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Reconnecting the technology characterisation of the hydrogen economy to contexts of consumption

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Abstract

This paper addresses a partial but powerful view of the hydrogen economy known as 'technology characterisation' (TC). TC offers particular representations of the supply of hydrogen technologies through 'measuring' the 'state of the art'. This view is seen as an important means of generating political and policy support for technological developments through outlining technical 'possibilities' and 'options' in relation to 'costs'. Through drawing on 10 TC documents a series of practices and issues are outlined. These documents are subjected to critical interrogation as a means of saying not how TC *should* be applied but in outlining how it often *is* applied. Our analysis of these documents claims that TC conceives of technological change through a process of narrowly framing understanding of what 'relevant' costs and technological possibilities are. We claim, through this critique, that this dominant way of narrowly characterising technological change in terms of the supply of technology would benefit from an appreciation of alternative 'ways of seeing' the development of hydrogen technologies, particularly in relation to 'contexts' of their appropriation, consumption and development. We suggest that this can be done through the development of two alternative ways of seeing: a Large Technical Systems approach which addresses wider systemic considerations, and localised 'niche' developments in nurtured spaces of reflexive social learning. Through subjecting the practices of a dominant way of seeing technological development—TC—to critique this opens up the possibilities for TC practitioners to reflect on the strengths and shortcomings of their own practices. This, in addition to outlining ways of seeing the appropriation and innovation of hydrogen technologies in specific contexts, through an LTS and niche approach, offers the potential for a dialogue between the supply and the contextualised appropriation of hydrogen technologies and thus for engaging disconnected areas of research. It also provides a basis for research which opens up the possibilities for sensitising policy interventions to contexts of appropriation and use in addition to Technological Characterisations of supply.

Keywords: Technology; Characterisation; Hydrogen

1. Introduction

The movement to a hydrogen economy (or economies) is undoubtedly controversial. Yet the potential development of hydrogen is often hailed as positive with Jeremy Rifkin (2002) suggesting in the subtitle to his recent book that the economy will be underpinned by 'the creation of the world wide energy web and the redistribution of power on earth' (Rifkin, 2002; Billings, 2000). This enthusiasm has also become embodied in policy discussion at a variety of scales. Rifkin acts as an advisor to Romano Prodi, who as President of the European Commission, was committed to realising the 'hydrogen revolution' in Europe (Prodi, 2003). George W Bush in his 2003 State of the Union address announced $1.2 billion in research funding 'so that America can lead the world in developing clean, hydrogen-powered automobiles' with the expectation that this will 'make our air significantly cleaner, and our

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country much less dependent on foreign sources of energy' (Bush, 2003). Whilst at the world city 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 about the possibilities of the hydrogen economy. Yet the ability to make such claims rests on, often hidden, assumptions about what the hydrogen economy can 'deliver'. Moving beyond these rhetorical visions necessitates different ways of understanding hydrogen economies. That is to say, it is possible to conceive of different 'ways of seeing' the hydrogen economy. It is our claim, for example, that a dominant 'Technology Characterisation (TC)' view of technology 'frames' our understanding of the hydrogen economy in very specific and particular ways which relate to narrowly conceived conceptualisations of 'costs' and 'technical capabilities' in the *supply* of technologies. Alternative ways of seeing the hydrogen economy, through a Large Technical Systems (LTS) view for example, outline the complex array of relationships, institutions, vested interests, regulations and so on which offer a systemic 'seamless web' (Hughes, 1987) or a series of interrelationships which support the 'functioning' of a particular technology. Another view, a socio-technical niche approach, highlights the importance of creating 'protected spaces', in some ways 'separated' from the system, where attempts to develop technological innovation are supported and cultivated (Geels, 2002a; Hoogma et al., 2002).

Our focus here is in critically examining the assumptions that underpin TC, as a particularly powerful and very prevalent way of seeing hydrogen technologies. TC focuses on an assessment of the 'state of the art' in the supply of hydrogen technology looking at what different components can 'deliver in principle' in terms of their technical, economic and environmental characteristics. The paper examines, through documentary analysis, 10 documents that each provide a 'characterisation' of hydrogen technologies (see Reference section—Emblematic papers). We do this on the basis that our documentary analysis approach rests on a view of TC documents which sees them not as neutral artefacts which independently report social reality but are 'media through which social power is expressed' (May, 2001, p. 183). In critically engaging with the TC approach—an approach which has hitherto been offered limited critical attention—we are not saying that this analysis is exhaustive. Rather the documents we draw upon are 'emblematic' because they are authored by recognised experts in the field, are frequently cited in hydrogen-related academic papers and policy reports and address a broad range of hydrogen technologies from production, storage, distribution, to fuel cells. The principal shared aim of these documents is to identify 'technical possibilities and costs' (e.g. Marsh et al., 2002) of hydrogen technologies.

In doing this, we are not saying how TC *should* be applied but are analysing how it often *is* applied. The importance of this is that a critical engagement with TC highlights its associated practices as narrowly conceived with the consequence that the hydrogen economy is seen in terms of highly partial costs and technical possibilities and also through representations of the hydrogen economy as constituted by technological 'building blocks' and 'architectures'. Instead, our approach opens up the possibilities and potential for TC practitioners in the R&D community to reflect on their practices but through highlighting their strengths and shortcomings opens up the potential for engagement with a neglected area of their narrowly framed analysis, that is, contexts of appropriation and use of hydrogen technologies. In short, it provides a basis for addressing the role of TC practitioners in the R&D community, the supply of hydrogen technology and its relationship to different social contexts and thus of sensitising future policy interventions to the mutual relationships between society and technology. In doing this, we suggest that a critical appreciation of the people, practices and consequences of a TC approach, and thus its strengths and weaknesses, offers a basis to engage a variety of disconnected research interests.

The rest of this paper is structured in five sections. Section 2 reviews the objectives, processes and outcomes of TC. Section 3 undertakes a comparative review of the key features of hydrogen TCs focusing on their representations of the hydrogen economy, the social interests producing these documents and then a review of how they frame an understanding of hydrogen technology. Section 4 undertakes a critical review of these TCs by building a deeper understanding of the issues involved in their production and the partial understanding of hydrogen technologies that is generated by the approach. Section 5 provides an outline of alternative—LTS and niche—approaches that offer the possibilities for bringing together currently disconnected research approaches concerned with the supply and the appropriation and use of hydrogen technologies. Section 6 concludes with a review of key findings and their political and policy implications.

2. Technology characterisation as a way of seeing the hydrogen economy

TC can be most usefully understood as a set of practices that attempt to identify the empirical features and monetary values of a technology. There are three key elements to this approach. The first is the purpose of TC. TC has been defined as 'the measurement of the state of technology against primarily technical criteria' (Taylor, 1978, p. S-1). The predominant rationale for TC within the 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).

While these are very specific purposes, there are close affinities with the objectives of the 10 hydrogen TC reports that for example, provide a 'survey of the economics of hydrogen technologies'; 'cost and performance comparison of stationary hydrogen fuelling appliances'; and 'technoeconomic analysis of different options for the production of hydrogen'. TC has also been viewed as a necessary precursor of technology assessment (TA) where 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 commercialisation' (Taylor, 1978, p. 8). There are clearly potential overlaps between both approaches as a complex set of energy technologies move at differential rates from R&D to commercialisation.

The second features are the practices of TC. While TCs may encompass three broad methods—the 'empirical', the 'analytical' and 'systems engineering'—there is an assumed common linearity between these methods (Taylor, 1978). This starts with a process of defining the technology, followed by the selection of parameters to characterise the technology, choosing scales for the parameters, positioning the technology against the scales, and then application (Taylor, 1978). The US DOE stressed that the importance of TC is in developing a set of 'standardised procedures' that can 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 the process focuses largely on economic characteristics, technical characteristics and environmental issues that would provide a 'data base which would be useful for broad-based activities' (OAO Corp., 1979, section III-1). The process also needs to distinguish between technologies' stage of development—whether a technology is a 'near term technology' or at a 'relatively early stage' of development (OAO Corp., 1979, section III-2).

Finally, the third feature of TC is its intended impact and outcomes. The importance of using TCs is to confer 'certainty' to an understanding of technology, through abstraction and perceived implicit technological neutralism. Yet there is also the broader political aim of '[e]stablishing credibility on the Hill' with the US Congress (OAO Corp., 1979, section I-2). The stabilising of technical characteristics, and also bringing a certainty to economic characteristics, offers a way of representing the supply of technology that may resonate with policy makers. A number of the 10 TCs reviewed here are prepared for government departments (e.g. Myers et al., 2002) and used to inform policy (e.g. Marsh et al., 2002). Raising the issue of influencing political opinion, and indeed wider 'public opinion' via the channels of the mass media, highlights the prospect that TCs, whilst often perceived superficially to be driven by a technological neutralism, offer *one way* of understanding hydrogen technologies. To 'capture' the technical characteristics and costs of technologies brings an 'order' to chaotic processes of technological development.

A 'successful' TC would therefore be based on 'high quality, unbiased data' (OAO Corp., 1979, section II-1), maintain a 'record of the most up-to-date information' thereby negating a 'constant "reinventing of the wheel"'; and ensure 'that there is a single official set of estimates for characteristics of a technology'. This would mean that 'all official estimates of technology characteristics are based on constant underlying assumptions' (OAO Corp., 1979, section I-2). 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).

There are, however, important issues involved in attempts to create 'certainties' around technological developments. In particular, it requires us to look critically at 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. For instance, a research project attempting to reduce uncertainties by developing a TC approach concluded that:

> For R&D planning purposes and for projecting commercialisation 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? And also, how might we understand these practices and processes and the implications of this for how we see the hydrogen economy (-ies)?

3. Producing the hydrogen economy through technology characterisations

A TC approach offers a particular, and partial, way of understanding technologies and technological change. This section of the paper focuses on how this form of understanding is produced and constructed and what its consequences are for the representation of hydrogen technologies and the hydrogen economy. The use of 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[1] which rests on the questions as to who produces TCs? How do they produce TCs? What does the hydrogen economy look like through TCs?

3.1. Who produces hydrogen technology characterisations?

This leads us to ask who is involved in the production of TCs? The vast majority of the TCs were undertaken by or for agencies of the state, predominantly in the US and UK. Myers and colleagues' paper (2002), for example, was prepared for the Office of Power Technologies at the US DOE. Similarly, the work of Padró and Putsche (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 as part of the UK Department of Trade and Industry (DTI) Sustainable Energy Programmes. In other examples the context within which papers were constructed was a research 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 DOE.

3.2. How are these technology characterisations produced?

There were three critical features of the processes that produced TC that cut across the 10 documents.

First, the possibilities of hydrogen technologies were often reduced to narrow economic considerations. So, for example, there was discussion 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). The documents consistently 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'. This leaves an obvious question as to how the notion of cost is conceptualised and framed. That is, to what does cost refer?

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 CO_2 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).

[1] '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.

Table 1
Framing consumption: vehicle key assumptions for modelling (ETSU/IC, 2000)

Vehicle	Daily distance (km)	Annual distance (M)	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 day/yr.
Source: Watkiss and Hill (2002, p. 24).

Second, 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 Table 1, 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/yr and consume 5.88 ton of hydrogen per year whilst a taxi would travel 105,000 km/yr consuming 0.935 ton 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).

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?

Finally, there were consistent attempts to standardise data and move it unproblematically from one context to another, thereby implicitly inferring that the data was transferable between contexts but also, more problematically, re-inforcing, over- and under-estimations and certain assumptions. For instance 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).

Overall, 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 attempts to standardise the assumptions and costs of a variety of different reports from a number of countries suggests that the technologies were disembedded from their own particular contexts and then represented according to other criteria. Interestingly, the data from this report then subsequently informs many other documents (including Dutton, 2002; Watkiss and Hill, 2002). A series of different papers and assumptions, furthermore, informed Watkiss and Hill's graphical representation

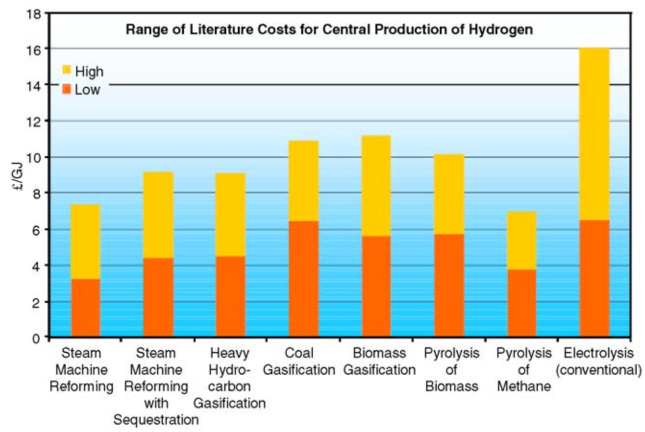

Fig. 1. Framing hydrogen expertise. (*Source*: Watkiss and Hill (2002, p. 17).)

(below) of a range of literature costs for central production of hydrogen (Fig. 1).

3.3. *What does the hydrogen economy look like through technology characterisation?*

Analysis of the people, practices and processes involved in the production of TCs of hydrogen technologies highlights that TCs offer a partial, but powerful, way of understanding a future hydrogen economy (-ies). This, we suggest, manifests itself through diagrammatic representations—or representational devices—of future hydrogen economies (Figs. 2 and 3).

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

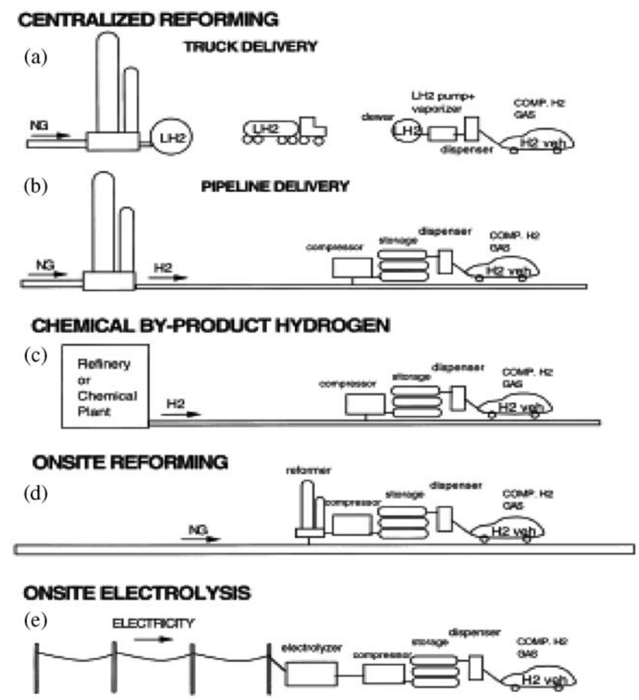

Fig. 2. Visualising the hydrogen economy.

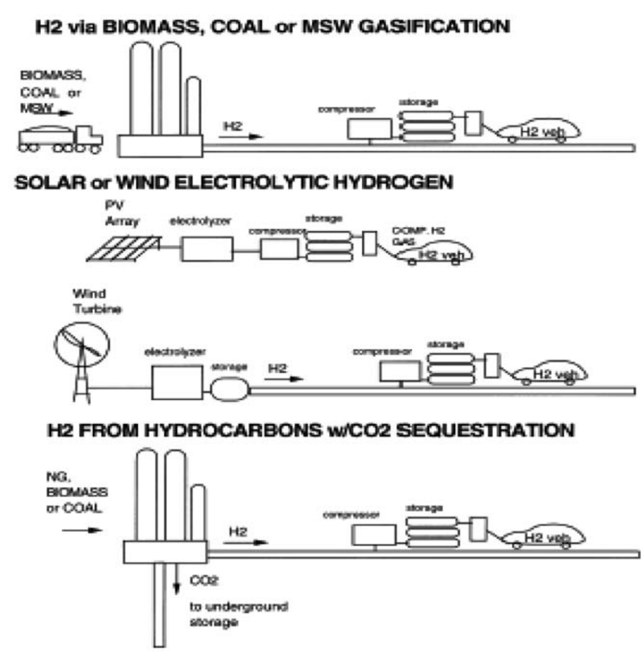

Fig. 3. Long term hydrogen supply options. (*Source*: Ogden (1999)).

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), including often narrowly defined economic costs and technical possibilities, to the exclusion of other aspects including social contexts of innovation, appropriation and consumption in use.

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).

4. Interrogating technology characterisation: Beyond products to process

The power of these diagrams is in their representation of TC's search for 'certainty', 'abstraction' and 'universalism' in its understanding of hydrogen technologies. 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 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 potential of the hydrogen economy. The second is in trying to understand the ways in which TCs frame a partial, privileged understanding of hydrogen technologies and the hydrogen economy (-ies) and, thus, how TC and its focus on the supply of technology may engage with understanding of the contexts of appropriation and consumption of hydrogen technologies.

4.1. Conceptualising and problematising TCs: Framing and calculation

The process of framing calculation in TCs 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 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, p. 185). TCs offer an important but challengeable 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.

5. Engaging disconnected research areas? Technology supply, systems and innovation

TCs work at a level of abstraction dealing with the supply of technologies in relation to costs and technical capabilities. If we return to the political proclamations (from the contexts of the US, the EU and London) at the beginning of this paper we acknowledge, at least implicitly, the relationship of developing a hydrogen economy to particular places. Yet, TC as a dominant way of seeing the hydrogen economy says little about the notion of place. The issue then is: how do we think about linking the supply of technologies (through costs and possibilities) to embedding hydrogen technologies within particular social contexts? In detailed case study fieldwork, we have discussed elsewhere (Hodson and Marvin, 2005) the difficulties of translating Technological Characterisations, or understandings of what the technology can 'deliver in principle', have been highlighted by numerous actors who, whilst coming from a technological background, have grappled with attempts to develop a hydrogen economy 'on the ground'. As an example,

> I think there's a big dichotomy between the global, societal benefits that you can get from transitioning to hydrogen versus what does it give to the public in the street. The first hydrogen [fuel] station that you build somewhere or the first project that you implement locally…it's difficult to demonstrate the very immediate local benefit because you have to speak to these more global concerns all the time.

At an even more 'mundane' level:

> Let me take an example, like putting one [a fuel cell] into a school. You say well this is hydrogen, as a petro-chemical professional, I know how to design safe hydrogen installations or chemical plants. How do you take something which is engineered to be safe in that environment and re-engineer it to be safe in a school?

Likewise, if government, beyond TC, is uncertain as to how the hydrogen economy may develop 'on the ground' the issue becomes how do they go about addressing this in particular societal contexts?

> We have been saying to DTI [UK Department of Trade and Industry], if you are serious about developing a hydrogen economy but are not sure what it is going to be then we on Teesside can provide a national scale experimental platform. So come and play around and do it here until you know what you want it to be.

These questions and quotes pose challenges in terms of researching different policy interventions (i.e. R&D and the supply of technology and local level developments appropriating these technologies) which impinge on the same overall hydrogen economy agenda. As a means of connecting issues related to the supply and consumption or appropriation of hydrogen technologies it is useful to think about alternative ways of seeing the hydrogen economy. Thomas Hughes (1987), in his work on 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).

A key point is…'the reason these system elements come together does not depend solely on attractive economics' (Watson, 2002, p. 11). This permits us to think of the stability or path dependencies of existing technical systems, through deeply embedded interrelationships. Technological change is not merely about costs and technical possibilities but is bound up with a series of relationships of utility providers, regulators, vested interests, consumers, etc in particular national and sub-national contexts. Attempting to radically alter these relationships is difficult in that:

> Such reconfiguration processes do not occur easily, because the elements in a sociotechnical configuration are linked and aligned to each other. Radically new technologies have a hard time to break through, because regulations, infrastructure, user practices, maintenance networks are aligned to the existing technology (Geels, 2002a, p. 1258).

This focus on the stability of existing incumbent technologies and the webs of relationships which underpin their functioning largely answers the question: 'why [are] such [novel] technologies not introduced into the market when their benefits to society are so evident'? (Hoogma et al., 2002, p. 12). It, however, ignores how novel hydrogen technologies begin to develop processes of building such interrelationships, forms of knowledge and learning.

The idea of socio-technical niches is of '"protected" spaces at the local level in which actors learn in various ways about new technologies and their uses' (Geels, 2002b, p. 365), where innovation and processes of learning by trying keep alive novel technological developments which otherwise may be 'unsustainable'. This requires 'special conditions created through subsidies (including government) and an alignment between various actors' (Geels, 2002b, p. 367). This necessitates a process of network building and an alignment of actors including various users, producers and political actors. 'In the niche model, lock-in and path dependency assumptions are relaxed…. Niches may also persist because actors such as firms and governments act strategically by keeping certain options alive which might be important for future competition or other broader societal goals' (Hoogma et al., 2002, p. 26). Important in this process is learning about the potential uses and limitations of a novel technology on the basis of a series of issues including: technical and design aspects; the role of policy in stimulating applications of technology; addressing symbolic aspects around technology; constructing; shaping markets for technology in relation to consumers; etc (Geels, 2002b, p. 368).

6. Conclusion

This paper has addressed a partial but powerful view of the hydrogen economy known as TC. 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 emblematic documents highlighted. Through these documents a series of people, practices and processes were outlined in the production of TCs. 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 critically examining processes of producing and constructing TCs. It, however, also looked 'outward' through the use of the notion of 'framing' (Callon, 1998a, b) 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) and localised 'niche' developments in nurtured spaces of reflexive social learning (Geels, 2002a; Hoogma et al., 2002).

The development of a critical engagement with TC, and the discussion of two other ways of seeing, allows us to conceive of an engagement and connection between understandings of the supply and appropriation of hydrogen technologies; between the technical and 'cost' possibilities, the constraints of existing systems and the potential of innovations in socio-technical niches. This then offers the capability to analyse the relationships between the 'global' and the 'local' concerns highlighted in the quote above. It also offers a framework within which we can begin to understand the process by which 'costed' hydrogen and fuel cell technologies can be understood in terms of their local use, for example in schools, but also how this may or may not link-up to an existing energy system. The key issue is that this approach offers possibilities for an academic analysis of different policy interventions (for example in terms of R&D understandings of the supply of hydrogen technology; to addressing novel state or regionally funded hydrogen demonstration projects) and their interrelationships and thus sensitising policy to the relationships between technological possibilities and societal contexts.

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