WORKING PAPER 2
May 2004

Opening the 'Black Box' of the Hydrogen Economy

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Introduction

The issue of a hydrogen economy or economies is undoubtedly controversial. Yet, seemingly paradoxically, the development of a hydrogen economy is hailed almost exclusively as positive (Rifkin, 2002; Billings, 2000). In this respect a predominant writer on the hydrogen economy, Jeremy Rifkin (2002), suggests as the subtitle to a recent book that such an economy will be underpinned by 'the creation of the world wide energy web and the redistribution of power on earth'. This enthusiasm has become embodied in a range of policy discourses at a variety of levels of governance. Interestingly, in this respect, Rifkin acts as an advisor to Romano Prodi, the President of the European Commission, who in this position has committed the Commission to the 'hydrogen revolution' (Prodi, 2003). Similarly, George W Bush in his 2003 State of the Union address committed $1.2 billion in research funding 'so that America can lead the world in developing clean, hydrogen-powered automobiles' (Bush, 2003)[i]. The premise of such a development is in the expectation that it will 'make our air significantly cleaner, and our country much less dependent on foreign sources of energy' (Bush, 2003). The development of hydrogen technologies and the move to a hydrogen economy, it is suggested, is both good for the economy and the environment. Whilst at the regional level, in London for example, the public transportation system, given its large number of taxis, buses and delivery vans, 'offers a massive opportunity for developing the use of hydrogen' (Mayor of London, 2004, p.86).

Much of this enthusiasm operates at a rhetorical level making a multiplicity of claims of the possibilities of the hydrogen economy. The ability to make such claims rests on certain assumptions about what the hydrogen economy(-ies) can 'deliver'. Yet, moving beyond these rhetorical visions necessitates different ways of understanding the hydrogen economy(-ies). It requires asking what a hydrogen economy(-ies) might look like. How can we understand it? We address this, here, through one particularly powerful and prevalent way of seeing hydrogen technologies known as technology characterisation (TC). A strong version of TC is outlined as encapsulating a view which focuses on the supply of technology as related to the 'state of the art', or what the technology can 'deliver in principle'. The claim, subsequently, is that there has been, and there remain, difficulties in 'realising' this strong version in TC analyses yet that this remains a powerful way of seeing hydrogen technologies.

The paper moves onto scrutinise 10 documents that seek to represent the future hydrogen economy(-ies), through a series of TC practices. In particular, we highlight seven themes from these documents and their representations of the hydrogen economy. These relate to: diagrammatic attempts to frame the hydrogen economy; examining who is behind these documents; key issues of technology, environment, consumption, economics and expertise. These 10 documents, we claim, are 'emblematic' in that they are authored by recognised names in the field, are frequently cited in hydrogen-related academic papers and address a broad span of hydrogen technologies (in that they deal with issues of production, storage, distribution, fuel cells, etc). The use of these documents is related to the raising of a series of issues, underpinned by an understanding of the social and cultural contexts of the construction and production of TCs[ii]. The aim of these papers was principally to identify 'technical possibilities and costs' (e.g. Marsh *et al*, 2002) of hydrogen technologies if with different agendas in terms of 'outcome'. The relationship between costs and technical performance was important in that it provided a number of, and set limits to, possibilities and options for future development of hydrogen technologies. It offered examples of what hydrogen technologies 'can in principle deliver'. It, furthermore, reduced the complexity of possibilities of hydrogen technologies and acted as a kind of ordering methodology where uncertainties and controversies become simplified into a series of options. Numerous papers set their analysis of hydrogen technologies up in terms of offering an analysis of the 'state of the art' (Dutton, 2002; Brandon and Hart, 1999). For some of the papers this entailed a broad sweep of hydrogen technologies, including technical, economic and environmental characteristics, whilst many others drew on elements of this approach. These papers, generally, offer a particular way of thinking about, and seeing, the hydrogen economy. In many ways, they resonate with the notion of technology characterisation (TC).

TCs offer a particular and partial way of understanding technologies and technological change. It is how this way of understanding is produced and constructed and its consequences for the representation of hydrogen technologies and the hydrogen economy(-ies) which are of interest here. The partial nature of TC processes and practices are interrogated here, through the notion of 'framing' and the related concepts of 'disentanglement', 'externalities' and 'overflows' (Callon, 1998a; 1998b), and possibilities are outlined for future dialogue between exponents of TCs and those of other, partial, ways of seeing future hydrogen economies[iii].

Technology Characterisation as a Way of Seeing the Hydrogen Economy

A key issue is the role TCs play in creating expectations and understandings of the hydrogen economy(-ies). Though there are numerous examples of what could be considered performances of TCs, there appears to be scant literature related to the history and genealogy of the term 'technology characterisation'. Through searches of a variety of databases, search engines and bibliographic sources[iv] only three sources (OAO Corp, 1979; Taylor, 1978; Chandra, 1995) explicitly addressed the notion of technology characterisation as distinct from performing or undertaking TCs.

TC is defined by one author as 'the measurement of the state of technology against primarily technical criteria' (Taylor, 1978, p.S-1). Given this broad definition it is understandable that not all authors of what may be termed technology characterisation recognise their own work as encompassed by that rubric. It is, however, interesting to address the notion of TC in relation to the 10 reports where, for example, authors give a sense of how TCs may be synonymous with a 'survey of the economics of hydrogen technologies'; 'cost and performance comparison of stationary hydrogen fueling appliances'; 'technoeconomic analysis of different options for the production of hydrogen from sunlight, wind and biomass'; and 'fuel cell technology and economics'. A further issue is that there may be a variable degree of overlap between TC and technology assessment (TA). It has been suggested that there are often overlaps between TC and TA and that TC can often be a necessary precursor of TA (Taylor, 1978). The distinction has been made that 'the greatest need for TC is in the early stages of R&D, while TA is normally applied to technologies which are at least approaching commercialization' (Taylor, 1978, p.8). The degree of overlap relates to issues of definition of both terms. Whilst acknowledging difficulties in defining and 'capturing' TC, one report has suggested that TC encompasses three broad approaches: the empirical approach; the analytical approach; and the systems engineering approach. Yet, across these three approaches, there is a prescriptiveness and linearity (albeit with a degree of feedback) to conducting TCs. The process starts with defining the technology, followed by selecting parameters to characterise the technology, choosing scales for the parameters, positioning the technology against the scales, and then application (Taylor, 1978).

One agency of the US Government was able to note a quarter of a century ago, within its own institutional context, that, 'technology characterization activities have been occurring for a long time and…they are likely to continue' (OAO Corp, 1979, section I-10). The predominant rationale for TC, within this context of the US Department of Energy (DOE), was to 'institutionalize the development, collection and maintenance of technical information needed for preparation of RD&D strategies, analysis of budget priorities, communications outside the Department, and development of the Department's annual reports (OAO Corp, 1979, section I-1). The importance of TC was in developing a 'set of standardized procedures' which would inform a 'quantitative description of technology, process or conservation option'; 'an estimate of future energy project costs and the uncertainty associated with these estimates'; and 'an estimate of the funding required to develop the technologies required'. TC, furthermore, involved the creation of official Department data files and a process for 'developing and updating' these data files (OAO Corp, 1979, section I-1). In this respect this report focuses largely on 'economic characteristics', 'technical characteristics' and environmental issues (OAO Corp, 1979). TC, in this report, is seen as referring largely to 'generic technology' where characterisation would pertain to a 'data base which would be useful for broad-based activities' (OAO Corp, 1979, section III-1). The notion of generic also has a dimension which is relative to 'their stages of development' or whether a technology is a 'near term technology' or at a 'relatively early stage' of development (OAO Corp, 1979, section III-2). The suggestion was that the support and acceptance of TC amongst DOE staff required 'high quality, unbiased data' (OAO Corp, 1979, section II-1). Importantly, in this particular instance, a 'successful' TC was one which maintained a 'record of the most up-to-date information' thereby negating a 'constant "reinventing of the wheel"'. It would also ensure 'that there is a single official set of estimates for characteristics of a technology'. It would mean that 'all official estimates of technology characteristics are based on constant underlying assumptions' (OAO Corp, 1979, section I-2). The strong understanding of TC, which this report propounds, highlights a number of issues in its attempts to create 'certainties' around technological developments. In particular it requires us to look at not only what is important in this approach, but also what is problematic with it and to whom its practices are oriented.

The desire for certainty both informs what seeks to be achieved in the name of TC but also highlights that there are extreme difficulties with chasing such an ideal. One report, for example, form a project attempting to reduce uncertainties through developing a TC methodological approach suggested:

> For R&D planning purposes and for projecting commercialization dates of new energy technologies, it would be desirable to be able to describe the state of development of

> various technologies in a comparative, unambiguous and systematic way. Contractor difficulties in finding such criteria for defining the stage of development of new technologies led to the termination of the research effort about midway through the project (Taylor, 1978, p.v).

This suggests, whilst there were aspirations to characterise technologies in 'unambiguous and systematic' ways, that developing practices and processes to 'achieve' this were often problematic. This leads us to ask: what sorts of practices and processes constitute TCs? But also, how might we understand these practices and processes and the implications of this for how we see the hydrogen economy(-ies)?

A further related issue is in addressing what 'work' TC documents are doing. The importance of using TCs to confer 'certainty' to understandings of technology, through abstraction and perceived implicit technological neutralism, for example, also had the broader political aim of '[e]stablishing credibility on the Hill' (i.e. with the US Congress) (OAO Corp, 1979, section I-2). The stabilising of technical characteristics, and also bringing a certainty to economic characteristics, offers an interesting way of representing the supply of technology which may resonate with many in the policy and political classes in contemporary neo-liberal economies. This approach is illustrated through a number of the 10 papers drawn upon here being prepared for government departments (e.g. Myers *et al*, 2002) and, in some instances, used to inform policy (e.g. Marsh *et al*, 2002). The raising of the issue of influencing political opinion, and indeed wider 'public opinion' via the channels of the mass media, highlights the prospect that TCs, whilst perhaps perceived superficially to be driven by a technological neutralism, offer one (broadly speaking) way of understanding technological possibilities and in particular hydrogen technologies amongst a number. To 'capture' the technical characteristics and costs of technologies brings an 'order' to chaotic processes of technological development and allows costs to be attached. To put it another way, it allows the 'use of a sound approach to incremental benefit/incremental cost questions given…large uncertainties' (OAO Corp, 1979, section I-2).

Framing the Hydrogen Economy

The idea that TCs offer a partial, but powerful, way of understanding a future hydrogen economy(-ies) leads us to address the practices and processes involved in the production and construction of TC representations of hydrogen technologies. In particular it moves us to examine how TCs offer a 'way of seeing' the hydrogen economy(-ies) as partial – as framing

- as inclusive and exclusive of certain interests and practices. This, we claim here, can be understood through diagrammatic representations – or representational devices - of future hydrogen economies which are underpinned through a series of themes and issues, including: who is involved in such processes of representation; but also the ways in which TC practices and processes frame issues related to the technologies, the environment, consumption, economics and expertise.

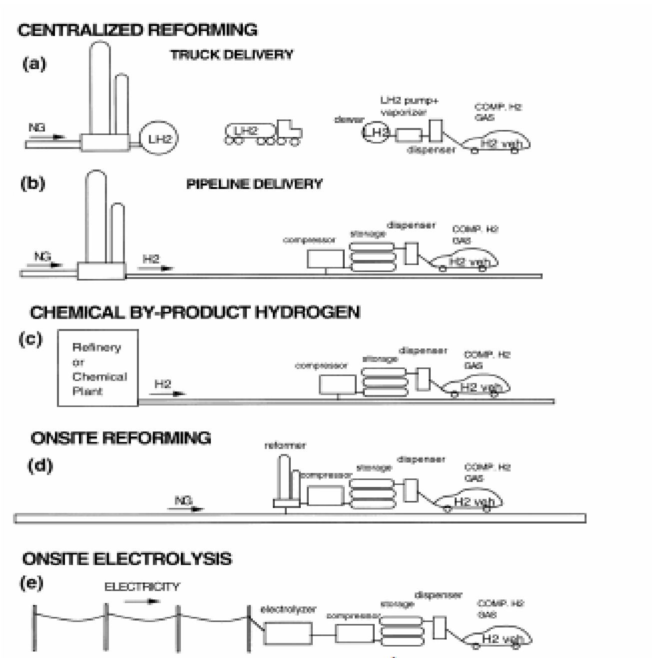

Fig. 1. Near term gaseous hydrogen supply options.

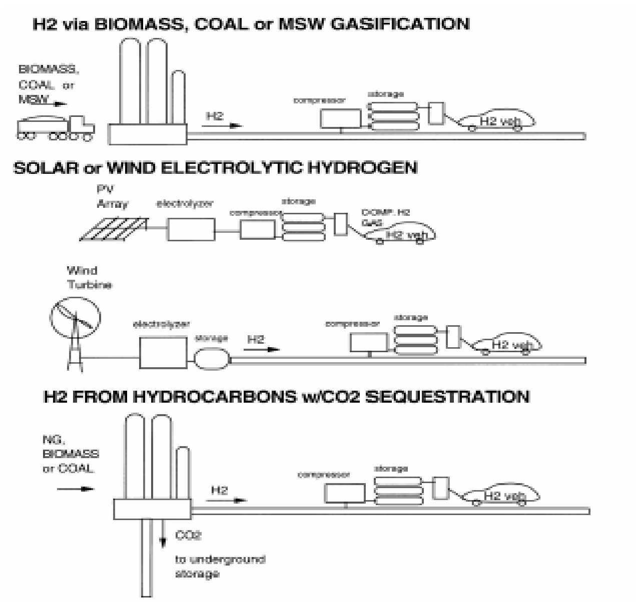

Fig. 5. Long term hydrogen supply options.

Source: Ogden (1999).

The significance of diagrammatic representations, such as those above, at one level is in their power to influence debate and dialogue:

> What is so important in the images and in the inscriptions scientists and engineers are busy obtaining, drawing, inspecting, calculating, and discussing? It is, first of all, the unique advantage they give in the rhetorical or polemical situation. "You doubt what I say? I'll show you". And without moving more than a few inches, I unfold in front of your eyes figures, diagrams, plates, texts, silhouettes, and then and there present things that are far away and with which some sort of two-way connection has now been established. I do not think the importance of this simple mechanism can be overestimated (Latour, 1990, p.36).

Diagrams and representational devices have an important role to play in furthering and forwarding the interests of those who produce and construct them and who may draw upon these representations. This making visible of TCs also offers the possibility for their mobility across organisational, institutional and national boundaries not only as rhetorical devices but also as sources utilised in other TCs. This involves not only the mobilisation of diagrams but of networks of individuals, institutions, artefacts, etc, which constitute diagrams. With this in mind, how do we arrive at diagrams like those above? Of importance are the frequency with which this and similar diagrams (e.g. Schoenung, 2002), tables, graphs (e.g. Padró and Putsche, 1999) and schematics (e.g. Brandon and Hart, 1999) occur in TCs but, also, the ways in which the practices and processes which constitute these diagrams, graphs and tables privilege certain aspects of the hydrogen economy(-ies) (e.g. often narrowly defined economic costs and technical possibilities) to the exclusion of other aspects (e.g. social contexts of innovation, appropriation and consumption in use).

Who's Framing Who?

This leads us to ask who is involved in the production and construction of these representations? The vast majority of the TC representations were undertaken by or for agencies of the state, predominantly in terms of the US and UK. Myers and colleagues' paper (2002), for example, was prepared for the Office of Power Technologies at the US Department of Energy. Similarly, the work of Padró and Putsch (1999) was undertaken at Midwest Research Institute where a US Department of Energy Laboratory operates. In another instance, Lakeman and Browning's (2001) paper was contracted by the Defence Evaluation and Research Agency (DERA) as part of the UK DTI Sustainable Energy

Programmes. In other examples the context within which papers were constructed was an academic one, both in the US (Ogden, 1999) and the UK (Brandon and Hart, 1999). This said, the networks within which such papers were implicated straddled the domain of the US Department of Energy Hydrogen R&D Program (Ogden, 1999) and the UK DTI (Dutton, 2002) - the work of Dutton was sponsored by the UK Tyndall Centre which is funded by three research councils and the DTI. These representations were, as such, implicated within a web of relationships of institutional funding, institutional cultures, the agendas of a variety of actors and the specific organisational settings within which they were produced and constructed.

Much of the literature drawn upon by these documents, as sources, was from the US and the UK context, with a limited number of documents from other countries, particularly Japan and the rest of Europe. This could reflect the fact that all the documents analysed had their roots in the US or UK context. It may also be that the dissemination of these reports in the medium of the English language, and also via databases and the World Wide Web, narrowed the scope of documents which could be accessed. It is also, however, predominantly due to the dominant role which the US occupies in terms of technical and economic analyses of hydrogen technologies, and in particular the US Department of Energy (DOE).

Framing Technology

Many of the documents articulated and represented issues such as, ‘typical plant sizes’, ‘readiness for large scale application’, ‘estimated capital and running costs’ (Dutton, 2002), the ‘technical feasibility and economics’ of comparing various hydrogen refuelling options (Ogden, 1999), ‘fuel cell efficiency’ and ‘fuel cell system costs – now and predicted’ (Brandon and Hart, 1999), whilst others looked for the ‘most cost effective option’ (Myers *et al*, 2002) and time scales often of 10, 20 and 50 years (Dutton, 2002), or ‘near-term and long-term’ (Ogden, 1999). Ogden (1999), for example, assessed ‘in detail several near-term possibilities’. The paper by Lakeman and Browning opened up the possibility of making the ‘universalistic’ statement, ‘there will be a 30 year transition phase to the full implementation of the hydrogen economy’, whilst often underplaying issues of place, space or context and the reference to time being reduced to ‘current’ and ‘future’ (Lakeman and Browning, 2001).

Often a ‘number of initial assumptions’ (Schoenung, 2002, p.3) were made in documents, although it was sometimes unclear where these were derived from. In Schoenung’s work, for example, on hydrogen refuelling station alternatives it was seemingly unapparent as to why 'base cases' assumed that there should be capacity to refuel 100 vehicles per day. This may have been, to some extent, as she suggested she had outlined this elsewhere. It may, however, be that these assumptions were in some way axiomatic. There was a considerable degree of re-citing secondary documentation, across the representations, with little discussion of the methodological underpinnings of these documents. In many instances they were seemingly offered up unproblematically from one context to another, thereby implicitly inferring that the data was transferable between contexts but also, more problematically, re-inforcing errors, over- and under-estimations and certain assumptions.

Framing Environment

Some documents also talked of 'more conventional technologies' (Dutton, 2002). The explicit, and implicit, aims of those writing the documents were varied. For some it was, at least notionally, to assess the possibilities of hydrogen technologies in terms of a 'long-term role in greenhouse gas reduction' (Dutton, 2002). In doing this, representations of environmental issues were in developing 'a range of "bottom-up" estimates of carbon dioxide emissions from the UK energy sector up to 2050, and to identify the technical possibilities and costs for the abatement of these emissions' (Marsh *et al*, 2002, p.iii). Addressing carbon emissions was frequently in terms of the 'costs of production', largely in terms of secondary data (Watkiss and Hill, 2002). Similarly, Schoenung (2002, p.10) drew on secondary sources to detail an 'emissions analysis' where the 'primary figures of merit for this part of the study were fuel economy and emissions'. Often environmental issues were framed narrowly in terms of 'costs'. One paper, for example, attempted to identify a range of 'technical possibilities and costs' for the abatement of CO2 emissions (Marsh *et al*, 2002, p.iii). A rider, in this case, was added suggesting that the results 'are not forecasts [but] an analysis of what technology can in principle deliver, and of what the costs and effects on emissions might be'. With an eye to future developments and costs, the acknowledgement was that this 'will turn on many factors including the policies implemented, the social acceptability of the technologies, the readiness of householders and business to invest in energy efficiency and the rate of innovation' (Marsh *et al*, 2002, p.2).

Framing Consumption

Similarly, the framing of consumption, illustrated in a tabular representation below, was often in terms of estimations and assumptions of, for example, transportation use.

Table 10. Vehicle key assumptions for modelling (ETSU/IC, 2000).

Vehicle	Daily distance (km)	Annual distance (km)	H2 consumption (kg/day)	H2 consumption (t/yr)	H2 consumption (kWh/yr)
Urban Bus	200	70,000	16.80	5.88	196,000
LGV	150	52,500	2.82	0.987	32,900
Taxi	300	105,000	2.67	0.935	31,167

NB: vehicle operates 350 days/yr

Source: Watkiss and Hill (2002, p.24).

Ogden (1999), for example, addressed fuel consumption in the Los Angeles area. Data was obtained from the South Coast Air Quality Management District for current and projected numbers (to 2010, then 'extrapolated linearly to estimate vehicle populations to 2020' by Ogden) of automobiles, trucks and so on. This, according to Ogden, based on the assumption about numbers of new cars and light trucks as zero emissions vehicles (ZEVs) from 2003, allowed the ZEV population for the Los Angeles Basin to be calculated by year. This projection of ZEVs then took the assumption that 50 per cent of ZEVs would be hydrogen fuel cell vehicles after 2005. This, in addition to the 'assumed characteristics of hydrogen fuel cell vehicles' (fuel economy, miles/year, fuel storage, hydrogen use per year, etc) permitted the estimation of total hydrogen demand in the South Coast Basin.

Framing Economics

The possibilities of hydrogen technologies, in many ways, were reduced to narrow economic considerations. So, for example, there was talk of 'the relative merits of hydrogen storage systems and comparison of costs' (Dutton, 2002, p.17). Or: 'The capital cost of infrastructure and the delivered cost of hydrogen are estimated for each hydrogen supply option' (Ogden, 1999, p.709). This leaves an obvious question as to how the notion of cost is conceptualized and framed. That is, to what does cost refer?

Many of the papers calculated technological and/or economic performance data on the basis of estimates. These estimates often rested on assumptions. Watkiss and Hill (2002), for example, in their paper highlighted a variety of 'key assumptions for modelling' (see above, sourced from ETSU/IC). These assumptions included that a vehicle would operate 350 days a year, that an 'urban bus' would travel 70,000 km per year and consume 5.88 tonnes of hydrogen per year whilst a taxi would travel 105,000 km per year consuming 0.935 tonnes of hydrogen a year. The interesting point to note here is that there was little sensitivity to, and appreciation of, the context in which such vehicles may operate, other than the broad term 'urban'.

The data used in calculating estimates were from a number of sources, sometimes primary sources such as local environmental monitoring bodies and 'industry sources' (Ogden, 1999), but largely from secondary sources (Padró and Putsche, 1999). Some of the assumptions upon which calculations rested could and should be questioned. Ogden (1999, p.711), for example, suggested that the primary data she received for vehicle populations, for her study, only stretched to 2010. Ogden was concerned to extend this time horizon to 2020 and so 'extrapolated linearly to estimate vehicle populations to 2020'. Similarly, in another example: 'Gaps in data time series were filled by interpolation and extrapolation' (Marsh *et al*, 2002, p.8). In the case of hydrogen fuelling appliances, Duane B. Myers and colleagues, using the DFMA Methodology, suggested that the cost of any component part of the fuelling appliances could be calculated through direct material cost, manufacturing cost and assembly cost. The cost of materials was usually based on 'either historical volume prices for the material or vendor price quotations'. However: 'In the case of materials not widely used at present, the manufacturing process must be analyzed to determine the probable high-volume price for the material' (Myers *et al*, 2002, p.6). This asks the question: why the high-volume price?

Methodologies used were explicitly characterised, for example in terms of DFMA Methodology (Myers *et al*, 2002), but also implicitly contained within the text of documents to a greater or lesser degree – sometimes as they had been articulated in other reports by the author(s) (Ogden, 1999; Schoenung, 2002) whilst in other instances with limited explanation (Brandon and Hart, 1999). This, of course, may be as the methodological underpinnings had been published elsewhere, the authors may not have considered them 'relevant' to their expected or intended audience, or readers may have been assumed to have developed the 'necessary' forms of knowledge to appropriate such documents.

Framing Expertise

Within a number of the papers analysed there was a degree of the same papers, as sources, constantly recurring. In Padró and Putsche's (1999, p.50) paper, drawing on more than 100 publications and surveying the economics of hydrogen technologies, standardisation was undertaken to 'ensure level comparisons among the technologies, they were converted to a standard basis because each report used its own assumptions and methods', drawing on assumptions from a variety of secondary sources and also 'engineering judgement'. This begs the question: what is meant by 'engineering judgement'? Standardisation was only for the:

> capital and major operating costs for each technology…Unit operating costs (e.g., fuel price) were modified to match the standard value and capital costs were scaled to mid-1998 US dollars using the Chemical Engineering C&E index of 387. If a source did not provide the dollar-year estimate, then it was assumed the same as the publication year (Padró and Putsche, 1999, p.51).

As many of the sources drawn upon in the report used currencies other than US Dollars then a conversion to Dollars was made using a conversion table:

> No attempt was made to match the dollar-year used in the publication with the currency conversion for that year. After converting costs to US dollars, the values were escalated to 1998 dollars as described earlier (Padró and Putsche, 1999, p.53).

This attempt at standardisation appears to be less a methodological reflection on the underpinnings of the sources used and more a means of an administrative mechanism aiding comparison across sources. That is, there is little attempt to reflect on the basis of the assumptions and methods of other papers rather more an attempt to standardise their data. The authors are from the US-based National Renewable Energy Laboratory. The attempts to standardise the assumptions and costs pertaining to a variety of different reports from a number of different countries suggests, at least implicitly, that the authors tried to disembed the assumptions, costings and findings from various contexts and standardise them in terms of their own abstract criteria. Interestingly, the data from this report then subsequently informs numerous other documents (including Dutton, 2002; Watkiss and Hill, 2002). A series of different papers and assumptions, furthermore, informed Watkiss and Hill's graphical representation (below) of a range of literature costs for central production of hydrogen.

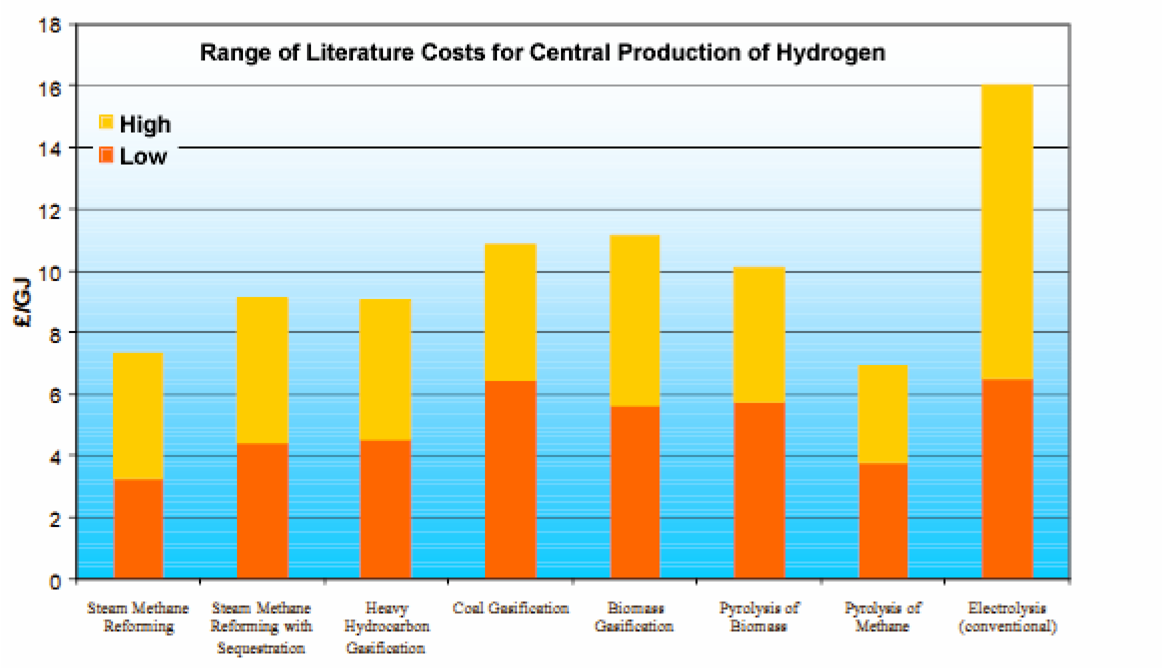

Figure 3 Costs of Hydrogen Production.

Source: Watkiss and Hill (2002, p.17).

Interrogating Technology Characterisation: Beyond Products to Process

The claim raised with regard to TCs previously is the paradox that its aspirations for 'certainty', 'abstraction' and 'universalism' offer one way, in amongst numerous others, of understanding hydrogen technologies. Importantly, there are not only numerous ways of understanding hydrogen technologies but there are also possibilities to reflect on who may be involved in producing and constructing different ways of understanding, from which position(s) and drawing on what sorts of resources. This is particularly important when there is significant controversy around an issue, as there is with hydrogen technologies and the hydrogen economy(-ies), before (often temporary) closure or stabilisation (Pinch and Bijker, 1987) has been achieved and where there may be significant 'interpretative flexibility' (Bijker *et al*, 1987).

There are, thus, two intricately linked issues here. The first is in trying to understand the ways in which TCs frame a partial, privileged understanding of hydrogen technologies and the hydrogen economy(-ies). The second relates to trying to gain greater understanding of the processes of TCs, and their social construction and production, as the consequence of such a way of understanding. The scope of this paper permits us to begin addressing through documentary analysis the first point but also to make headway in raising issues for subsequently addressing the second issue.

A key concern from a social science perspective is the emphasis on inputs and outputs, but also the opening up of the 'black box' of technology (Latour, 1987) with regard to processes of producing and constructing TCs. Technology, in TCs, is often characterised as a number of options predicated on the calculation of a series of inputs to outputs. There is little attempt to unlock the black box of TCs. We often deal with 'ready made' TC rather than TCs 'in the making', to borrow from Bruno Latour (Latour, 1987). The unsettled and controversial nature of the debates around the hydrogen economy(-ies) allows a process of 'flashback', moving back through the, as yet unstabilised, debate:

> The impossible task of opening the black box is made feasible (if not easy) by moving in time and space until one finds the controversial topic of which scientists and engineers are busy at work. This is the first decision we have to make: our entry into science and technology will be through the back door of science in the making, not through the more grandiose entrance of ready made science (Latour, 1987, p.4).

In doing this, through the use of emblematic documents, we can begin to follow engineers and scientists in their production and construction of such documents. We can do this through understanding the previously black boxed calculations, and representational devices, as being 'framed' (Callon, 1998). This offers the possibility of movement between the abstraction and 'universalism' of ready made TC and the construction, negotiation, and context which are TCs in the making and which exposes the 'taken-for-granted' assumptions of the former.

Opening the 'Black Box' of TC

The notion of TC is useful in helping us to think through the range of issues in respect of the 10 documents highlighted previously. Our starting point was in the framing of diagrammatic representations of the hydrogen economy. Importantly, we should note that:

> When scientists use diagrams to accompany texts and lectures, they make multiple references: to the phenomena overtly represented; to analogous phenomena or devices; and to previous pictures and their conventions of pictorial representation. When formulating diagrams they have to delimit the phenomenon, choose and organize components, and render onto a flat surface three-dimensional entities and processes that change over time. They must do all this in a manner that facilitates the viewer's comprehension of the diagrams, illuminates their theory and, more broadly, generates support of their scientific agenda (Taylor and Blum, 1991, p.276).

This resonates with the characterisation of the technology of the hydrogen economy(-ies). Many TCs, as outlined above, draw on tables and diagrams as powerful illustrations, reducing the complexity of the various assemblages which constitute such diagrams. Through the processes of calculation, outlined above, an artefact or object may be diagramatically produced and constructed. A series of these may be pieced together as assemblages offering a forceful visual representation of hydrogen infrastructures.

Diagrams, through their publication, are ‘framed’ on a flat and rectangular printed page (Taylor and Blum, 1991). Such processes of framing, in this case in the context of TC of hydrogen technologies, may demarcate hydrogen energy infrastructures not only from their social production and construction – through what is included and excluded and the masked processes through which the negotiation of expertise unfolds – but also from their contexts of appropriation, use and innovation. Diagrammatic representations often offer a linear characterisation of hydrogen infrastructures. The key issue here is that: ‘In linear perspective, no matter from what distance and angle an object is seen, it is always possible to transfer it – to translate it – and to obtain the same object at a different size as seen from another position’ (Latour, 1990, p.27).

Processes of framing diagrams are interesting not only through the ways in which a paper page frames a diagram but also for the stark manner in which the assemblage is divorced from issues ‘external’ to the frame. This framing not only suggests that ‘an analyst can observe the system as a whole from the outside’ (Taylor and Blum, 1991, p.284), but also that there is a process of what may be included and excluded from the diagrammatic frame. The page cannot encapsulate everything. The scale of hydrogen infrastructures is reduced to the dimensions of the page.

A heterogeneous network of resources, therefore, underpins each component part of an assemblage. In its two-dimensional representation this may then exclude issues of time, space and place. If not totally excluded time, for example, may be characterised by an annotation in the diagram. It is this abstraction, particularly from place, which may allow the ‘universalism’ of the diagrammatic representation of hydrogen infrastructures to be ‘self-evident’. It also offers a ‘generalisability’ of such diagrams. This, then, allows the documents ‘to travel’. Padró and Putsche (1999) and Ogden (1999), from their work produced in the US context, were widely cited by Dutton (2002), who was based in the UK. Similarly, Watkiss and Hill’s

(2002) UK-based work drew on Padró and Putsche which, itself, was based on more than 100 publications, examining the economics of hydrogen technologies. The sources that Padró and Putsche utilised were often originally produced within a series of different contexts, with various assumptions and temporal frames. 'Standardisation' of documents was undertaken, by Padró and Putsche, where to 'ensure level comparisons among the technologies, they were converted to a standard basis because each report used its own assumptions and methods' (Padró and Putsche, 1999, p.50).

The static image on the paper also does little to highlight the dynamic nature of developments in hydrogen infrastructures and the interplay between hydrogen technologies, and systemic and local contexts. Attempts to capture this dynamism may be limited to arrows showing feedback or the 'direction of change'. What is of interest here are the ways in which these components of hydrogen infrastructures come to be produced and constructed as discreet, calculable, separative technologies (Slater, 2002) and how these are then assembled into options of infrastructures for certain periods of time. This requires an understanding of the heterogeneous resources which are drawn upon in the 'laboratory' context including theories, assumptions, equipment, and so on. That is to say: 'Any account which divorces RDs [representational devices, such as diagrams, graphs and tables] from the contexts of *praxis* that define and concretely situate such devices clearly ignores a salient – perhaps *the* salient – influence on the construction and utility of RDs' (Tibbets, 1990, p.72, original emphasis). The issue of whether these diagrams, and TCs more broadly, are solely the construction of R&D workers in the 'laboratory' or the representation of a 'natural object' is a false distinction to make. Tibbetts (1990, p.71, original emphasis) suggests that '*the* salient issue is the extent to which realist and constructivist elements are mutually at work and interactive in the design and utilization of RDs [representational devices] in scientific contexts'.

Conceptualising and Problematising TCs: Framing and Calculation

This leads us to claim that the focus on a series of emblematic papers, authored by individuals or a small number of authors, should not lead to the reduction of processes of TCs of hydrogen technologies to the calculative agency of those authors. Rather, the process of framing calculation is embedded within fluid social and cultural networks. 'Calculating…is a complex collective practice which involves far more than the capacities granted to agents by epistemologists and certain economists' (Callon, 1998a, p.4), including entangled webs of human relations, institutions, artefacts and so on. The calculation involved in TCs, therefore, requires the drawing of boundaries 'between the relations which the agents will take into account and which will serve in their calculations and those which will be thrown out of the calculation as such' (Callon, 1998a, p.16). Entangled webs and relationships of goods and agents must be disentangled and framed. Frame is in the sense, it was developed by the US sociologist Erving Goffman (1974), of establishing 'a boundary within which interactions – the significance and content of which are self-evident to the protagonists – take place more or less independently of their surrounding context' (Callon, 1998b, p.249). Framing allows for the definition of individuals, groups, objects, goods and so on in that they can be disentangled or disassociated from entangled webs and relationships. Framing, thus, permits us to conceive and 'calculate' 'separative technology' (Slater, 2002), where in this case TCs take hydrogen technologies as distinct and individuated.

Andrew Barry and Don Slater, in a discussion of Michel Callon's work *The Laws of the Markets*, suggest that, 'the capacity to calculate depends on a set of technical devices and discursive idioms that make calculation possible. In the case of markets, 'calculativeness' depends upon the separation or individualization of objects into discrete transactable entities, with (temporarily) stabilized properties, that can be placed within a frame of calculation' (Barry and Slater, 2002, p.181). This discussion of calculativeness and markets also resonates with calculativeness and TCs. It permits a degree of delineation through framing, the consequence of which may be stability of a framework and 'certainty' upon which 'calculation' can be premised and transferred between contexts (Slater, 2002). It also encompasses tacit expectations and agreements within the frame which relies on a physical framework – in TCs a laboratory, scientific papers and books, maybe lecture theatres, seminar rooms, or other shared spaces for dialogue, and so on – and an institutional framework – including perhaps tenure, safety regulations, funding streams and on – 'which help to ensure their preservation and reproduction' (Callon, 1998b, p.249). Through delineation, framing 'puts the outside world in brackets, as it were, but does not actually abolish all links with it' (Callon, 1998b, p.249). The drawing on scientific papers, for example, in conducting TCs acknowledges that these papers also have their own histories often outside of the frame.

This then, as Callon highlights, suggests possibilities for two particular emphases: one which focuses on stabilisation or closure and mutual agreement between players within the frame and the second being the links between the frame and the outside world in terms of 'overflows'. The distinction here is one between focusing on micro-level interactions and the other being the ‘factors that sustain these interactions’ (Callon, 1998b, p.250). The focus on the micro-level context of the ‘laboratory’ is one of the creation, acquisition and circulation of forms of knowledge. It also raises the issue of how various forms of ‘local’ knowledge come to be translated in to ‘universal’ abstract knowledge. It is important not only to understand the forms of such knowledge, but also processes of knowledge creation/acquisition, communication/circulation, and also the implications of such in interplay.

The process of framing with regard to TCs, in terms of issues raised above, suggests that the representation of TCs in emblematic documents as abstract and ‘universalist’ is underpinned by processes of disentanglement within which a series of externalities are ignored (Callon, 1998b). Externalities, as Callon (1998a; 1998b) points out, is a term used in economics to refer to ‘all the connections, relations and effects which agents do not take into account in their calculations…’ (Callon, 1998a, p.16). A common negative externality may thus, for example with relevance to hydrogen technologies, be the wider consequences and ‘costs’ of fossil fuel production in terms of air pollution, pollution of rivers, CO2 emissions and so on. The calculations of fossil fuel providers may, to a variable extent, take little account of such externalities. Importantly, ‘acts of framing and disentanglement necessarily involve cultural knowledge, and actually bring cultural issues into the heart of economic action’ (Slater, 2002, p.242). Thus, the framing and disentanglement of hydrogen technologies through TCs needs also to be understood in terms of the entanglement outside the frame which informs it and is itself informed by it dialectically.

In much economic theory, from which the concept of externalities is drawn, the inability of the frame to stop such ‘leaks’ indicates imperfect markets. Thus, much emphasis is placed on plugging the leaks in the frame. This may be seen to be analogous to many approaches to TCs. This, however, suggests an exercise in attempting to rectify deficiencies in *the* way of understanding rather than acknowledging the permeability, negotiability and incompleteness of the unfolding development of the frame where these overflows rather than being leaks to be plugged are ‘the rule’ (Callon, 1998b, p.253). Framing is, thus, seen as an ongoing and precarious achievement.

Given the uncertainty and contestation about hydrogen technologies and the development of a hydrogen economy(-ies), it serves us well to remember that ‘the construction of expertise and relations between experts and non-experts is profoundly political’ (Faulkner *et al*, 1998, p.7).

The framing of TCs may be seen to narrow the issues for debate around hydrogen technologies. Yet, this should not be taken for granted in that 'far from limiting the possibility for political conflict and negotiation, framing forms something like a surface on which forms of political reflection, negotiation and conflict can condense' (Barry and Slater, 2002, p185). TCs offer an important but challengeable way of understanding which outlines one way, broadly speaking, amongst many for understanding hydrogen technologies and the hydrogen economy(-ies). This addresses issues about why 'some occupational groups are more effective than others in claiming expert status for their knowledge and skills. This raises questions about who gets to be seen as skilled or expert' (Faulkner *et al*, 1998, p.7). It also highlights issues about how we might understand the partial knowledge, skills and expertise which constitute TCs in relation to other ways of seeing the hydrogen economy.

The 'Parameters' of TCs and Hydrogen Technologies

TCs work at a level of abstraction dealing with costs and technical capabilities. This focus neglects to situate technological possibilities within systemic contexts. Thomas Hughes (1987), in his work on large technical systems (LTS), points out that the development of technologies is not merely to do with cost or technical issues but needs to be understood within the institutional and organisational arrangements of current systems. 'If a component is removed from a system or if its characteristics change, the other artefacts in the system will alter characteristics accordingly' (Hughes, 1987, p.51). In the case of the development of hydrogen technologies, costs and technical capabilities need to be considered not in isolation but alongside vested interests and current systemic arrangements which may include utility providers, manufacturers, financiers and regulators and also may address issues of novelty, prestige and risk-taking. A key point is…'the reason these system elements come together does not depend solely on attractive economics' (Watson, 2002, p.11). This is particularly pertinent given that much of the development of energy and utility infrastructure in the UK context was undertaken historically through state-owned utility companies. Interesting issues and a great deal of uncertainty remain with regard to hydrogen technologies and the privatised and liberalised provision of utilities.

Furthermore, the abstraction of TCs fails to address more local contexts of innovation. In particular, the focus of TCs on cost-efficiency ignores the idea that various forms of 'fledgling' innovations, which may be seen as less than 'efficient', may be nurtured and developed within the protected spaces of niches (Hoogma *et al*, 2002). It may, however, be that what ‘works’ in one niche may not necessarily develop in other niches despite its ‘general promise’ – the example here may be the use of fuel cells in space applications (Rip and Schot, 2002).

Both the LTS and the niche approaches suggest shortcomings in the TC view of standardisation and abstraction underpinning economic and technical characterisation. Thus, we should not only be seeking to problematise the processes and practices of TCs but also trying to build dialogue between the different interests implicit in ways of understanding the hydrogen economy(-ies) as not only an ‘R&D’ issue but also in systemic and localised contexts. We need to look to creating a ‘nurtured space’ (Hoogma *et al*, 2002) which permits a dialogue between TC exponents in the R&D context and representatives of various interest groups which attempts to draw closer processes of supply, existing systems and infrastructures and local contexts of controversy and innovation.

Such a view, articulated by proponents of constructive technology assessment (CTA) (Schot, 1998), moves beyond viewing technology as either a technological fix or a social/cultural fix and seeks to address the co-production of technological development. In doing this, ‘barriers’ to technological change are addressed through attempts at synergising, via ‘experiments’, the anticipations of hydrogen technologies and the hydrogen economy(-ies) of different actors through unfolding ‘reflexivity’ and social learning. Learning may happen in two ways. First in terms of cultivating articulations of the specifics and definition of particular ways of understanding. But second, and related, through second order learning understanding the assumptions and articulations which characterise specific ways of understanding and the consequences and possibilities which this opens up.

Summary

This paper has addressed a partial but powerful view of the hydrogen economy known as technology characterisation. This offers particular representations of the supply of hydrogen technologies through ‘measuring’ the ‘state of the technology’ or the ‘state of the art’. In its strong focus it has an emphasis on creating ‘certainty’ and informing attempts to ‘plan’ and ‘project’ through ‘unambiguously’ seeking to generate ‘constant’, ‘unbiased’ single ‘official’ sets of data for ‘generic’ technologies, to inform future technological development and ‘projection’ of costs. This view was seen as an important means of generating political and policy support for technological developments through outlining technical ‘possibilities’ and 'options' in relation to 'costs'. The 'achievement' of this ideal of TC was problematic, as analysis of 10 documents highlighted. Through these documents a series of practices could be seen as offering an approach to TCs that focused on certain issues (technology, environment, consumption, economics and expertise). The use of diagrams, in particular, as symbolic representations of partial but powerful TCs of the hydrogen economy(-ies) was addressed.

The paper looked 'inward' in terms of initially examining processes of producing and constructing TCs. It, however, also looked 'outward' through the use of the notion of 'framing' (Callon 1998a; 1998b) as offering only a partial window of understanding. The characterisation of hydrogen technology options on the basis of cost, technical capabilities and sometimes environmental criteria may be better understood alongside alternative 'ways of seeing' the development of hydrogen technologies in terms of wider systemic considerations (Hughes, 1987), localised 'niche' developments in nurtured spaces of reflexive social learning (Hoogma, 2002) and the ways in which these partial ways of understanding may offer scope for processes of anticipation and unfolding and mutual learning (Schot and Rip, 1997) with regard to development of the hydrogen economy(-ies). The key point is that this then opens up the possibility for articulating different ways of understanding the hydrogen economy(-ies), and the creation of a dialogue between these different frames of understanding. The importance of this is that it allows a broadening of the agenda and of interests, and potentially a degree of 'democratisation', in influencing the early stages of technological change and the development of the hydrogen economy(-ies).

Acknowledgements
We would like to thank Will Medd and Malcolm Eames for critically supportive comments on earlier drafts of this paper and colleagues at Salford and the Policy Studies Institute for more general discussions around some of the ideas presented here. We also acknowledge the financial support of the UK Sustainable Hydrogen Energy Consortium.

Annex: Contents of Papers

1. Geoff Dutton, 'Hydrogen Energy Technology', April 2002, Tyndall Centre for Climate Change Research.

2. Joan Ogden, 'Developing an Infrastructure for Hydrogen Vehicles: a Southern California Case Study', 1999, International Journal of Hydrogen Energy, vol.24, pp.709-30.

3. George Marsh, Peter Taylor, Heather Haydock, Dennis Anderson, Matthew Leach, 'Options for a Low Carbon Future', February 2002, AEA Technology PLC.

4. Duane B. Myers, Gregory D. Ariff, Brian D. James, John S. Lettow, C.E. (Sandy) Thomas, and Reed C. Kuhn, 'Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances', April 2002, Directed Technologies Inc. paper prepared for the Hydrogen Program Office, Office of Power Technologies, US Department of Energy, Washington DC.

5. J.B. Lakeman and D.J. Browning, 'Global Status of Hydrogen Research', 2001, Contractor, Defence Evaluation and Research Agency as part of the DTI Sustainable Energy Programmes.

6. C.E. Grégoire Padró and V. Putsche, 'Survey of the Economics of Hydrogen Technologies', September 1999, National Renewable Energy Laboratory, a US Department of Energy Laboratory, operated by Midwest Research Institute.

7. Paul Watkiss and Nikolas Hill, 'The Feasibility, Costs and Markets for Hydrogen Production', September 2002, AEA Technology Environment for British Energy.

8. Nigel Brandon and David Hart, 'An introduction to fuel cell technology and economics', July 1999, Imperial College Centre for Energy Policy and Technology, Occasional Paper 1.

9. Timothy E. Lipman, Jennifer L. Edwards and Daniel M. Kammen, 'EconomicAnalysis of Hydrogen Energy Station Concepts: Are 'H2E-Stations' a Key Link to a Hydrogen Fuel Cell Vehicle Infrastructure'?, November, 2002, Renewable and Appropriate Energy Laboratory, Energy and Resources Group, University of California, Berkeley, CA 94720.

10. Susan M. Schoenung, 'Hydrogen Technical Analysis on Matters Being Considered by the International Energy Agency – Transportation Infrastructure', 2002, Proceedings of the US DOE Hydrogen Program Review, NREL/CP-610-32405.

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Notes

[i] http://www.whitehouse.gov/news/releases/2003/01/20030128-19.html Accessed 15/10/2003.

[ii] 'TC' refers to the notion of technology characterisation. 'TCs' is the plural of this and is used here to highlight that each TC whilst sharing an approach with other TCs is also distinct in that it is produced and constructed within 'locally' specific circumstances.

[iii] This paper and subsequent empirical work in the 'laboratory' relate to a wider body of work being developed by the authors and colleagues, which links issues, developments and expectations from the wider policy and economic 'landscape', to the development of three 'ways of seeing' or understanding hydrogen technologies, of which this paper is one. Further papers, by the authors, will focus on relationships between case study developments of regional and international hydrogen economies within contexts, in terms of addressing relationships between niche demonstration developments and large technological systems. An approach for understanding the conceptual and theoretical framework which links these elements together into a broader understanding of the development of hydrogen economies, and the distinctive and common elements of them, is being developed.

[iv] The sources included: ETDEWEB; Energy Citations Database; OCLC; BIDS; Energy Technology Data Exchange; MIMAS ZETOC; Science Direct; Scirus; numerous journals, and many other sources. Searches drew upon both the English 's' and the US 'z' in spelling characterisation. Furthermore, a wide variety of terms which may be broadly synonymous with TC were used.