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08

水素利用国際クリーンエネルギーシステム技術(WE-NET)

サブタスク3　全体システム概念設計(都市規模での予測評価)

平成9年3月

新エネルギー・産業技術総合開発機構

委託先 ロンドン・リサーチ・センター
インペリアル・カレッジ・コンサルタント

「水素利用国際クリーンエネルギーシステム技術（ＷＥ－ＮＥＴ）
サブタスク３．全体システム概念設計（都市規模での予測評価）」

「ロンドン・リサーチ・センター
インペリアル・カレッジ・コンサルタント」
「平成９年３月」　　「７０頁」

今年度の研究では、昨年度に引き続き、ロンドンの中心部、市内、および市外のそれぞれ３㎞四方の範囲で、天然ガスに水素を混ぜるハイタンシナリオに加え、便益の高い特定の用途に水素を集中的に利用するターゲット・ハイタンシナリオ、ガソリンに水素を混ぜるシナリオ、その他の排出抑制技術である触媒技術について比較検討を行い、水素を都市の燃料経済に導入する最善の方法について検討した。

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WE-NET Subtask 3 - Conceptual Design of the Total System

prepared by IC Consultants and London Research Centre

Preface

The Japanese Government is concerned about the long term availability and cost of fossil fuels, as well as the environmental consequences of their use. As a result, over the past 20 years, it has played an active part in the development of new energy sources.
Hydrogen could be a significant energy source for Japan in the future. In 1992 the Agency of Industrial Science and Technology in the Ministry of International Trade and Industry (MITI) drew up proposals for the International Clean Energy Network Using Hydrogen Conversion (WE-NET: World Energy Network) project as part of the New Sunshine Project. The WE-NET project was entrusted to NEDO (New Energy and Industrial Technology Development Organization) from MITI. NEDO started this project from 1993.

The WE-NET project aims at the efficient utilisation of energy from renewable resources. These resources are not evenly distributed around the world. The project seeks to establish the technologies necessary for the construction of a worldwide hydrogen energy network. The system will include the use of renewable energy resources to produce hydrogen from water, the conversion of the hydrogen into a form suitable for transportation, and the distribution of hydrogen for use as a fuel in cities, to industry and for power generation. The world-wide diffusion of hydrogen-related technologies would contribute to the reduction in carbon dioxide emissions, help to meet international energy demand, create opportunities for additional energy production, and provide those countries which have ample renewable energy resources with a means of exporting them.

The project is divided into three phases, and will extend over a period of 28 years from 1993 to 2020. Work within the first phase is divided into 9 Subtasks.

During 1994 NEDO invited the Imperial College of Science, Technology and Medicine and the London Research Centre in the United Kingdom to participate in the programme of research. The focus of this research is on Subtask 3: Conceptual Design of the Total System. This is the third annual report of results. Imperial College and the London Research Centre have been assisted in their studies by the Fuji Research Institute Corporation in Tokyo.

April 1997

実施体制

本調査は、新エネルギー・産業技術総合開発機構の委託により、インペリアル・カレッジ・コンサルタントとロンドン・リサーチ・センターが共同して実施した。

また、調査の一部については、㈱富士総合研究所に再委託を行っている。

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EXECUTIVE SUMMARY

The Purpose of the Project

This report follows directly from the Full Report for Fiscal 1995 and develops further the analysis into the introduction of hydrogen into an urban fuel economy.

The general guidelines for this phase of the project were set up in April 1995 and require a number of scenarios to be analysed. These each consider a different approach to the introduction of hydrogen. The scenarios that are considered in this report are one in which hythane® is targeted to transport applications (**targeted hythane® scenario**), one in which hydrogen is added to gasoline to improve its performance (**hydrogen as an additive for liquid fuels**), and one in which catalytic conversion is assessed as an alternative to hydrogen (**alternative methods of emissions control**).

Conclusions

1. This work confirms previous findings from the earlier phase of the study that the use of hydrogen as a transport fuel in urban areas can have substantial environmental benefits. In the earlier phase the benefits were assessed for the distribution of hydrogen as hythane® (a mixture with natural gas) indiscriminately to all users. In the present phase, similar benefits have been identified for hythane® targeted to transport applications and for the use of hydrogen as an additive to gasoline internal combustion engines. In all these cases the value of the hydrogen was assessed by a direct valuation of the reduction it brought about in external environmental costs.

$$\text{Premium for Hydrogen (\$/GJ)} = \frac{\text{Reduction in Externality Costs (\$)}}{\text{Hydrogen Supplied (GJ)}}$$

2. In all cases there can be circumstances in which the value of hydrogen so assessed is large compared to its likely cost of production. Work in the earlier phase showed that the environmental benefits of hydrogen in applications other than transport were substantially less. The use of hydrogen for urban transport therefore appears to be the most effective way of introducing hydrogen into the energy supply structure.

3. The work in this phase has also made an alternative assessment of the value of hydrogen as a transport fuel by calculating the costs *avoided* in alternative means of emission control. The alternative studied was catalytic conversion because this is the most commonly adopted technique for reducing emissions from transport. We can show the equivalent value of hydrogen as follows.

Scenario	Emissions Reduction	Infrastructure Cost	Amount of Hydrogen
Hythane	E_H	C_H	X
Catalysts	E_C	C_C	-

$$\textit{Net Benefit of Using Hythane} = E_H - C_H$$
$$\textit{Net Benefit of Using Catalysts} = E_C - C_C$$

$$\textit{Net Benefit of Hythane compared to Catalysts} = (E_H - C_H) - (E_C - C_C)$$

Expressed per unit of hydrogen:

$$\textit{Net Benefit of Hythane compared to Catalysts} = \frac{(E_H - C_H) - (E_C - C_C)}{X}$$
$$\textit{or } \frac{(E_H - C_H)}{X} - \frac{(E_C - C_C)}{X}$$

4. The study shows that the cost-benefit performance of the various technologies for reducing environmental impact (distributed hythane®, targeted hythane®, hydrogen-gasoline, catalytic conversion) is very sensitive to assumptions made about the costs of environmental impacts. The different technologies depend differently on these assumptions and this dependence can be shown conveniently by the concept of the "technologically efficient frontier".

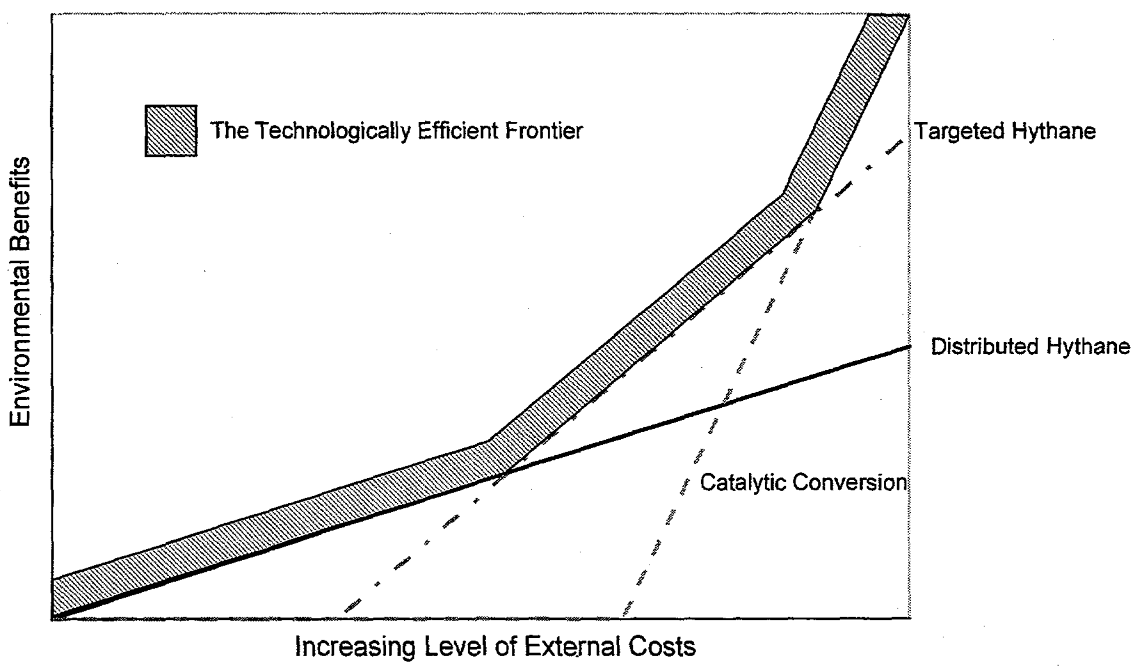
   By comparing the scenarios it is possible to note which are the most efficient in each area of London and for each level of externality cost assumption. The table below summarises the findings of the report.

Comparison of all scenarios

	Optimum		
	Central	Inner	Outer
High	*TH*	*TH*	*C*
Median	*H*	*H*	*H*
Low	*H*	*N*	*N*

(assuming production cost of 6$/GJ)

The results can then be plotted on a curve to show the points at which one technology becomes more efficient than another. The curve below represents an arbitrary area in which distributed hythane® provides the greatest environmental benefits for a given amount of money invested at low external costs. Targeted hythane® is the most efficient given median external costs and catalytic conversion only at high levels of external cost.



The 'Technologically Efficient Frontier'

5. Under the assumptions adopted for this study there is no single preferred technology for environmental improvement. The optimal choice is a function of both the damage costs assumed for the environmental impacts and whether the technology is to be used in central, inner or outer areas of the city.

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			84,953	
Reference	30,939		-	55,796	
Hythane	30,605	136	4,154	22,938	**211**
Difference	334	- 136	- 4,154	32,858	
Proportion	0.01	- 1.00	- 1.00	1.43	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			19,267	
Reference	7,230			11,484	
Hythane	7,171	29	1,662	4,806	**173**
Difference	59	- 29	- 1,662	6,677	
Proportion	0.01	- 1.00	- 1.00	1.39	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			2,328	
Reference	793			1,099	
Hythane	791	3	1,038	490	**-124**
Difference	3	- 3	- 1,038	609	
Proportion	0.00	- 1.00	- 1.00	1.24	

High Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	34	34	26
SO_2	25	16	15
VOC	24	23	20
CO_2	0.053	0.053	0.053
CO	5.8	4.0	2.5
Particulates	21	15	8

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the amount of hydrogen

The Value of Hydrogen in Three Areas of London

The tables above show the value of hydrogen in three areas of London when it is used as 'targeted hythane®'. It is noticeable that this value changes significantly with a change in the assumed externality costs, and an understanding of the methodology behind the calculation is essential in order to use these values in a sensible manner.

6. The assumptions made in the analysis are quite severe and the conclusions must be treated with caution, but the calculations suggest that for high value of environmental damage costs, targeted hythane® is superior. Catalytic conversion is only the technology of choice when high damage costs are assumed and the calculations are made for Outer London. These conclusions are very tentative.

7. It is worth noting that the analysis suggests that catalytic conversion is only cost-effective with the assumption of high environmental damage costs. This is a surprising, and we believe novel, result. It suggests that the higher values of environmental damage costs are more appropriate because they are implied in the decision to adopt catalytic conversion to reduce vehicle emissions.

8. Taking the analysis as a whole, while recognising the sensitivity of the conclusions to the assumptions, there does appear to be a strong case for suggesting that the use of hythane® in vehicles could be the most cost-effective initial application of hydrogen and the most appropriate market to develop first.

Tentative Observations on Infrastructure Development

1. Some tentative observations can be made concerning the implications of this finding for infrastructure development and transitional strategies. If transport applications of hythane are to be envisaged as the initial market for hydrogen, then the infrastructure for the distribution of hythane® needs to be designed and developed in a manner that will also facilitate the availability of pure hydrogen for pure hydrogen using technologies. This suggests that the hydrogen should be added to the natural gas within the city; *not* at the boundaries as we have assumed in our calculations thus far. This in turn implies that the supplementary infrastructure should be designed for distributing hydrogen, not hythane®. A somewhat different cost structure will need to be considered in further analysis.

2. It is also important to note that once targeted hythane® has been introduced by

mixing hydrogen and natural gas within the city, distributed hythane® is unlikely to be cost-effective as an intermediate step to pure hydrogen. This is because the major value of distributed hythane® - reducing emissions in the transport sector - has already been obtained.

Emissions from power generation within London are small, so that targeting hythane® to reduce them is relatively costly although using distributed hythane® is still an attractive option. Using targeted hythane® in transport is far more cost-effective. However, if substantial emissions reductions from introducing targeted hythane® into transport have already been achieved then the overall reductions from subsequently introducing distributed hythane® will be small. In this case there may be no point in introducing the distributed hythane® concept.

3. A mechanism for targeting hythane® would be to deliver hydrogen to hythane® refuelling stations for large fleet users, e.g. buses. The hydrogen would be added to natural gas at site. Pure hydrogen could then be available for other technologies, as they become cost-effective. These might include fuel cells for power generation.

4. Such an approach would lead to an "island" development of hydrogen centres. The least cost, low risk manner of providing hydrogen to these centres would initially be by vehicle. As demands for hydrogen increase at these centres it may be cost effective to develop pipeline delivery to the larger centres, displacing hydrogen carrying vehicles that can be used to supply new, small centres.

5. As different hydrogen using technologies became cost-effective it may not be necessary to rely on transport applications for the initial load. Large commercial centres might adopt hydrogen fuel cells for power and thermal conditioning.

Future Work

1. During the second half of FY1996, we have identified and collated some data on energy use in Japanese cities, and in Tokyo in particular. This is in preparation for more detailed application of our existing methodologies to Tokyo, which will be undertaken during FY1997. One objective during FY1997 will be to establish whether the conclusions drawn in earlier stages of the study are equally valid for

Japanese cities as for London.

2. The method of analysis that we have used up to now is based upon an examination of a typical urban environment (central, inner and outer). It is inadequate for analysing the spatial aspects of the infrastructure development because vehicles that move in different areas do not necessarily refuel there.

3. For a deeper understanding of the infrastructure needs it is necessary to take a more holistic view of the city and the possibility of targeting specific uses. In turn this will require spatial information on the refuelling patterns of large fleets (buses, commercial vehicles). This methodology will be developed in the FY1997 phase of the project.

4. For completion of the objectives of the project it will also be necessary to demonstrate how other uses of hydrogen can be most effectively developed around these islands. This will also be a topic in the next two phases of work, in FY1997 and 1998.

日本語概要

研究開発目標

本報告書は平成７年度に引き続き、比較的少量の水素を都市の燃料経済に導入する最善の方法を確認することを目的としたものである。

本調査研究では、平成７年４月に決めたガイドラインに沿って、いくつかのシナリオを分析し、それぞれ別の水素導入手法について検討している。検討したシナリオには、ハイタンを輸送手段に利用することを目的としたシナリオ（ターゲットハイタンシナリオ）、水素をガソリンに添加し、その性能改善（液体燃料の添加物としての水素）を狙いとしたシナリオ、そして触媒を水素の代替として評価するシナリオ（その他大気汚染物質排出抑制シナリオ）がある。

平成８年度の研究開発成果

１．シナリオについての分析結果

(1) 今年度の研究においても、初期の水素利用方法として、水素を都市部で輸送燃料として利用することが環境に大きな便益をもたらすことが確認された。昨年度では、水素をハイタンとしてすべてのユーザーに供給した場合（ハイタンシナリオ）の評価が行われた。今回は、ハイタンを集中的に輸送手段に用いる場合、またはガソリン使用の内燃機関に添加剤として水素を利用した場合に、同様のメリットが得られるかどうかを検討した。これらすべてのケースにおいて、水素の価値は外部環境コストの減少分を直接評価して行った。

水素のプレミアム（＄／ＧＪ）＝外部コスト減少分（＄）／水素供給量（ＧＪ）

(2) この結果、全てのケースにおいて、水素の価値が予想される製造コストを上回る状況が存在することがわかった。前年度の研究結果によると、輸送以外の用途に水素を利用した場合、大きな環境メリットは得られないことが確認されている。従って、エネルギー供給構造へ水素を導入する場合、都市部において輸送手段として水素を利用することが最も効果的な方法と考えられる。

(3) また、輸送燃料としての水素の価値を、その他の大気汚染物質排出抑制手段と比較し、回避される費用を算出する（触媒技術とハイタンの社会的純便益を比較する）ことにより評価した。その他大気汚染物質排出抑制手段として触媒技術を取り上げた。この技術

は、輸送手段による排ガス低減対策として用いられている最も一般的な方法である。水素の価値は次のように示すことができる。

シナリオ	排出削減	インフラコスト	水素量
ハイタン	E_H	C_H	X
触媒	E_C	C_C	-

$$\textit{Net Benefit of Using Hythane} = E_H - C_H$$
$$\textit{Net Benefit of Using Catalysts} = E_C - C_C$$

$$\textit{Net Benefit of Hythane compared to Catalysts} = (E_H - C_H) - (E_C - C_C)$$

単位水素量当たりでは：

$$\textit{Net Benefit of Hythane compared to Catalysts} = \frac{(E_H - C_H) - (E_C - C_C)}{X}$$
$$\textit{or } \frac{(E_H - C_H)}{X} - \frac{(E_C - C_C)}{X}$$

(4) 環境への影響を低減する各種技術（ハイタン、ターゲットハイタン、水素ガソリン、触媒技術）の費用効果は、環境コストの想定によって大きく左右されることが明らかになった。また、技術に応じて想定コストへの依存度に差があり、この依存度は「技術的最高効率領域」のコンセプトによって示すことができる。

シナリオを比較することにより、各外部コストの想定に応じて、ロンドンの各地域においてどのシナリオが最も能率的であるかを特定できる。

全シナリオの比較

	最適条件		
外部コスト	**中心地**	**市街地**	**郊外**
高い	*TH*	*TH*	*C*
中位	*H*	*H*	*H*
低い	*H*	*N*	*N*

（生産コスト 6$/GJ を想定）
TH：ターゲットハイタン、　H：ハイタン、
C：触媒、　N：該当なし

比較結果を図に示すことにより、それぞれの技術において他と比較して有益となる点を明確にすることができる。低い外部コストで特定の投資額の条件のもとでは、シナリオの中ではハイタンが環境に最大の有益性を有することが分かる。また、中位の外部コストではターゲットハイタンが、また高い外部コストでは触媒技術がそれぞれ最も有益性が高くなる。

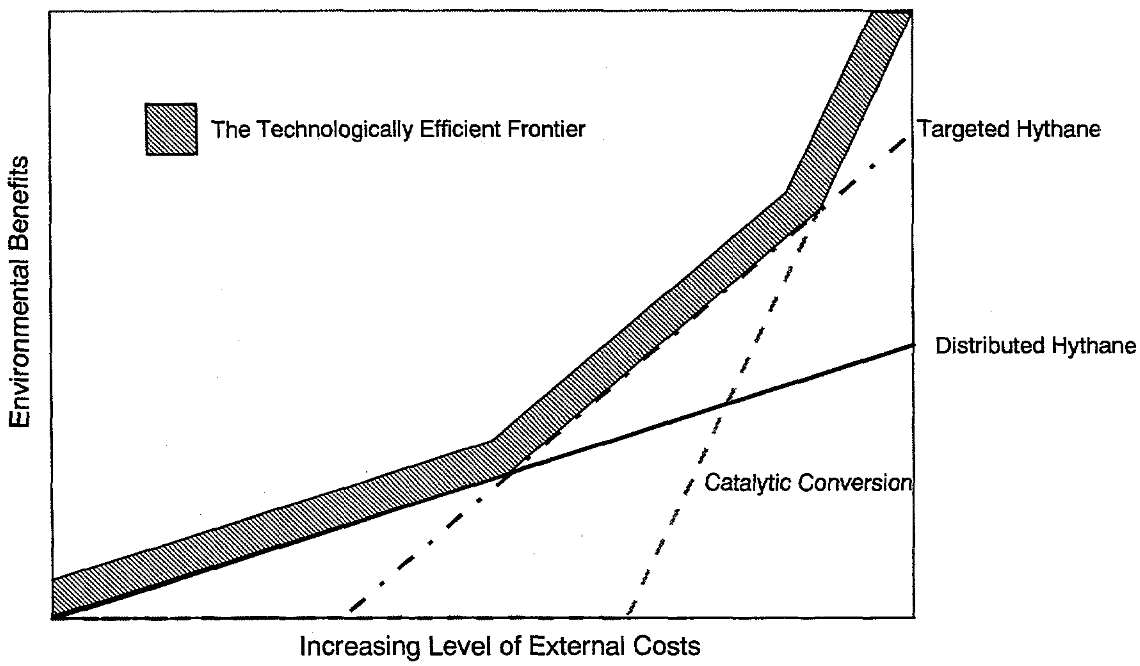


図　技術的最高効率領域

(5) この条件のもとでは、環境改善のために優先すべき技術が一つではない。最適な選択基準は、環境影響に対して想定される損害費用、およびロンドンの中心部、市街地あるいは郊外のどこで技術を適用するかの両面から決まる。

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			84,953	
Reference	30,939		-	55,796	
Hythane	30,605	136	4,154	22,938	**211**
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High Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	34	34	26
SO_2	25	16	15
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CO_2	0.053	0.053	0.053
CO	5.8	4.0	2.5
Particulates	21	15	8

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the amount of hydrogen

表　ロンドン市内における水素の価値（ターゲットハイタン時）

上記の表は、ロンドンの3つの地域で水素を“ターゲットハイタン”として利用したときの値価を示している。この価値は推定される外部コストによって大きく変動しており、これらの価値を実際に用いるには、推計方法を理解することが必要になる。

(6) この分析を行う際には仮定条件を厳しく設定しているため、ここから得られる結果は慎重に扱わなくてはならないが、分析より、環境損害費用が高くなる場合はターゲットハイタンが優先すべき技術であるといえる。触媒技術は、高額な損害費用を想定した場合、ロンドン郊外においてのみ選択すべき技術である。

(7) 触媒技術は、高い環境損害費用を想定したときのみ費用効果的であるとする分析結果は注目に値する。この結果は、車両からの排出を抑える理由で触媒技術の採用を決定する際には高い対策費用が見込まれていることを意味しており、よって環境への損害費用は高く想定する方がより妥当といえる。

(8) 全体を通じて分析データを見た場合、仮定条件に対する結果の感度を踏まえる必要はあるが、初期的な水素利用法としては、車両へのハイタンの使用が最も費用効果的であり、まずはじめに育成すべき最適市場であることが考えられる。

2．インフラ整備についての仮説

(1) 1．の検討結果を踏まえ、インフラ整備及び移行シナリオに対して、いくつかの仮説がたてられる。ハイタンの輸送手段への利用を初期的な水素市場として検討した場合、純粋水素利用技術に使用する水素にも利用できるように、ハイタンの供給基盤を設計し、開発する必要がある。このことは、我々が推計の際に想定した都市境界部でなく都市部において水素を天然ガスに添加すべきだということを示唆している。さらにインフラを新たに整備する場合には、ハイタンでなく純粋水素に対して設計すべきだということも示している。今後の分析においては、幾分異なる費用構成を考慮する必要が生じると考えられる。

(2) さらに重要な点は、都市内で水素と天然ガスを混ぜることによりターゲットハイタンを導入してしまえば、すべてのユーザにハイタンを供給するハイタンシナリオは純粋水素への移行技術として費用効果的ではなくなることである。その理由は、ハイタンは輸送部門での排出量の低減という意味で重要であり、これはすでに達成されていることになるためである。

ロンドン市内の発電所からの排出量は少ないため、ハイタンの導入ターゲットを発電所からの排出量低減とすることは比較的割高になるが、ハイタンシナリオの導入はまだ魅力的な選択肢の一つとして残る。ターゲットハイタンによって、ハイタンを輸送手段として利用する方が費用効果ははるかに高い。しかし、ターゲットハイタンの輸送手段への導入によって、排出量の低減を達成してしまえば、その後にハイタンシナリオを導入しても効果は低く、この場合、ハイタンシナリオ導入には意味がない。

(3) ターゲットハイタンの供給メカニズムとしては、例えばバスなど大量輸送ユーザを対象とするハイタン供給ステーションに水素を供給し、現地で水素を天然ガスに添加することが考えられる。これにより、純粋水素は、他の技術が費用効果が高くなりしだい、利用できる可能性がでてくる。これらの用途としては、例えば、発電所の燃料電池などがある。

(4) 以上のような手法は水素センターの“アイランド”開発構想へ結びつく。水素を最小限の費用と低いリスクで水素センターに供給する方法は、まず車両による方法である。これらのセンターで水素の需要が伸びるにつれ、大規模センターへの供給パイプラインを整備し、不要になる水素搬送車両は、新しい小規模センターへの供給に利用する。

(5) 他の水素利用技術の費用効果が大きくなるにつれ、初期的利用として輸送手段に依存する必要がなくなる。例えば、大型商業センターでは発電と空調用に水素燃料電池を採用する可能性が考えられる。

3．今後の進め方及び課題

(1) 平成８年度の下半期に、日本の諸都市、特に東京でのエネルギー利用に関するデータを確認し照合した。これは、本研究での手法を東京に適用するための準備段階であり、平成９年度中に分析を実施する予定である。平成９年度の目標の一つは、本研究の初期段階で得た結論がロンドンと同様に日本の都市にも有効であるかどうかを検討することである。

(2) 我々が現在まで用いてきた分析方法は、典型的な都市環境（中心部、市街地、郊外）を分析することにより行われた。この手法は、インフラ開発に必要な空間的要素を分析するには、異なる地域間を移動する車両が同一地域で燃料補給するとは限らないため、不十分である。

(3) インフラの必要性に対して十分理解するには、都市全体及び特定用途への適応可能性に

ついて包括的に考察する必要がある。また、そのためにはバス、商用車などの大きな運搬車両の燃料補給パターンに関する空間的データが必要となる。この方法は平成9年度に検討する予定である。

(4) 本調査研究の目的遂行のためには、これらの“アイランド”の周囲において他の水素利用用途を最も効果的に開発する方法を示すことが必要となる。これは平成9年度及び平成10年度に検討する予定である。

WE-NET Subtask 3 - Conceptual Design of the Total System

prepared by IC Consultants and London Research Centre

1. Introduction

SUMMARY

This report describes work undertaken within the third phase of a research contract awarded to Imperial College and the London Research Centre under the WE-NET Project (Phase I) - International Clean Energy Network Using Hydrogen Conversion. The overall goal of the work reported here is to refine assessments of the value of hydrogen as a fuel in terms of its environmental benefits and to begin analysis of the most appropriate and cost-effective arrangements for distribution.

1.1 Background

This report describes work undertaken between 1/4/96 and 30/9/96 within a research contract awarded to the London Research Centre and IC Consultants under the WE-NET Project (Phase I) - International Clean Energy Network Using Hydrogen Conversion. The contract relates to Sub task 3 - Conceptual Design of the Total System. This work is based on the complementary experience of Imperial College in the assessment of energy technologies and the London Research Centre on urban energy studies. It depends also on the existing collaboration between Fuji Research Institute Corporation and the London Research Centre on energy and urban studies.

The overall objectives of Subtask 3 are:

- development of a conceptual design encompassing the total system, including electricity generation using renewable energy, hydrogen production, transportation, storage and utilisation, and technological and economic evaluation.

- estimation of the effects of the introduction of hydrogen energy on long-term energy supply and demand, both from a global viewpoint and from the viewpoint of each country.

- development of safety measures and evaluation technologies.

1.2 Achievements in Previous Phases

The primary goal of the project in fiscal 95 was to identify the most cost-effective use of a given volume of hydrogen for energy supply in urban areas taking into account the environmental benefits and the infrastructure requirements.

This work concluded tentatively that the reduction in environmental damage caused by using hydrogen as a fuel could be significant and that the economic case for hydrogen and the definition of the most cost-effective mechanisms of penetration depended strongly on these environmental benefits. The study drew particular attention to the benefits of using hydrogen as an additive to natural gas in transport applications. The analysis suggested that the premium value of hydrogen as a fuel could be as high as $48/GJ, depending on the circumstances and on the values assumed for the damage costs associated with environmental impacts.

1.3 The Goal of the IC/LRC Project in this Phase

The overall goal in fiscal 96 is to consolidate and refine this analysis and to strengthen the justification for some of the underlying assumptions. In particular the work reported in this period compares the advantages of this approach to other methods of emission control, examines the extent to which it is cost-effective to target hydrogen-natural gas mixtures to the most favourable applications and puts forward some preliminary ideas on how the creation of an infrastructure for the distribution of hydrogen-natural gas mixtures could be part of a transitional strategy for the development of a hydrogen economy.

1.4 Specific Objectives in this Phase

The specific objectives of this phase are to:

- to continue the review of previous and current studies of hydrogen technology in the EU;

- to consolidate the analysis undertaken in the previous fiscal year and to strengthen the justification;

- to test the conclusions against the cost-effectiveness of other techniques of emission control;

- to extend the analysis to Tokyo;

- to begin to devise transition strategies to a hydrogen economy.

1.5 Structure of the Report

The structure of this interim report follows broadly the arrangement of the detailed objectives specified in 1.3. It is also the structure which is expected to be adopted for the final report. The implementation of the IC/LRC project depends principally on six man-months of time for a research associate; in this fiscal year this time has been used in the first six-months of the year and the analytical work is completed. The present interim report therefore contains most of the substance of the final report, with the exception of the review of European programmes (which is a continuing process) and the extension of the work to Tokyo (which will be initiated later in the year).

Chapter 2 of the report briefly revisits the methodology adopted, (which is essentially the same as that employed in the studies undertaken in fiscal 95). Chapter 3 will contain the ongoing review of European programmes (to be completed in the second half of the year) and Chapter 4 presents the updated database on external costs, emissions and infrastructure costs. Chapters 5,6 and 7 in various ways attempt to consolidate the conclusions of fiscal 95; Chapter 5 examines the advantages of targeting hythane to the most favourable applications; Chapter 6 considers whether there is any advantage in using hydrogen as an additive to liquid fuels and Chapter 7 compares the use of hythane with conventional catalytic conversion as a means of emission control. Chapter 8 compares the scenarios while Chapter 9 draws conclusions and includes some preliminary examination of the implications for transitional strategies. No extension to Tokyo has yet been made, but some preliminary contacts with relevant institutions are being developed and a note on the work to be done in Japan in the remainder of the year is included in Chapter 10.

2. Methodology

The methodology employed in our analysis is a combination of welfare cost-benefit analysis and scenario analysis applied to typical parts of London. It has been fully described in the report for Fiscal 95, but a brief overview and a note of some modifications is given here.

2.1 Environmental Externalities

The welfare cost-benefit analysis involves identification of the financial and environmental costs associated with various technological configurations. The environmental costs are incorporated by assigning notional damage costs to each emission. These damage costs are assessed by various means and their value is controversial. More details of the methodologies used to assess them are given in Chapter 3 of the final report for Fiscal 95.

Our previous work shows that the cost-effectiveness of hydrogen is strongly linked to its environmental benefits and therefore to the manner in which those benefits are expressed. In Fiscal 96 we have therefore continued to review the literature on these external costs with the intention of narrowing the range of values and permitting a more precise determination of the environmental benefits of hydrogen and therefore of its value as a fuel. This review forms a part of the updated data-base described in Chapter 4.

Unfortunately the additional information on external costs reviewed during Fiscal 96 has not narrowed the range of estimates, which remains wide. We have therefore continued to use the same high and low values of the external costs as those which we used in Fiscal 95. We have also chosen to make our calculations using a median value, which should reflect a more likely outcome than either extreme, but does not express any definitive number.

2.2 Case Study areas

We have continued to use the same areas of London as case study areas, typical of central, inner and outer urban environments. These are fully described in the report for Fiscal 95.

2.3 Scenarios

In our previous work we used a Reference Scenario which was intended to represent a likely pattern of fuel usage in London in the future in the absence of hydrogen as a fuel. We then considered the introduction of hydrogen in two derived scenarios: the hythane and niche markets scenarios. In the first case a mixture of hydrogen and natural gas was widely distributed to all gas consumers regardless of their specific applications and in the second case the same volume of pure hydrogen was targeted at the most cost-effective niche markets.

This work showed that the use of hydrogen-natural gas mixtures in transport applications appeared to be very cost-effective and suggested very substantial economic values for hydrogen, comparable to or higher than likely costs of production. In Fiscal 96 we have maintained the scenario approach, and have examined a range of new scenarios designed to confirm this finding and to demonstrate that it is robust. In particular we wished to test:

- whether the benefits of targeting hydrogen-natural gas mixtures to the most environmentally beneficial cases would exceed the infrastructure costs of targeted distribution;
- whether hydrogen might not be better employed in reducing emissions from dirtier fuels than natural gas e.g. gasoline engines;
- whether conventional methods of emission control through catalytic conversion were not more cost-effective than hydrogen.

To investigate these three hypotheses we have constructed three further scenarios: the targeted hythane scenario, the gasoline-hydrogen or 'Hypet' scenario and the catalytic conversion scenario. These scenarios and the results obtained are described in Chapters 5, 6 and 7.

3. The Emissions and Externalities Database

3.1 Overview

For the purposes of the WE-NET study it has been necessary to collect a large amount of data on conventional technologies in the power generation and transport fields, and to make some advised estimates as to future emissions standards and background pollutant levels. In addition to this, there is substantial literature available on the subject of environmental externalities (discussed in detail in the Final Report for Fiscal 95), and as much of this as possible has also been collated.

This chapter concerns the database which has been set up to contain the externality values, and Appendix 1 details the sources from which the data have been obtained. Comments regarding the reliability of the sources have been included in the Appendix where this has been felt to be necessary.

3.2 Emissions Factors

Emissions factors indicate how much of a pollutant is emitted from a particular process such as power generation. We require these factors for current technologies and for their projected future improvements, and also estimates for possible new technologies. This information then gives us the possibility of comparing the different systems. Typical emissions factors state how much of a particular pollutant is emitted per unit of power generated or fuel consumed, for a particular process or cycle. For example, burning natural gas in combined cycle gas turbines (CCGT) might emit 5 grams of NO_x per kWh of electricity produced, where a coal plant would produce 10 grams. Thus, in simple terms, a coal-fired power plant is more polluting for NO_x than a CCGT. These simple factors are important in the analysis which we are conducting in that they enable comparisons between different technologies from an environmental point of view. However, it is still difficult to compare a plant which produces small amounts of NO_x but a lot of CO_2 with one which does the opposite, and for that we must use some further adjustments in the form of environmental externality costs.

3.3 Environmental Externalities

Environmental externality costing is a branch of economics which is viewed as increasingly important within the environment field, despite some reservations as to how it is carried out and how relevant particular values may be. The point of the discipline is to try to attach economic values to such things as crop damage and increased mortality rates due to environmental pollution. There is a full discussion on the methodologies which are used in Chapter 3 of the fiscal 95 Final Report.

By allocating costs to particular pollutants it is possible to value the whole of a pollutant stream with many constituents from a particular source and compare it with a pollutant stream from another source. For example, during one year of operation a coal-fired power station may produce large amounts of sulphur and CO but little NO_x, whereas an oil-fired plant may produce less CO but more NO_x for the same power output. By valuing all the pollutant effects using externality costs it is possible to compare the two plants without having explicitly to judge the relative effects of the NO_x or CO.

This chapter illustrates graphically the range of values which have been found in the literature for each pollutant which is listed in Appendix 1. It is difficult to compare the various results as different methodologies have been used for each study, with different geographical distributions and in different currencies. However, we have used the results in our analysis by taking the highest and lowest values quoted to find a possible spread within which the true values may lie, and also by adopting a median value as an estimate of the costs which may be considered reasonable. It is impossible to say that this median value is correct since there are too many site-specific factors to be taken into consideration, but we have adopted it in order to move away from the very high and low estimates which may also be misleading.

The values which we have adopted are then used to compare the emissions of different technologies which are more or less interchangeable - conventional CHP plants fired by natural gas can be replaced by fuel cells fired by natural gas, and the pollutant streams will provide significant differentiation. Other differences between technologies such as space occupied and noise have not been considered in this analysis.

3.4 Using Emissions Factors

Data for emissions coming from conventional power plants and transport are available, though they vary somewhat according to their geographical distribution. Data for emissions from new technologies can only be estimated from modelling or from prototypes, so wherever this has been necessary we have tried to include the worst case scenarios in order to avoid giving the newer technologies an unfair advantage. We have also had to distinguish between emissions which occur locally and regionally, which has made it difficult to rank some technologies. This is the case, for example, when valuing the two emissions streams coming from a local boiler providing heat from natural gas and from a power plant producing electricity, and comparing them with the emissions from a local CHP plant which is producing both heat and electric power. We have only been able to include the boiler in our analysis as we feel that the urban emissions inventory is important to our model. This inaccuracy is in some measure counterbalanced by the fact that we assume hydrogen to be shipped in to the edge of the city, rather than taking into account the need to produce and transport it to the urban boundary, and the emissions associated with that. The emissions data which we have used is contained within the worksheets and summarised in Appendix 1.

3.5 Externality Studies

Considerable research is being carried out into the costs associated with environmental externalities in a number of countries, primarily in the developed economies. Studies vary from the small and highly site-specific to the large and general, and inevitably the estimates vary considerably. This is in part because different methods are used to make the evaluation, in part because different impacts are included or not considered, and in part because different pollutants will have different impacts in different areas.

In most cases the dominant impact appears to be health related, and since our study is relevant to urban areas it seems sensible to assume that health costs will play an important rôle in our analysis. This suggests that we are able to accept the figures as they are, rather than modifying them. If, for example, acidification from SO_x emissions was a major contributor to the costs then we would have to be very careful about our use of the figures, since problems arising from acidification depend substantially on local soil types and habitat.

The consideration of global warming is also a complex issue. It must be viewed as a regional problem yet may significantly affect our results, which are primarily concerned with local effects. CO_2 emissions are the most significant contributors to the greenhouse effect, but some local pollutants such as NO_x and hydrocarbons have multiple effects. These include not only local pollution but also contributions to stratospheric ozone depletion. We have chosen to include the cost of global warming in our scenarios.

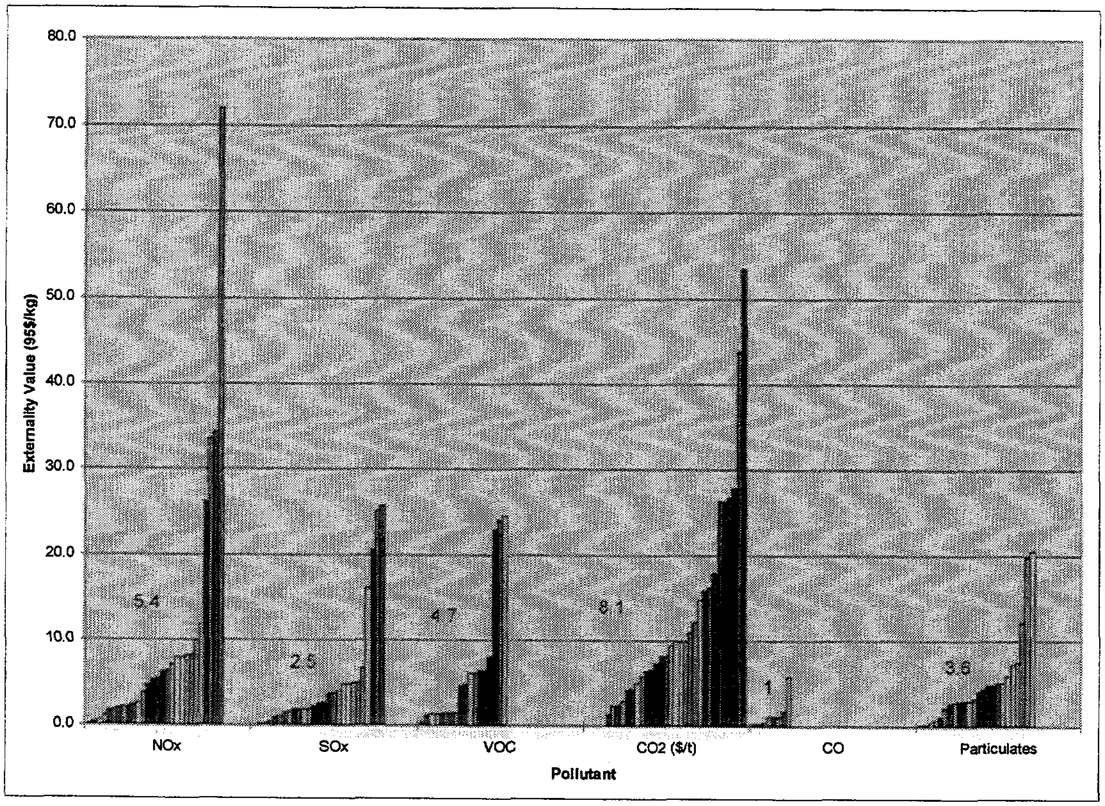


Figure 1: Externality Costs of the Main Pollutants by Study

Figure 1 shows the broad spread of cost estimates from the literature we have surveyed to date, with the number above each group of bars showing the median value. The full list of data is given in Appendix 1. As can be seen, the values vary widely, with the costs associated with NO_x having a particularly wide spread, though this is exaggerated by one value from the South Coast Air Quality Management District (SCAQMD) in California. We have ignored this value in the analysis.

Emissions factors have been included specifically in the relevant scenario analyses (e.g. targeted hythane® or catalytic conversion) and it was felt that compiling them into a separate set of sheets in the Appendix was not necessary.

4. Targeted Hythane®

4.1 Overview

It has already been established in the previous phase of this study that the addition of small quantities of hydrogen to natural gas (to produce hythane®) generates large environmental benefits, but that these benefits are not proportionally increased with an increase in the amount of hydrogen added (detailed in the WE-NET Report for FY 1995). In our previous hythane® scenarios we have indiscriminately added hydrogen to the full natural gas supply system and used the existing infrastructure, resulting in a spread of emissions reductions across the different technologies. In this scenario we endeavour to introduce the hydrogen into the natural gas supply where it has the greatest effect, thereby 'targeting' it and increasing the value of the hydrogen which is used. This has the secondary effect of increasing the amount of infrastructure which is required, sometimes resulting in duplication of the natural gas supply system. It is important to investigate whether the costs resulting from this necessary duplication are matched or bettered by the extra benefits of targeting the hydrogen in this way. The full mathematical analysis is shown in Appendix 2.

4.2 Costs of Targeting Hythane®

We have assumed in our reference scenario that by our nominal time horizon of 2015 30% of cars and 50% of heavy vehicles will run on natural gas. Implicit in this assumption is the assumption that a substantial natural gas filling station infrastructure has also been developed. In this case the targeting of hythane® will be much less expensive than it would be if an entirely new distribution network had to be constructed. Existing studies (Berry, 1996) suggest that it is cheaper to add the hydrogen to the natural gas before distributing it via pipeline than it is to mix in the hydrogen at the point of use, despite the extra pipeline costs which will be incurred. In the second case it is also important to consider the environmental implications of the emissions from the extra delivery vehicles required for transportation of the hydrogen. We have therefore assumed that the hythane® is piped from our city boundary to the filling stations in a separate delivery network, leaving the existing natural gas infrastructure to deliver gas to stationary users.

The cost of a delivery pipeline system is estimated to be $650,000 per kilometre (Berry, 1996), and we have based our infrastructure costs on this figure. There will be approximately 30 km of main supply pipeline necessary to take hythane® into the centre of the city, and then spurs and smaller pipes will be required for the final distribution to be made. It seems reasonable to allocate lower costs to the inner and outer sectors than to the central region, and we have chosen to do this by assigning a reduced portion of the cost of the main 30 km distribution pipe to these areas.

4.3 Technical Requirements of Targeting Hythane®

It was first necessary to select the applications whose emissions were reduced most by the introduction of hydrogen into the original natural gas. This was achieved by using the results from the hythane® scenarios detailed in the report for FY 95. The major source of benefit was seen to be the transport sector. In view of this it was considered that all hythane® should be targeted at the projected natural gas vehicle market. In order for a natural gas engine to burn hythane® efficiently minor adjustments are required, but there are no significant technical problems which must be overcome.

4.4 Benefits of Targeting Hythane®

The main value which will be added by targeting hythane® arises because the emissions from the transport sector form a significant part of the urban pollution problem. If these can be reduced then the impact on urban air quality would be large. In general, the internal combustion engine in a vehicle is less efficient than a stationary engine, and this is compounded by the fact that it is not able to operate in a steady-state condition where emissions could also be minimised. Small-scale power generation from gas turbines and fuel cells fuelled by natural gas is both extremely efficient (particularly in cogeneration mode) and pollutes relatively little. As shown in our previous report, the value of changing from natural gas to hythane® when using stationary power sources is much smaller than introducing hydrogen to natural gas in vehicles, and an increase in costs brought about by targeting this change is likely to outweigh the additional benefits.

The benefits of targeting hythane® will be calculated in the same way as the benefits in the other scenarios which have been addressed - in the form of emissions reductions. Once again, it is felt that the wide spread of externality cost estimates is best taken into account by conducting two scenario analyses, with the highest and lowest externality values incorporated. We have also conducted a further calculation based on a median value of externality costing, but it must be stressed that we feel this should only be viewed as an indicator of possible costs for the short term.

4.5 Valuation of Infrastructure Costs - Discounted Cash Flow Analysis

The infrastructure costs which have been included in the scenario have been calculated on the basis of a 20 year life and a 15% discount rate. This is in order to ensure that they are representative of the higher end of possible costs, since it is likely that in practice they would have a longer lifespan, and lower discount rate might be applied in the case of a large project.

The net present value of the infrastructure is calculated and annualised at a discount rate of 15%. This annual cost is then set against the specific benefit which arises from the replacement of natural gas vehicles with hythane® vehicles rather than supplying hythane® to all natural gas using devices. Annualised infrastructure costs for the pipeline are given in Table 1.

Table 1: Pipeline Infrastructure Costs

Area of London	***Cost (M$)***
Central	*4.15*
Inner	*1.66*
Outer	*1.04*

4.6 Calculating the Value of Targeting Hythane®

In order to asses the value of putting hythane® into vehicles a similar procedure to the one used in the original hythane® scenario was adopted. The calculation is based on a reference scenario which assumes a certain percentage of natural gas vehicles (full details are given in the Final Report for FY 95). It is assumed that all these vehicles will be run on hythane® and thus that the emissions they produce will be reduced by a specific amount relative to those produced when natural gas is used. The overall difference in polluting emissions is then calculated for the scenario and a benefit assigned on the basis of high, low or median externality costs. The value of the extra infrastructure requirement is then subtracted from this benefit and the resultant amount divided by the amount of hydrogen used in the vehicles. This is given in the formula shown below.

$$\textit{Premium for Hydrogen } (\$ / GJ) = \frac{\textit{Reduction in Environmental Costs - Infrastructure Costs } (\$)}{\textit{Hydrogen Supplied } (GJ)}$$

4.7 The Targeted Hythane® Scenario

Table 2 gives the energy balance for the Hythane® scenario as calculated for Central London for the FY 95 report. Table 3 gives the corresponding balance for the Targeted Hythane® scenario.

Table 2: Hythane® Scenario - Energy Balance for Central London (TJ)

ACTIVITY	FUEL					TOTAL
	Electricity	Hythane®	Heat	Diesel	Petrol	
PRIMARY SUPPLY	***-2,397***	***29,197***	***0***	***2,056***	***1,750***	***30,605***
CONVERSION	***9,795***	***-23,852***	***8,905***			***-5,152***
Fuel Cells	*5,343*	*-11,131*	*4,452*			***-1,336***
Gas Turbines	*4,452*	*-12,721*	*4,452*			***-3,816***
FINAL SUPPLY	***7,398***	***5,345***	***8,905***	***2,056***	***1,750***	***25,453***
CONSUMPTION	***7,398***	***5,345***	***8,905***	***2,056***	***1,750***	***25,453***
Commercial	*6,448*	*2,166*	*7,363*			***15,976***
Domestic	*344*	*323*	*1,097*			***1,764***
Industrial	*606*	*131*	*445*			***1,181***
Automobiles		*1,090*		*1,038*	*1,661*	***3,790***
Buses		*568*				***568***
Motorcycles					*88*	***88***
Heavy Goods Vehicles		*130*		*124*		***255***
Light Goods Vehicles		*347*		*331*		***678***
Medium Goods Vehicles		*392*		*374*		***766***
Taxis		*198*		*189*		***387***

Table 3: Targeted Hythane® Scenario - Energy Balance for Central London (TJ)

ACTIVITY	FUEL Electricity	Natural Gas	Hythane	Heat	Diesel	Petrol	TOTAL
PRIMARY SUPPLY	**-2,397**	**26,470**	**2,726**	**0**	**2,056**	**1,750**	**30,605**
CONVERSION							
fuel cells	5,343	-11,131		4,452			**-1,336**
gas turbines	4,452	-12,721		4,452			**-3,816**
FINAL SUPPLY	**7,398**	**2,619**	**2,726**	**8,905**	**2,056**	**1,750**	**25,453**
CONSUMPTION	**7,398**	**2,619**	**2,726**	**8,905**	**2,056**	**1,750**	**25,453**
Commercial	6,448	2,166		7,363			**15,976**
Domestic	344	323		1,097			**1,764**
Industrial	606	131		445			**1,181**
Automobiles			1,090		1,038	1,661	**3,790**
Buses			568				**568**
Motorcycles						88	**88**
Heavy Goods Vehicles			130		124		**255**
Light Goods Vehicles			347		331		**678**
Medium Goods Vehicles			392		374		**766**
Taxis			198		189		**387**

It can be seen that although the scenarios are almost identical, the second one, in which targeted hythane® is investigated, has columns for both natural gas and hythane®. The latter column is only used for vehicle applications, with other applications continuing to run on natural gas. In this scenario the efficiency of use of the two fuels is considered to be identical and thus the energy balance remains unchanged between the two scenarios.

4.8 The Premium on Hydrogen in Hythane®

The premium for hydrogen in the original hythane® scenario as calculated in a previous phase of this work is shown in Table 4. As can be seen, the value attached to the high externality cost case is particularly significant and likely to be above the costs of manufacture of hydrogen. In the low case the cost may well be close to or below the cost of manufacture.

Table 4: The Premium on Hydrogen in Hythane® by Area and Cost

Value ($/GJ)	*Area of London*		
Externalities	*Central*	*Inner*	*Outer*
High	**48**	**44**	**36**
Median	**10**	**9**	**8**
Low	**7**	**5**	**4**

4.9 The Value of Targeted Hythane®

The value of targeting hythane® is calculated using the methods previously described. The calculations have been carried out using high, low and median values for externality costs. The value can be seen to vary considerably between the different areas of London due to the changes in infrastructure density and in potential emissions reductions. The full results are presented in tabular form in Table 5 and graphically in Figure 2.

Table 5: The Premium on Targeting Hythane® by Area and Cost

Value ($/GJ)	*Area of London*		
Externalities	*Central*	*Inner*	*Outer*
High	**211**	**173**	**-124**
Median	**8**	**-20**	**-262**
Low	**-23**	**-50**	**-292**

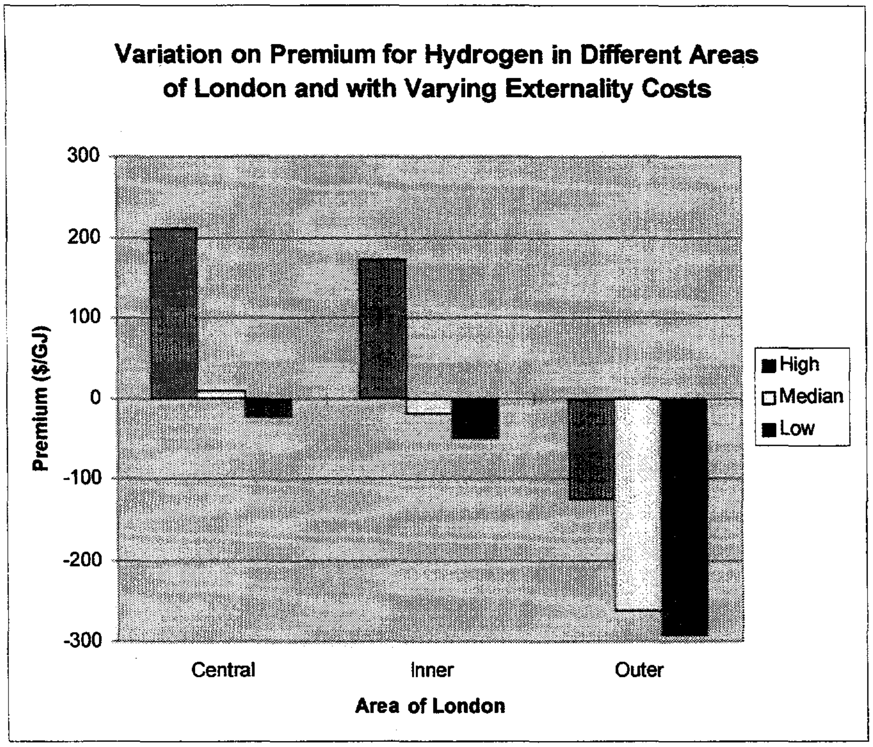


Figure 2: Hydrogen Premium in Targeted Hythane® Scenario

In this case the spread of values is very large, partly because of the range of externality costs which has been used but also because of the significant influence of infrastructure density on the costs. The lowest premiums - in Outer London - show that the cost of the infrastructure development would far outweigh the limited environmental benefits to be gained, even using high externality values. Even in the centre of London the value of externalities needs to be around the median mark before the hydrogen introduction has a net benefit. In this case it is \$8/GJ which is significant in terms of the cost of fuel. Using high estimates for the externality costs gives a large premium for the introduction of hydrogen - \$211/GJ in the Centre of London.

The implication is that it may be worthwhile to target hythane® in city centres where the problems of urban pollution are greatest and the extra cost of infrastructure development can be offset against the environmental benefits. This analysis seems to be highly sensitive to the pollution load of an area and each example must therefore be examined with particular care.

5. Hydrogen as an Additive for Liquid Fuels

5.1 Introduction

The concept of adding hydrogen to fuels is not new, but only limited work has been conducted on the practicalities, drawbacks and benefits which are associated with it. Adding hydrogen to natural gas has been discussed in previous reports, and has been shown to have a beneficial effect in terms of improving combustion properties and reducing polluting emissions. Adding hydrogen to any hydrocarbon fuel should produce similar results, because it raises the hydrogen : carbon ratio of the mixture, and alters the thermodynamic properties such that higher air : fuel ratios can be used, resulting in the advantages of a lean-burn engine. Research is also being carried out into the addition of hydrogen to gasoline for use in a standard internal combustion engine, and while this is in a very early laboratory stage the emissions reductions which can be achieved seem to be significant. Appendix 3 details the analysis.

5.2 Hydrogen in Gasoline

The addition of hydrogen to gasoline results in a mixed fuel which has combustion properties that are better than the gasoline when used on its own. The high flame speed of the hydrogen aids complete combustion of the fuel and also enables the engine to be run at a lean mixture. This enables emissions of NO_x, HC and CO to be much lower than when using pure gasoline. CO_2 will also be reduced, but only by the same amount as carbon is replaced by hydrogen in the fuel. For example, adding 20% of hydrogen by volume to gasoline would result in the original CO_2 emissions being reduced by 20%.

Current research at Zhejiang University in China shows that the emissions from a spark-ignition IC engine vary noticeably with different proportions of hydrogen in the gasoline/air mixture. The results produced are difficult to evaluate as the researchers have also varied the power output of the engine, but with a hydrogen component of about 18% by weight (39% by energy content) HC and NO emissions are halved and CO emissions are about 5% of their usual value at that point on the operating curve.

5.3 Hydrogen in Gasoline in London

A basic analysis has been conducted into the effects of introducing hydrogen in small volumes into the fuel supply of petrol-engined vehicles in London. These vehicles would carry hydrogen on-board and inject the fuel directly into the cylinder as the petrol is introduced, meaning that a number of design and infrastructure issues would have to be confronted relevant to the refuelling of vehicles carrying both hydrogen and petrol. Initial assessment has been carried out without taking into account the extra costs associated with these technology and infrastructure developments.

5.4 Valuing Hydrogen in Gasoline

The value of introducing hydrogen into gasoline has been calculated in the same way as for hydrogen in natural gas, by valuing the emissions benefits gained from its introduction and the costs associated with it. These are taken into account and compared with the amount of hydrogen utilised, in order to give a value for the premium of hydrogen in $/GJ. This value seems to be larger than the equivalent value for introducing hydrogen into natural gas, though the extra infrastructure and technology costs have not yet been considered.

A weakness in this approach is the fact that the data on the use of hydrogen in petrol are limited and it is difficult to extrapolate across the fleet of vehicles. This is particularly true as the figures which are given are only quoted in full for one engine power rating and gasoline/hydrogen ratio. However, based upon this operating point the reduction in pollution is significant.

5.5 Technical Requirements for Hydrogen/Gasoline Fuelling

Unlike the use of hythane® in natural gas vehicles, which can be accomplished with minimal equipment adjustment, there are two major considerations when using hydrogen in gasoline. The first is that the hydrogen must be added at the point of use of the gasoline, i.e. injected into the cylinder in a separate operation from the gasoline input. This requires not only some significant modification to the engine but also a separate tank, filled with hydrogen, to provide the fuel feed. The second problem is that the additional hydrogen tank will require a separate filling infrastructure, albeit a much smaller one than if hydrogen was used in isolation. The cost of this infrastructure may largely offset the value of the environmental benefits gained from the reduced emissions, and the complexity of the refuelling system (having to refuel twice with different fuels) could deter people from using it. The reductions in emissions need to be very substantial to make the scenario viable as a transitional strategy.

5.6 Additional Costs for the Use of Hydrogen in Gasoline

The hydrogen in gasoline (hydrogen in petrol, or hypet©) scenario takes into account not only the reduction in emissions due to the introduction of hydrogen into the gasoline refuelling system, but also the additional costs accruing from the added complexity of the infrastructure and technology requirements. These costs have been considered on the following basis:

Pipeline: \$5/GJ (Berry, 1996, modified)
Equivalent Filling Stations: \$3.67/GJ (calculated[1])
Hydrogen cylinder: \$2/GJ (Berry, 1996, modified)
Engine modification: considered part of evolutionary change - no cost
Infrastructure: \$1.50/GJ (calculated[1])

Total additional cost: \$12.17/GJ

These costs are incorporated into the model calculating the overall premium value of hydrogen in petrol. The calculation is carried out on a similar basis to the hythane® scenarios but the additional electricity generated is not relevant in this scenario and the infrastructure costs are significant. The full formula is:

$$\textit{Premium for Hydrogen (\$ / GJ)} = \frac{\textit{Reduction in Externality Costs - Increase in Infrastructure Costs (\$)}}{\textit{Hydrogen Supplied (GJ)}}$$

5.7 Calculating the Benefits of Hydrogen in Gasoline

The environmental benefits arising from the reduction in emissions due to the introduction of hydrogen to gasoline vary significantly according to the specific conditions under consideration. Figure 3,

Figure 4 and Figure 5 show the emissions reductions of NO, CO and HC which can be achieved given a specific and constant (70 g/hr) flow of hydrogen into a single cylinder engine at different output powers. The only point at which all information is known is for the 30% power rating, so we have considered this in our calculations. We feel that this is valid partly because 30% represents an average power usage for an automobile in inner city

[1] Full details of the calculation are given in Appendix 3.

driving, and although the usage drops closer to 15% in central areas the difference is felt to be within the confidence intervals of the data.

In order to calculate the benefits we assume that all petroleum engined cars are fitted with the necessary equipment to inject hydrogen into the fuel/air mixture. We then calculate the reduction in the specific pollutants emitted on the basis of a 30% average power use, and subtract this amount from the original level of polluting emissions. The difference is valued using the externality costs discussed in chapter 4, with high, low and median valuations considered. The median values should not be taken as representing *actual* values, as these will vary both with local geography and economic situations They are merely intended to act as a guide as to values which might be employed in certain circumstances today.

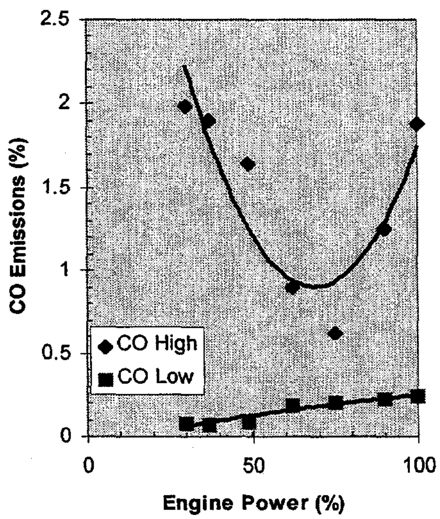


Figure 3: Variation in CO Emissions

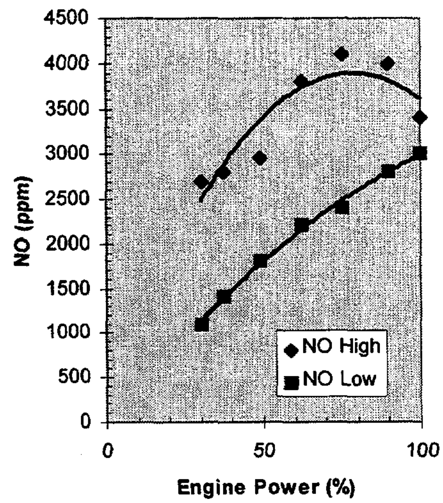


Figure 4: Variation in NO Emissions

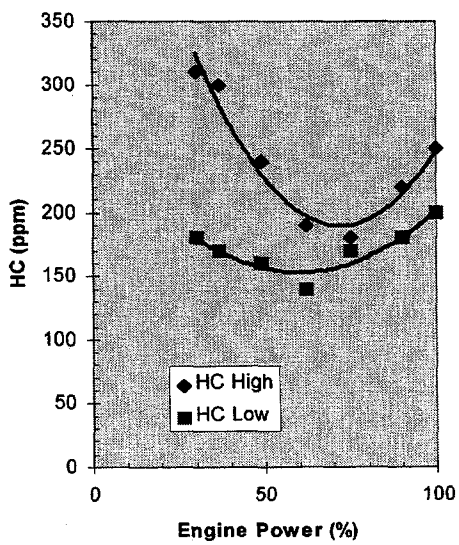


Figure 5: Variation in HC Emissions

5.8 The Hypet Scenario

Table 6 gives the energy balance for the reference scenario in Central London, and Table 7 gives the corresponding balance for the Hypet scenario. As can be seen, the two are very similar, with the only difference the substitution of a small amount of hydrogen for petrol which has been incorporated into the fuel supply. Unlike the previous analyses we have no information on the relative efficiencies of automobiles fuelled with gasoline or with a hydrogen-gasoline mixture, so we have assumed that they remain constant. This means that the overall energy consumption figure does not change.

Table 6: Reference Scenario - Energy Balance for Central London (TJ)

ACTIVITY	FUEL					TOTAL
	Electricity	Natural Gas	Heat	Diesel	Petrol	
PRIMARY SUPPLY	**-2,063**	**29,197**	**0**	**2,056**	**1,750**	**30,939**
CONVERSION	**9,461**	**-23,852**	**8,905**			**-5,486**
Fuel Cells	5,009	-11,131	4,452			**-1,670**
Gas Turbines	4,452	-12,721	4,452			**-3,816**
FINAL SUPPLY	**7,398**	**5,345**	**8,905**	**2,056**	**1,750**	**25,453**
CONSUMPTION	**7,398**	**5,345**	**8,905**	**2,056**	**1,750**	**25,453**
Commercial	6,448	2,166	7,363			**15,976**
Domestic	344	323	1,097			**1,764**
Industrial	606	131	445			**1,181**
Automobiles		1,090		1,038	1,661	**3,790**
Buses		568				**568**
Motorcycles					88	**88**
Heavy Goods Vehicles		130		124		**255**
Light Goods Vehicles		347		331		**678**
Medium Goods Vehicles		392		374		**766**
Taxis		198		189		**387**

Table 7: Hypet Scenario - Energy Balance for Central London (TJ)

ACTIVITY	FUEL Electricity	Natural Gas	Heat	Diesel	Hypet	TOTAL
PRIMARY SUPPLY	**-2,063**	**29,197**	**0**	**2,056**	**1,750**	**30,939**
CONVERSION	**9,461**	**-23,852**	**8,905**			**-5,486**
Fuel Cells	*5,009*	*-11,131*	*4,452*			***-1,670***
Gas Turbines	*4,452*	*-12,721*	*4,452*			***-3,816***
FINAL SUPPLY	**7,398**	**5,345**	**8,905**	**2,056**	**1,750**	**25,453**
CONSUMPTION	**7,398**	**5,345**	**8,905**	**2,056**	**1,750**	**25,453**
Commercial	*6,448*	*2,166*	*7,363*			***15,976***
Domestic	*344*	*323*	*1,097*			***1,764***
Industrial	*606*	*131*	*445*			***1,181***
Automobiles		*1,090*		*1,038*	*1,661*	***3,790***
Buses		*568*				***568***
Motorcycles					*88*	***88***
Heavy Goods Vehicles		*130*		*124*		***255***
Light Goods Vehicles		*347*		*331*		***678***
Medium Goods Vehicles		*392*		*374*		***766***
Taxis		*198*		*189*		***387***

5.9 The Value of Hydrogen in Gasoline

The value of introducing hydrogen into gasoline to form hypet is calculated using the method described earlier. It is different in each area of London as the infrastructure density and externality costs change. The calculations have been made using three sets of externality costs - the high and low extremes and a median set. The overall results are summarised in Table 8 and presented graphically in Figure 6.

Table 8: The Premium on Hydrogen used in Hypet by Area and Cost

Value ($/GJ)	*Area of London*		
Externalities	*Central*	*Inner*	*Outer*
High	**134**	**108**	**57**
Median	**14**	**14**	**9**
Low	**7**	**7**	**3**

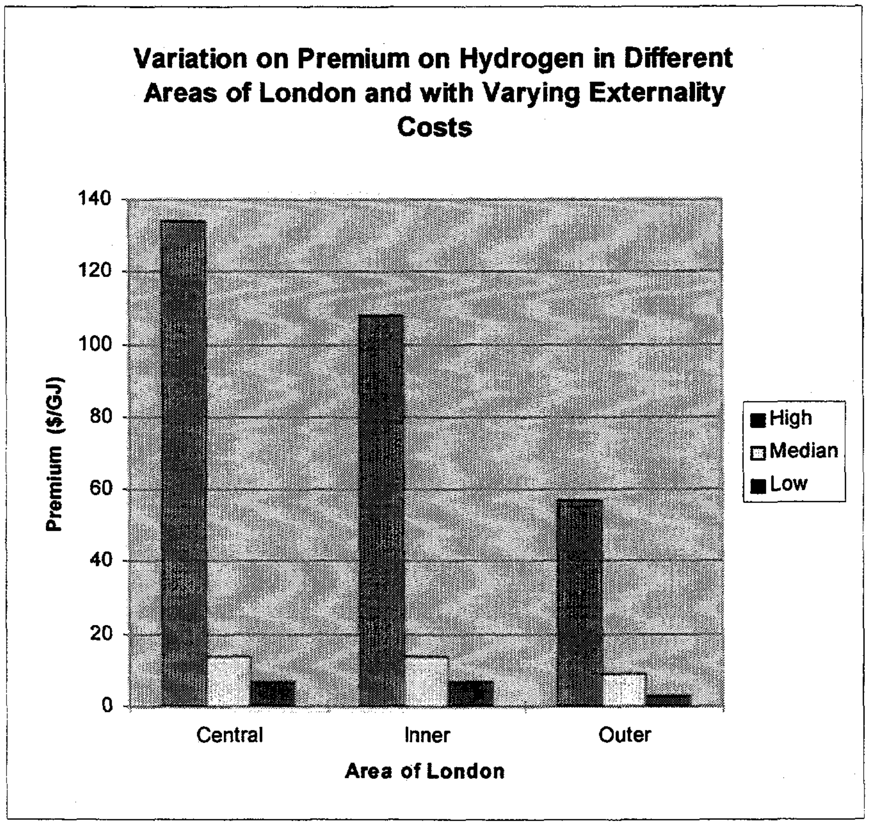


Figure 6: Hydrogen Premium in Hypet Scenario

The results show a wide spread between the highest and lowest values, corresponding to the spread found in the externality values detailed in chapter 4. However, even the lowest value of $3/GJ - in outer London with low externality costs - is significant in comparison with the ex-tax cost of petrol at the pump in London - about $8/GJ. The highest premium of $134/GJ, in the central area of the city and assuming high externality costs, is significantly higher than the cost of petrol and also exceeds current estimates of the cost of producing hydrogen by a factor of two in the worst case.

The numbers quoted in Table 8 suggest that hydrogen in petrol is more valuable than in hythane®, but a number of caveats must be stated:

1. The hypet scenario does not include many of the extra technology costs which would be required, such as the extra tank on board the vehicle. This is because detailed costs are unavailable but causes the hypet scenario to look better than it is.

2.The emissions reductions in the hypet scenario are significant but start from a higher base than the hythane® scenario. This means that final emissions may be higher and may not be acceptable in future legislation. This includes the European Euro III legislation and the Californian regulations regarding low emission vehicles or LEVs. Further details are given below.

3. The hypet scenario is affected less by density than the targeted hythane® scenario because of the lower infrastructure costs.

4. The analysis is based on very limited experimental evidence. Although the breakdown suggests that the hypet scenario can generate greater benefits than hythane®, more experimental work would be useful to confirm the results of adding hydrogen to petrol.

5. It would be valuable to continue to analyse this scenario but until more experimental data are available we feel that the results could be misleading.

If the levels of pollutant emitted are still above acceptable levels then additional forms of emissions control such as particulate traps or catalytic conversion may be required. In this case a catalytic converter would be difficult to utilise since the modified gasoline engine would be running at a very lean ratio. This would produce an oxidising environment in the exhaust output and the required NO_x reduction catalyst would be unable to function correctly. However, any end-of-pipe treatment would add significantly to the cost of the scenario and bring into question the value of introducing the hydrogen rather than simply using alternative means of emissions controls in their own right.

6. Alternative Methods of Emissions Control

6.1 Overview

There is only one established method of controlling regulated emissions from motor vehicles - the catalytic converter - although it does slightly increase the amount of CO_2 emitted. We have therefore investigated catalytic converters as an alternative to introducing hydrogen into the fuel stream. Methods such as exhaust gas recirculation reduce NO_x emissions but are not effective on other pollutants, and it is only possible to reduce CO_2 emissions by reducing the amount of carbon in the fuel or by using less. It is important to gauge whether using catalytic converters on natural gas vehicles will be more or less cost-effective than introducing hydrogen into the gas to reduce emissions. In order to do this we have considered the extra costs which using catalytic conversion impose on vehicles, and represented those costs in terms of the quantity of hydrogen necessary to reduce emissions by the same amount.

6.2 Catalytic Converters - an Introduction

The most common method of reducing or eliminating exhaust emissions from vehicles is by the use of catalytic converters. These devices can be attached to the exhaust system of a vehicle and will reduce the amount of pollutant which reaches the external environment. They achieve this by the use of catalysts to induce or speed up chemical reactions with the pollutant compounds.

There are two basic types of catalytic converter, the older two-bed pellet type and the three-way catalyst (TWC). A pellet type catalytic converter is made up of a container in which are two catalytic cells. These contain pellets coated in platinum or palladium as the catalytic elements, with a large active surface area. The converter is inserted into the exhaust system between the engine and the silencer, where it takes in untreated exhaust gases. The first cell provides a reducing environment where nitrogen oxides are converted into nitrogen and oxygen, but where some oxidisation of the carbon monoxide (CO) and hydrocarbons (HC) may take place using the excess oxygen. Air from outside the system is then mixed with the gases and the mixture passed to the second element, where the HC and CO are oxidised to form carbon dioxide and water.

In the more modern TWC there is only one chamber, which contains a metal or ceramic honeycomb for increased surface area, upon which a coating of platinum, rhodium and/or palladium is deposited. It is necessary to use all three of these 'platinum group metals' because each performs a slightly different function in the conversion process. The platinum is most active in converting CO and HC, and is also robust against poisoning by fuel impurities. It also becomes active quickly after a cold start, but is poor at reducing NO_x emissions. Rhodium is very effective against NO_x and also works well with the other pollutants, but is too expensive to be viable in large amounts. Palladium is slower to start functioning than platinum and more susceptible to poisoning but reasonably effective against all three pollutants.

The converter itself is small but the active catalytic area is about 10,000 m^2 (the size of two soccer pitches), and exhaust gases passed over this surface are treated for NO_x, CO and HC simultaneously. In a fully-functioning catalytic converter about 90% of the polluting emissions from the engine exhaust should be converted to carbon dioxide, nitrogen and water vapour, though percentage reductions in the high nineties are conceivable. Because of this the CO_2 emissions from vehicles with converters are higher than from those without.

6.3 Oxidation and Reduction Catalysts

In order to act successfully on CO, NO_x and HC - the main regulated pollutants from internal combustion engines - two types of catalyst are required. One of these is an oxidation catalyst and one a reduction catalyst, meaning that the engine must be operated in a regime very close to stoichiometric[2] combustion ($\lambda=1$), which is itself neither strongly oxidising nor reducing. However, many newer engines are being designed to be lean-burn ($\lambda>1$). They generate less NO_x but operate with a high air/fuel ratio and therefore in an oxidising environment. Since the remaining NO_x requires a reduction catalyst to remove it, the fact that the engine is lean-burn actually hinders the further reduction of NO_x emissions. A representation of the variation in emissions with air/fuel ratio is shown in Figure 7. In practice a conversion efficiency of over 80% for all three of the regulated pollutants is only attainable with air/fuel ratios within 0.1 of stoichiometric (a ratio of 14.7:1).

[2] Stoichiometry is the point at which the oxygen in the air is exactly sufficient to burn the fuel in the mixture. Traditional IC engines have peak engine power just rich of this point, but are most economic on the lean side.

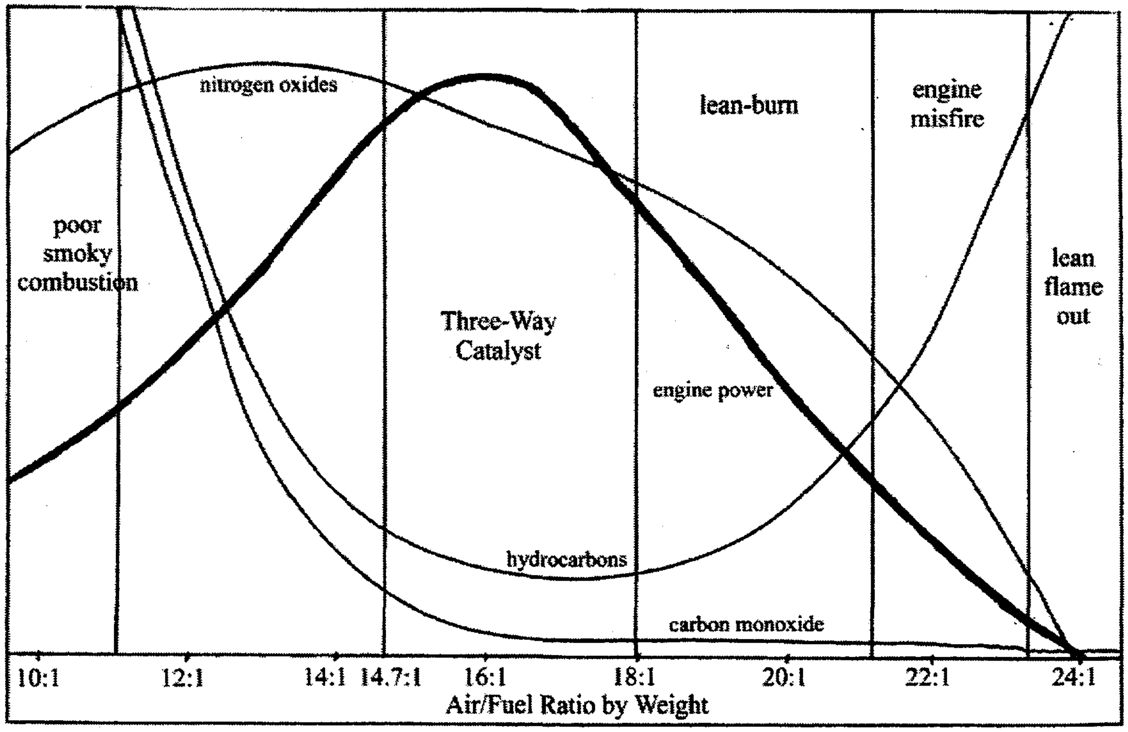


Figure 7: Emissions Variations over a Range of Air/Fuel Ratios

A further difficulty with the use of catalytic converters is the fact that they must reach a temperature of between 250 and 300°C before they will operate effectively. This may take a few minutes. Since the majority of journeys made are less than 10 miles (LRC, 1994), and the majority of emissions produced by a car come in the first few minutes of a journey when the engine is cold, the catalyst may not reach its optimum temperature until the journey is almost complete and most of the pollutants have already been emitted.

An estimate in the US indicates that it costs about $1,200 per vehicle to install a catalytic converter. This is not only because of the cost of the catalyst itself (about $800 of that), but also because of the necessity for tight control of the air/fuel mixture. This means that fuel injection is preferred to carburetion, and closed-loop controls for the fuel mixture must be used, including a lambda sensor for keeping the mixture close to stoichiometric. Introducing a converter into the exhaust system also generates some back pressure, increasing fuel consumption by between 2 and 10%, so this added cost must also be taken into account.

6.4 Valuing the Costs of Catalytic Conversion

In order to calculate the costs of introducing catalytic converters to vehicles it is necessary to make some basic assumptions. These are detailed in Appendix 4, but broadly outlined below.

A catalytic converter adds approximately \$650 to the price of an average car, so we shall assume this as a cost. By law in the UK a catalytic converter must have a life of 50,000 miles. If we also assume an average fuel economy of 30 miles per UK gallon (c. 11 km/l) then we can calculate the amount of energy consumed during the lifetime of the converter. We must also make a correction for the increased fuel consumption of the vehicle because of the inefficiencies introduced by the converter. These figures allow us to calculate the extra cost of adding a catalytic converter to a vehicle, as shown in Appendix 4.

If we assume a catalyst life of 50,000 miles and a rise of 2% in fuel used then this cost is approximately \$2.90 per gigajoule of energy consumed, rising to nearly \$5 for a 10% decrease in fuel economy.

6.5 Valuing the Benefits of Catalytic Conversion

The benefits of adding catalytic converters to vehicles can be calculated in the same manner as previously, in terms of the emissions reductions which result from their use. As has been done in the previous scenarios, the reductions in emissions have been valued by using externality cost estimates. High and low estimates have been adopted and also a median scenario which is intended to offer an intermediate set of values. It should be stressed that the median scenario is not supposed to be representative of current established estimates, but is intended to show a possible scenario within the high and low boundaries. Once the emissions reductions have been calculated then a comparison can be made between adding hydrogen to natural gas and using catalysts.

The third method of the three mentioned above for ranking the two alternatives is to assume that the emissions reductions due to the converter have actually been achieved by adding hydrogen. By comparing the premium on each of the two scenarios the more cost-effective option can be identified.

For example, if we consider the targeted hythane® scenario with high externality costings in Central London then we have a premium value of \$211/GJ for the introduction of hydrogen (as shown in chapter 5). If the introduction of catalytic converters and their associated costs produces emissions reductions to give a value as high or higher than this, then catalytic converters can be seen to be cost-effective in comparison with hythane®.

6.6 Other Considerations

It is also possible to consider the value to catalytic converters of introducing hydrogen into the fuel mix and thus reducing the emissions stream that enters the converter. Catalyst life depends partly on these emissions and may thus be prolonged by the use of hydrogen, resulting in less frequent maintenance and replacement. We could equate the cost savings associated with this and the hydrogen used, to give a premium for the use of hydrogen. This possibility is not investigated in detail in the following analysis.

6.7 Comparing Catalysts and Hydrogen

In order to compare the catalytic converter with the alternative of utilising hydrogen we must calculate the benefits that can be derived from its use, and the cost associated with introducing it into the system. We can then equate this cost with the amount of hydrogen that would have been required to produce the same emissions reductions and value the catalyst implicitly.

It is possible to represent this concept graphically by incorporating the terms representing the hythane® and catalytic converter scenarios into an equation and by plotting it on a graph. We can do this using the following notation:

Scenario	Emissions Reduction	Infrastructure Cost	Amount of Hydrogen
Hythane	E_H	C_H	X
Catalysts	E_C	C_C	-

$$\textit{Net Benefit of Using Hythane} = E_H - C_H$$
$$\textit{Net Benefit of Using Catalysts} = E_C - C_C$$

$$\textit{Net Benefit of Hythane compared to Catalysts} = (E_H - C_H) - (E_C - C_C)$$

Expressed per unit of hydrogen:

$$\textit{Net Benefit of Hythane compared to Catalysts} = \frac{(E_H - C_H) - (E_C - C_C)}{X}$$

$$\textit{or } \frac{(E_H - C_H)}{X} - \frac{(E_C - C_C)}{X}$$

We can represent this space on a graph as follows. The two axes represent the net benefits of the two control technologies. The y-axis represents the value of hydrogen in hythane® while the x-axis represents the value of catalytic conversion. It shows the net benefit of catalytic conversion divided by the amount of hydrogen required to do approximately the same job. Effectively it represents an estimate of the value of hydrogen in terms of the catalytic converter alternative. This is shown in Figure 8.

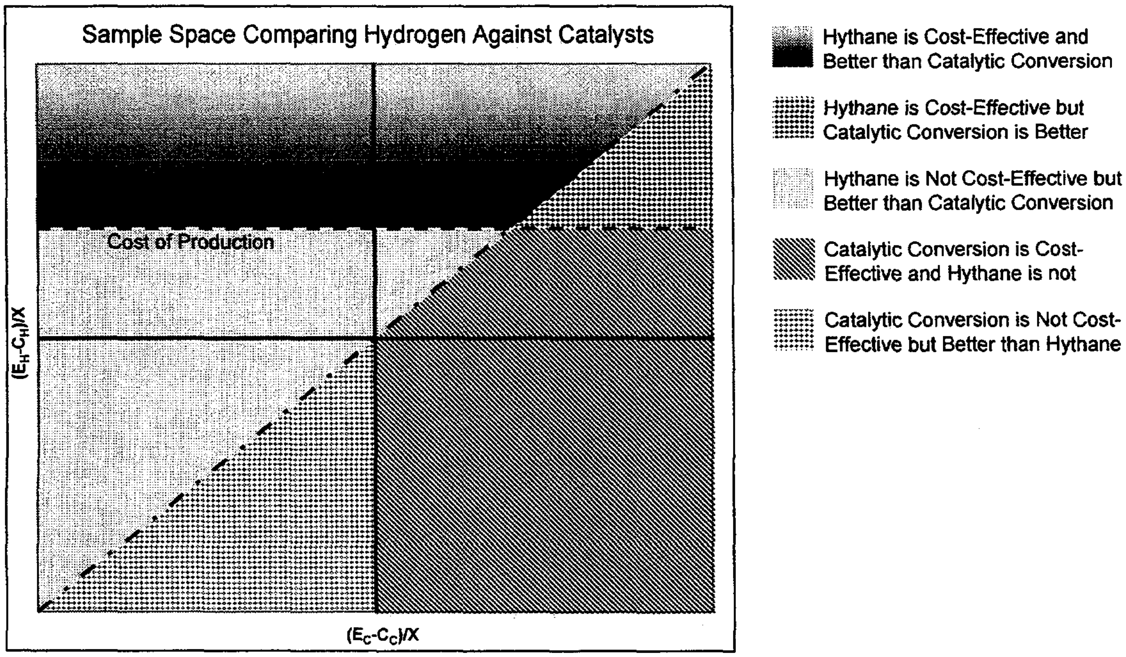


Figure 8: Sample Space Comparing Hydrogen Against Catalysts

From the graph above we can make the following statements:

- In area A hythane® is *both* cost-effective and better than catalytic conversion.
- In B hythane® is *not* cost-effective but still better than catalytic conversion.
- In C hythane® *is* cost-effective but not as good as catalytic conversion.
- In D catalytic conversion is cost-effective *and* better than hythane®.
- In E catalytic conversion is *not* cost-effective but better than hythane®.

As a numerical example we can consider the following theoretical values:

E_H=15 M$, E_C=13 M$,

C_H=10 M$, C_C=9 M$.

X=100,000 TJ

This gives rise to the following:

$$or\ \frac{(E_H - C_H)}{X} - \frac{(E_C - C_C)}{X}$$

$$i.e.\ \frac{(15 - 10)x10^6}{100,000} - \frac{(13-9)x10^6}{100,000}$$

$$= \frac{1x10^6}{100,000} = 10\$ / GJ$$

We can carry out the same comparison between hythane®, targeted hythane® and catalysts.

6.8 The Alternative Emissions Control Scenario

In Table 9 we can see the value of introducing catalytic converters into vehicles with respect to a nominal amount of hydrogen (5% of natural gas supplied to transport). The same information is represented graphically in Figure 9.

Table 9: The Value of Hydrogen in Replacing Catalytic Conversion

Value ($/GJ)	***Area of London***		
Externalities	*Central*	*Inner*	*Outer*
High	**116**	**113**	**70**
Median	**-22**	**-23**	**-24**
Low	**-67**	**-67**	**-64**

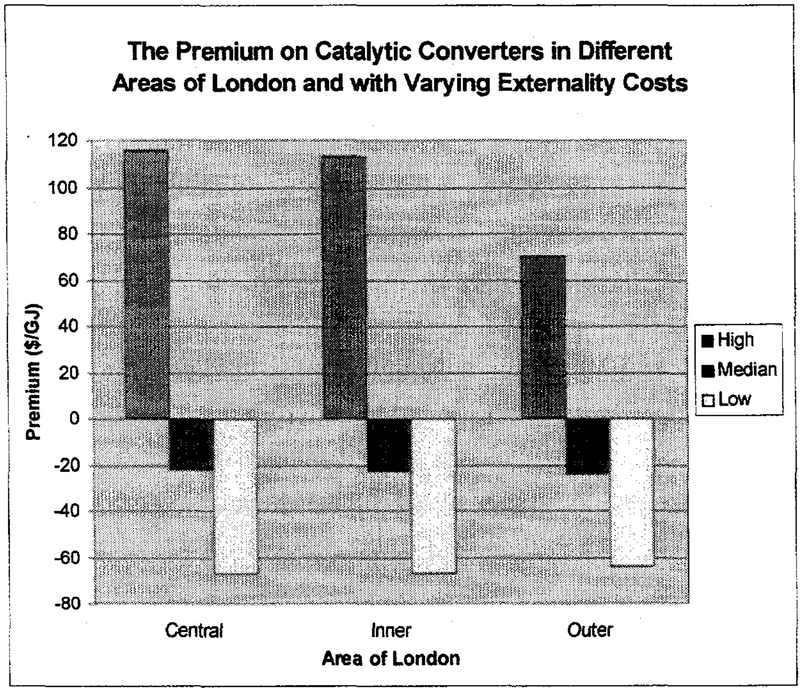


Figure 9: Value of Hydrogen replacing Catalytic Converters

Once again the spread of values is large, because of the net effect of summing two large quantities - the costs and benefits.

The figure appears to show that it is only cost-effective to introduce catalysts if externality costs are assumed to be high, because of the substantial cost of the converter and the associated increase in CO_2 emissions. This has interesting connotations for the introduction of catalysts at present as it suggests by implication that since they *are* being introduced then the externality costs being considered *are* high.

7. Comparing Scenarios

We can compare the values of hydrogen as inferred from the avoided costs of catalytic conversion (shown in Table 10) with the values of hydrogen calculated directly from the environmental benefits in the hythane® scenario (Table 11) and in the targeted hythane® scenario (Table 12).

Table 10: The Value of Hydrogen in Replacing Catalytic Conversion

Value ($/GJ)	***Area of London***		
Externalities	*Central*	*Inner*	*Outer*
High	**116**	**113**	**70**
Median	**-22**	**-23**	**-24**
Low	**-67**	**-67**	**-64**

Table 11: The Premium on Hydrogen in Hythane® by Area and Cost

Value ($/GJ)	***Area of London***		
Externalities	*Central*	*Inner*	*Outer*
High	**48**	**44**	**36**
Median	**10**	**9**	**8**
Low	**7**	**5**	**4**

Table 12: The Premium on Hydrogen in Targeted Hythane® by Area and Cost

Value ($/GJ)	***Area of London***		
Externalities	*Central*	*Inner*	*Outer*
High	**211**	**173**	**-124**
Median	**8**	**-20**	**-262**
Low	**-23**	**-50**	**-292**

If we assume a cost of production for hydrogen of approximately $6/GJ (ETSU 1996) then we can construct summary tables to show which scenarios would be cost-effective and which should be preferred over the others. Comparisons of catalytic conversion and targeted hythane® are made in Table 13 and of catalytic conversion and distributed hythane® in Table 14. The overall comparison of the three options is made in Table 15. The notation TH represents targeted hythane® as the best option, H shows that distributed hythane® is best, C that catalytic conversion is more cost-effective and N that none is viable.

Table 13: Comparison of Targeted Hythane® and Catalyst Scenarios

	Optimum		
	Central	Inner	Outer
High	*TH*	*TH*	*C*
Median	*H*	*N*	*N*
Low	*N*	*N*	*N*

(assuming production cost of 6$/GJ)

Table 14: Comparison of Distributed Hythane® and Catalyst Scenarios

	Optimum		
	Central	Inner	Outer
High	*C*	*C*	*C*
Median	*H*	*H*	*H*
Low	*H*	*N*	*N*

(assuming production cost of 6$/GJ)

Table 15: Comparison of all scenarios

	Optimum		
	Central	Inner	Outer
High	*TH*	*TH*	*C*
Median	*H*	*H*	*H*
Low	*H*	*N*	*N*

(assuming production cost of 6$/GJ)

Applying the comparison to the tables listed above suggests that it is only valuable to introduce catalytic conversion in Outer London with high externality costs, whereas targeted hythane® is viable in Central and Inner London. Distributed Hythane® is viable in all three areas even with median externality costs, and in Central London assuming the lowest possible costs. It is only because of the cost of production of hydrogen that forces the final two columns to show that none of the scenarios is cost-effective.

The results in Table 13, Table 14 and Table 15 can be understood graphically through the concept of the 'technologically efficient frontier'. This is shown in Figure 10, and further illustrates the different points at which each form of emissions control becomes more beneficial than the others.

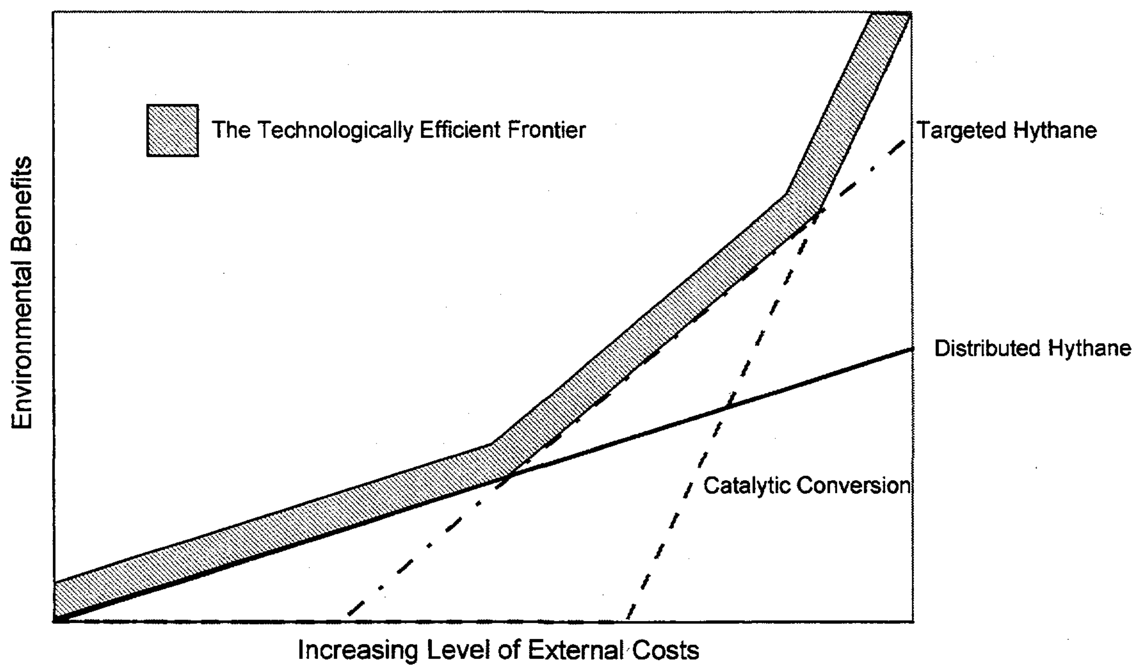


Figure 10: The 'Technologically Efficient Frontier'

Figure 10 illustrates the efficient frontier for emissions control technologies. It includes high capital costs and good reductions (targeted hythane®) and low capital costs with lower reductions (hythane®). The use of catalytic conversion varies by area. The slope of the line is mainly affected by CO_2 reductions because local emissions are considered to be already low.

The efficient frontier is the most efficient technological solution to a given problem with specific costs and benefits. In the situation illustrated above the costs are environmental externalities and the benefits are the value attributed to each solution - in this case calculated net of the production, infrastructure and technology costs of hydrogen and catalytic conversion. These are shown on the x- and y-axes respectively. The environmental externality costs have been calculated as a 'lumped' value in the sense that NO_x, CO, etc., have been valued individually and the results added to produce a value for the total emissions stream from a technology. This is the approach which we have adopted in all of our scenario modelling.

It can be seen that distributed hythane®, with negligible infrastructure costs, has value even if minimal externality costs are allocated. Externality costs must be higher if targeted hythane® is to be introduced, but provide proportionally less benefit than catalysts, as shown by the shallower gradient of the line. Catalytic conversion gives the most benefit once it becomes viable, as shown by the steep gradient of the line furthest to the right of the graph, but is only cost-effective at high values of externality costs - denoted by the point at which the line turns away from the horizontal.

We recognise that the conclusions drawn in this section depend very strongly on the assumptions which we have used. Considerable refinement is necessary. However, we believe that this analysis well demonstrates the fundamentals of the cost-benefit relationships which underlie the choice of technical systems for reducing vehicle emissions in urban environments.

8. Conclusions and Implications for Infrastructure

8.1 Conclusions

1. This work confirms previous findings from the earlier phase of the study that the use of hydrogen as a transport fuel in urban areas can have substantial environmental benefits. In the earlier phase the benefits were assessed for the distribution of hydrogen as hythane® (a mixture with natural gas) indiscriminately to all users. In the present phase, similar benefits have been identified for hythane® targeted to transport applications and for the use of hydrogen as an additive to gasoline internal combustion engines. In all these cases the value of the hydrogen was assessed by a direct valuation of the reduction it brought about in external environmental costs.

2. In all cases there can be circumstances in which the value of hydrogen so assessed is large compared to its likely cost of production. Work in the earlier phase showed that the environmental benefits of hydrogen in applications other than transport were substantially less. The use of hydrogen for urban transport therefore appears to be the most effective way of introducing hydrogen into the energy supply structure.

3. The work in this phase has also made an alternative assessment of the value of hydrogen as a transport fuel by calculating the costs *avoided* in alternative means of emission control. The alternative studied was catalytic conversion because this is the most commonly adopted technique for reducing emissions from transport.

4. The study shows that the cost-benefit performance of the various technologies for reducing environmental impact (distributed hythane®, targeted hythane®, hydrogen-gasoline, catalytic conversion) is very sensitive to assumptions made about the costs of environmental impacts. The different technologies depend differently on these assumptions and this dependence can be shown conveniently by the concept of the "technologically efficient frontier".

5. Under the assumptions adopted for this study there is no single preferred technology for environmental improvement. The optimal choice is a function of both the damage costs

assumed for the environmental impacts and whether the technology is to be used in central, inner or outer areas of the city.

6. The assumption made in the analysis are quite severe and the conclusions must be treated with caution, but the calculations suggest that for high value of environmental damage costs, targeted hythane® is superior. Catalytic conversion is only the technology of choice when high damage costs are assumed and the calculations are made for Outer London. These conclusions are very tentative.

7. It is worth noting that the analysis suggests that catalytic conversion is only cost-effective with the assumption of high environmental damage costs. This is a surprising, and we believe novel, result. It suggests that the higher values of environmental damage costs are more appropriate because they are implied in the decision to adopt catalytic conversion to reduce vehicle emissions.

8. Taking the analysis as a whole, while recognising the sensitivity of the conclusions to the assumptions, there does appear to be a strong case for suggesting that the use of hythane® in vehicles could be the most cost-effective initial application of hydrogen and the most appropriate market to develop first.

8.2 Tentative Observations on Infrastructure Development

1. Some tentative observations can be made concerning the implications of this finding for infrastructure development and transitional strategies. If transport applications of hythane are to be envisaged as the initial market for hydrogen, then the infrastructure for the distribution of hythane® needs to be designed and developed in a manner which will also facilitate the availability of pure hydrogen for pure hydrogen using technologies. This suggests that the hydrogen should be added to the natural gas within the city; *not* at the boundaries as we have assumed in our calculations thus far. This in turn implies that the supplementary infrastructure should be designed for distributing hydrogen, not hythane®. A somewhat different cost structure will need to be considered in further analysis.

2. It is also important to note that once targeted hythane® has been introduced by mixing hydrogen natural gas within the city, distributed hythane® is unlikely to be cost-effective as an intermediate step to pure hydrogen. This is because the major value of distributed hythane® - reducing emissions in the transport sector - has already been obtained.

3. A mechanism for targeting hythane® would be to deliver hydrogen to hythane® refuelling stations for large fleet users, e.g. buses. The hydrogen would be added to natural gas at site. Pure hydrogen could then be available for other technologies as they become cost-effective. These might include fuel cells for power generation.

4. Such an approach would lead to an "island" development of hydrogen centres. The least cost, low risk manner of providing hydrogen to these centres would initially be by vehicle. As demands for hydrogen increase at these centres it may be cost effective to develop pipeline delivery to the larger centres, displacing hydrogen carrying vehicles which can be used to supply new, small centres.

5. As different hydrogen using technologies became cost-effective it may not be necessary to rely on transport applications for the initial load. Large commercial centres might adopt hydrogen fuel cells for power and thermal conditioning.

8.3 Future Work

1. The method of analysis which we have used up to now is based upon an examination of a typical urban environment (central, inner and outer). It is inadequate for analysing the spatial aspects of the infrastructure development because vehicles which move in different areas do not necessarily refuel there.

2. For a deeper understanding of the infrastructure needs it is necessary to take a more holistic view of the city and the possibility of targeting specific uses. In turn this will require spatial information on the refuelling patterns of large fleets (buses, commercial vehicles). This methodology will be developed in the next phase.

3. For completion of the objectives of the project it will also be necessary to demonstrate how other uses of hydrogen can be most effectively developed around these islands. This will also be a topic in the next two phases of work.

9. Extending the Study to Tokyo

The studies that have been undertaken so far in this project subtask have used data from the London Energy Study. This has been taken as being indicative of energy demand by different sectors of the economy (residential, commercial, industrial and transport), and the relative intensity of demand in different parts of the city (central city, inner suburbs and outer suburbs), in large cities generally.

The London Energy Study was undertaken as part of the European Union's Regional and Urban Energy Management Programme, and completed in 1993. It provided an analysis of the use of electricity, gas, oil and solid fuels by each sector. Within the transport sector, for example, the demand was assessed for cars, light, medium and heavy trucks, buses, taxis, and motor cycles. It was also calculated for diesel and electric trains, water transport and aviation. The data was compiled for each 1 x 1 kilometre cell in a grid covering 1,940 square kilometres. This included the whole of the administrative areas of Greater London as well as some adjacent areas.

This data has provided a satisfactory basis for analysis in the early stages of the study. However, the extent to which differences between the pattern of energy use in London and in Japanese cities, particularly Tokyo, may affect the conclusions drawn so far is unclear. There are very few comparative studies of urban energy use in cities, and none that are detailed. Nevertheless, it is clear from national data that there are differences, which may be significant. For example, domestic air conditioning systems are more common in Japan than in London, and peak electricity demand occurs in the summer as a result of their use. In London, peak demand occurs in the winter as a result of the use of domestic heating systems and electrical equipment (kettles, microwaves, cookers and dishwashers).

During the second half of FY1996, we sought to identify the data that is available on energy use in Japanese cities, and in Tokyo in particular. This is in preparation for more detailed comparative work, which will be undertaken during FY1997. The objective during FY1997 will be to establish whether the conclusions drawn in earlier stages of the study are equally valid for Japanese cities as for London.

During March 1997 we visited the Bureau of Environmental Protection at Tokyo Metropolitan Government (TMG). Although TMG does not have any responsibility for energy supply, it was concerned with environmental protection issues relating to the operation of district heating schemes. There are currently 62 schemes serving a total area of 1,253 hectares.

TMG is promoting district heating primarily as a means of controlling air pollution. In order to evaluate schemes, TMG collects data on the heating and cooling loads of individual buildings. TMG provided information from the database of buildings in four areas of Tokyo with a range of heating and cooling loads, as well as the default values that are used in calculations where there is no data on individual buildings. These are 'average' values and include offices, commercial, hotel, hospital, cultural, theatre and assembly hall, education, recreation, housing and other buildings. This information can be compared with similar data for buildings in the UK in order to identify differences and similarities in their energy demand.

During March 1997 we also visited the Institute of Energy Economics (IEE). The IEE provides independent advice on energy issues to business and government, and completed a study of the "Energy Demand and Supply Structure in Tokyo" in May 1996. The study report includes graphs and tables of energy supplied categorised by fuel type and sector for 1980 to 1993, and demand by fuel type and sector for the same period. It also includes a schedule of diesel and gasoline consumption for the 23 wards, towns and villages in the TMG area for cars, trucks, buses, etc. for 1980, 1985, 1988, 1990 and 1994. The data also includes highway lengths in each area.

The study does not include Tokyo-specific data on the sub-division of demand within sectors (e.g., heating, cooling, hot water, lighting, etc.). However, the "Handbook of Energy and Economic Statistics in Japan" which is prepared by IEE but published by The Energy Conservation Centre contains some of these data for Japan as a whole.

The Institute of Behavioural Sciences also holds data on energy use in Tokyo including residential, commercial, industrial road transport, aircraft and shipping, as well as by fuel type. Information is available for the 23 wards, all Tokyo and for 500 metre and 1 kilometre grid cells.

A simple comparison of the IEE data for Tokyo and the London Energy Study data for London confirms that there are significant differences between the two cities in their energy use. Almost half (47 per cent) of London's total energy needs are met by natural gas (methane) whereas town gas only meets 18 per cent of Tokyo's energy requirements. In contrast, electricity meets almost twice as much (31 percent) of Tokyo's energy demand as it does in London (16 per cent).

The population of Tokyo (11.8 million) is significantly larger than London's population (6.7 million) and this is reflected in overall energy demand. However, energy demand per person is significantly lower (73 per cent) in Tokyo than in London. Transport energy use per person is almost the same, commercial and industrial energy use per person is slightly higher in London, but the largest difference is in the residential sector where energy use per person in London is over double (239 per cent) that in Tokyo.

Table 16, Table 17 and Figure 11 summarise the date for London and Tokyo. During FY1997 further comparisons will be made between energy use in London and Tokyo, and the implications of the differences assessed in relation to the hydrogen scenarios.

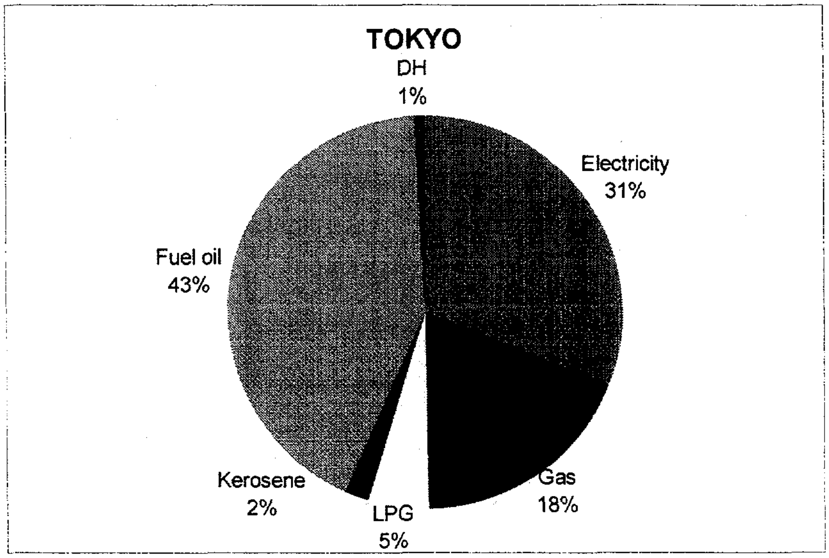
Some data has also been collected on energy use in Toyohashi as part of the work of Sub-Task 7. This will be compared with data on energy use in Leicester in the UK. Both towns are much smaller than Tokyo and London, and the comparison may show differences between the capital cities and smaller cities as well as between cities in Japan and the UK.

Table 16: Final Energy Demand in Tokyo (Petajoules)

	Residential	Commercial	Industrial	Transport	**Total**
Electricity	58.2	133.1	33.1	10.5	**234.9**
Gas	74.9	42.3	21.4	0.0	**138.6**
LPG	9.6	5.4	4.6	19.3	**38.9**
Coal	0.0	0.0	0.0	0.0	**0.0**
Kerosene	14.7	0.0	0.0	0.0	**14.7**
Fuel oil	0.0	20.1	31.8	268.4	**320.3**
DH	0.4	5.0	0.0	0.0	**5.4**
Total	**157.8**	**206.0**	**90.9**	**298.1**	**752.8**

Table 17: Final Energy Demand in London (Petajoules)

	Residential	Commercial	Industrial	Transport	**Total**
Electricity	37.1	43.9	8.9	5.8	**95.6**
Gas	169.0	69.3	36.4	0.0	**274.7**
LPG	0.0	0.0	0.0	0.0	**0.0**
Coal	0.0	0.4	4.2		**4.6**
Kerosene	0.0	0.0	0.0	0.0	**0.0**
Fuel oil	6.1	30.2	17.4	154.2	**207.9**
DH	0.0	0.0	0.0	0.0	**0.0**
Total	**212.1**	**143.8**	**66.8**	**160.0**	**582.8**



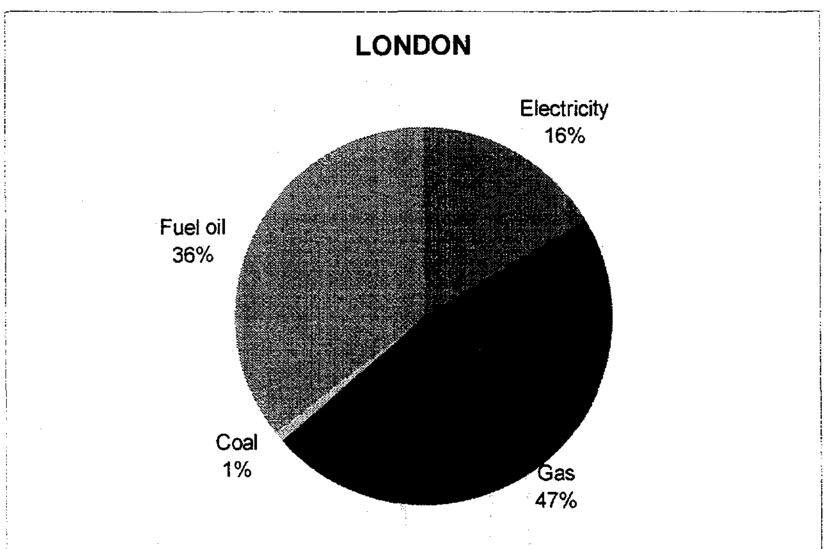


Figure 11: Final Energy Demand in Tokyo and London by Percentage

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Appendix One

Externality Cost Estimates

A Summary of Externality Cost Evaluations:

Transport				
Mode		£/pkm or tkm	Source/Basis	Geographical Scope
Car/Van	passenger	0.0136	Tinch, DoT (1995) All pollution, health and other effects	urban (London)
Bus	passenger	0.0129	Tinch, DoT (1995) All pollution, health and other effects	urban (London)
M.bike	passenger	0.0200	Tinch, DoT (1995) All pollution, health and other effects	urban (London)
HGV	tonne	0.0176	Tinch, DoT (1995) All pollution, health and other effects	urban (London)

NOx				
Original Values:		95$/kg	Source/Basis	Geographical Scope
1.89	93ECU/kg	2.5	Swedish taxation today (Kageson 1993 p44)	?
4800	93ECU/t	6.4	NOx and VOC combined (cost of 50% abatement)(Kageson 1993 p60)	rural (Europe)
910	89$/t	1.1	Wang and Santini, Argonne (1995) damage based, low	urban (US)
9800	89$/t	11.7	Wang and Santini, Argonne (1995) damage based, high	urban (US)
5220	89$/t	6.2	Wang and Santini, Argonne (1995) control cost based, low	urban (US)
21850	89$/t	26.1	Wang and Santini, Argonne (1995) control cost based, high	urban (US)
6767	90$/t	7.8	Tellus (Martin 1995)	
3251	90$/t	3.8	Chernick (Martin 1995)	
1707	90$/t	2.0	Pace (Martin 1995)	
25504	89$/t	33.6	Schilberg (Martin 1995)	
1832	89$/t	2.2	New York State (Putta 1989) control cost	? - questionable
31448	92$/t	34.4	Southern California Edison & San Diego Gas & Electric	
9120	92$/t	10.0	Pacific Gas and Electric	
7467	92$/t	8.2	attainment areas	
7200	92$/t	7.9	Massachusetts - control cost based	
68.8	92$/t	0.1	Minnesota - low	
1640	92$/t	1.8	Minnesota - high	
7480	92$/t	8.2	Nevada - control cost based	
6524	92$/t	7.1	New York - recommended	
2000	92$/t	2.2	Oregon - low	
5000	92$/t	5.5	Oregon - high	
3.4	90$/lb	1.8	Tellus - NREL paper	
4.65	90$/lb	2.4	CEC - NREL paper	
0.96	90$/lb	0.5	NYS - NREL paper	
137	90$/lb	72.0	SCAQMD - NREL paper	?
0.86	90$/lb	0.5	Pace - NREL paper	
2949	95£/t	4.7	ExternE - health only - low	
3298	95£/t	5.3	ExternE - health only - high	
0.03	90$/lb	0.0	BPA - NREL Paper - low	
0.4	90$/lb	0.2	BPA - NREL Paper - high	
3.18	90$/lb	1.7	Sweden - NREL Paper	

NOx low	*1.1*	*Wang and Santini, Argonne (1995) damage based, low*
NOx high	*33.6*	*Schilberg (Martin 1995)*

SO$_2$				
Original Values:		95$/kg	Source/Basis	Geographical Scope
1.87	93ECU/kg	2.5	Swedish taxation today (Kageson 1993 p44)	
2000	92DM/t	1.6	Derived from a marginal cost of a 60-80% reduction (Kageson 1993 p53), low	
5000	92DM/t	4.0	Derived from a marginal cost of a 60-80% reduction (Kageson 1993 p53), high	
2190	89$/t	2.6	SOx- Wang and Santini, Argonne (1995) damage based, low	urban (US)
4030	89$/t	4.8	SOx- Wang and Santini, Argonne (1995) damage based, high	urban (US)
3130	89$/t	3.7	SOx- Wang and Santini, Argonne (1995) control cost based, low	urban (US)
13480	89$/t	16.1	SOx- Wang and Santini, Argonne (1995) control cost based, high	urban (US)
1562	90$/t	1.8	SOx - Tellus (Martin 1995)	
1907	90$/t	2.2	SOx - Chernick (Martin 1995)	
4226	90$/t	4.9	SOx - Pace (Martin 1995)	
19050	89$/t	25.1	SOx - Schilberg (Martin 1995)	
832	89$/t	1.0	New York State (Putta 1989) control cost	? - questionable
23490	92$/t	25.7	Southern California Edison & San Diego Gas & Electric	SOx
4486	92$/t	4.9	Pacific Gas and Electric	SOx
1720	92$/t	1.9	attainment areas	SOx
1700	92$/t	1.9	Massachusetts - control cost based	SOx
0	92$/t	0.0	Minnesota - internalised costs	SOx
300	92$/t	0.3	Minnesota - current market prices of emissions allowances	SOx
1716	92$/t	1.9	Nevada - control cost based	SOx
1367	92$/t	1.5	New York - recommended	SOx
0.78	90$/lb	0.4	Tellus - NREL paper	SOx
9.07	90$/lb	4.8	CEC - NREL paper	SOx
0.43	90$/lb	0.2	NYS - NREL paper	SOx
39.2	90$/lb	20.6	SCAQMD - NREL paper	SOx
2.12	90$/lb	1.1	Pace - NREL paper	SOx
2321	95£/t	3.7	ExternE - health only - low	SOx
4144	95£/t	6.6	ExternE - health only - high	SOx
0.2	90$/lb	0.1	BPA - NREL Paper - low	SOx
1.8	90$/lb	0.9	BPA - NREL Paper - high	SOx
1.19	90$/lb	0.6	Sweden - NREL Paper	SOx

SO$_2$ low	1.0	New York State (Putta 1989) control cost
SO$_2$ high	25.1	SOx - Schilberg (Martin 1995)

VOC				
Original Values:		95$/kg	Source/Basis	Geographical Scope
0.94	93ECU/kg	1.3	Swedish taxation today (Kageson 1993 p44)	
320	89$/t	0.4	ROG - Wang and Santini, Argonne (1995) damage based, low	urban (US)
5110	89$/t	6.1	ROG - Wang and Santini, Argonne (1995) damage based, high	urban (US)
5100	89$/t	6.1	ROG - Wang and Santini, Argonne (1995) control cost based, low	urban (US)
19250	89$/t	23.0	ROG - Wang and Santini, Argonne (1995) control cost based, high	urban (US)
5517	90$/t	6.4	Tellus (Martin 1995)	
18218	89$/t	24.0	Schilberg (Martin 1995)	
22462	92$/t	24.5	Southern California Edison & San Diego Gas & Electric	ROG
4236	92$/t	4.6	Pacific Gas and Electric	ROG
1301	92$/t	1.4	attainment areas	ROG
5900	92$/t	6.4	Massachusetts - control cost based	
1180	92$/t	1.3	Minnesota - low	
1200	92$/t	1.3	Minnesota - high	
1298	92$/t	1.4	Nevada - control cost based	
4400	92$/t	4.8	New York - recommended	
2.77	90$/lb	1.5	Tellus - NREL paper	
2.61	90$/lb	1.4	CEC - NREL paper	
15.2	90$/lb	8.0	SCAQMD - NREL paper	

VOC low	0.4	ROG - Wang and Santini, Argonne (1995) damage based, low
VOC high	24.0	Schilberg (Martin 1995)

CO₂				
Original Values:		**95$/t**	**Source/Basis**	**Geographical Scope**
0.04	93ECU/kg	53	Swedish taxation today (Kageson 1993 p44)	
15	93$/t	16	Wang and Santini, Argonne (1995): past estimates based on control costs	
1.1	89$/t	1.3	New York State (Putta 1989) control cost	? - questionable
5	91£/tC	2.5	CO2 equivalent - Nordhaus (1991) assuming damage as 1% GWP	
8.6	91£/tC	4.2	CO2 equivalent - Nordhaus (1991) assuming damage as 2% GWP	
12.9	91£/tC	6.3	CO2 equivalent - Nordhaus (1991) assuming damage as 3% GWP	
5	91£/tC	2.5	CO2 equivalent - Cline (1991) assuming damage as 1% GWP	
10	91£/tC	4.9	CO2 equivalent - Cline (1991) assuming damage as 2% GWP	
15	91£/tC	7.4	CO2 equivalent - Cline (1991) assuming damage as 3% GWP	
5.9	91£/tC	2.9	CO2 equivalent - Cline (1991) assuming damage as 1% GWP. Revisions - low	
11.7	91£/tC	5.8	CO2 equivalent - Cline (1991) assuming damage as 2% GWP. Revisions - low	
16.5	91£/tC	8.1	CO2 equivalent - Cline (1991) assuming damage as 3% GWP. Revisions - low	
8.3	91£/tC	4.1	CO2 equivalent - Cline (1991) assuming damage as 1% GWP. Revisions - high	
16.5	91£/tC	8.1	CO2 equivalent - Cline (1991) assuming damage as 2% GWP. Revisions - high	
24.7	91£/tC	12.1	CO2 equivalent - Cline (1991) assuming damage as 3% GWP. Revisions - high	
23	90$/t	26.7	Tellus (Martin 1995)	
24	90$/t	27.8	Chernick (Martin 1995)	
14	90$/t	16.2	Pace (Martin 1995)	
15	89$/t	17.9	Schilberg (Martin 1995)	
9	92$/t	9.8	Southern California Edison & San Diego Gas & Electric	
9	92$/t	9.8	Pacific Gas and Electric	
9	92$/t	9.8	attainment areas	
24	92$/t	26.2	Massachusetts - control cost based	
5.99	92$/t	6.5	Minnesota - low	
13.6	92$/t	14.9	Minnesota - high	
24	92$/t	26.2	Nevada - control cost based	
8.6	92$/t	9.4	New York - recommended	
10	92$/t	10.9	Oregon - low	
40	92$/t	43.7	Oregon - high	
0.012	90$/lb	6.3	Tellus - NREL paper	
0.004	90$/lb	2.1	CEC - NREL paper	
6E-04	90$/lb	0.3	NYS - NREL paper	
0.007	90$/lb	3.7	Pace - NREL paper	?
0.003	90$/lb	1.6	BPA - NREL Paper	
0.02	90$/lb	10.5	Sweden - NREL Paper	

CO_2 low	1.3	New York State (Putta 1989) control cost
CO_2 high	53	Swedish taxation today (Kageson 1993 p44)

CO				
Original Values:		**95$/kg**	**Source/Basis**	**Geographical Scope**
1410	89$/t	1.7	Wang and Santini, Argonne (1995) control cost based, low	urban (US)
4840	89$/t	5.8	Wang and Santini, Argonne (1995) control cost based, high	urban (US)
906	90$/t	1.1	Tellus (Martin 1995)	
960	92$/t	1.0	Massachusetts - control cost based	
1012	92$/t	1.1	Nevada - control cost based	
423	92$/t	0.5	New York - recommended	
0.45	90$/lb	0.2	Tellus - NREL paper	
0.43	90$/lb	0.2	SCAQMD - NREL paper	

CO low	1.1	Tellus (Martin 1995)
CO high	5.8	Wang and Santini, Argonne (1995) control cost based, high

Particulates				
Original Values:		95$/kg	Source/Basis	Geographical Scope
2450	89$/t	2.9	PM10 - Wang and Santini, Argonne (1995) damage based, low	urban (US)
17200	89$/t	20.5	PM10 - Wang and Santini, Argonne (1995) damage based, high	urban (US)
2400	89$/t	2.9	PM10 - Wang and Santini, Argonne (1995) control cost based, low	urban (US)
6060	89$/t	7.2	PM10 - Wang and Santini, Argonne (1995) control cost based, high	urban (US)
4164	90$/t	4.8	Tellus (Martin 1995)	
2477	90$/t	2.9	Pace (Martin 1995)	
333	89$/t	0.4	TSP - New York State (Putta 1989) control cost	? - questionable
6804	92$/t	7.4	PM10 - Southern California Edison & San Diego Gas & Electric	
2624	92$/t	2.9	PM10 - Pacific Gas and Electric	
4608	92$/t	5.0	PM10 - attainment areas	
4400	92$/t	4.8	TSP - Massachusetts - control cost based	
166.6	92$/t	0.2	TSP - Minnesota - low	
2380	92$/t	2.6	TSP - Minnesota - high	
4598	92$/t	5.0	PM10 - Nevada - control cost based	
3642	92$/t	4.0	New York - recommended	
2000	92$/t	2.2	TSP - Oregon - low	
4000	92$/t	4.4	TSP - Oregon - high	
2.09	90$/lb	1.1	TSP - Tellus - NREL paper	
6.11	90$/lb	3.2	TSP - CEC - NREL paper	
0.17	90$/lb	0.1	TSP - NYS - NREL paper	
23	90$/lb	12.1	TSP - SCAQMD - NREL paper	
1.24	90$/lb	0.7	TSP - Pace - NREL paper	
3680	95£/t	5.9	PM10 - ExternE - health only - low	
12350	95£/t	19.8	PM10 - ExternE - health only - high	
0.08	90$/lb	0.0	BPA - NREL Paper - low	
0.8	90$/lb	0.4	BPA - NREL Paper - high	

Part. low	0.4	TSP - New York State (Putta 1989) control cost
Part. high	20.5	PM10 - Wang and Santini, Argonne (1995) damage based, high

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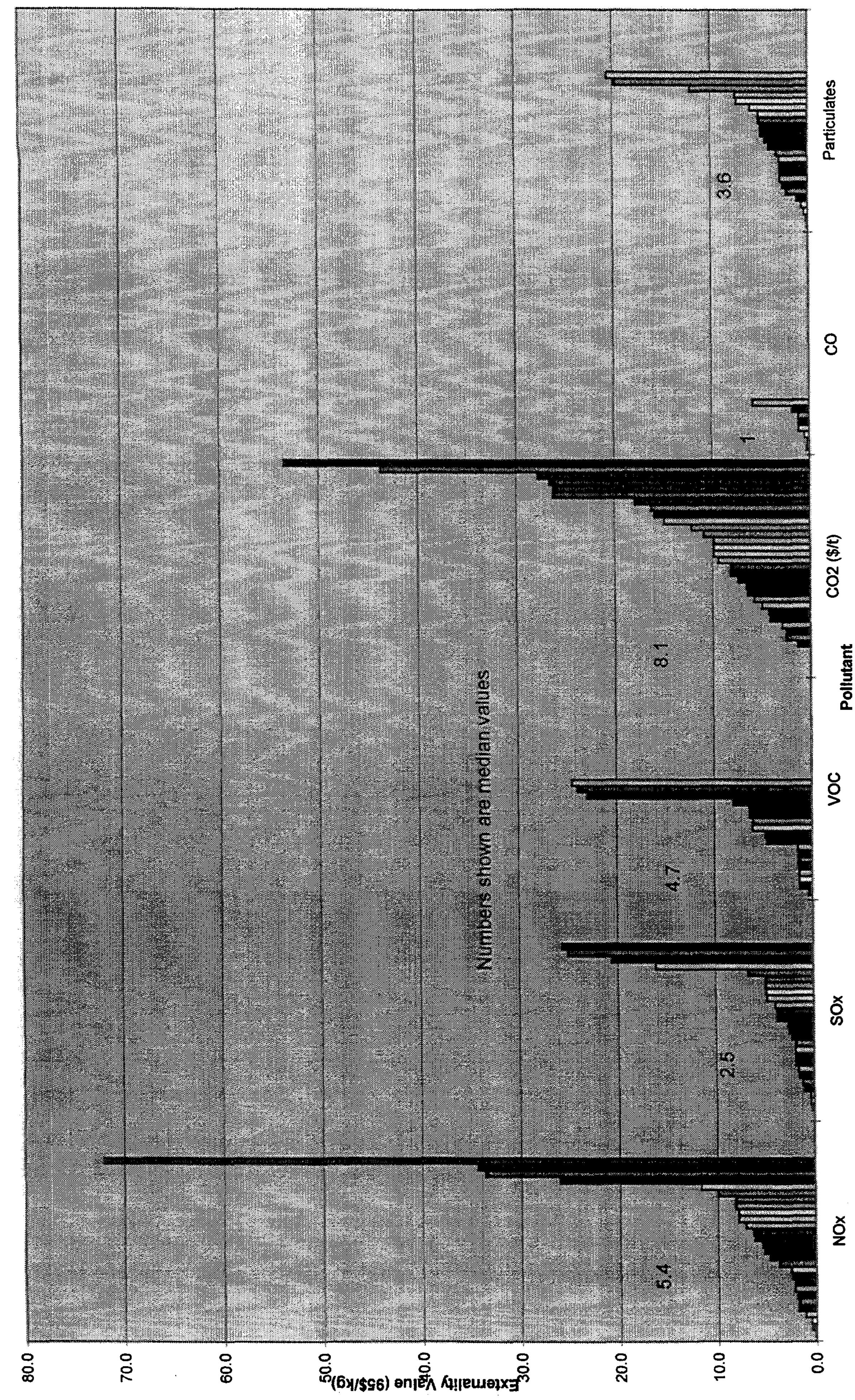


Externality Value (95$/kg)
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
5.4
2.5
4.7
8.1
1
3.6
Numbers shown are median values
NOx
SOx
VOC
CO2 ($/t)
CO
Particulates
Pollutant

Appendix Two

Targeted Hythane Scenario

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			84,953	
Reference	30,939		-	55,796	
Hythane	30,605	136	4,154	22,938	**211**
Difference	334	-136	-4,154	32,858	
Proportion	0.01	-1.00	-1.00	1.43	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			19,267	
Reference	7,230			11,484	
Hythane	7,171	29	1,662	4,806	**173**
Difference	59	-29	-1,662	6,677	
Proportion	0.01	-1.00	-1.00	1.39	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			2,328	
Reference	793			1,099	
Hythane	791	3	1,038	490	**-124**
Difference	3	-3	-1,038	609	
Proportion	0.00	-1.00	-1.00	1.24	

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the amount of hydrogen

High Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	34	34	26
SO_2	25	16	15
VOC	24	23	20
CO_2	0.053	0.053	0.053
CO	5.8	4.0	2.5
Particulates	21	15	8

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			13,376	
Reference	30,939		-	8,928	
Hythane	30,605	136	4,154	3,637	**8**
Difference	334	- 136	- 4,154	5,291	
Proportion	0.01	- 1.00	- 1.00	1.45	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			3,046	
Reference	7,230			1,867	
Hythane	7,171	29	1,662	774	**-20**
Difference	59	- 29	- 1,662	1,093	
Proportion	0.01	- 1.00	- 1.00	1.41	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			-	
Reference	793			220	
Hythane	791	3	1,038	93	**-262**
Difference	3	- 3	- 1,038	128	
Proportion	0.00	- 1.00	- 1.00	1.37	

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the amount of hydrogen

Median Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	5	5	5
SO_2	3	3	3
VOC	5	5	5
CO_2	0.008	0.008	0.008
CO	1.0	1.0	1.0
Particulates	4	4	4

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			4,815	
Reference	30,939		-	2,414	
Hythane	30,605	136	4,154	1,402	**-23**
Difference	334	- 136	- 4,154	1,011	
Proportion	0.01	- 1.00	- 1.00	0.72	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			1,274	
Reference	7,230			509	
Hythane	7,171	29	1,662	299	**-50**
Difference	59	- 29	- 1,662	210	
Proportion	0.01	- 1.00	- 1.00	0.70	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			-	
Reference	793			60	
Hythane	791	3	1,038	36	**-292**
Difference	3	- 3	- 1,038	25	
Proportion	0.00	- 1.00	- 1.00	0.69	

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the amount of hydrogen

Low Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	0.56	0.56	0.56
SO_2	0.72	0.72	0.72
VOC	0.40	0.40	0.40
CO_2	0.005	0.005	0.005
CO	1.10	1.10	1.10
Particulates	8.00	8.00	8.00

Appendix Three

Hydrogen in Gasoline Scenario

Central London

Scenario	Energy (TJ)	Hydrogen (TJ)	Infrastructure ($'000)	Emissions ($'000)	Value ($/GJ)*
Status Quo	31,562			438,688	
Reference	30,939		-	145,380	
Hythane	30,939	682	8,212	45,606	**134**
Difference	-	- 682	- 8,212	99,775	
Proportion	-	- 1.00	- 1.00	2.19	

Inner London

Scenario	Energy (TJ)	Hydrogen (TJ)	Infrastructure ($'000)	Emissions ($'000)	Value ($/GJ)*
Status Quo	7,739			135,845	
Reference	7,230			80,542	
Hythane	7,230	156	1,876	61,784	**108**
Difference	-	- 156	- 1,876	18,758	
Proportion	-	- 1.00	- 1.00	0.30	

Outer London

Scenario	Energy (TJ)	Hydrogen (TJ)	Infrastructure ($'000)	Emissions ($'000)	Value ($/GJ)*
Status Quo	887			13,842	
Reference	793			7,910	
Hythane	793	25	303	6,180	**57**
Difference	-	- 25	- 303	1,730	
Proportion	-	- 1.00	- 1.00	0.28	

High Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	34	34	26
SO_2	25	16	15
VOC	24	23	20
CO_2	0.053	0.053	0.053
CO	5.8	4.0	2.5
Particulates	21	15	8

* Calculated as the value of emissions reductions minus extra infrastructure costs, divided by the amount of hydrogen

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			77,382	
Reference	30,939		-	25,685	
Hythane	30,939	682	8,212	8,232	**14**
Difference	-	- 682	- 8,212	17,453	
Proportion	-	- 1.00	- 1.00	2.12	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			26,294	
Reference	7,230			14,830	
Hythane	7,230	156	1,876	10,743	**14**
Difference	-	- 156	- 1,876	4,087	
Proportion	-	- 1.00	- 1.00	0.38	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			3,356	
Reference	793			1,792	
Hythane	793	25	303	1,271	**9**
Difference	-	- 25	- 303	521	
Proportion	-	- 1.00	- 1.00	0.41	

* Calculated as the value of emissions reductions minus extra infrastructure costs, divided by the amount of hydrogen

Median Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	5	5	5
SO_2	3	3	3
VOC	5	5	5
CO_2	0.008	0.008	0.008
CO	1.0	1.0	1.0
Particulates	4	4	4

Central London

Scenario	Energy (TJ)	Hydrogen (TJ)	Infrastructure ($'000)	Emissions ($'000)	Value ($/GJ)*
Status Quo	31,562			43,464	
Reference	30,939		-	14,568	
Hythane	30,939	682	8,212	1,767	7
Difference	-	- 682	- 8,212	12,801	
Proportion	-	- 1.00	- 1.00	7.25	

Inner London

Scenario	Energy (TJ)	Hydrogen (TJ)	Infrastructure ($'000)	Emissions ($'000)	Value ($/GJ)*
Status Quo	7,739			10,080	
Reference	7,230			3,375	
Hythane	7,230	156	1,876	406	7
Difference	-	- 156	- 1,876	2,969	
Proportion	-	- 1.00	- 1.00	7.31	

Outer London

Scenario	Energy (TJ)	Hydrogen (TJ)	Infrastructure ($'000)	Emissions ($'000)	Value ($/GJ)*
Status Quo	887			1,257	
Reference	793			428	
Hythane	793	25	303	52	3
Difference	-	- 25	- 303	376	
Proportion	-	- 1.00	- 1.00	7.22	

* Calculated as the value of emissions reductions minus extra infrastructure costs, divided by the amount of hydrogen

Low Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	0.56	0.56	0.56
SO_2	0.72	0.72	0.72
VOC	0.40	0.40	0.40
CO_2	0.005	0.005	0.005
CO	1.1	1.1	1.1
Particulates	8.0	8.0	8.0

Appendix Four

Catalytic Converter Scenario

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			84,953	
Reference	30,939		-	38,783	
Hythane	30,605	136	9,814	13,202	**116**
Difference	334	- 136	- 9,814	25,581	
Proportion	0.01	- 1.00	- 1.00	1.94	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			19,267	
Reference	7,230			8,121	
Hythane	7,171	29	2,090	2,760	**113**
Difference	59	- 29	- 2,090	5,361	
Proportion	0.01	- 1.00	- 1.00	1.94	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			2,328	
Reference	793			804	
Hythane	791	3	250	309	70
Difference	3	- 3	- 250	495	
Proportion	0.00	- 1.00	- 1.00	1.61	

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the equivalent amount of hydrogen

High Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	34	34	26
SO_2	25	16	15
VOC	24	23	20
CO_2	0.053	0.053	0.053
CO	5.8	4.0	2.5
Particulates	21	15	8

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			13,376	
Reference	30,939		-	8,928	
Hythane	30,605	136	9,814	2,055	**-22**
Difference	334	- 136	- 9,814	6,873	
Proportion	0.01	- 1.00	- 1.00	3.35	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			3,046	
Reference	7,230			1,867	
Hythane	7,171	29	2,090	438	**-23**
Difference	59	- 29	- 2,090	1,430	
Proportion	0.01	- 1.00	- 1.00	3.27	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			406	
Reference	793			220	
Hythane	791	3	250	52	**-24**
Difference	3	- 3	- 250	168	
Proportion	0.00	- 1.00	- 1.00	3.20	

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the equivalent amount of hydrogen

Median Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	5.4	5.4	5.4
SO_2	2.5	2.5	2.5
VOC	4.7	4.7	4.7
CO_2	0.008	0.008	0.008
CO	1.0	1.0	1.0
Particulates	3.6	3.6	3.6

Central London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	31,562			4,815	
Reference	30,939		-	1,991	
Hythane	30,605	136	9,814	1,329	-67
Difference	334	-136	-9,814	662	
Proportion	0.01	-1.00	-1.00	0.50	

Inner London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	7,739			1,274	
Reference	7,230			424	
Hythane	7,171	29	2,090	283	-67
Difference	59	-29	-2,090	141	
Proportion	0.01	-1.00	-1.00	0.50	

Outer London

Scenario	*Energy (TJ)*	*Hydrogen (TJ)*	*Infrastructure ($'000)*	*Emissions ($'000)*	*Value ($/GJ)**
Status Quo	887			174	
Reference	793			60	
Hythane	791	3	250	34	-64
Difference	3	-3	-250	27	
Proportion	0.00	-1.00	-1.00	0.78	

* Calculated as the value of emissions reductions *minus* extra infrastructure costs, divided by the equivalent amount of hydrogen

Low Externality Costs

Externality Costs by Area (95$/kg)			
	Area of London		
Pollutant	*Central*	*Inner*	*Outer*
NOx	0.56	0.56	0.56
SO_2	0.72	0.72	0.72
VOC	0.40	0.40	0.40
CO_2	0.005	0.005	0.005
CO	1.1	1.1	1.1
Particulates	8.0	8.0	8.0

Appendix Five

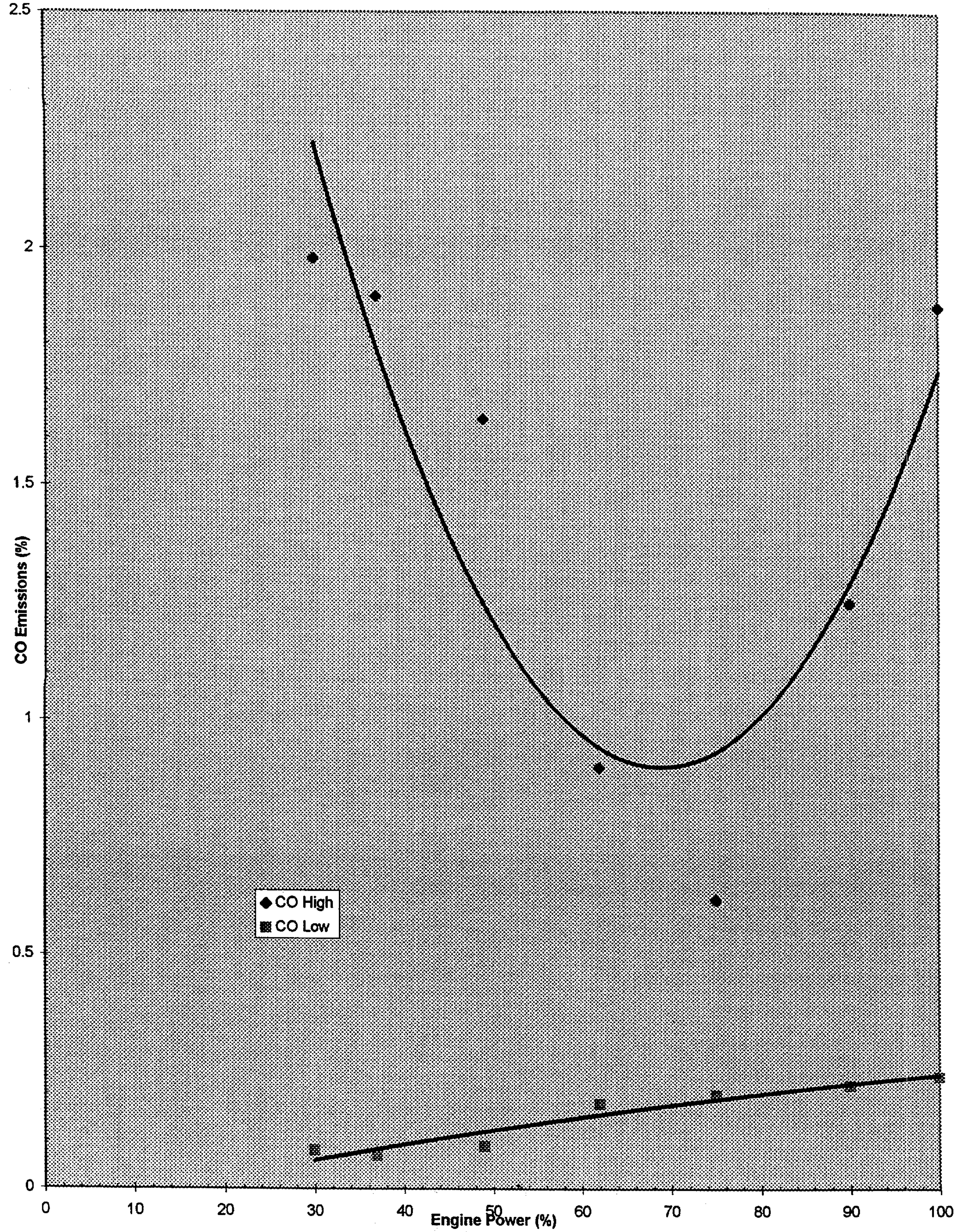
Estimating the Benefits of Hydrogen in Gasoline

Engine Power	10%	20%	**30%**	40%	50%	60%	70%	80%	90%	100%
hydrogen (g/h)	70.00	70.00	**70.00**	70.00	70.00	70.00	70.00	70.00	70.00	70.00
gasoline (g/h)	-26.94	142.01	**310.97**	479.93	648.89	817.84	986.80	1155.76	1324.72	1493.67
hydrogen (MJ/h)	8.41	8.41	**8.41**	8.41	8.41	8.41	8.41	8.41	8.41	8.41
gasoline (MJ/h)	-1.16	6.10	**13.36**	20.61	27.87	35.13	42.38	49.64	56.90	64.15
Total Fuel (g/h)	43.06	212.01	**380.97**	549.93	718.89	887.84	1056.80	1225.76	1394.72	1563.67
Total Fuel (MJ/h)	7.26	14.51	**21.77**	29.03	36.28	43.54	50.80	58.05	65.31	72.57
hydrogen (%w/w)	163%	33%	**18%**	13%	10%	8%	7%	6%	5%	4%
hydrogen (%e/e)	116%	58%	**39%**	29%	23%	19%	17%	14%	13%	12%

CO emissions			**4%**							
HC emissions			**58%**							
NO emissions			**41%**							
CO2 emissions	90%	80%	**70%**	60%	50%	40%	30%	20%	10%	0%

AlphaE=(alphaG x alphaH)/(alphaG + alphaH)
AG=GA/(GGxLOG), thus GG=GA/(AGxLOG)
AH=GA/(GHxLOH), thus GA=AH*(GHxLOH)

Power:	30%		GG=	0.31 kg/h
AE:	1.72		GA=	12.05 kg/h
AG:	2.6			
AH:	5		rho H2=	0.08988 kg/m^3
GH:	0.07 kg/h		rho petrol=	kg/m^3
LOG:	14.9 kg			
LOH:	34.42 kg			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CO Emissions (%)
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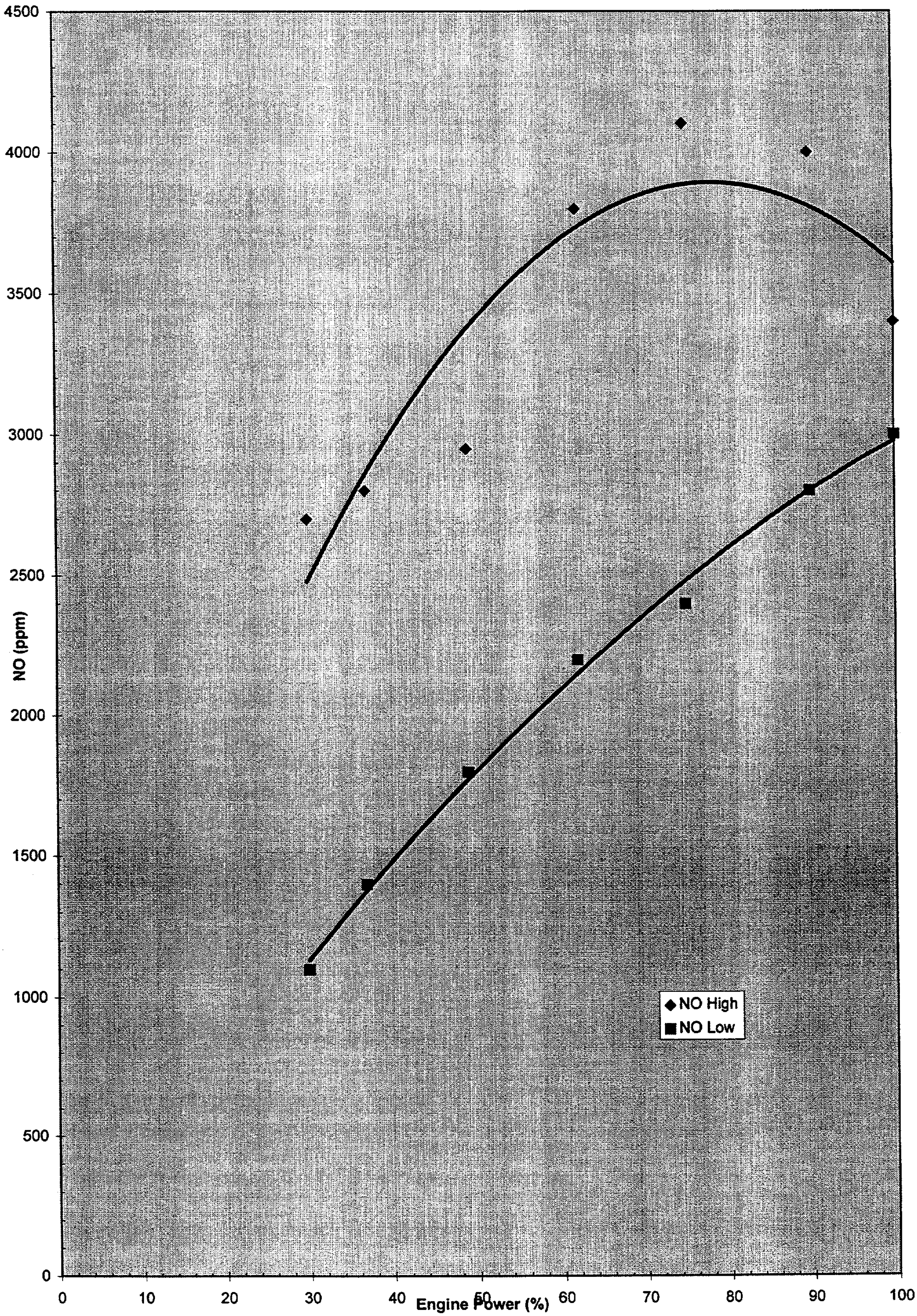
100
Engine Power (%)
CO High
CO Low



4500
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3500
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2500
2000
1500
1000
500
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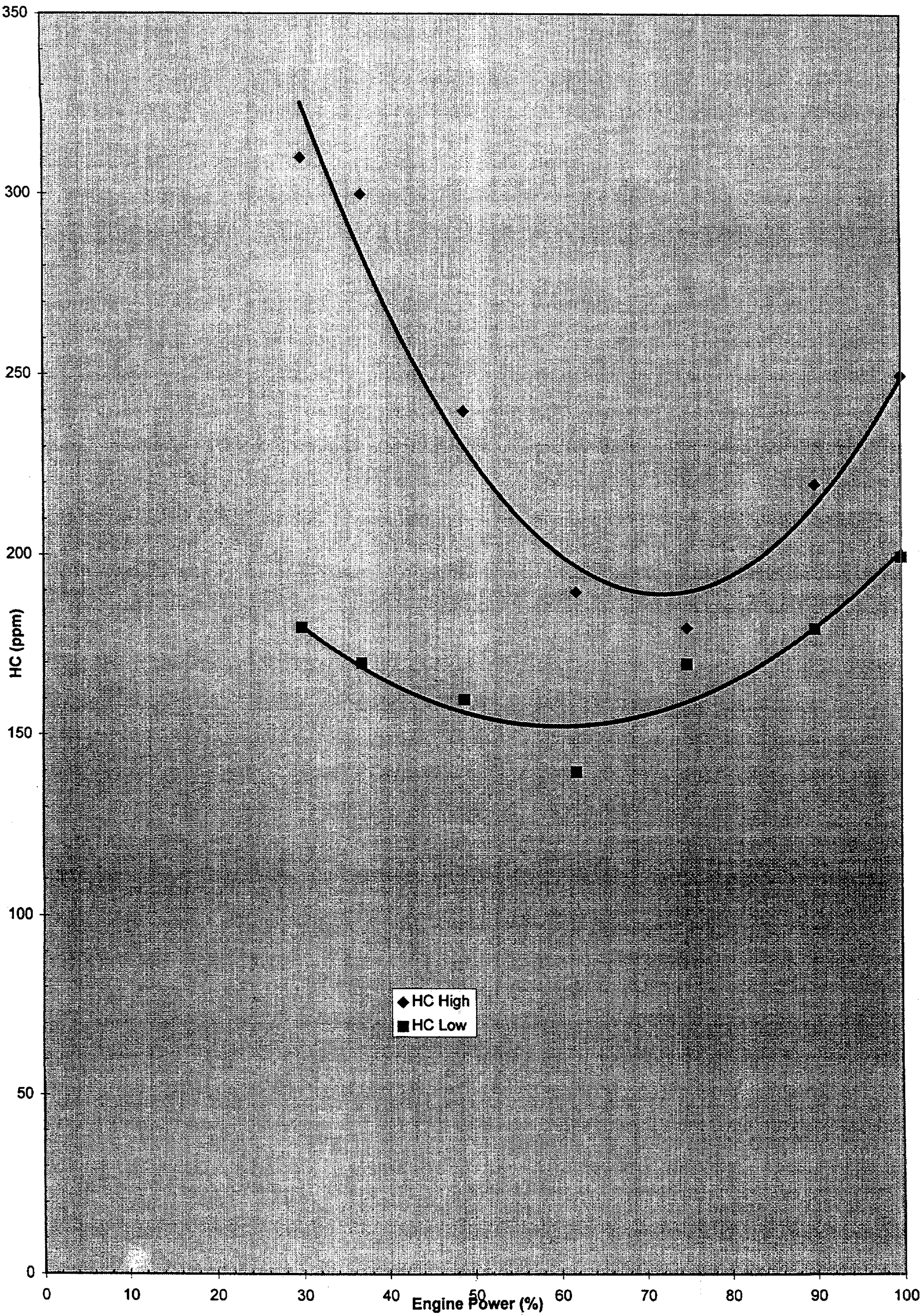
0
10
20
30
40
50
60
70
80
90
100
Engine Power (%)
◆NO High
■NO Low



350
300
250
200
150
100
50
0
HC (ppm)
0
10
20
30
40
50
60
70
80
90
100
Engine Power (%)
HC High
HC Low