will be to show the practicality of co-producing hydrogen and electricity from the same plant and to act as a platform for testing, proving and optimising new concepts in this field. Overall, the HYPOGEN project should have significant impact on the growth of the European economy in the near term.

To clarify the HYPOGEN concept, the Institute for Energy of the Joint Research Center (JRC) of the European Commission has been working on the issues that concern the definition and the development and implementation/realisation of the project, aiming to identify the main financial, technological, socio-economic, legal and environmental constraints. In addition to its own work, the JRC has sponsored and guided external studies and has organized three workshops with stakeholders to seek their advice and recommendations. This report summarizes the views of JRC's Sustainable Energy technologies Reference and Information System (SETRIS). The report should be considered as an aid to thinking about HYPOGEN and to stimulating further discussion with all relevant stakeholders. It should not be used as a blueprint for any specific plant design or the formulation of a detailed proposal.

In principle, HYPOGEN could use any type of primary energy for its operation. However, in line with the proposal of the Commission and in accordance with the proposed short-medium term timescale, HYPOGEN should be based on fossil fuels, i.e. coal/lignite or natural gas, from which the carbon dioxide (CO₂) produced is captured and stored or used. Coal, lignite and natural gas fuel all have their advantages and disadvantages, especially as the choice of fuel tends to dictate the conversion technology that has to be used, which in turn impacts on plant capital costs and the efficiency of conversion. However these fuels also need to be assessed with regard to security of energy supply, European economic competitiveness, and the possibility of their use in a number of European sites in fully commercial plants based on experience gained from the HYPOGEN test facility.

Conventional fossil fuel power plants are not deemed suitable as a basis for the co-production of hydrogen and electricity, indicating that processes based on steam reforming of natural gas or gasification of coal would form the basis for the HYPOGEN facility. These processes also provide a convenient means for the capture of CO₂ for subsequent storage. It is also considered vital that the HYPOGEN plant should be able to switch the ratio of hydrogen to electricity production to maximise plant utilisation.

To fulfill its role as a promoter of growth and innovation, the HYPOGEN plant should not be strictly viewed as a commercial venture, although the profitability of the facility should not be neglected. As the first of its type and as a vehicle for technology verification, demonstration and roll-out, the commercial prospects, in the early years, may prove difficult. During the initial years much of the plant output will be electricity, with the hydrogen likely to be burnt in gas turbines, although it is possible that some large chemical plants would be willing to buy the hydrogen. With respect to CO₂, the gas could be sold to a suitable market, such as for enhanced oil recovery or polymer manufacturing. It is also possible that the emissions trading mechanism could provide additional financial rewards. To construct the

facility, the financial instruments, presented in the Growth initiative, should be further refined.

The HYPOGEN facility will need to be designed to be environmentally friendly, with potential impacts on the local area being taken fully into account. The facility will need to comply with existing legislation that applies to power generation and chemical plants, and the transmission of gases over long distances through pipelines. Furthermore, as geological storage of CO₂ is an inherent aspect of HYPOGEN, the design and operation of the plant will need to be in compliance with any new legislation or codes of practice that relate to this area.

On the larger scale, however, the HYPOGEN concept needs to be linked in the public mind to the issues of global warming, security of energy supply and future economic growth. The presentation of the concept to the public will be important, in gaining public acceptance and political support for HYPOGEN as one of the routes to enhancing growth and strengthening the European economic competitiveness.

“HYPOGEN –A Large Scale Test Facility for Production of Hydrogen and Electricity¹”

1. Introduction

The HYPOGEN project is intended as a large-scale test facility for the production of hydrogen and electricity. This project is an integral part of the European Initiative for Growth, proposed by the European Commission and endorsed by the Council in December 2003¹. A Communication of the Commission provides the necessary background information². HYPOGEN has stemmed from the need to provide Europe with a sustainable energy system, which includes hydrogen, as an additional energy carrier, as well as to boost knowledge and expertise in cutting-edge technologies thereby promoting economic growth, employment and competitive edge. The Commission view is that HYPOGEN will play a key role in Europe's advancement towards the hydrogen based economy. Hydrogen is deemed to be one of the ways to lead Europe to a sustainable future. The perception is that a hydrogen economy will improve the security of energy supply, will reduce the emissions of greenhouse gases, and will also lessen the impact of energy production and conversion on the local environment, whilst creating opportunities for Europe's industrial competitiveness.

To help the HYPOGEN project take off, the Joint Research Centre (JRC) of the European Commission has been working on the issues that relate to the definition and the development of the project. The aim has been to identify the main financial, technological, socio-economic, legal and environmental barriers, with the intention of providing guidance to overcome these problems.

Although much of this work has been done at the Institute for Energy, a number of complementary activities have been sponsored and guided by the Institute for Energy, together with the Institute for Prospective Technological Studies. One such initiative, was a general study by the Institute für Energetik und Umwelt in Leipzig on “Pathways for the Production of Hydrogen in Europe at the 2020 Horizon and Beyond”. This study compared some of the technologies by which hydrogen could be produced. A workshop was held to discuss its findings. More relevant to HYPOGEN was a “pre-feasibility study” of a project, to produce hydrogen and electricity from a fossil fuel, which addressed the main technological and socio-economic issues. The study was undertaken by a team of European research institutions, which included ENEA, Risø and Fraunhofer ISI. These three organisations joined together under the European Science and Technology Observatory (ESTO) to produce a study that is commonly referred to as the JRC/ESTO “HYPOGEN Pre-feasibility” Report. This report became available in November 2004. However, certainly in terms of its technological content, the “pre-feasibility” study should not be regarded as “blueprint” for the construction of a HYPOGEN facility.

In addition, contact was made with leading representatives from industry and academia, via two other workshops, co-organised by DG JRC and DG RTD, to inform them about the JRC/ESTO study, to seek their contribution and to discuss issues, which relate to HYPOGEN. Many of the representatives were associated with EU funded projects, which are of relevance to HYPOGEN. In the light of these activities the JRC has started to identify the main issues that need to be considered in the HYPOGEN project. It is as yet too early to identify a specific design approach for the production of hydrogen and electricity, or even the

¹ Communication from the Commission: A European Initiative for Growth. Investing in networks and knowledge for growth and jobs. Final report to the European Council, COM (2003) 690 final/2, Brussels, 21.11.2003.

fuel to be used. Nevertheless, preliminary investigations, by the JRC, have revealed that HYPOGEN cannot be a straightforward modification of an existing commercial plant or process. It needs to produce both hydrogen and electricity efficiently and economically, with the hydrogen being of a sufficient purity that would be suitable for the hydrogen economy. Although there are a variety of ways in which this might be done, there are no off-the-shelf designs that can do this. Some could be adopted without too much difficulty, although it is not clear at this stage, what would be the best way of modifying these designs. Hence the HYPOGEN facility will be very much a research and development project, even if it is based as much as possible on existing technology. Much ancillary equipment, such as a hydrogen fuelled gas turbine, will need to go through an R&D phase. There may, indeed, be the necessity to construct a pilot plant before moving to a full scale facility.

Overcoming technological obstacles is not sufficient to ensure the construction of the facility. Such a project will require some thought to its financial backing, as its profitability, in its early stages cannot be ensured. Similarly, as the plant will be the first in Europe of its type, it is likely to stimulate much public interest relating to the overall concept of producing hydrogen from a fossil fuel, and the implications of locating plants at specific sites.

This report summarises the views of JRC-SETRIS on the issues that need consideration in the financing, project planning, detailed design and operation of a test facility that co-produces hydrogen and electricity. The report should be used as an aid to thinking about HYPOGEN. Hopefully it should be useful to those formulating development programmes, during which specific design concepts, fuels, plant locations and CO₂ storage sites are being considered.

In so doing, the report reviews the HYPOGEN concept and examines fuel choices, technology options, and socio-economic issues. It relies on three pillars: (i) the in-house work being done at the JRC on issues relating to HYPOGEN that permit the JRC to form an objective and neutral view, (ii) the results of the aforementioned “pre-feasibility” study, and, (iii) the input of the stakeholders who have been involved in the process.

2. The Quickstart Programme and the HYPOGEN Project

The HYPOGEN project was introduced as one of the key elements of the **European Initiative for Growth**. It needs to be seen as an integral part of this Initiative. Overall, the Growth Initiative aims to accelerate economic recovery in Europe, as the European economic performance in the past years has been below that needed to reach the targets set in the Lisbon Agenda. Hence the Initiative is intended to mobilise investment in areas that can reinforce ongoing structural reforms, stimulate growth and increase employment. The Initiative focuses on public and private investment as well as knowledge, identifying a number of key areas to target its effort. One of these areas is the investment in knowledge, through specific actions, to boost growth in leading edge technologies. One of the principal technology sectors that was identified in the Growth Initiative is *the use of hydrogen as a source for energy and electricity*.

The first stage of the Growth Initiative is a “**Quick-Start Programme**”. The aim of this Programme is to support key priority investment projects of European interest. Projects, which comprise the Quick-Start Programme, need to meet four criteria, as summarised below:

- *Maturity*: Projects should be mature enough to start at present or in the near future, in terms of project planning and financing. The aim is to ensure that substantial investment is committed before the end of 2006.

- *Pan-European dimension:* It is politically and economically important that projects have an impact on a European level.
- *Growth and innovation aspects:* Projects should engender economic growth and the creation of employment, through the better integration and mobilisation of resources, and by enhancing the capacity of Europe for innovation. This will keep Europe at the cutting edge of technological development. In this context, *the Growth Initiative makes explicit reference to the use of hydrogen as a source of energy and electricity.*
- *Environmental Impact:* Projects should offer strong environmental benefits. Again, *the Initiative for Growth sets, as examples, projects linked to the hydrogen economy.*

Two projects of the Quick Start Programme are linked to the hydrogen economy². These are HYPOGEN and HYCOM. HYPOGEN refers to a large-scale test facility for production of hydrogen and electricity and is the subject of this report. HYCOM refers to the establishment of a limited number of “hydrogen communities” around the Union, using hydrogen as source for energy for heat and electricity and fuel for vehicles.

3. The HYPOGEN Concept

There have been discussions among key EU stakeholders as to what HYPOGEN entails, as discussed in the two JRC/ESTO Workshops set up by the JRC and DG RTD in May and October 2004, and at an Information and Brokerage Event, organized by DG RTD in Potsdam, in September 2004. It is clear, however, that the Initiative for Growth describes what is expected from the HYPOGEN project. HYPOGEN, as defined in the Growth Initiative, has the following attributes:

- It is a major R&D, as well as a production facility, intended to be available to research organisations for evaluating novel equipment and concepts
- It a large scale unit, that will have significant effect on the growth of the European economy
- The main role of this facility is to show the practicality of producing hydrogen and electricity from the same plant
- It must be able to act as a vehicle for testing, proving and optimising new concepts which relate to the production of hydrogen and electricity

These points are examined in more detail below.

As a project HYPOGEN covers the design, construction and operation of a single plant, a single facility, that will be used to test and validate technologies and components that may be used for the co-production of hydrogen and electricity. Although it is possible that the size and plant design will be similar to that of commercial designs, HYPOGEN should not just be

² The endorsement of the Quick Start projects by the European Council is one of the latest milestones on the road to the deployment of a hydrogen economy in Europe. The advantages, however, that hydrogen can offer, have been recognized by the European Union for some time. The first step to the realisation of a hydrogen economy was made in October 2002 when the Commissioners for Energy and for Research requested a High Level Group, made up from representatives from the industry, research and the policy makers, to define a European vision for hydrogen and fuel cells. The results were presented in a major conference in June 2003 in Brussels, under the auspices of the President of the Commission. In September 2003, the Commission endorsed the main conclusions of the conference, launching the European Partnership for the Hydrogen Economy (www.hfpeurope.org). Subsequently, the Commission proposed the hydrogen economy as one of the project areas of the European Initiative for Growth.

viewed as a commercial venture. Rather, HYPOGEN should be regarded as a flagship for European research, development and demonstration on hydrogen production. In this way it will meet with the spirit of the Quick Start Programme, expanding knowledge in cutting edge technologies, investing in the European R&D potential, by giving a huge boost to the development of the hydrogen economy providing a cleaner and sustainable energy future. However, given the likely scale of the facility, the question of the profitability of the facility should not be overlooked.

The Initiative for Growth does not offer more than general guidance about the shape and form of the HYPOGEN project. Neither the type of fuel to be utilised for hydrogen production, nor the basic technology are indicated. Some insights can be gained by reviewing the requirements of HYPOGEN against the criteria for Quick Start projects, as detailed in Section 2. The main issues are:

- Since the Quick Start Programme calls for the commitment of a large investment in the near term, the HYPOGEN facility would need to be based on proven or near-commercial concepts. This does not imply, nevertheless, that new technologies should be discounted. On the contrary, the HYPOGEN facility should be seen as a test-bed and a development tool for new concepts. However, it is essential that the core of the facility should be based on proven technology, to attract investment and assure the success of the project.
- HYPOGEN should not be seen as a one-off plant that meets the requirements of those organisations that contributed to its funding, nor as a facility to meet the requirements for niche applications. The plant design and fuel should be relevant to other localities and operators elsewhere in Europe.
- HYPOGEN, being a test facility, should promote innovation and enhance knowledge in the field of energy conversion and help Europe secure its position as a key international player in the transformation and use of energy.
- HYPOGEN, compared to existing means of power generation, should have a substantial effect on improving the local and global environments, vis-à-vis the reduction of greenhouse gas emissions, through reduction of air and water pollution, and minimisation of the impact of solids disposal.
- The hydrogen from the HYPOGEN facility should be a significant energy stream, rather than a secondary product of a plant that is essentially designed to produce electricity.

In the light of the work at the JRC, and through its contacts with organisations working on hydrogen, the consensus is that the HYPOGEN project should be based on decarbonised fossil fuels. That is, hydrogen and electricity should be produced using coal or natural gas as primary energy sources, whilst the carbon dioxide that is produced in the conversion process should be captured and stored, or used elsewhere. The view is that this offers the most practical and economic means of producing hydrogen in the short to mid-term. Furthermore, this fits in with current thinking that fossil fuels will be the backbone of the European energy system for the next 20-30 years. In progressing to a renewable-based hydrogen economy it makes sense to consider using fossil fuels to produce hydrogen, which can be used in a wide number of energy consuming sectors. More detailed arguments, which relate to fossil fuelled HYPOGEN are given in subsequent sections, as are the arguments against the use of renewable energy and nuclear energy as primary energy sources for HYPOGEN, given the timescale with which it needs to comply.

One critical issue in the Initiative for Growth is the proposed timescale for HYPOGEN and the other Quick Start projects. The relevant Communication of the Commission stated that work and investment should be under way within three years, i.e. by 2006, while most of the investment should be mostly used by 2010. To this end, a tentative schedule has been suggested for HYPOGEN, and an amount of €1.3 billion has been proposed by the Commission, which has been endorsed by the Council. Of this, 230 M€ should be used in the period 2005-2007. 700 M€ in should then be used in the period 2007-2012. The expenditure during the final period, 2013-2015, is estimated to be 370 M€.

Whether HYPOGEN can keep completely to this timetable remains an open question. Discussions with stakeholders indicate that they would require a major incentive to consider completing the construction of such a plant by 2012. Their concern is that the lack of a hydrogen market makes such an investment unattractive. In this respect, the promoters of HYPOGEN face what is often a typical techno-commercial barrier. Without a plant to produce hydrogen, no one will try to create a sufficiently large group of consumers. On the other hand without a market no one will put up the capital to build a plant.

Fortunately there are some ways through this difficulty. Discussions at one of the workshops revealed that the timelines indicated in the Initiative for Growth should be considered as rough guidelines only, so it may be possible to delay construction, to a slightly later date than originally envisaged. This would not inhibit the starting of serious work on the basic design of the facility, and how the facility could combine profitable operation with it being a research facility.

There are other options that could improve the near-term profitability of the HYPOGEN plant. Once the plant has been commissioned, it may spend its early years producing electricity, not necessarily capturing and storing CO₂ at this early stage. This should provide an income stream during the early days. In this context, niche markets, of the chemical plant type, which could make use of hydrogen, should be given serious consideration. If this were so, a key requirement, is that the HYPOGEN plant should be designed so that it would be of a type that could be of use in most of Europe.

To improve its attractiveness, the facility, should be capable of varying the ratio of hydrogen to electricity. This would permit the plant to operate at full load continuously, producing electricity during peak hours and hydrogen in the off-peak hours.

There is a need to focus on CO₂ capture as an integral part of HYPOGEN, as this too could provide an income stream. Markets for CO₂ should also be considered to improve the economics, such as the petrochemical industry that may use the CO₂ for enhanced oil recovery, or for the manufacture of polymers. If the plan were to use or to store the gas, in depleted oil and gas fields in the North Sea, it would be imperative to opt for early construction of the facility. This would give an incentive for the operators of existing oil and gas production infrastructure to maintain it in a serviceable condition. If HYPOGEN was seriously delayed, most or all of this equipment would have to be rebuilt, greatly adding to costs.

4. The Issue of Carbon Mitigation

During the early stages of the hydrogen economy, hydrogen will probably have to be produced in Europe from fossil fuels. An unavoidable consequence will be the generation of carbon dioxide (CO₂), the dominant anthropogenic greenhouse gas that is responsible for over 60% of the enhanced greenhouse effect, based on radiative forcing estimates, which leads to climate change.

Accordingly, the European Union has made the reduction of the emissions of greenhouse gases a top priority. The Union is now committed to the Kyoto Protocol and has introduced measures and policies to achieve significant cuts in CO₂ emissions. Because of emissions trading policies, European power utility companies will suffer financial penalties from excessive emissions of CO₂. Therefore designers and utilities are giving serious consideration to the capture of CO₂ from power plants of the future. It will be apparent, that the HYPOGEN concepts, whatever their form is decided to be, can easily be adopted to capture the CO₂ which is formed in the course of producing hydrogen and electricity. As an integral part of the project, HYPOGEN would need to demonstrate, at a reasonably early stage in its operations, the ability of the plant to capture CO₂ efficiently and economically, and then to dispose of the gas in a satisfactory way. Section 9 of this report, dealing with technology, indicates how this may be done.

Much more of an issue is that of finding methods by which CO₂ can be disposed of. These need to be of a type which are generic to conditions that prevail across the EU. Niche options such as using CO₂ for chemical production, or options where the gas eventually finds its way into the atmosphere would not be viable. Transport of CO₂ to a site where it was being used or stored does not impose any new technological obstacles. The gas is currently transported, over land, in high-pressure steel pipelines at 100-200 bar pressure. Similar techniques can be used for transport to exhausted offshore gas and oil fields. With respect to undersea storage, tankers carrying liquid CO₂ appear to be economic. The main issue would be the costs of capturing, transporting, and disposing of the gas. These costs can be offset. An option to improve the economics of carbon management is CO₂ utilisation. The largest potential for CO₂ utilisation is offered for EOR providing that the timescales of its construction and operation fit in with those for EOR in the North Sea. Here, the injection of CO₂ into oil wells will increase oil production, simultaneously storing CO₂ underground. However, this process is marginally competitive for the given range of today's oil prices.

An alternative use of CO₂ is for Enhanced Coal Bed Methane (ECBM) recovery. This is accomplished by injecting CO₂ into coal strata that cannot be mined. There is only one demonstration plant and one pilot plant worldwide, both situated in N. America. The EU is currently funding the first project of its kind in Europe, located in Poland. The European potential for ECBM recovery appears to be modest, located in specific areas in Europe, for example in the upper Silesian basin in Poland and the Czech Republic, and in the Saar/Lorraine basin in Germany and France.

Both EOR and ECBM recovery, although in some respects limited, are worth considering in conjunction with the HYPOGEN facility, as they could bring in an income stream to offset the costs of the project. They would also have the added benefit of helping to show that the concept of geological storage of CO₂ was economic and safe. Storage in geological structures is to a very large extent a well established technique. Disposal of chemicals and periodic storage of natural gas in geological formations is a widely accepted industrial practice, with long accumulated experience. Furthermore, potential storage sites, such as depleted oil and gas reservoirs and deep saline aquifers are widely dispersed and plentiful in number, characteristics that make geological storage the most favourable CO₂ storage option today. The prospects for storage of CO₂ in the chemical form in minerals or in clathrates seem remote, and should not be relied on in this project

The challenge of geological storage, which HYPOGEN would need to consider, is the assessment of storage capacity and retention times; monitoring and verification; legal complications, as mentioned in a following section; and safety and assessment of risks associated with leakage of CO₂ from storage sites. Currently, there is only one commercial

application of geological CO₂ storage, in a saline aquifer in North Sea, the Sleipner Project, where one million tonnes of CO₂ are injected and stored annually (equivalent to the emissions of a 140 MW power plant). A number of projects co-funded by the EU are intended to study the behaviour of injected CO₂ (e.g. SACS, CO₂SINK). Possible storage sites in a number of European countries have been identified in the frame of the GESTCO project.

5. Financing

5.1 Background and Options

As mentioned in the introduction, the construction and operation of the HYPOGEN facility will necessitate specialised financing, as it would be a test facility, it is not expected to be profitable in the short term. Only after the HYPOGEN concept has been proved to be feasible, commercialisation of a set of similar plants could begin.

In assessing the funding for the HYPOGEN project, a vital factor is the market for the electricity and hydrogen that it will produce. There will certainly be an electricity market, although here too there will be some challenges. During the first years of operation of the test facility, reliability and output are likely to be questionable, particularly with a HYPOGEN facility that uses coal (it is well recognised that plant reliability, particularly of IGCC plants during the initial years of operation is poor). Even during the post-commissioning phase of its operation, plant output may be irregular due the need to test new process schemes and make time for installation of trial equipment. In such a situation the income from electricity sales is likely to be modest, as HYPOGEN will not be viewed as a reliable supplier. Reliability, would however, be likely to be greatly enhanced if the carbon storage component of the project was delayed for a few years, and this option does need consideration. How reliable the plant will be, will greatly depend on the plant complexity and innovatory aspects of its design, and these matters need to be kept in view.

The expected profitability of the HYPOGEN facility will determine the level of private investment, which is attracted to the project. Profitability will be strongly associated with a European, and perhaps a world-wide post-Kyoto framework, which is intended to promote investment in energy systems that have less environmental impact, making their higher costs affordable under competitive market conditions. This favourable framework largely depends on financial incentives to reduce greenhouse gas emissions, such as the emissions trading mechanism. These incentives in turn, affect the development of a hydrogen market for stationary and transport applications. This framework requires that all the barriers related to CO₂ management (e.g. legal and regulatory aspects of CO₂ storage, public acceptance) will be overcome.

The development of this financial framework in next few years will be of great concern to those organisations that intend to build and operate the plant, and provide financial support to the HYPOGEN project. The private sector will need assurances that devices such as the emissions trading mechanism will be properly operating when the time comes to building a series of commercial plants of the HYPOGEN type. Additional funding arrangements for the project will need to be devised, as it is most likely that it will be able to offset some of its costs through emission trading. The organisations responsible for the design, construction and operation of such a plant would anticipate having some rights in the building of follow-on plants, so as to help recoup their investment.

Another means of increasing the profitability of a HYPOGEN facility is to utilise the captured CO₂ in large-scale applications, such as for Enhanced Oil Recovery (EOR). However, EOR would require a constant and high flow of CO₂. This might greatly

compromise the degree of innovation and sophistication, which could be designed into the HYPOGEN facility. Hence, on balance, it does not seem that EOR could be relied upon as a source of finance for such a test facility, at least in the first phases of its operation.

If CO₂ could not be sold, this would imply further financial penalties, which may need to be recognised by funding agencies. The HYPOGEN facility should be given a few years grace on the question of capturing and storing CO₂, on the basis of it being a test facility. It is unlikely that such a plant would be allowed to release CO₂ to the atmosphere indefinitely. It will be therefore essential to identify locations, probably on-shore where CO₂ could be stored. Nevertheless, there are likely to be substantial costs in obtaining permission to deploy CO₂ pipelines and environmental permits for such activities unless they can be harmonised with other European programmes for storing carbon dioxide.

The prospects of sales of hydrogen from the facility are likely to be limited in the near future, unless this is tied to a niche market, such as a chemical plant. The concern is that there would be a temptation to design the facility, as one optimised for a specific chemical process, influencing such aspects as hydrogen purity and plant flexibility. Such a plant would be a niche design for a niche market, providing limited information for plants of more general use. Another possibility is to use hydrogen in a hydrogen community (in the frame of the HYCOM project).

The most likely option for the facility is that, for a number of years, any hydrogen that the plant will produce would be used as fuel in gas turbines, within the HYPOGEN facility itself, for power generation. Alternatively the majority of it would be piped a distance (e.g. a few tens of kilometres) to be used as substitute for coal, in a steam boiler plant, or to replace natural gas in a combined cycle gas turbine system, again to produce electricity. Where the sales of hydrogen were of the “across the fence type” it is likely that a subsidy would be needed to make the economics attractive. Here again the facility needs to be designed with a view to the future hydrogen economy, not just for a short-term power generation market.

As indicated earlier, where the HYPOGEN facility produces only electricity for the first few years, whilst hydrogen communities are growing up, there is a vital need for the plant to be designed with the highest possible flexibility. That is, the plant should be able to change the ratio of hydrogen to electricity. A fully commercial plant, producing a fixed ratio of hydrogen to electricity, would need to sell into two separate markets, one for gas the other for power. There are obvious commercial risks in this. A much better option is for a HYPOGEN plant to tailor its output so that at night time, for example, when the demand for electricity falls, it would be able to produce all of its energy output as hydrogen. In the daytime when electricity demand rises, the plant would move towards 100% electricity generation. In this manner a HYPOGEN type plant would be able to run a base load output for many years, reducing the impact of capital costs.

Flexibility of conventional plants is a major issue even at the present time, as some electricity generating plants have to be shut down at night and weekends. The times when such plants have to be shut down can be scheduled days or even months in advance, so that plant engineers can formulate a timetable to cover the start up or shut down. In a future dominated by electricity from wind and solar sources, it will be very difficult to operate a conventional power plant as we do now. In contrast HYPOGEN type plants will be able to run at base load, at a constant and high throughput of fossil fuel, switching from electricity to hydrogen as the demand changes.

5.2 European Funding Sources and the Growth Initiative

To offset likely financial uncertainties with a HYPOGEN facility; there will be a need to rely on other sources of funding than those coming from the companies involved in constructing and operating the plant. It is unlikely that these organisations will be able to raise the necessary finance out of their own capital reserves or from loans from banks, as is the norm for conventional power plants. A strong public/private partnership has to be put in place to raise the necessary capital, as the facility will cost substantially more than a conventional plant and will have higher operating costs and lower rates of return.

As the market forces are insufficient to carry on this initiative, public funds (regional, national and European) will be essential for the success of the programme and play a key catalytic role in promoting private investments in the HYPOGEN facility.

The Communication on the European Initiative for Growth suggests current and new financial tools to support projects of the Quick Start Programme, like HYPOGEN. According to this document, Community level support for Hypogen covers, *inter alia*, the Union's research budget and the Structural and Cohesion Funds. Moreover, an active role of the European Investment Bank (EIB), in the frame of collaboration with the Commission, is planned.

In particular, EIB could be involved by:

- Investing in research, development and innovation.
- Supporting innovation through risk capital to innovative projects, using the European Investment Fund (EIF).
- Reinforcing its financial capability under the structured finance capability, contributing to increase the availability of debt finance for the early, pre-construction phase of the projects.

Furthermore, new innovative financing techniques are under evaluation in facilitating access to private funding for the European Growth Initiative. According to the Communication of the Commission, such techniques include:

- A new EU Guarantee Instrument, which covers specific commercial risks for projects in their post-construction phase.
- Securitisation, that can help to increase the available pool of resources from financial markets and to reduce the balance sheet and liquidity constraints of banking institutions active in the fields covered by the Growth Initiative.

The issue of the instruments and conditions for funding research, development and demonstration activities of hydrogen technologies is under discussion in the Initiative Group of Financing and Business Development, established by the European Hydrogen and Fuel Cell Technology Platform. The findings of these reviews could be helpful to HYPOGEN and should be considered by the stakeholders.

National and regional funds may also contribute to the financing of HYPOGEN. Funds are available at national level for the development of sustainable energy systems, even if the possibility for a Government to support private initiatives is often limited by the rules of market competition.

Finally, the European Union will contribute to the financing of the project through the research framework programme. Already in FP6, 5-6 million euros will be provided by the

Commission to co-finance related research activities. It is expected that this effort will intensify in FP7.

This discussion reveals that the coordination of different funding sources could represent a difficult and time-consuming task. The JRC/ESTO report proposes two different forms of a possible public-private partnership (PPP):

- PPP of a purely contractual nature, in which the partnership between the public and the private sector is based solely on contractual links
- PPP of an institutional nature, involving cooperation between the public and private sector within a distinct entity.

The former option offers flexibility to the partnership and provides for a clear distinction of responsibilities between the private and public sectors. The latter option is more rigid, offering, however, a higher level of control by the public partners over the development of the project.

5.3 Patenting and IPR

Although the HYPOGEN facility will be largely based on existing technology, it will offer new challenges in terms of plant integration, economies in hydrogen and electricity production, and operating parameters, which will lead to IPR (Intellectual Property Rights). IPR will, at the very least, give the owners a commercial edge when promoting their designs for subsequent plants. In some circumstances IPR can form part of a licensing agreement. In other cases the IPR may represent genuinely innovative findings, and be patentable. Taken on a European basis, this could be an important benefit of HYPOGEN.

6. Public Acceptance and Education

History has shown that the public can become concerned when a new technology is deployed, without the associated risks and impact having been thoroughly explained, and sceptical when they feel excluded from the decision making process. It is not rare to see cases where obstacles set by the public are more difficult to overcome than technological and economic barriers. This can ultimately stop the deployment of what would be economic and technologically viable technology. To this extent, and given the increased sensitivity of the public over issues related with the environment and climate change during the recent years, it is expected that HYPOGEN will be closely scrutinised by environmental groups and the public at large.

Public awareness of global climate change, and its main cause, man-made emissions of carbon dioxide, should, in theory, make it easier to get the public to support the construction of a HYPOGEN facility. Getting public support will need to go well beyond the need to seek permission for the construction of a pilot or demonstration plant. HYPOGEN will need to be used in promoting the benefit of such plants to the long-term economy of Europe.

Environmental groups may suggest that a fossil fuelled based HYPOGEN project would be welcome only if it is a part of a sound strategy that accelerates the penetration of renewable energy sources and improves efficiency of the energy conversion chain. The role of carbon storage in this strategy would need to complement other carbon management options, aiming to offer deeper emissions reductions in the short to medium term, until the other carbon management options start producing results. A rigorous research, development and demonstration programme, capable of providing robust answers to questions regarding safety,

effectiveness and impact on the environment and the ecosystem would be a prerequisite. Those who will be involved in the construction and operation of the HYPOGEN facility will need to reach out to the public with good, timely and objective information. This in itself needs to be a well thought concerted scheme, with all the players pulling in the same direction.

In discussing the environment, there is a tendency to focus on global climate change and the CO₂ storage issues. One of the conclusions of the JRC/ESTO report is that storage is an issue that has not even begun to penetrate public consciousness. The view of the limited sample of people, who have been approached on this matter, is that the public perception is likely to be that geological storage is simply a method to continue using fossil fuels.

Hence, carbon sequestration will almost certainly be one of the main points of discussion at public enquiries about the construction of the HYPOGEN facility. On the one hand the proponents of HYPOGEN will be making the case for how HYPOGEN will be a major boost to the hydrogen economy in Europe. The main arguments against this are likely to come from those who wish Europe to move to a fully renewable energy economy, dispensing with fossil fuels as quickly as possible. As the ESTO report suggests, these arguments tend to be put forward by those who have their own agenda, for example, proponents of wind power or energy saving schemes. These arguments will centre on the point that hydrogen should be produced from renewables, as this imposes no carbon impact on the environment at all.

To the belief that we can quickly move to an energy economy, in which the sole primary energy input is renewables, the following points could be made in support of HYPOGEN:

- Renewables cannot supply all of Europe's energy needs,
- If the energy gap, between supply and demand, cannot be filled with fossil fuels, the only alternative would be nuclear energy
- HYPOGEN plant designs can be made to capture all CO₂, if desired.
- Biomass is to be investigated as a supplementary fuel in HYPOGEN plants which will actually remove carbon from the biosphere
- Experience with the HYPOGEN facility will form the basis for replacing older power plants in Europe with lower emission units

7. Legal Frame

Having appropriate legislation in place will be a necessary condition to have a robust framework for the construction and operation of the HYPOGEN facility. Regulation is needed to ensure that the risks and impact associated with running the plant and transporting and storing of CO₂ are minimised. The main legal issues associated with HYPOGEN can be grouped into three categories: (i) hydrogen production (ii) power generation and (iii) carbon capture, transport and storage. Hydrogen production and power generation aspects of HYPOGEN will not be significantly different from the currently applicable practices in Europe. Hydrogen is produced, stored and transported in Europe within the frame of a well developed legal framework. A point that could give rise to much debate would be whether the facility should be viewed as chemical or power plant. There are permits for each of these, but they will require modification to cover both simultaneously.

The quantity of CO₂ captured from the HYPOGEN facility is likely to be transported via pipelines of high pressures (in excess of 100 bar). There is no precedence of the construction and operation of such pipelines in Europe. Nevertheless, a long pipeline network, of 3,000 km in length, does exist in the USA and experience with this would be applicable to Europe.

It is likely that the licensing of such pipelines in Europe would follow processes similar to those already in place for the transport of similar substances, such as natural gas, hydrogen, crude oil and naphtha. Although CO₂ is neither explosive nor flammable, unlike the above-mentioned substances, it may cause asphyxiation, as it is heavier than air and can accumulate in depressions after leakage. As recommended in the JRC/ESTO report, CO₂ should be transported and stored as “sweet”, that is hydrogen sulphide free gas. The presence of hydrogen sulphide makes the CO₂ extremely toxic, and would greatly increase concerns by the public and regulatory authorities.

Carbon dioxide may be stored in suitable geological structures in Europe, many of which are in the North Sea. Others are on the European Continental land mass. Some organizations are looking to the North Sea for storage, but here the legal situation is somewhat unclear.

There are two sets of international agreements that are pertinent. The London Convention, which basically applies to dumping from ships etc., and the OSPAR convention, which is directed to preserving the marine environment. The London Convention³, signed in 1972, prohibits all dumping of industrial waste, with the exception of an approved list of substances. The issue of CO₂ disposal in the context of the London Convention was brought up for discussion in 1991, but a consensus was not reached on whether the gas should be classified as an industrial waste.

The Convention does, however, allow the disposal of “wastes and other matters” that arise from the exploration, exploitation and associated off-shore processing of sea-bed mineral resources. The Sleipner project, in which CO₂ is reinjected, comes into this exemption⁴. Nevertheless, despite the above-mentioned example, the Convention generally prohibits the storage of CO₂ generated from other sources, using ships and offshore platforms for transport and injection. Furthermore, a Protocol to the London Convention has been prepared in 1996, which is not yet in force, which includes a list of allowed substances to be discarded at sea, the bed and the subsoil. It however, does not include CO₂. A point at issue is still, whether CO₂ originating from a European source and transported, via a pipeline, to below the seabed, falls under the auspices of the London Convention.

The other treaty that may be applicable is that of the OSPAR Convention⁵ for the protection of the marine environment of the North East Atlantic. Specifically, this Convention prohibits “... *the introduction by man, directly or indirectly, of substances or energy into the maritime area⁶ which results, or is likely to result, in hazards to human health, harm to living resources and marine ecosystems, ...*”. The Convention also includes discharges from inland sources and explicitly mentions the use of pipelines, although any discharges and releases are subject to authorisation by competent national authorities. However, again CO₂ is not included in list, given in Annex II of the OSPAR Convention of permitted discharges.

Much will depend on whether, with both Conventions, the subsea disposal of CO₂ meets the spirit of the agreements. Even in the case that CO₂ storage under the seabed is exempt from the OSPAR Protocol, national laws have jurisdiction and require an ecological impact study

³ For the full text of the Convention see www.londonconvention.org

⁴ Objections have been raised about the legality of the Sleipner Project by environmental groups, claiming that the project is in violation of the London Convention because the platform used to produce natural gas is not the same platform that injects the CO₂ into the ocean floor, thus CO₂ storage is not an integral part of natural gas recovery.

⁵ Official Journal of the European Communities, L 104, 03/04/1998, p. 2-21.

⁶ "Maritime area" means the internal waters and the territorial seas of the Contracting Parties, the sea beyond and adjacent to the territorial sea under the jurisdiction of the coastal State to the extent recognised by international law, and the high seas, including the bed of all those waters and its subsoil, situated within well-specified limits in North-eastern Atlantic.

before a permit can be granted to allow this activity. However, the current state of scientific knowledge regarding carbon storage may not be sufficient to meet this burden of proof, hence there is a need for continued research and experiments on topics related to safety, permanence and monitoring. The main safety issue is whether the CO₂ will leak. With respect to EOR it still has to be clarified from a legal point of view whether EOR is ‘*dumping*’ and ‘*pollution*’, or ‘*utilisation*’.

The legal issues connected with geological storage onshore, in Europe, will be determined by national and regional legislation. Any deliberations will be strongly influenced by how similar activities have been controlled and regulated. These would include underground storage of natural gas in much of Europe and, in Germany, compressed air for peak load power generation.

The main concerns of regulators would be to ensure that the CO₂ would never escape to the atmosphere or contaminate an aquifer that might be used for drinking water. However, different authorities may be involved to assess the compatibility of the HYPOGEN facility with different pieces of legislation (e.g. public safety, drinking water quality, mining laws, etc). As there is no precedence, it is likely that there are no procedures in place to process an application for CO₂ storage for HYPOGEN.

In conclusion, a legal framework to regulate carbon storage is not in place to minimise risks and set the procedures for utilizing storage sites. International Conventions, agreed before carbon storage was considered as a carbon management option, could pose significant but not insurmountable obstacles in the deployment the HYPOGEN project.

8. Fuel Options

8.1 Background to Fuel Choice Options

Hydrogen and electricity can be produced using a variety of primary energy resources, the three main categories being fossil fuels, nuclear power and renewables. The arguments for the use of any particular fuel must be properly addressed. There may be a tendency to begin with a fuel, suitable for a niche-type site, which then leads to a specific method of producing electricity and hydrogen. The end result could be that much effort is expended on a concept that does not have the European dimension or one that is not really suitable for producing hydrogen. Accordingly, the focus in this section is much more towards the issue of fuel supply for a number of future commercial units based on HYPOGEN, rather than the issues that may affect the fuel choice for the HYPOGEN facility.

In the opinion of the JRC-SETRIS, the chances of a HYPOGEN plant being based on nuclear and renewable energy, in the short term, at least, is problematic. Nuclear power currently provides the base load in a number of European countries, so that there would be little prospect of using “spare” electricity for the electrolysis of water. Spare electricity is here defined as power that is surplus to the immediate need, when the demand decreases. Furthermore, electrolysis plants, which use spare electricity, will only be running part of the time, this having an adverse impact on the economics. If nuclear power were to be used, it would therefore need to be new construction, which for a very long time has had little public support across Europe. Combining the arguments for “new nuclear” and with those for the hydrogen economy, suggests that the arguments about this could go on for years.

Wind and solar power, as renewables are beginning to make a contribution to the production of electricity. However power prices from these are extremely high at the present time. In the future, the prospects for wind and sun would be very much better, as they would be ideal for

the small scale, localised generation of electricity. Any electricity, which is in surplus, could be routed through an electrolysis plant to produce hydrogen, to add to that from HYPOGEN.

Within the medium term it is unlikely that biomass could supply the needs of large scale HYPOGEN plant because of the very large input of biomass that such a plant would require to make it economic. Nevertheless it may well be worth exploring the use of biomass as supplementary fuels, as carbon in the biomass could be completely taken out of the natural “carbon cycle” through the storage of CO₂. Hence fuelling by biomass could be one of the HYPOGEN research programmes, if the particular process was suitable for such a feedstock.

Only three fuels, natural gas, coal and lignite should be considered as the primary energy sources for HYPOGEN. Each fuel has its merits and Sections 8.2, 8.3 and 8.4 review the main considerations in more detail. As will be clear, the JRC-SETRIS has no strong views on any of these three. We are, however, concerned about designs for the HYPOGEN facility that would need to use coal and natural gas at the same time (no matter how attractive this might seem). Operators of such a plant would have **to buy** two fuels not just one, and a price escalation of either could put the profitability of the plant in jeopardy.

These fuels do have a common failing that is sometimes overlooked. All can give rise to methane emissions, a much more powerful green house gas than carbon dioxide. With natural gas, much of this comes from badly maintained pipelines. This, in principle can be rectified. The emissions from coal and lignite mines are characteristic of the means of extraction. In principle, such emissions need to be taken into account, along with carbon dioxide, on a life cycle basis. Simple calculations indicate that to produce 1 tonne of hydrogen, 2 tonnes of methane (i.e. the main component of natural gas) are needed. From these reactions 5.5 tonnes of CO₂ are produced. The amount of CO₂ emitted following the coal gasification route is even higher. Although it depends on the composition of coal, in general terms, the production of 1 tonne of hydrogen requires 3 tonnes of coal and produces 11 tonnes of CO₂.

8.2 Natural Gas

Natural gas is an easily transportable fuel and has been used for the production of pure hydrogen or hydrogen containing gases, for many years using catalytic steam reforming, as described in Section 9.2. Plant capital costs are low in comparison to any competing power generation technology that relies on coal, and the impact on the environment in terms of pollutants and toxic substances is negligible. In many respects it is a mature technology, but in the standard design, natural gas is needed to fuel the reforming furnace. The carbon dioxide, produced during heating of the furnace, escapes to the atmosphere, and can be up to 30% of the carbon in the natural gas. To reduce the level of CO₂ being released, the furnace would need to be fired using hydrogen, and this would have implications for the overall efficiency and design of the plant.

In addition to this problem with conventional steam reforming, natural gas has several downsides. Reserves of natural gas from the North Sea and the Netherlands are in decline, and Europe will need to import gas from locations much further afield, increasing the vulnerability of the supply chain. This obviously is going to influence costs and it is commonly acknowledged that the price of natural gas will increase much more than coal in the future, as its price is related to that of oil.

There are also technical issues with respect to natural gas, as a fuel for HYPOGEN, which may be highlighted by energy professionals. Some also might argue against the logic of converting natural gas into another gas, with the efficiency losses that this process entails, especially as natural gas is the most efficient fuel with which to produce electricity. The

benefit of CO₂ storage, to eliminate carbon in a natural gas plant, may appear weak, as natural gas, of all the fossils fuels, has the lowest carbon content.

8.3 Hard Coal

The main advantage of coal is that, although European reserves have fallen, it can be imported from a large number of countries, so that price stability should be good compared to oil or gas. If coal was to be used, it would be delivered at main European ports or sent via barges along Europe's extensive river systems, to suitably located HYPOGEN plants. In most cases, such ports, whether they are on the seacoast or on rivers, are situated close to major urban or industrial conglomerations. Significant reserves of coal can be built up, adding to price stability.

The drawback to coal is that as a solid, it is less easy to use than natural gas, thereby adding to the complexity and cost of a HYPOGEN plant. The conversion of coal into other forms of energy produces ashes, slags, chlorine and sulphur-based compounds, and depending on the conversion process, toxic substances such as soot, phenols and tars, also adding to plant complexity. Such materials will need safe disposal, which would require the input of other materials such as limestone and chemicals to the site. Hence, in evaluating various coal based HYPOGEN plant concepts, it would be necessary to consider the environmental impact of such factors.

8.4 Lignite and Brown Coals

Europe has substantial deposits of lignite and brown coals and although most of the present production is situated in Germany, other countries such as Greece, Poland, the Czech Republic, and Hungary have good reserves. Many other regions have also reasonable reserves. However, the quality of the lignite, throughout Europe, is not uniform, and it is sometimes extremely wet.

Lignite shares with coal the same problems. It is difficult to handle and the ash content can be extremely high. In addition, the calorific value of lignite, even when dried, is between a half to two thirds of coal, making it uneconomic to transport even short distances. Most power stations have to be situated within a short distance of an open-cast lignite mine. This may give difficulties in the location of HYPOGEN plants. Certainly, in evaluating the prospects for lignite, it is important to recognise that a design concept that works in one region of the EU may require substantial changes if it is to work elsewhere.

9. Technology Options

9.1 Hydrogen and Electricity from Conventional Power Plants

Electricity, produced from fossil fuels can be used in the electrolysis of water. If CO₂ capture was not required, electrolysis would seem to be a reasonable approach, as electricity production from new plants is quite efficient, whether running on coal in a conventional steam cycle or natural gas in combined cycle.

Both of these common means of producing electricity, that is steam plant or combined cycle, can be modified to enable much of the carbon dioxide to be removed. The basic modification is to devise methods to increase the level of CO₂ in the flue gas from the plant, enabling the carbon dioxide to be separated out more easily. In coal based steam plant this could, in principle, be done by using oxy-fuel combustion, plus recirculation of flue gases. In combined cycle, flue gas recirculation, with and without oxy-fuel combustion, could also

used to enhance CO₂ levels. Obviously, in addition to the efficiency loss, resulting from the elimination of carbon dioxide, there is a significant increase in capital costs.

These modifications to conventional power plant technology are likely to reduce the efficiency of electricity production to well below 35%, in the case of a coal fired steam plant, and to below 45% for a natural gas combined cycle. If hydrogen is to be produced from these systems by electrolysis, and given an electrolyser efficiency of 80%, a coal based plant would turn less than 30% of its energy into hydrogen, and a combined cycle gas fired plant just over a third. In addition, the need to recirculate flue gas, and add on an oxygen plant, if oxy-fuel combustion is to be used, will greatly add plant capital costs and increase its complexity. This extra complexity would negate much of the benefit of basing the plant on standard power generation practice.

9.2 Steam Reforming

The most common method for the production of hydrogen is by catalytic steam reforming, wherein a mixture of steam and a light hydrocarbon, such as natural gas or naphtha, is passed over catalyst in the 850-950°C temperature range, to produce a mixture of hydrogen, carbon monoxide, carbon dioxide and methane, plus a large quantity of unreacted steam. The reaction is endothermic hence the catalyst that is needed is held in tubes about 20-30 metres long and about 150 mm in diameter, which are strongly heated in a reforming plant furnace. After cooling to about 400°C, this mixture is passed over a “shift” catalyst, whereby most of the carbon monoxide reacts with the steam to produce more hydrogen.

The carbon dioxide, which is produced as a result of this reaction, is removed by absorbing it with an alkaline solution such as MEA (Methyl Ethyl Amine). Even after this treatment, the gas contains 5-10% methane, with lesser quantities of carbon dioxide and carbon monoxide, as well as hydrogen. As most types of natural gas contain some nitrogen, this gas is also present.

Purification consists in passing this gas through a Pressure Swing Adsorption (PSA) system, in which, as the name suggests, impurities are removed by adsorbing them on activated carbon or zeolites. The hydrogen that is produced can be up to 99.999% pure, and the stream of hydrogen that is produced is at plant pressure. The drawback is that about 10-15% of the hydrogen has to be used to regenerate the PSA beds. This subsequently appears as a stream of hydrogen at atmospheric pressure, contaminated with methane, etc. This “tail gas” can be burnt in the reforming plant furnace.

With steam reforming, the hydrogen produced can either be sent directly via pipelines to the consumer or it can be burnt in a gas turbine/combined cycle plant to produce electricity. This is not the usual practice in steam reforming as the hydrogen is used in some subsequent chemical process.

Although steam reforming is the most common method of producing hydrogen, as capital costs are low and the process is reasonably efficient. The main drawback is that steam reforming occurs at relatively low pressures, around 25 bar, which is too low for long distance transmission of hydrogen. In consequence, such a plant would require a method to increase the outlet pressure. As noted earlier, to recover more carbon dioxide, hydrogen would need to be burnt in the reforming furnace.

Because of these restrictions, and to reduce the capital costs of a reforming plant and to increase its reliability, some newer concepts have been introduced. A common feature of

these has been the use of oxygen, with and without steam, to effectively partially combust the natural gas catalytically within a reactor decreasing the amount of methane. Commercial processes adopting this technique still require a reformer, but pressures can be raised to just under 40 bar. Concepts such as these are in a state of rapid development, and it is not clear which systems will become the standard used by industry.

Steam reforming plants do not require large amounts of electricity to run the ancillary equipment and can easily be made to be self sufficient in terms of power. This implies that such plant can have great flexibility in varying the ratio of hydrogen to electricity. The hydrogen that is produced will be burnt, in a gas turbine in a conventional combined cycle arrangement to produce electricity.

9.3 Coal Gasification

As indicated in Section 8.1, there are serious drawbacks to conventional steam plant if, as well as producing a stream of carbon dioxide for storage, the electricity is used to produce hydrogen by the electrolysis of water. Given this constraint, the only near term practical method is to gasify the coal, to produce a syngas that can be subsequently treated to produce a hydrogen stream of the required quality. As such gasification is a pre-combustion process and forms the basis of Integrated Gasification Combined Cycle (IGCC) plants that are now operating commercially in Europe and North America.

The IGCC basically consists of a gasifier, which produces a fuel gas that can be burnt in a Combined Cycle Gas Turbine (CCGT). The heat generated from the gasification process, which is around about 20% of the energy input to the gasifier, is used to produce steam. This is united with the steam coming from the heat recovery boilers in the CCGT, so as to produce additional power from the steam turbine section of the plant.

Carbon capture variants of the IGCC have also been envisaged. Here the raw gas from the gasifier is reacted with steam in a shift converter, as described in the section on steam reforming, to produce hydrogen, which would be burnt as in a gas turbine, as previously described in the section on steam reforming. More importantly, the shift reaction produces a high concentration of carbon dioxide in the gas stream, which makes the process ideal for capturing this gas, using liquid absorbents.

In many ways the most attractive of these processes, in terms of gasifiers for IGCC systems, are the high temperature entrained bed concepts. In these, a mixture of steam and oxygen reacts with a stream of coal particles travelling down an elongated, pressurised, reactor. Temperatures are around 2000°C. The advantage of such processes is that, due to the high temperature, virtually all the carbon in the coal is gasified, eliminating the need to dispose of tars and phenols. In addition, because of the high temperature throughout the reactor, reactor output is very high, reducing capital costs. A drawback of entrained bed gasifiers is the need for an air separation unit to produce a stream of oxygen for the gasifier, which increases costs and adds significantly to the power demands.

Other gasification processes working at lower temperature, only partly gasify the coal, and a considerably amount of the char that is formed has to be burnt separately producing steam for power generation. It implies that electricity as well as hydrogen would need to be produced all the time. To minimise capital costs some of these gasifiers utilise air rather than oxygen for gasification. This would greatly complicate CO₂ capture.

The other main procedure, in IGCC systems, is to eliminate the sulphur compounds in the gas, so that it can be safely burnt in a gas turbine. Accordingly, the fuel gas consists of CO,

H₂, plus some methane, all of which are combustible. There are, in addition, a fairly high proportion of other gases that do not burn, which are in a typical IGCC fuel gas.

These non-combustible gases originate from the coal, or as residuals in the oxygen from the air separation plant, and from need to use nitrogen to “transport” the pulverised coal to the gasifier. They are not a problem in IGCCs, as these gases add to the mass of gases passing through the turbine, giving additional power. Neither would they be regarded as a problem in a carbon capture type of IGCC. On the contrary, such gases would be regarded as serious contaminants in an IGCC modified to produce hydrogen of a purity acceptable to the hydrogen economy.

It is apparent that an IGCC, as the basis of a HYPOGEN plant, would need more than simple changes, even with the carbon capture variant. Hydrogen quality would need to be at a much higher standard, although not necessarily equal to the purity levels coming from electrolysis plants. Producing hydrogen of an appropriate purity would need to be done with minimal losses, and with minimal impact on plant capital costs.

One other serious issue, with the standard form of IGCC is that, as with steam reforming plants, outlet pressures are too low for long distance transmission, as current plants have been designed to deliver a fuel gas to a gas turbine, which only needs pressures in the 30 bar range.

One feature of the IGCC-hydrogen concept, which is design specific, is the degree of integration. For the conventional IGCC, a high degree of integration is mandatory so as to make best use of the steam generated in the gasifier. This is joined with the steam from the heat recovery boiler. There is also, on today’s plants integration via the air separation unit, so as to use the nitrogen for coal transport and suppression of NO_x from the gas turbine.

It is not so clear what should be the most advantageous level of integration in a HYPOGEN facility. Presumably for a plant that would be producing, at the same time, hydrogen and electricity, there would be an optimum split between the electricity-to-hydrogen ratio in terms of coal-to-energy efficiency, thereby minimising CO₂ emissions. Given the likely difference between the price of hydrogen and that of electricity, this is unlikely to be the best split for plant profitability. As the price of electricity varies during the day, it follows that ideally a HYPOGEN facility should be able to vary the ratio of hydrogen to electricity, without this having a high penalty effect on efficiency.

9.4 Lignite Gasification

Lignite can be regarded as a low-grade coal, but its characteristics are quite different from that of hard coal, that is the type of coal referred to in the previous section. These differences originate, in part, from the low calorific value of lignite, even when it is in the dry condition. Water and ash contents can be very high, so that much energy can be wasted in evaporating the water or melting the ash. Because of this extra lignite needs to be used, requiring more oxygen, and since carbon dioxide and steam tend to be produced, rather than carbon monoxide and hydrogen, there is a decrease in the calorific value of the syngas. This would feed through in a HYPOGEN plant, to give a reduced hydrogen output, the problems increasing as the reaction temperature increases. In entrained bed systems, where the temperature is high and ash is melted, the wastage of energy and increased oxygen demand are particularly high.

Many lignites are extremely reactive, and can be gasified at relatively low temperatures, below the melting point of the ash. Hence these are highly suitable for fixed bed gasifiers, whereby the lignite is loaded at the top of the gasifier, moving progressively down towards

the reaction zone. Even so the low average reaction temperature results in a low throughput. Accordingly a large number of gasifiers would need to run in parallel.

Again, since the gasification temperature is relatively low, the syngas will contain fairly high levels of methane, as well as tars, naphtha and phenols. Disposal of these liquid by-products of gasification complicates the design of the downstream plant, and special thought should be given to the handling of the methane in the syngas. The use of lignite implies more complex gas treatment and creates more concern about the impact of the plant on the local environment than would a coal fuelled system.

9.5 The HYPOGEN Test Facility for Advanced Technology Evaluation

One of the aims of the HYPOGEN programme is that the facility should provide a basis for the development and testing of new ideas. The configuration of the demonstration plant should be so arranged that it would be possible to test new concepts. Although it may be considered best to do this on a pilot plant, so as to minimise costs, there are drawbacks with this approach. Many new concepts, once passed through laboratory evaluation and verification, need to be tested at quite a large scale. Trying to add such a unit, for example a membrane shift conversion test rig, onto a pilot plant, may be very disruptive to its operation.

On the other hand, on a full scale plant it is usually possible to take off a sizeable proportion of the flow, via a bypass, to allow testing of a new concept. The flow, passing through the test unit, can either be returned to the plant or flared off. This capability need would need to be designed into the HYPOGEN facility. For example, the usage of waste heat in the plant should not be so critical that abstracting a small part of the flow through the plant, for test purposes, would stop it working. In addition, if the HYPOGEN facility was used in this way, it should be built with appropriate valves and tee offs, so that, when needed, a bypass system could readily be installed.

Of the innovative concepts, which could be assessed, are:

- Improved air separation systems
- High temperature acid gas removal processes
- Optimised heat recovery systems in gas turbine sections of the steam plant
- Improved methods of hydrogen purification
- Membrane steam reforming processes
- Membrane shift reforming
- Innovated gas turbine concepts
- Biomass gasification
- Industrial sized fuel cells
- Effect of gas purity on micro sized fuel cells
- A location for hydrogen power vehicles

10.Competition to HYPOGEN

In analysing the prospects for the HYPOGEN project, it is important to assess whether there are any technical developments in the near future that could be a threat to large scale use of such plants. Conversely, it is worth reviewing, whether, even if HYPOGEN did not succeed in its present form, the investment would pay off in other ways.

Perhaps the main threat comes from arguments that improvements in conventional power plants will make a significant difference to CO₂ emissions. For coal based plants, these ideas have some substance. Due to the outburst in plant construction during the sixties and

seventies, the efficiency of most operating plants is well below 40%. Generating plants built now or in the near future could be expected to give an efficiency of just about 50%, which would give considerable reduction in emissions. Similar developments would be possible with CCGT plants, but here because of the relatively small amount of carbon in natural gas, the environmental gains would be less. Nevertheless, despite all of these improvements to non-capturing power plants, CO₂ emissions would still be unacceptably high.

For this reason much work has been done on electricity generating concepts, which utilise carbon capture. Some are based on IGCC systems; others are closely based on pulverised coal steam plants or CCGT systems. With these systems, to maximise plant output and efficiency most of these concepts only capture 90% of the CO₂, so there is still some release of carbon dioxide to the atmosphere. Because the hydrogen from a HYPOGEN plant has to be virtually pure, all the CO₂ produced during the process has to be removed. This would be required even not all of the CO₂ was subsequently stored.

One major concern about electricity only plants, of whatever type, is that there appears to be little consideration of the fact that at some point in their life, they will cease to be base load, either because of the penetration of renewables in the power generation sector, or because more efficient plants are built. This will obviously have a major impact on the economic viability of the plant itself and associated CO₂ storage system. As has been described, HYPOGEN is intended to operate round the clock, at 100% capacity, switching from electricity to hydrogen production as the market dictates.

Conversely, a plant producing hydrogen only, is likely to find it difficult to cover its costs as the price that can be obtained from the sales of hydrogen would be less than that of electricity.

If HYPOGEN did not succeed, much of the technology of coal based units could be adapted for advanced IGCC systems, which due to the development of gas turbines, will probably offer better coal to electricity efficiencies than even the best pulverised fuel plants. It is also conceivable that the HYPOGEN plant could be adapted to produce a synthetic natural gas, as was envisaged after the 1973 and 1979 energy crises.

11. Plant Location

The question of plant location is intimately linked to that of public acceptance, and this in turn will greatly depend on the type and size of a HYPOGEN plant. Unless the public and its representatives are convinced by the merits of HYPOGEN the chances of a successful go-ahead for construction are unlikely. Providing that the arguments for carbon storage are accepted, it should be far easier to gain the support of the public, than with, for example, the construction of an airport or a new nuclear power plant.

The economic factors pointing HYPOGEN plants to specific locations will, for once greatly help rather than hinder. A big coal based HYPOGEN plant, for example, would probably be constructed near existing coal facilities, that is a port or an inland site that was already being used for coal imports, with good railway or river borne barge connections. It would be quite likely that a disused coal fired power station or a disused steel works would be on the same site. It would make an ideal location for the HYPOGEN facility. The public reaction to the construction of a HYPOGEN plant would probably be neutral or even supportive in such instances.

If natural gas were to be used for hydrogen and electricity production, it is likely that such plants would have to be based within a few tens of kilometres from potential markets.

Judging from the size and environmental impact of early steam reforming plants (using liquid fuels for synthetic natural gas production) and combined cycle gas turbine generation systems, it should be possible to erect a steam reformer HYPOGEN type plant on most brownfield sites, without much public opposition.

Turning now to other criteria which relate to plant location, there is a reasonable amount of flexibility here also, although the likelihood is that plants, whatever their fuel or design, will be situated close to existing users. An important factor is the electricity market, where ideally the plant should be replacing an existing power station, permitting the use of the grid. Getting rights-of-way for a new hydrogen pipeline or an electricity grid may be the time determining factor, rather than the actual process of construction.

Energy losses, which result from long distance transmission of hydrogen, electricity and captured CO₂, need proper consideration. Pressure drops through the hydrogen pipeline system are an important factor, as there are difficulties in recompressing large volumes of this gas. This could set a distance of around 100km for large scale HYPOGEN plants from potential markets, unless a pipe was somewhat oversized in terms of its carrying capacity, compared to one carrying natural gas.

12. Local Environmental Aspects

Broad based environmental considerations, specifically concern about the greenhouse effect, are some of the driving forces behind the HYPOGEN project, dictating to a very large extent the nature and form of fossil plants designed to produce hydrogen and electricity and capture CO₂. For the community living in the vicinity of a HYPOGEN facility, carbon capture and storage would not be an issue of real significance, unless the gas was stored locally. The legal and regulatory matters referred to previously would be applicable. Of rather greater significance will be the way in which the emissions and discharges from the plant could impact on the local environment.

Here HYPOGEN has something positive to offer. HYPOGEN should and can offer low levels of NO_x and, depending on the plant design, low or even negligible amounts of particulates and SO₂. These levels would be significantly lower than from a conventional pulverised coal steam plant and would be typical of a conventional natural gas fired combined cycle plant.

With any type of coal fuelled plant there may be problems with some types of liquid discharges, and the issue of ash and slag disposal will need careful consideration. Up to 20% of the input of a coal plant is in the form of ash, and if limestone were added to control slag viscosity in a gasifier, this would add to the burden of solids removal.

The removal of sulphur in gasification systems is no problem. This can be removed by absorbing sulphur as H₂S, using part of the same absorption plant as would be used to capture carbon dioxide. The H₂S is then put through a Claus Kiln to produce pure sulphur as a saleable product. More of a difficulty would be the presence of ammonia and HCl in the gas stream. These would eventually have to be eliminated and neutralised before they could be discharged. Certain types of gasifier, notably fixed bed, and to a lesser extent fluidised bed processes, may produce tars and phenols. These should not be a problem on a well run plant during normal operation, but they may present some hazard to site personnel during heavy maintenance periods. Codes of practice and maintenance procedures should be considered at the design stage to mitigate these risks.

13. Plant and Transmission System Safety

People living in the locality of the HYPOGEN facility will need assurances over plant safety. Due to what may be termed the Hindenburg (hydrogen airship) syndrome, anything to do with hydrogen is viewed with concern. In actual fact in some respects hydrogen is rather less of a risk than many hydrocarbon gases and fuels. Nevertheless it is likely these matters would come up at a public enquiry and need to be addressed in advance.

The safety aspects of transmitting hydrogen to users, and carbon dioxide to the storage site, by pipeline will also need to be reviewed. In both cases the assumption will be that the same levels of pipeline integrity will be used as are currently being specified for natural gas transmission. Leakages do occur occasionally, mainly from man-made accidents. If this were to occur, the risks to the public would appear to be rather lower than with natural gas escapes. The low density and low calorific value of hydrogen, compared to natural gas, should reduce the explosion risk. With carbon dioxide there is no explosion hazard, but there is a risk of asphyxiation, if there was a significant escape. Clearly the risk to the public would be much reduced by locating the HYPOGEN plant as close to the storage site as possible. In terms of the design of the pipeline itself there are separate issues. For hydrogen it seems possible that it may not be feasible to use high strength steels for pipeline construction, to eliminate the risk of hydrogen embrittlement. For carbon dioxide, this gas will be innocuous providing it is dried. As this is standard practice in the transmission of natural gas there is nothing unusual about this requirement.

14. Conclusions

This report has outlined the thinking of JRC-SETRIS on the HYPOGEN Project and is intended to stimulate constructive thinking and initiate discussions on the subject. As well as the technical issues, the legal and socio-economic background has been kept in view.

One of the key areas identified in the Growth Initiative with a potential to stimulate growth is the development of the hydrogen economy. HYPOGEN is a near to medium term project, which relates to this. The aim is to construct and operate a large-scale test facility to evaluate methods of co-producing hydrogen and electricity.

It would appear, given the timescale, that the facility would have to use a fossil fuel as primary source of energy. The carbon dioxide that is produced during the co-production of hydrogen and electricity would need to be captured and stored safely and permanently.

The proposed HYPOGEN facility will probably need to be at a commercial or near-commercial size and output, to attract serious involvement from industry and energy based organisations. It needs to be understood, by these stakeholders, that the facility would be a site for long term R&D activities, to investigate improved methods for the co-production of hydrogen and electricity. The specification for the plant should reflect this requirement. The basic design of the facility would be used as the forerunner for similar units that could be also used throughout Europe.

It follows that using the criteria, applicable to all projects under the Growth Initiative, the design for HYPOGEN facility will need to be mature (i.e. feasible) enough to be able to attract investment. It should have a pan-European dimension, promoting growth and innovation demonstrating environmental benefits. It follows that HYPOGEN should have the following attributes:

- (i) It relies on proven or near commercial technologies to ensure that a large-scale facility could be constructed in the near future.

- (ii) It is a facility to evaluate innovative technologies in the co-production of hydrogen and electricity.
- (iii) It is based on a generic design that could be used throughout Europe, rather than on a one-off unit tailored for a specific energy utility or chemicals producer.
- (iv) It makes a contribution to the reduction of greenhouse gas emissions and does not add to local pressures on the environment.

Given the current state of the art, a successful HYPOGEN facility could be designed to operate on natural gas, coal or lignite. It appears that the basic options are some form of steam reforming for natural gas, and for solid fuels, gasification. Current off-the-shelf designs using these fuels would require modification, when used as the core of a HYPOGEN plant, and some of the main issues are identified in the report. The CO₂ would need to be captured and then stored in a geological reservoir, or utilised commercially for EOR or for the production of chemicals.

The financing of the HYPOGEN facility needs due consideration. For example in its early stages, it is unlikely that the HYPOGEN facility could benefit from the emissions trading mechanism. Furthermore the HYPOGEN facility would have to fit into an existing electricity supply system, as well as to contribute to the evolving hydrogen market. This could be problematic during the initial post-commissioning period, as energy production would be irregular. In fact there could always be a problem with continuity of electricity generation with a plant that is being used to evaluate new developments, unless the initial design made allowances for this.

The demand for hydrogen will be small, given the timeframe during which the plant is expected to be erected. Initially, hydrogen will probably have to be used in the plant to generate and sell electricity. The possibility of sales of carbon dioxide from the HYPOGEN facility for enhanced oil recovery or polymer manufacturing should be examined, although the timescale limitations associated with the former makes that particular prospect dubious. If there is the possibility of using the CO₂ for the production of chemicals, it is vital, as noted earlier, that the design should not be tailored for one specific user.

The economics of the facility would be improved if the plant were able to change the ratio of hydrogen to electricity, so as to meet the electricity demand profiles, but keeping the plant throughput high, by producing hydrogen at night time. This, in fact, would need to be a principle requirement in the specification for commercial units that can co-produce hydrogen and electricity using technology stemming from the HYPOGEN Project.

In short the commercial situation for a novel plant, with a significant R&D remit, such as that of the HYPOGEN facility, could be difficult. This would need to be recognised with the support funding. Accordingly the support instruments proposed in the Growth Initiative should be further explored.

A legal framework will be needed to cover the construction and operation of the HYPOGEN facility, including the issues associated with the storage of CO₂ generated by the facility. There is vast European experience in the production, transmission and use of hydrogen and also in the generation of electricity. Hence, only minor legal and regulatory changes would be needed in connection with the HYPOGEN facility itself. The biggest problem may come with the storage of CO₂. Here the legal and regulatory situation needs further work. International treaties and insufficient national legislation could become major hurdles for the project. These could be avoided by permitting the facility to emit the captured carbon dioxide during its first years of operation, until these issues are resolved. Ultimately, the success of the

HYPOGEN project will be dictated by the acceptance of the public. To this end, a proper information campaign is needed to inform the public about the merits of the Project.

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A large-scale test facility for the production of hydrogen and electricity

The HYPOGEN Project: A JRC-SETRIS Perspective

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Abstract

The HYPOGEN (HYdrogen POWER GENERation) project refers to a large-scale test facility for the co-production of hydrogen and electricity. HYPOGEN will be a clean fossil fuel design in which the CO₂ will be captured and stored. Although this facility will be used to demonstrate the technology, it is emphasised that the design should be able to vary the ratio of hydrogen to electricity for commercial plants to be economic. The HYPOGEN concept will engender much interest from industry and the public, as an integral aspect in the development of a hydrogen-based energy economy in Europe.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national

